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September 15-17, 2010
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# Abstract Volume

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**Indoor Positioning and Indoor Navigation**

# IPIN

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# Abstract Volume

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# Content

## RF RSS (ZigBee, FM, General RF), Fingerprinting

Auditorium G7

Wednesday, September 15, 10:30 – 11:45 & 13:15 – 15:30

# A Single Anchor Direction of Arrival Positioning System Augmenting Standard Wireless Communication Technology

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## 1 Summary

This paper presents an effective, compact and easy to deploy system for Direction of Arrival (DoA) indoor localization techniques. It is based on a Switched Beam Antenna (SBA) a signal multiplexer and the Received Signal Strength Indicator (RSSI); it is fully compatible with available commercial transceivers [1].

We describe the system architecture as well as the approach adopted for the DoA estimation which is a derivation of the widely adopted MUSIC technique [1]. We also propose a demonstration of its characteristics and by the exploitation of the indoor positing features in a realistic indoor environment of about 25 square meters, for which the SBA is the single anchor placed in the centre of the room ceiling. The system is capable to localize a target node with a precision of about 50 cm in the area below the SBA, while an error within 1 m is observed in a region covering about the 90% of the test area of the room. The system is capable to locate a target node and due to its effectiveness to track the motion within the room, finally it is also suitable as part of application layer for the most of the wireless access technologies.

## 2 Introduction

Nowadays wireless positioning is becoming a critical issue of many distributed systems to full satisfy the needs of context-aware applications.

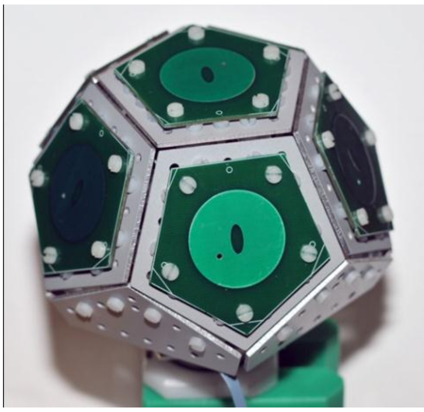

Fig 1. The Switched Beam Smart antenna employed in the experiment

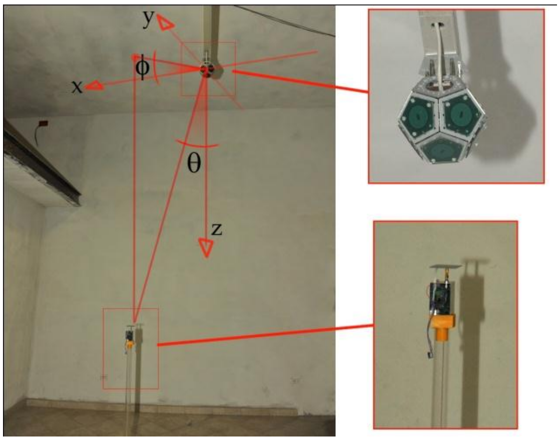


Fig 2. Target located thanks to the DoA referred to the BS.

We propose a DoA localization technique based on the measure of the signal strength at the SBA antenna elements, whose structure is configured as a dodecahedron hemisphere, see Fig. 1. The six printed antenna elements composing the SBA – working at 2.45 GHz – are activated sequentially and are able to iso-tropically cover a wide angular region thanks to their regular disposition, thus receiving different signal strengths from the same target position. The operation in Circular Polarization (CP) grants the possibility of reliable links regardless of the relative orientation of the target with respect to the anchor and thus making the link more robust to multipath. This SBA is intended to be placed on the ceiling of a indoor space, a location unobtrusive for users to make the line of sight link more reliable. The position of the target node in the room is determined by the estimation of the spherical coordinate (theta and phi angles). Knowing the anchor position and assuming known the target height over the floor, the two angles immediately leads to the target absolute position in the room. In our experimental set up, the CC2430 SoC transceiver working in accordance with the IEEE 802.15.4 PHY layer, controls the operation of the anchor and the target node and provides a reliable signal transmission over wireless channels.

While the target is active, each antenna of the anchor is sequentially connected to the RSSI block of the CC2430 and the readings are proportional to the power pattern of the specific active antenna element, which is in turn a function of the direction expressed as the theta and phi angles. Exploiting the Multiple Signal Classification (MUSIC) technique with the RSSI readings as the input, the DoA finally estimated.

To full cope with the unpredictable effects of multipath impairments and to avoid the need of a full characterization of the antenna elements in a anechoic chamber, our technique exploits a pattern calibration procedure to improve the accuracy of the DoA estimation.

## 3 Results and Conclusions

Our system was successfully employed to determine the position of a free target node placed in a room of 5.2 x 4.6 meters. The anchor is placed on the ceiling at x=2.35, y=2.45, z=1.8 meters over the plane where the target node is constrained. The position of the target was localized in each point of a 10x9 grid covering almost the room area.

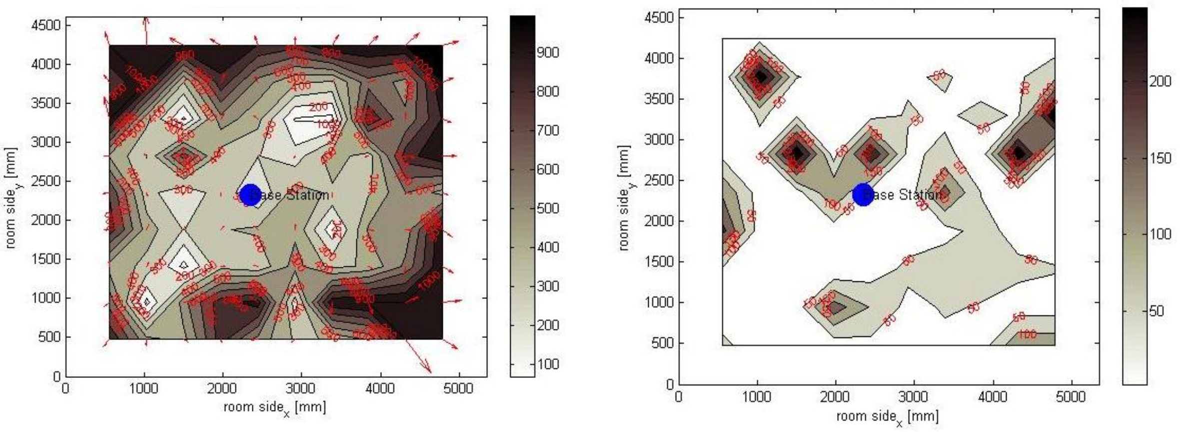


Fig 3. Localization Accuracy (mean error, left) and precision (variance, right) obtained with the described system.

The root mean square errors shows a mean less than 72 cm, which reduces to 56 cm in the region below the anchor, the variance of the localization error is below 30 cm over the entire room. The percentage of the room area where the error is below the 1 meter threshold is around 90%, with the higher error located over the boundary of the room.

The system capability and performance will be exploited in a live demonstration.

## 4 References

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[2] *A. Cidronali, S. Maddio, G. Giorgetti, I. Magrini, S. Gupta, and G. Manes,"A 2.45 GHz Smart Antenna for Location-Aware Single-Anchor Indoor Application," in Proceedings of International Microwave Symposium (IMS), 2009*

# Enabling Low-power Localization for Mobile Sensor Nodes

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## 1 Summary

One of the most challenging issues in the design of localization systems is to improve the battery lifetime of the mobile nodes as much as possible. In a previous work of the authors [1] a novel low-power scheme for RSS-based localization is proposed. This scheme provides, in an efficient way, the necessary information for the position calculation trying to minimize the energy consumption of the mobile node. In this paper we describe the first implementation of our proposal in a non-beacon enabled IEEE 802.15.4 sensor network and evaluate its performance.

## 2 Protocol Description

The low-power scheme tries to reduce the energy consumption of the mobile nodes by reducing the idle listening and increasing the sleep periods. The main operation of our proposal is described in Fig 1. By using a synchronization algorithm, three different phases are defined over the time. The anchors (nodes with known positions) maintain the information related to the synchronization. In phase 1 the mobile node (MN) broadcasts a localization request at a defined transmission power. The anchors answer indicating the duration of the phases. If the MN does not receive an answer in a certain time, it tries to send another localization request at a higher transmission power. This process is to ensure that the nearest anchors to the MN can answer first. When the MN receives the first answer, it goes into sleep mode and waits for the following phase. In phase 2 the MN randomly broadcasts packets containing the address of the “selected anchor”, which is the anchor that answered in phase 1. Between transmissions the MN sleeps. The anchors average the RSS measurements of each received packet. In the phase 3 the anchors send the averaged RSS value to the selected anchor. This anchor can either calculate the MN´s position, or send the information to a central computer. If the MN needs to know its position it can send a request to the selected anchor in the next phase 1.

## 3 Analysis and implementation

For the performance evaluation a testbed was built with 802.15.4 nodes. An address-based routing was implemented on a tree topology. We designed an addressing scheme that allows to decrease the number of re-associations (typical problem of a mobile 802.15.4 network) minimizing the MN´s energy consumption. A low-power synchronization algorithm was also designed for the selected topology. The localization algorithm “Weighted Centroid Localization” (WCL) is taken as example and executed by the anchor. The more transmitted packets in phase 2 the more reliable the averaged RSS is. We analyze the probability that a MN, which needs to transmit, finds the channel free in the phase 2 ($P_f$). This probability depends on the phase´s duration, how many MNs are in the same region and how many packets the MNs send during the phase. The Fig 2a shows the case when each MN tries to transmits 10 packets. As expected, Pf decreases as the number of MNs increases. Furthermore if the phase 2 is longer it is more probable that the MN finds the channel available to transmit, but at expense of a higher delay. By using timestamps it is possible to measure the duration of the transmission process in a MN. Fig.2b shows the averaged difference between the timestamp at the transmission request (realized by the application to the MAC layer) and the timestamp when the packet is transmitted ($T_a$). Here the duration of the phase 2 is 100ms and each MN transmits 10 packets. This time increases, when there are more MNs in the same region, due to the long waiting time required by the backoff process (CSMA).

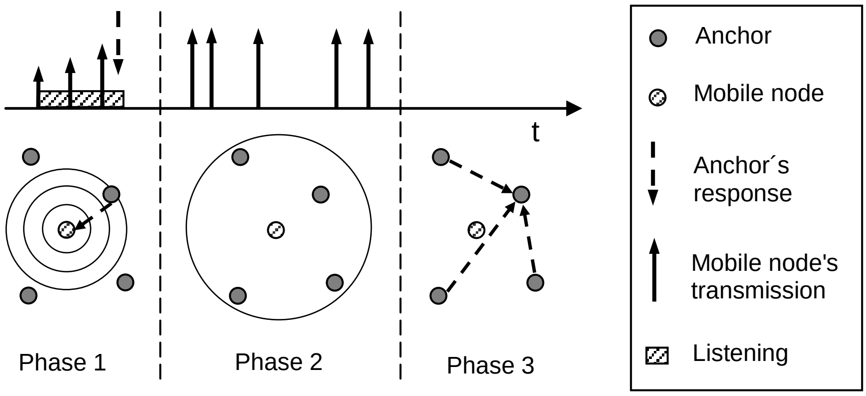
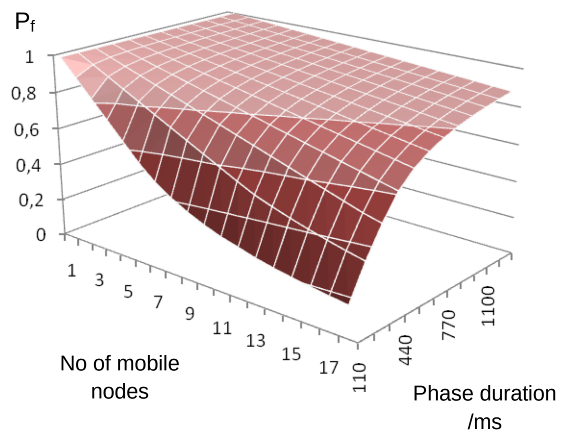
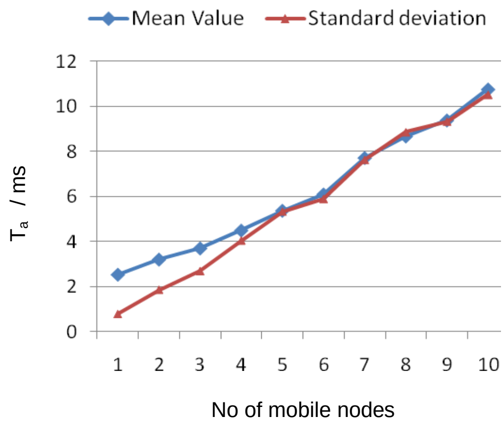



Figure 1: Operation of the low-power scheme for a mobile node over the time.




(b)

Figure 2: a) Probability that a mobile node finds the channel free in phase 2. b) Averaged time between a transmission request and the effective transmission of the packet in phase 2.

## 4 Conclusions

This paper describes the analysis and the implementation of a low-power scheme for localization in a non-beacon enabled IEEE 802.15.4 network. In this proposal the MN can sleep during long time saving energy. A more detailed description of our proposal will be given in the final version of the paper.


[1] Robles, J.J; Tromer, S.; Quiroga, M.;Lehnert, R.: A Low-power Scheme for Localization in Wireless Sensor Networks, 16th EUNICE International Workshop, Norway June 2010.

# A Novel 5-Dimensions RF Signal Strength Indoor Localization Method Based on Multipath Propagation*

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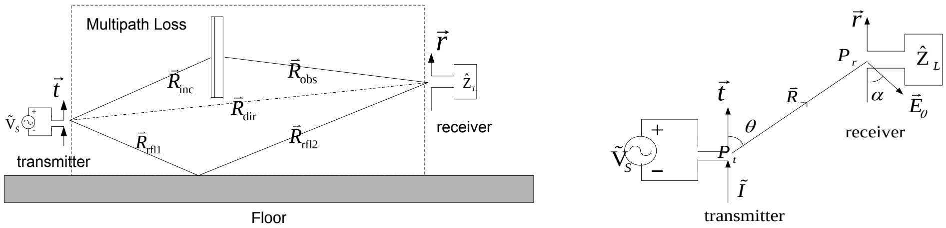
## 1 Summary

The radio received signal strength (RSS) method is widely applied for indoor localization and navigation systems. In order to realize it and get the optimal performance, we have to analyze some factors such as choosing the initial value for the Levenberg-Marquardt (LM) nonlinear optimization method, the placement of the RF receivers relative to the source transmitter, the estimation of the noise in the environment, and especially the multipath fading of the electromagnetic wave. The simulation experiments show the feasibility and anti-noise property of the proposed localization method.

## 2 Received Signal Strength Model in Indoor Environment with Multipath Fading

In an indoor environment the RF signal fades rapidly with shadowing, reflection and scattering by the presence of furniture, objects and walls, because of the induced diffraction, multipath effects. Figure 1(a) shows the actual total propagation path is divided into direct, reflected and scattered signals and the theoretical RF signal propagation model for transmitter and receiver can be described as Figure 1(b).




(a) Multipath Loss in Indoor Environment (b) The Proposed Propagation

Figure 1: Schematic Description of the RF Signal Transmitting and Receiving for Dipole Antennas

Assume that the transmitter's position vector is $(x_t, y_t, z_t)$ and orientation vector is $\vec{t}\ (m_t, n_t, p_t)$, the receiver's position vector is $(x_r, y_r, z_r)$ and orientation vector is $\vec{r}\ (m_r, n_r, p_r)$. The signal *A* vector at a distance *R* for the dipole are derived from an electromagnetic propagation formula and presented as following equations respectively:

$$\vec{A} = \frac{\mu I l}{4\pi R}\left(\cos\theta\vec{a}_R - \sin\theta\vec{a}_\theta\right) \quad (1)$$

The induced voltage in the receiver antenna can be presented as:

$$V = \vec{E}_r \cdot l \cdot N_\sigma = \frac{N_\sigma l}{\varepsilon\mu}\left[\nabla\times\left[\nabla\times\vec{A}\right]\right]\vec{a}_r = \frac{\beta\eta I l_t l_r}{4\pi R}\sin\theta\cos\alpha\cdot N_\sigma \quad (2)$$

where $\beta$ is the phase constant, $\eta$ is the medium intrinsic impedance, $N_\sigma$ is a Rayleigh random variable which simulates the multipath propagation model of indoor environment. In addition, two angles in equation (2) are presented as:

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$$\cos\theta = \frac{\vec{R}\cdot\vec{t}}{\|\vec{R}\|} = \frac{m_t(x_r - x_t) + n_t(y_r - y_t) + p_t(z_r - z_t)}{\sqrt{(x_r - x_t)^2 + (y_r - y_t)^2 + (z_r - z_t)^2}} \quad (3)$$

$$\sin\alpha = \frac{\vec{R}\cdot\vec{r}}{\|\vec{R}\|} = \frac{m_r(x_r - x_t) + n_r(y_r - y_t) + p_r(z_r - z_t)}{\sqrt{(x_r - x_t)^2 + (y_r - y_t)^2 + (z_r - z_t)^2}} \quad (4)$$

## 3 Localization Model

Provided that the number of receivers placed around the object is $N$ ($N >= 5$), the position and orientation of an object and receivers are $(x_0, y_0, z_0, m_0, n_0, p_0)$, $(x_i, y_i, z_i, m_i, n_i, p_i)$ $(i = 1, 2, \cdots N)$ respectively. Since $(x, y, z, m, n)$ is the solving solution for $(x_0, y_0, z_0, m_0, n_0)$, then the object localization function can be expressed as:

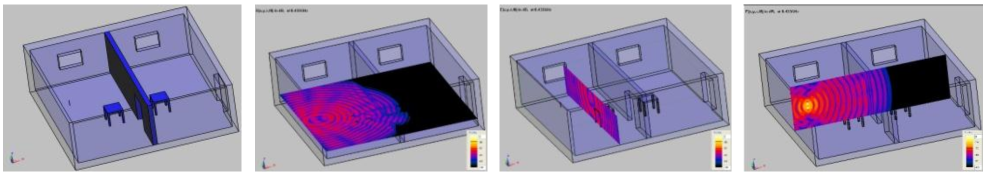
$$\min \sum_{i=1}^{N} \left( \frac{k\left(R_i^2 - \left(m(x_i - x) + n(y_i - y) + p(z_i - z)\right)^2\right)\cdot\left(R_i^2 - \left(m_i(x_i - x) + n_i(y_i - y) + p_i(z_i - z)\right)^2\right)}{R_i^6} - V_i^2 \right)^2 \quad (5)$$

where $R_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}$ , $k = \beta\eta I l_t l_r / 4\pi$ .

The localization model in equation (5) is nonlinear and the Levenberg-Marquardt (LM) optimization method can be applied to solve this problem for practicality.

## 4 Simulations

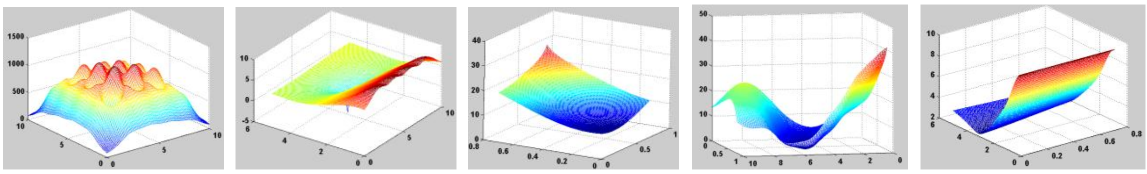
Simulations have been carried out in a 10m×10m×3m indoor environment as shown in Figure 2(a), which consists of two rooms and metal tables. Three cross sections of electromagnetic attenuation maps in Figure 2(b,c,d) demonstrate that floor, furniture and walls have an impact on the RF signal propagation.



a. b. c. d.

Figure 2: The simulation results of electromagnetic propagation attenuation
(a. Indoor environment model; b. The cross section in Z direction; c. The cross section in X direction; d. The cross section in Y direction)

At first three parameters of localization model are preset, then the localization error is estimated by changing the other two as shown in Figure 3. The average position error is around 1.5m and the average orientation error is around 5° in the proposed environment.



a. b. c. d. e.

Figure 3: The localization error in dependance of two parameters: a. *x,y* ; b. *x,z*; c. *m,n;* d. *x,m*; e. *z,m*

## 5 Conclusions and Outlook

The proposed localization method can get 5-D information of an object in the indoor scenario. In order to get an accurate position and orientation estimation result, this study focuses in particular on multipath fading. Our simulations show that the proposed localization method has satisfied accuracy when the initial guess of the parameters are within some predetermined ranges. In addition, future work will mainly focus on actual indoor channel estimation.

# DALE: A Range-Free, Adaptive Indoor Localization System Enhanced by Limited Fingerprinting

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## 1 Summary

A novel range-free algorithm is presented in this paper. DALE (DALE is Adaptive Localization with Enhancements) includes a two-stage algorithm and it is described as adaptive in the sense that it is able to incorporate fingerprints of specific locations when available in order to enhance localization accuracy. The proposed method is aimed in indoor environments and requires a strategic placement of nodes in each room. It is easily scalable to a large number of rooms and adaptable to rooms with complex geometry. Based on plain RSSI measurements, which are easily collected on inexpensive hardware, the range-free method returns an area wherein the mobile node lies, instead of a specific position fix. Simulation results are derived in order to evaluate the proposed algorithm and compared to relative research results in the literature, indicating that the proposed scheme achieves superior robustness and accuracy, while being less computationally extensive and using fewer beacons.

## 2 Extended Abstract

The rapid development of wireless communications along with the increasing interest in pervasive computing has made localization algorithms a research area of significant interest for many scientists and engineers. However, many indoor localization systems rely either on a costly and time consuming fingerprinting process to produce a wireless mapping of a room [1], complex hardware [2] or a large number of beacons [3].

The proposed system operates using plain RSSI measurements collected from a limited number of wireless nodes, placed appropriately in the localization environment, forming rectangles. These nodes are required to be equipped with antennas that offer the same transmitter gains and the transmitters are set on the same power level. When a localization request is made, the position of the node is estimated in two stages (Figure 1). The system first tries to decide which quadrant of the room the node resides in and then tries to further enhance the original position, either by using fingerprints in specific locations or by performing further calculations on the vector of the RSSI values received by the mobile node.

The basic concept of the system is a series of comparisons between the expected RSSI values and the actual measurements, combined with a simple threshold model used to compensate for the fluctuations in the mean value of the received power, due to large/small scale fading. Different variations of the algorithm have been evaluated with respect to the achieved accuracy they offer. Extensive simulation results are derived for each one of the proposed alternatives of the algorithm, demonstrating high localization accuracy and robustness.

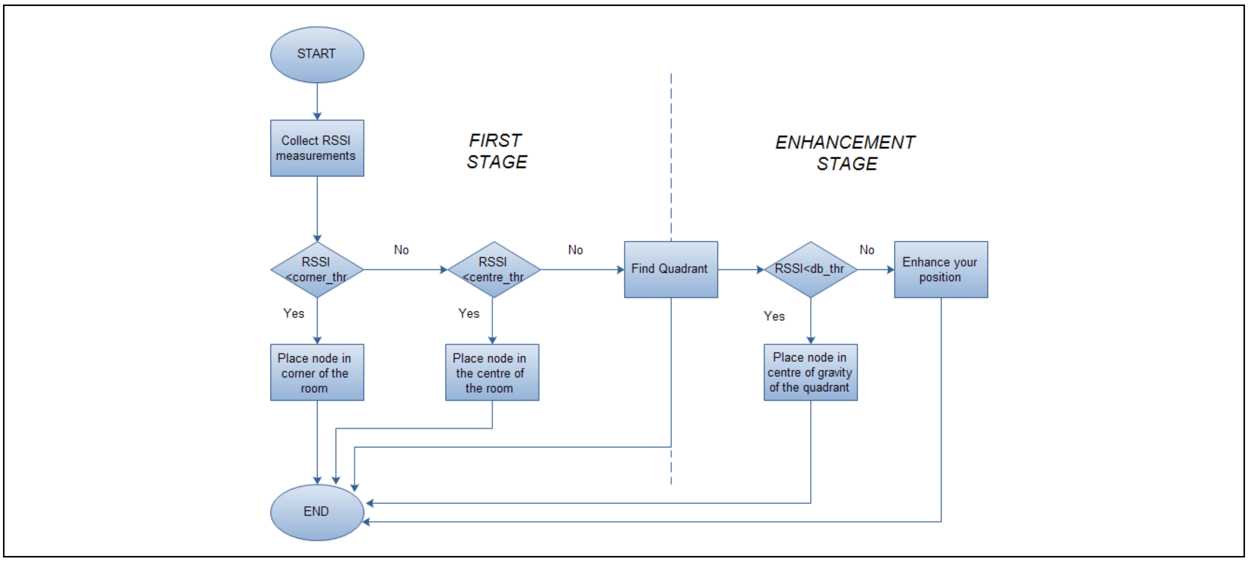


Figure 1: Overview of the proposed algorithm.

## 4 Conclusion and future work

The proposed solution tries to estimate the smallest possible area of the localization environment where the mobile node resides in. The accuracy of the algorithm is therefore dependent not only on the propagation characteristics of the specific space, but also on the dimensions of each room where the system is set up.

Results have shown a mean localization error of 70cm in a 5m-by-5m room, dropping to 60cm with an addition of five fingerprints. An adaptive, fully range-free version of the proposed system is also being explored, eliminating any need for fingerprinting. The system is also undergoing extensive testing in an in-house developed localization platform, namely, the WAX-ROOM system, in order to evaluate its' performance in real conditions [4].

This work is supported by (a) the “EMERGE” (EMERGE-IST-FP6-2006-045056), the “DITSEF” (DITSEF-FP7-ICT-SEC-2007-1-225404) and the “HMFM” (HMFM-FP6-AAL-2008-1/ΓΓΕΤ: 13591-07/07/2009) EU research projects, which are funded in part under by the European Commission and in part by the General Secretariat of Research and Technology (GSRT) of the Ministry of Development, Greece, (b) by a Ph.D. Fellowship of NCSR Demokritos and the Ministry of Development and (c) by a Post-Doctoral Fellowship of NCSR Demokritos and the Ministry of Development.

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# Ad-hoc Networks Aiding Indoor Calibrations

# Of Heterogeneous Devices for Fingerprinting Applications

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## 1 Extended Abstract

Fingerprinting approaches are based on experimental models which relate the measured Received Signal Strength (RSS) values directly to the position of the calibration points. These models are generated with the use of data collected off-line from several locations (calibration points) covering the area where positioning service is performed. Compared to other RSS-based methods, fingerprinting algorithms are more robust against the signal propagation fluctuations (Fig.1 and Fig. 2) and attenuations generated by environment characteristics, since they make use of location-dependent errors of radio signals. Even if more robust, the calibration phase of the fingerprinting is a very laborious and time consuming approach, especially if it has to be performed for heterogeneous devices with different wireless cards. Hence it represents a huge limitation when implementing mass market positioning applications for devices with vendor-related hardware characteristics, because different vendors produce different chipsets with different Radio Frequency (RF) modules developed with their own accuracy, range of power, sensitivity and scaling, which are key points for positioning applications [1]. Fig. 1 shows an example where two Mobile Stations (MSs) under test (NOKIA N800 and ASUS X51Lseries) are placed 1m away from the Access Point (AP). Even if the distance from the AP is the same, the RSSs detected at terminal level differ by more than 15dBs. Moreover, due to the intrinsic complexity of the indoor environment, measurements accuracy is highly dependent by the channel. Several error sources (such as multipath, signal blocking, shadowing, presence of humans, objects, overlapping channels, walls, noise and sensitivity of the wireless cards [1]) affect the signal propagation, causing huge fluctuations, detected at terminal level, for each calibration point (Fig. 2). Indeed inaccurate measurements fall into inaccurate final location estimations.

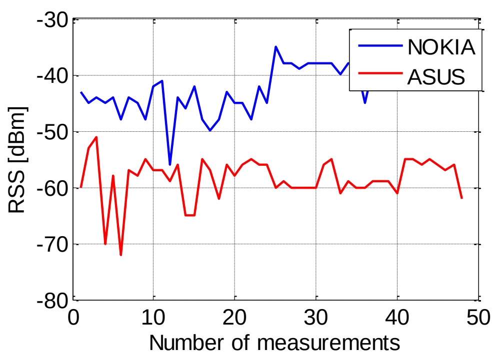


Figure 1 RSS for Heterogeneous Devices

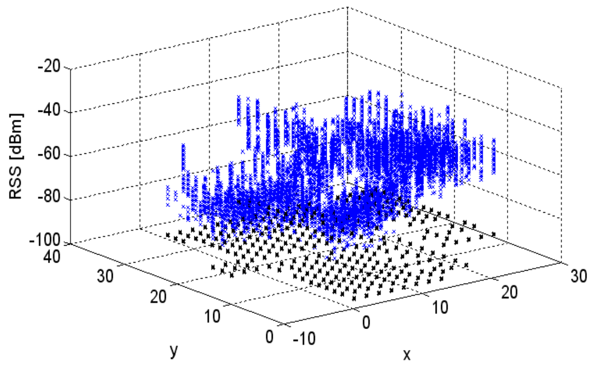


Figure 2 RSS Fluctuations: calibration points (black), RSS (blue)

In order to overcome the aforementioned drawbacks, we propose in this paper to exploit the RSS from ad-hoc connections among neighboring MSs by evaluating the spatial proximity among them (with the exploitation of empirical path-loss models for ad-hoc link) and using it as constraint for the database calibration and final positioning estimation of the MSs. Specifically (Fig. 3) the MS adopted in the conventional time-consuming calibration phase (namely the Cluster Head (CH)) implements *on-the-fly* RSS data-base corrections for the neighboring MSs (Cluster Members (CMs)). The RSS measured at AP-MS links in the estimation phase for the CMs (and the relative erroneous estimated position) will be evaluated by the CH and corrected with the constraint of the estimated distance among them. After some iteration, the final *correction factor* is sent to the CMs which correct and adapt the CH's fingerprint database now suitable according to their hardware characteristics.

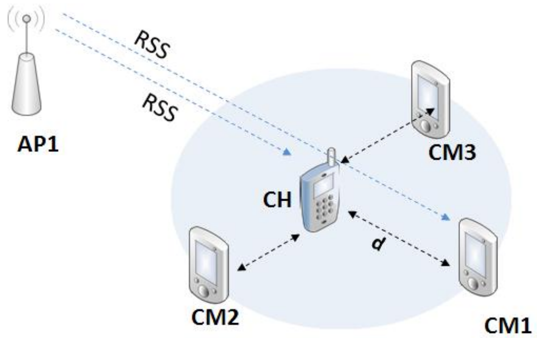


Figure 4 Ad-Hoc Measurements Aiding Calibrations

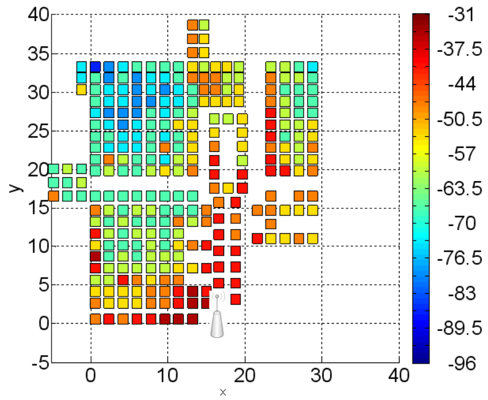


Figure 3 Radio Map 00:17:0F:D9:69:70

The test experiment is performed in the library of Tampere University of Technology (TUT), where the time-consuming calibration of the area (40x40m) has been performed by using a NOKIA N800 Internet Tablet (being the CH) and signals of 3 APs. As CMs two laptops with different wireless cards have been used, where a C++ application has been implemented for measuring the RSS, exchanging the data in ad-hoc mode and providing corrections in real-time. Fig. 1 shows the difference of RSS between The CH and one CM, while Fig. 4 shows the performed fingerprints of the CH to be modified on-the-fly for the CMs. It is worth mentioning that once one CM is calibrated (with the proposed technique) it can be elected as new CH and it can calibrate new CMs joining the ad-hoc network.

The technique proposed by the authors is able to avoid long time-consuming calibration phases to obtain suitable fingerprint databases for heterogeneous devices by exploiting the spatial proximity among the MSs connected in ad-hoc mode. In this work we will show: 1) How close the accuracy of the proposed technique, applied to the CMs, approaches the accuracy of the CH, 2) How the power consumption is decreased in the CMs calibration phase (since correction factors need to be added in the fingerprint database), 3) potentials and limits in the distance-dependence performances of the calibration phase (spatial proximity among MSs).

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# Real time calibration for RSS indoor positioning systems

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## 1 Summary

Most current indoor localization systems usually work with received signal strength (RSS) measurements gathered from different wireless technologies (WiFi, Bluetooth, ZigBee, etc.). The RSS signal random nature makes that most of the systems, either map-based or channel model based, need an off-line calibration phase, at least when starting the location system for the first time. Calibration usually is a resource and time consuming task, and its validity expires after a period of time, mainly due to continuous and unavoidable physical variations of the environment (e.g. changing people flow during the day, open or closed doors, furniture redistributions, etc.). In this contribution we present an algorithm which allows dynamic calibration of a channel model-based localization technique. The algorithm uses a Least Mean Squares technique to adaptively estimate the constants of the propagation model, using reference beacons, aiming at minimizing the error of a hyperbolic triangulation method. Simulated and real data show that the location error is effectively minimized after a number of training samples, making possible to avoid manual calibration and recalibration procedures when deploying a localization system.

## 2 Fundamentals: Localization scenario

We consider an indoor space covered by a network of anchor nodes (e.g. WiFi access points or Zigbee motes) which measure the RSS of a mobile node to be localized. Our localization system is based on using a propagation channel modeling to compute each distance mobile-anchor node and perform hyperbolic triangulation. The most popular channel model for RSS-based localization is the lognormal model:

$$P_{RX}(dBm) = P_{TX}(dBm) + A - 10\eta \log \frac{d}{d_0} + N(0,\sigma) \qquad (1)$$

where and $P_{TX}$ and $P_{RX}$ are the transmitted and received power (at the transmitting and receiving nodes, respectively), $d$ is the distance between transmitter and receiver, $A$ and $\eta$ are the parameters of the channel model and $N$ is a zero-mean Gaussian random variable with standard deviation $\sigma$.

Using eq. 1, given $A$ and $\eta$, the system estimates the distances $d$ from the received $P_{RX}$ (in practice the RSS), at least to three anchor nodes. To complete the real-time localization, a hyperbolic triangulation is used to localize the mobile node (detailed formulation is available in e.g. [1]).

However, in practice, both A and η need to be off-line experimentally determined and continually updated or calibrated (bad estimations of A and η might result in significant localization errors). A number of strategies dealing with this problem from different perspectives have been proposed (see [2], as an example).

In this context, our objective is to avoid any off-line experimental determination of A and η constants 1) to minimize the complexity of the calibration tasks when getting the location system to work for the first time and 2) to adapt the system's performance to real time environmental variations. To do so, we define a number of beacon or reference points in given geographic locations. These beacon points, easy to deploy (practical considerations will be described in the full paper), will be situated in waypoints (e.g. doors), attached to static objects (e.g. a printer in an office), or situated as part of the communications network. The anchor nodes continuously measure the RSS of the signals coming from these static beacon points and use the algorithm presented in the next section to compute $A$ and $\eta$ in real time.

## 3 The Least Mean Square (LMS) algorithm

The algorithm uses the measurements taken from the calibration points to iterative calculate the optimal values of $A$ and and $\eta$, i.e. those that minimize the error between the estimated and the (known) real position of the beacons

$$\varepsilon(n) = \sqrt{\left(x(n) - \hat{x}(n)\right)^2 - \left(y(n) - \hat{y}(n)\right)^2} \quad (2)$$

Assuming that a single channel model is used (in the final paper, results using not a single but several channel models will be included), the LMS algorithm is formulated as:

$$A(n) = A(n-1) - \mu_A \varepsilon(n) \cong A(n-1) - \mu_A \varepsilon(n) \frac{d\varepsilon(n)}{dA} \quad \ldots\ldots \quad (3)$$

$$\eta(n) \cong \eta(n-1) - \mu_\eta \varepsilon(n) \frac{d\varepsilon(n)}{d\eta}$$

where $\mu$s are the filter step sizes. After detailed computation (basically derivations and simplifications) on the formulas of hyperbolic triangulation the following expressions for *A(n)* and *η(n)* are obtained (details in the final paper):

$$A(n) = A(n-1) - \mu_A \frac{k}{\eta(n-1)} \left[ \left(x(n) - \hat{x}(n)\right) \cdot \sum_{i=2}^{N} c_i \cdot \left( \hat{d}_1^2(n) - \hat{d}_i^2(n) \right) + \left(y(n) - \hat{y}(n)\right) \cdot \sum_{i=2}^{N} D_i \cdot \left( \hat{d}_1^2(n) - \hat{d}_i^2(n) \right) \right] \quad (4)$$

$$\eta(n) = \eta(n-1) - \mu_\eta \frac{10 \cdot k}{\eta(n-1)} \left[ \begin{array}{l} \left(x(n) - \hat{x}(n)\right) \cdot \sum_{i=2}^{N} c_i \left( \hat{d}_i^2(n) \cdot \log \hat{d}_i(n) - \hat{d}_1^2(n) \cdot \log \hat{d}_1(n) \right) + \\ \left(y(n) - \hat{y}(n)\right) \cdot \sum_{i=2}^{N} D_i \left( \hat{d}_i^2(n) \cdot \log \hat{d}_i(n) - \hat{d}_1^2(n) \cdot \log \hat{d}_1(n) \right) \end{array} \right]$$

where:

$$k = \frac{-16 \cdot \ln 10}{\det \cdot 10 \cdot \eta}, \quad \hat{d}_i = 10^{\frac{A(n-1) - RSS_i}{10 \cdot \eta(n-1)}}, \quad c_i = x_i \cdot \left(y_2^2 + \ldots + y_N^2\right) - y_i \cdot \left(x_2 \cdot y_2 + \ldots + x_N \cdot y_N\right), \text{ and}$$

$$D_i = y_i \cdot \left(x_2^2 + \ldots + x_N^2\right) - x_i \cdot \left(x_2 \cdot y_2 + \ldots + x_N \cdot y_N\right) \quad (5)$$

## 4 Preliminary results and practical issues

Fig. 1 shows an example of how the LMS algorithm is able to reduce the location/estimation error by adaptively adjusting A and η. The case represented in Fig. 1a. starts with a value for $A_0$ just differing 5 dBs from the value used to simulate the RSS measurements ($A_s$). In this case, approximately 100 samples are needed to calibrate the model. When the difference between $A_s$ and $A_0$ is 15 dBs, around 600 samples are needed to stabilize the error value.

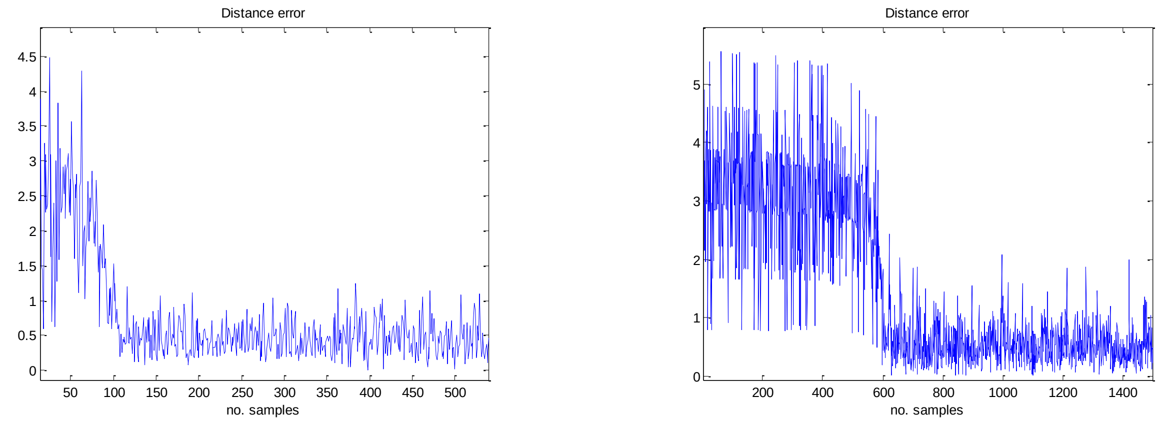


Figure 3: Evolution of the error in distance using a model with $\eta_0$=3, $\mu_A$=0.1, $\mu_\eta$=0.01 and two different values for A: a) $A_0$= -65 and b) $A_0$= -75. Scenario with 8 anchor nodes and 20 calibration/beacon points (zigbee motes)

The final paper will include the detailed description of the algorithm, an exhaustive performance evaluation, both using simulated and real measurements from our ZigBee network infrastructure and also a discussion on the effects of using various propagation models (for different anchors). Further, from a practical viewpoint, the full paper will elaborate on how to easily establish beacon points in real environments.

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# A Model-Switching Sequential Monte Carlo Algorithm for Indoor Tracking with Experimental RSS Data

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## 1 Introduction

In this paper we address the problem of indoor tracking using received signal strength (RSS) as position-dependent data. This type of measurements are very appealing because they can be easily obtained with a variety of (inexpensive) wireless technologies. However, the extraction of accurate location information from RSS in indoor scenarios is not an easy task. Due to the multipath propagation, it is hard to adequately model the correspondence between the received power and the transmitter-to-receiver distance. For that reason, we propose the use of a compound model that combines several sub-models, whose parameters are adjusted to different propagation environments. This methodology, called Interacting Multiple Models (IMM), has been used in the past either for modeling the motion of maneuvering targets [2] or the relationship between target position and the observations [1]. Here, we extend its application to handle both types of uncertainty, in the target dynamics and the RSS observations, and we refer to the resulting state-space model as a generalized IMM (GIMM) system. The flexibility of the GIMM approach is attained at the expense of an increase in the number of random processes that must be accurately tracked. To overcome this difficulty, we introduce a Rao-Blackwellized sequential Monte Carlo tracking algorithm that exhibits good performance both with synthetic and experimental data.

## 2 System Model

**Dynamic Model:** We formally represent the target dynamic state at time $t \in \mathbb{N}$ over a two dimensional region as a $5 \times 1$ real vector $x_{5,t} = [\omega_t, r_t, v_t]^T$, where the real $2 \times 1$ vectors $r_t$ and $v_t$ provide the target position and velocity, respectively. Each one contains two real scalars, $r_t = [r_{1,t}, r_{2,t}]^T$ and $v_t = [v_{1,t}, v_{2,t}]^T$, which are the coordinates of the position, $r_t$, and velocity, $v_t$, in the $x - y$ plane. $\omega_t \in \mathbb{R}$ denotes the variation, in radians, of the angle of the velocity at time $t+1$. The subscript $\ell$ in $x_{\ell,t}$ is used to indicate the state vector dimension. A popular dynamic model for $x_{5,t}$ is the so-called "coordinated turn" (CT) model [2], which completely characterizes the ability of the target to turn. By selecting different distributions for $\omega_t$ one can devise different motion models. Hence, we introduce an additional state variable, $a_t \in \{1, \dots, L\}$, such that $a_{t-1} = l$ implies that $\omega_t$ is generated according to the $l$-th motion model. Finally, the $6 \times 1$ state vector $x_{6,t} = [a_t, \omega_t, r_t, v_t]^T$ evolves according to the IMM equation $a_t \sim p(a_t|a_{t-1})$, $\omega_t \sim p(\omega_t|\omega_{t-1}, a_{t-1})$, $x_{4,t} = A(\omega_{t-1})x_{4,t-1} + Qu_t$. The transition matrix $A(\omega_{t-1})$ is a function of the turning angle $\omega_{t-1}$, $Q$ determines the covariance of the dynamic noise and the conditional pdf $\omega_t \sim p(\omega_t|\omega_{t-1}, a_{t-1})$ and the pmf $p(a_t|a_{t-1})$ are assumed known.

**Measurement Models:** We propose a scheme where RSS observations are collected from $J$ sensors. The measurement provided by the $j$-th sensor at time $t$ is denoted as $y_{j,t}$. We represent the relationship between the observed RSS, $y_{j,t}$, and the target position, $r_t$, with log-distance path-loss models. However, as this relationship depends tightly on the physical environment and may even change with time we propose to use an IMM approach, again, in order to handle the uncertainty. Specifically, we allow the observation $y_{j,t}$ to be represented using one out of $K$ different models, each one of them fitted to a different set of experimental data, using a measurement model incator variable $m_{j,t} \in \{1,\ldots,K\}$. The parameters of the function depend on the specific model and should be determined from field measurements collected in the scenarios where the tracking system may have to operate. In the complete paper we will give full details on the construction of the models.

## 3 Algorithms

In the paper, we will introduce a sequential Monte Carlo algorithm for the tracking of the state vector. We will show that the sequence of velocity vectors, $v_{0:t}$, as well as the vectors of model indices, $m_{0:t}$, can be integrated out analytically from the posterior distribution in such a way that only the position, $r_t$, the turning angles, $\omega_t$, and the dynamic model index, $a_t$, need to be sampled. The resulting algorithm falls in the class of Rao-Blackwellized particle filters (RBPF's) [2] and we have found that it is effective in the processing of experimental data. In the paper, we will also introduce an unscented Kalman filter (UKF) for the considered GIMM system, and compare it with the RBPF in terms of performance and complexity.

## 4 Brief preview of the experimental results

We have carried out experiments in a network consisting of nine ZigBee nodes located at fixed positions, acting as RSS sensors, and one extra node acting as the moving target. The nine nodes were deployed in a regular grid covering an area of $6 \times 10$ meters. We have collected data from the nine sensors following a moving target and, additionally, we have also simulated the observations from all sensors for the same trajectory, in order to compare the performance of the proposed RBPF with real and synthetic data. The results are shown in Figure 1. The left plot shows the nine sensors as solid squares, the target trajectory as a solid line and the trajectory estimated from synthetic data with a dashed line. The RMSE attained for 100 independent simulations for the same trajectory was 0.594 m (with a standard deviation of 0.663 m). The results with experimental data are shown in the right plot. It can be seen that the estimated trajectory is very similar to the one obtained with simulated data.

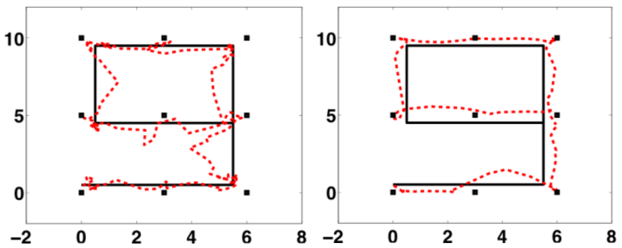


Figure 1: Comparison of the performance of the RBPF algorithm with synthetic (left) and experimental (right) data.

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# An Environment Adaptive ZigBee-based Indoor Positioning Algorithm

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## 1 Summary

We have developed and implemented an indoor positioning system that is able to carry out wireless sensor node location in real time and automatically adapts to changes in the environment. We present a descent gradient iteration algorithm, in order to calculate the blind node's position in the most accurate way. It is based on several matrices that can be dynamically updated with the information received from the reference nodes. The algorithm is running at a central server due to the computational limitations of this type of node and, as it is based on the measured RSSI levels, no extra hardware is required. The selected platform is a Texas Instruments' CC2430 WSN (Wireless Sensor Network) and the location estimation is calculated over ZigBee communication technology.

## 2 Introduction

Nowadays, indoor location is an unresolved issue many research groups are working on intensively. There are several techniques that have been developed seeking a solution; however, a definitive approach has yet to be found.

One of the most reliable existing solutions is fingerprinting, based on an RSSI calibration method, where several measurements are taken in order to describe the signal's propagation pattern in a particular scenario before the location phase begins. This technique needs a lot of pre-processing work though, and furthermore, the method is not useful when there are changes in the environment. Whenever changes take place, the RSSI fingerprint has to be built up again since all the previous measurements become useless.

Therefore, if we wish to obtain an accurate location, it is not enough to simply perform an initial calibration process. This calibration must be updated dynamically whenever location needs to be determined.

In order to accomplish this goal, we have developed a robust, easy-to-deploy and flexible positioning system based on ZigBee WSN. The reason why a ZigBee network has been chosen is that it is a low-cost, low-power, wireless mesh networking proprietary standard. It is important to note that the mesh networking provides high reliability, a wider range and also makes it easier to deploy the ZigBee nodes.

Our system consists of two main phases: calibration and location. The requested node's location is computed in the central server, and then it can be distributed to the network. Should a blind node need to be located, the system performs the calibration, so that changes in the environment are taken into account in the location phase, and thus making the system more robust and accurate.

## 3 Our positioning algorithm

The system is based on an RSSI measurement technique; although there are other signal measurement techniques, these would just add complexity to our system and make it more expensive. Moreover, RSSI is a parameter that is obtained directly from the messages exchanged between the ZigBee nodes.

There are two types of nodes in the system, reference nodes and blind nodes. Reference nodes will be strategically deployed throughout the scenario and their exact position will be known at all times. Blind nodes will be the ones to be located.

There are two phases we can distinguish: the calibration phase and the location phase. In the calibration process the system measures the RSSI value of the messages that each reference node sends to the others from its fixed position. We can therefore work out the relationship between the geometric distance and the RSSI values among all the references. In order to do so, we use a matrix method and then we calculate a distance vector called *dn* which shows the estimated distances from a particular blind node to each of the reference nodes.

Due to indoor propagation issues, it is impossible to obtain the real *dn* values. Therefore, we have developed a descent gradient iteration algorithm that can be used to calculate the blind node's position more accurately.

$$X_{k+1} = X_k + \alpha \cdot \sum_{i=1}^{m} \left(1 - \frac{dn_i}{fd(X_k, X_i)}\right) \cdot (X_i - X_k)$$

This algorithm analyses the *dn* vector and can deduce the nearest reference from the blind node. In the first iteration, the system assumes that the blind node is directly in the position of the closest reference and then, in the following iterations, the blind node's positions will be updated taking into account the influence of all of the reference nodes.

## 4 Algorithm testing

In order to determine whether the algorithm that has been developed is reliable or not, we tested it by introducing real scenario parameters. We calculated the real Euclidean distances between a hypothetical blind node's location and some well known references. Using these values we proved that the algorithm converges to the right position.

There are several parameters that can be changed to obtain more accurate results (transmitted power, number of exchanged packets, type of antennas, number of iterations, number of deployed references), and they have to be carefully selected, depending on the final application goal.

## 5 Conclusions and Outlook

The platform has been deployed in DeustoTech facilities, which is a real environment, with different separate furnished rooms. The system consisted of 8 reference nodes and 1 blind node, transmitting messages at 0 dBm. In our tests we performed 150 iterations and obtained significantly accurate results, with an average error of 3 meters. Other indoor positioning systems are far from offering better results; they require more pre-processing work and do not automatically take into account changes in the environment.

# Low Power Location Protocol based on ZigBee

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In typical ZigBee location applications, end devices are listening network messages for configuration and synchronization. These listening intervals often consume more than the transmission process reducing significantly the battery life time of the end devices. This paper describes a ZigBee communication protocol which has been implemented and provides a reduced power consumption of end devices. This is achieved by a simplification of the end devices firmware in order to increase their sleeping time and a proper development of routers and coordinator firmware.

This developed protocol allows two different forms of location estimation: proximity-based, where the position of the end device is related to its nearest reference node location; and multi-RSSI reference detection, which provides several neighbours RSSI values, being the base for more complex algorithms such as triangulation and fingerprinting.

The coordinator acts as a gateway of the network, allowing a communication between the wireless sensor network and the PC by a serial port. This device forwards the received messages by the ZigBee network to the serial port, and incoming messages on the serial port to the ZigBee network. *Blind-Node* is the end device (mobile node) whose position is desired to be estimated. After being registered in the network it will start an infinite loop where it falls asleep for a pre-defined interval and wakes up only in order to send a set of blast messages (broadcast messages of null APS payload and radius 1), followed by an end of transmission identification message.

The *Ref-Nodes* provide the location support, remaining in a permanent pooling mode, listening for messages. They listen for location messages from *Blind-Nodes*, configuration messages from coordinator and forwarding messages from other *Ref-Nodes*, processing them according to its individual role. These nodes represent the major system responsibility for messages processing on the network.

Through the high level application the user can choose a location based on proximity, where it is possible to identify all BlindNodes located in the area by matching the *Blind-Node* ID with the *Ref-Node* ID that detected its higher RSSI value. The other mode, called multi-RSSI reference detection, provides the base for a more precise location process, where a message with all *Ref-Node* IDs and the corresponding RSSI values of chosen *Blind-Nodes* will be sent to the coordinator. These location modes and their corresponding messages contents are described in Figure 1.

The selection of the location mode is managed by a graphical interface based on Java language, with the characteristic of easy and intuitive use. The developed interface provides the user with the visualization of *Blind-Nodes* based on the proximity or a more precise location based in a neural network. It also provides the configuration of the communication route and an identification of communication failures.

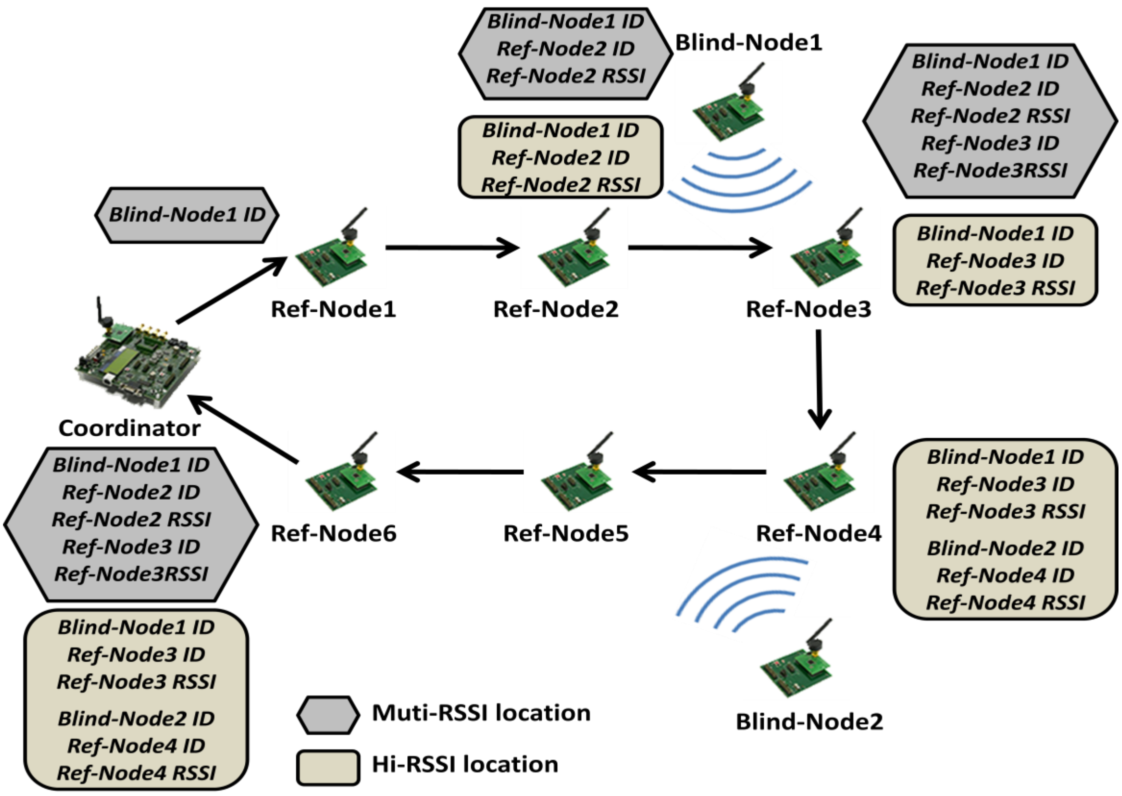


Figure 1: *Projected system for proximity and multi-RSSI location*

The main objective of this communication protocol is to achieve low power consumption of *Blind-Nodes*. Optimal sleep times and the number of sent numbers of blasts greatly depends on the system requirements for batteries life time and location refreshing time. Several possible solutions based on a 650mAH battery with different sleep cycles and corresponding life time duration are described in Table 1.

| | ***Life time (days)*** | | |
|---|---|---|---|
| | ***650 mAH*** | | |
| ***Sleep Cycle (ms)*** | ***1 Blast*** | ***5 Blasts*** | ***8 Blasts*** |
| 3000 | *469,2* | *107,4* | *72,4* |
| 5000 | *776,4* | *177,8* | *119,4* |
| 10000 | *1529,2* | *353,2* | *237,3* |
| 60000 | *8034,1* | *2045,9* | *1386,4* |

Table 1: *Blind-Node expected life time duration*

It is shown that batteries life time from several months to a few years can be easily achieved. These values can be greatly improved by configuring the modules in order to send fewer blast messages per cycle, or configuring them for bigger sleeping intervals.

This paper presents a new protocol and location engine scheme that can include any type of location algorithm. The main novelty is the reduced power consumption for mobile nodes. An improvement in the battery life time from several days to several months or years based on a simple indoor location protocol can be achieved.

# Improving ZigBee 2D5 localization in large buildings using Metric Description Graphs

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## 1 Summary

This work will propose a way of improving location estimations of a ZigBee RSSI based Indoor Localization System (ILS) in large buildings. ILS beacons are a network of fixed sensor nodes, linked with the ZigBee protocol, installed in convenient locations. A set of unknown objects, equipped also with ZigBee devices (blind nodes), can be located and tracked by the ILS. The localization system will provide 2.5 dimensions data (2D5) about blind nodes location: 2D metric information (X and Y axis) in every floor plus an indication of the floor number in height Z. The positioning of blind nodes is improved by fitting initial estimations into a building metric description graph which include connectivity among rooms and relative distances between graph nodes.

## 2 ZigBee Sensor Networks as Indoor Location Systems

In modern buildings a distributed Sensor Network (SN) allows to collect important information from any room of it: occupancy, temperature, lighting status, and many others. ZigBee based sensor nodes are a perfect way to deploy such a network with a minimum of installation efforts even while refurbishing old buildings.

This kind of sensory structure can be used as an Indoor Localization System (ILS) as well. Many other systems use the information sent or received from a set of RF beacons to extract sufficient parameters in order to determine the location of an unknown device inside their coverage area. ZigBee based beacons are a good and cost effective option to construct such an ILS.

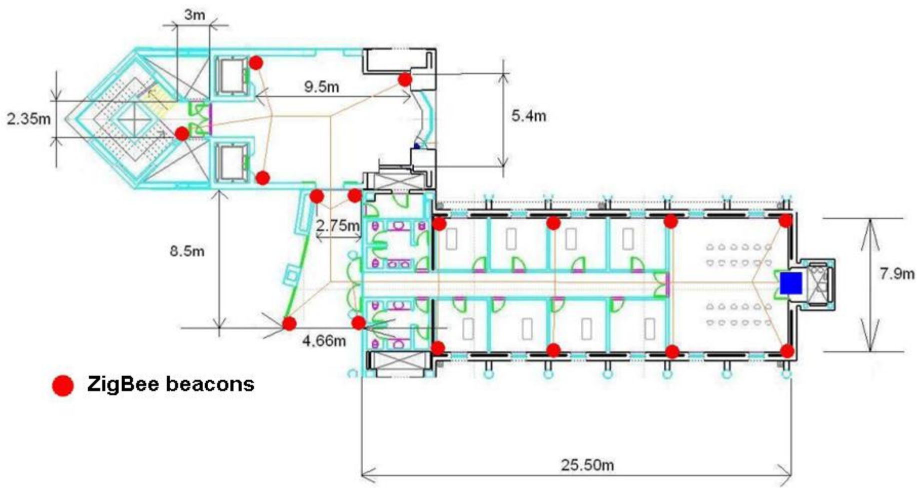


Figure 1: Experimental arrangement of ZigBee ILS beacons in the 3rd floor of the Electronics Department building.

However, ZigBee devices have been conceived as a low-cost, low-power and low-rate wireless communication system, although both processing power and RF stage are not optimized for location purposes. Nevertheless, RSSI from ZigBee devices is widely used as input for several algorithms suitable to provide useful location information. In the Electronics Department of the University of Alcala a layered ILS system has been installed in two consecutive floors (2nd and 3rd). This arrangement allows testing the ZigBee ILS performance for the purpose of locating devices including the height information inside a complex 3D RF field. An overview of one of the experimental setups is shown in Figure 1.

## 3 Improving ILS estimation: Metric Description Graph

In practical ILS too many external factors influence the theoretical signal propagation field and degrade the location estimation, mainly when radio ILS is used to locate pedestrians. One of the major error sources is the human body itself, making it extremely difficult to model such a dynamic system with sufficient accuracy in some applications: some kind of environment description should be added to the ILS in order to get the desired performance.

The central element of our proposal is a Metric Description Graph (MDG) which includes both metric and connectivity information about the environment where the ILS is deployed. The MDG allow integrating easily the information given by an ILS with other sources of information or services to users. Using the MDG as a framework, the RSSI measurements can be fused with additional knowledge about the location problem to be solved.

Here we present some results about locating and tracking people just using RSSI data from a ZigBee SN and a simplified dynamic model of pedestrian behaviour. Figure 2 show a sample run through a section of the map shown in figure 1. A pedestrian enters this section from the left side, goes for a while to a restroom and then continues walking along the corridor. In figure 2 the MDG (routes map) and two set of data can be seen: initial estimations coming from a ZigBee ILS; and the result of fitting ILS data to MDG with a simplified pedestrian dynamic model. The initial estimations were obtained from the X-Y outputs from the Location Engine of the CC2431 chip (Texas Instruments), improved by prefiltering of beacons' RSSI. The pedestrian dynamic model includes a maximum speed of 1m/s. Even such a simplified model helps to limit the variations along the map, leading to a more realistic and useful description of movements.

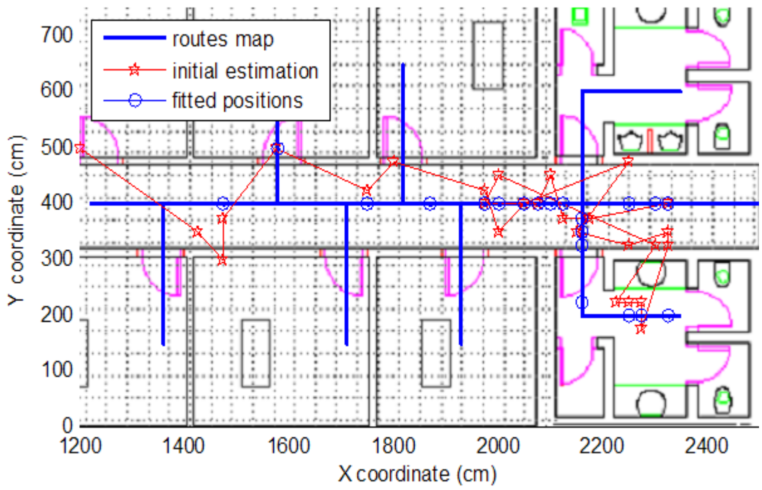


Figure 2: Tracking of a pedestrian walk, showing the initial set of position estimations and the fitted ones over the Metric Description Graph.

# User Positioning by means of pre-computed Attenuation Maps

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## 1 Summary

The proposed positioning technique is based on pre-computed attenuation maps of the received signal inside an indoor environment characterized by dense multipath fading effects. The attenuation maps are obtained through ray tracing modeling and they are validated against measurements by means of several Crossbow MICA2 devices operating at 433 MHz. The scenario is a conference room equipped with 8 transmitting anchor nodes (AP's). A network of calibration points is composed by 27 probe nodes. The goal is to obtain a satisfactory estimate of an user position based on the tuple $\{a_k\}$ of the attenuation values, where $k$ indexes the AP nodes.

## 2 Numerical modeling

Propagation prediction models involve interaction mechanisms of the signal with the environment. They provide descriptions of: a) large scale behavior, essentially path loss; b) small scale behavior, i.e. local field variations. A single deterministic description of an environment does not include signal fluctuations due to *geometrical noise* as it is induced by people moving around, different positions of furniture and objects, etc. On the other hand, a pure deterministic description of the channel response could neglect specific environment-related behaviors [1]. Hence, the numerical modeling is used to produce maps obtained perturbing the environment by placing randomly chosen scatterers to reproduce the received power fluctuations. Computed power maps were used to obtain – through a calibration procedure with comparison against measurements - an average description on the received power. The database is composed of 120 pre-computed maps with a given spatial resolution (0.1 x 0.1 $m^2$) considering 5 up to 10 scatterers of various dimensions. Scatterers are modeled as polygons having at least 10 sides and their dimensions are set in terms of the radius $r$ of the circumscribed circle (0.05 m ≤ $r$ ≤ 0.25 m). For each AP, the reference map is the average of the perturbed ones. These maps are used to evaluate localization capabilities under various possible scenarios.

The strategy is the following: a probe node (unknown location) is placed in the spatial domain, i.e. the indoor environment, at the probe location $(x_i,y_i)$ the tuple $\{a_k(x_i,y_i)\}$ of attenuation values is read from one of the perturbed maps in the database. The localization of the probe position is achieved by minimizing the cost function $K$, $K(j)=\sqrt{\sum_{k=1}^{N_{AP}}\left(<\mathrm{a_k}(x_j,y_j)>-\mathrm{a_k}(x_i,y_i)\right)^2}$ , where $<a_k(x_i,y_i)>$ is the attenuation average value from reference map at $(x_j,y_j)$ as experienced when $AP_k$ is transmitting. The outcome of the retrieval algorithm is $(x_j,y_j) \rightarrow K$ is minimum [2].

## 3 Progress results

Figure 1 shows the results of a preliminary test performed over 14 points. In the graph, one can observe the AP's locations and the deployment of the probe points. The number printed at the probe location indicates the RMSE localization error quoted in meter.

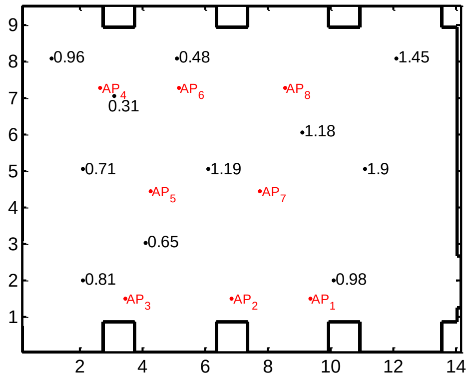


Figure 1: Example of localization algorithm and its performance: at the points locations, distance error [m] is the RMSE computed by using all the perturbed maps. Dimensions are meters.

By forcing an *a priori* knowledge about the probe motion, it is possible to include tracking capabilities. This was done under the assumption that the probe represented the displacement of a mobile user in the conference room, i.e. with an imposed velocity motion, Figure 2 reports the actual trajectory and the retrieved ones, on the left side, and the histogram of the distance error, on the right side.

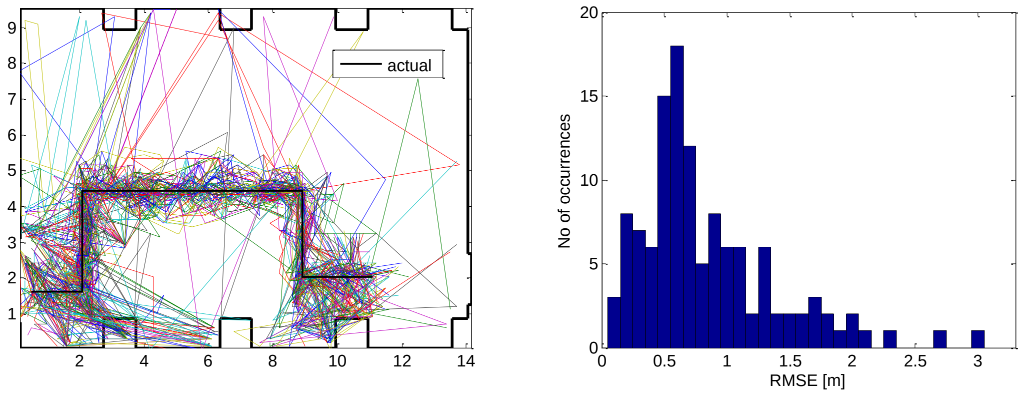


Figure 2: Example of tracking: actual and retrieved trajectories (left); histogram of the distance error (right).

At the conference the author will detail the effectiveness of the refinements achieved in both localization and tracking capabilities of the algorithm.

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# Indoor positioning using off-the-shelf FM radio devices

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## 1 Introduction

Indoor localization is important for many areas of ubiquitous computing research, such as activity recognition and prediction, assisted health care, tracking of people and objects, and others. The current de-facto standard of indoor positioning are Wi-Fi–based solutions. However, Wi-Fi coverage is limited in rural areas, developing countries and interference-sensitive environments. In cases when Wi-Fi infrastructure is not readily present, its deployment is expensive both in terms of hardware costs and required personnel qualification.

A cost-effective alternative to Wi-Fi is localization using FM radio signals. Previous works on FM positioning [1, 2] considered only outdoor environments and used specialised hardware. This paper, in contrast, focuses on indoor scenarios and FM receivers already present in many mobile devices, such as cellphones, MP3 players, pedometers, etc. The short-range FM transmitters used as beacons are available from conventional electronics shops, and are significantly cheaper than Wi-Fi access points. In this paper we present the results of experimental comparison of FM and Wi-Fi positioning accuracy. Also, we describe and evaluate a method for maintaining the system accuracy over time without any additional hardware.

## 2 FM indoor positioning

To evaluate the performance of FM positioning system, we placed three FM transmitters in corners of our lab (sized 12 by 6 meters). An HTC Artemis smartphone with an embedded FM tuner has been used to collect the received signal strength indicator (RSSI) values from each transmitter in different points of the lab. The measurement points formed a grid with 0.5 m step.

For location estimation we employed two machine learning methods, Gaussian processes regression and k-nearest neighbour (kNN) classification. The accuracy of the system has been evaluated using leave-one-out approach. One point was used for testing, while the other points were used as a training set; this was repeated for each point in the dataset. The median accuracy of the system was around 1 m for both methods (see Figure 1).

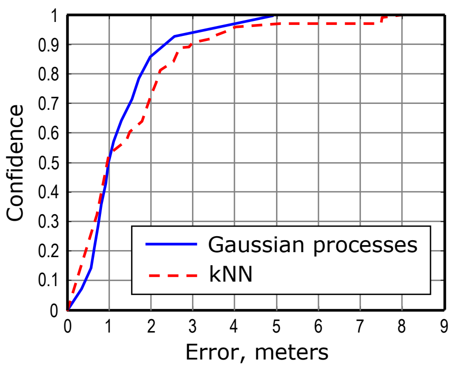


Figure 1: FM positioning accuracy

## 3 FM versus and with Wi-Fi

To compare the positioning accuracy of FM and Wi-Fi based solutions, we employed the other part of the collected dataset, which comprised Wi-Fi RSSI fingerprints from Wi-Fi access points collocated with FM transmitters. Unfortunately, due to firmware limitations, the mobile device reported Wi-Fi RSSI rather coarsely (6 distinct levels), while FM RSSI had about 50 levels. To mitigate this problem, we reduced the variety of FM RSSI values to 6 levels. This affects the positioning accuracy of FM, but ensures a fair comparison with Wi-Fi.

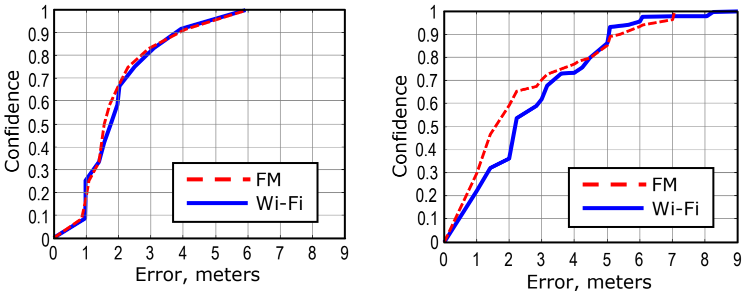


Figure 2: Comparison of FM and Wi-Fi positioning accuracy with Gaussian processes (left) and kNN (right)

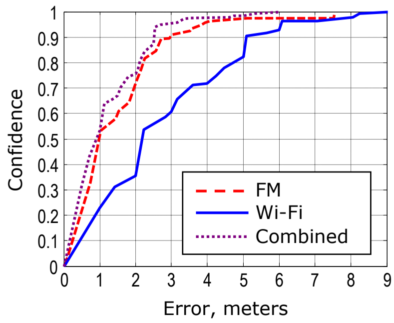


Figure 3: Accuracy of a combined FM+Wi-Fi system (kNN)

The comparison results are presented in Figure 2. As one can see, FM and Wi-Fi positioning have very similar performance. Moreover, if we merge the FM and Wi-Fi RSSI vectors into wider fingerprints, the accuracy of such a combined FM+Wi-Fi system becomes better than any of the underlying technologies alone (see Figure 3).

## 4 Spontaneous recalibration

A serious issue for fingerprinting-based systems is the temporal instability of RSSI fingerprints, which causes accuracy degradation. To maintain the positioning performance, one needs to perform periodic recalibration of the system, which is a tedious and expensive procedure.

In real life, however, the position of the client device can often be inferred from other context sources. For example, the device can detect when it is inserted in a desktop cradle, connected to a wall charger, or placed on a nightstand during nighttime. Knowing the true position of the mobile device, it is possible to update the fingerprint of the current and nearby points (using a simple signal propagation model). Thus the training set is being regularly updated in a way transparent for the user, and without any additional hardware. Figure 4 shows the change of the positioning accuracy over one-month period and the effect of spontaneous recalibration with five known positions.

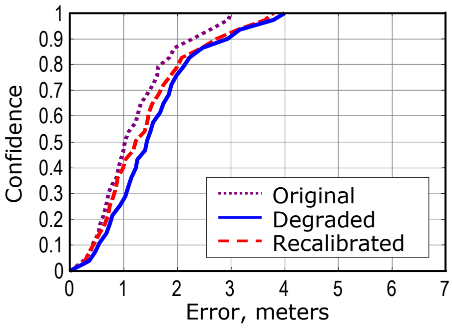


Figure 4: Effect of spontaneous recalibration (Gaussian processes, FM)

### Acknowledgements

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# RSSI localization with sensors placed on the user

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## 1 Extended Abstract

The presence of prospective high number of wireless transmitters in indoor spaces has motivated researchers to investigate whether their built-in received signal strength indicator (RSSI) could be exploited to gain information on the relative position of a receiver with respect to a number of transmitters. For this reason the RSSI range-based localization systems that use inexpensive, non-dedicated wireless devices have gathered great attention in the last years. Even though RSSI meters are not built to this end, but rather to give information to the higher communication protocol layers about the status of the communication link, their usage is highly attractive, because the information they give is obtained almost “for free”. As a consequence, many studies exist which, analytically, through simulations or through real measurements, analyse how a mobile can use RSSI relative to multiple wireless transmitters (anchors) to compute its position [1, 2]. This approach is popular because no additional hardware is required on the nodes for localization. In [3] the authors find that range-based methods perform better than connection-based ones under a given set of conditions. We find that these conclusions are consistent with the results sketched in our preliminary work. In [4] we concentrated on a single nomadic mobile, concluding that a Maximum Likelihood approach is able to exploit all available information, and has proven to be a powerful method to evaluate RSSI based localization methods.

The goal of this work is to expand the work in [4] by using a detailed ray-tracing simulation, in order to investigate the performance of indoor, single-room localization when multiple sensor nodes are placed on the mobile. This study does not lend itself to practical implementation of a localization method, but rather provides insight into performance assessment by using either one or more sensor nodes placed on the user. In other words, this study aims at answering the following questions: *How does the localization performance increase by using multiple sensors placed on the user? Is it possible to determine the direction where the user is facing?* We answer these questions by using a parameter estimation approach and by comparing three scenarios. The first scenario is based on only one sensor per user, and the other two scenarios with two and three sensors, respectively. Preliminary results show that the localization error decreases when passing from one to two sensors per user, but the performance does not significantly increase when using three sensors. This is expected, because the maximum likelihood method we use is able to take advantage of any added information. This means that adding receivers will certainly improve the accuracy of localization. However, since the method requires a precise map of the power distribution in the room and non-trivial computations, it is not directly applicable in practice. Its usefulness lies in its capacity to compare different solutions and put a high boundary on the ability of a given configuration to provide accurate localisation.

## 2 Preliminary results

We conducted preliminary simulations using the map of an office room at ISTI, CNR, in Pisa. Its size is 7.00 by 4.95 m, its height is 3.12 m. The room has a double door, a magnetic white-board, and a low metallic cabinet in the corner. The walls are made of gasbeton, the floor is wooden and there is a lightweight dropped ceiling. Both, the mobile and the anchors use a λ/2 dipole – λ being the wavelength at the 2$^{nd}$ channel of the IEEE 802.15.4 standard – which is about 62 mm. We use a three-dimensional deterministic propagation model based on an inverse ray-tracing algorithm which accounts for contributions up to third order reflections. The model evaluates first-order edge diffractions through heuristic UTD (UniformGeometrical Theory of Diffraction) dyadic diffraction coefficients, valid for discontinuities on impedance surfaces, and accounts for conductivity and permittivity of the wall materials. The grid of the map is narrow enough that we can assume we have all the information about RSSI on the considered plane. Let's now look at reflections inside the room, and how much they affect the RSSI pattern. Figures 2 and 3 show that the RSSI patterns are very complex, and even movements of a few centimetres can change the received value significantly. At the same time, for each given RSSI value, there are many, even far-apart locations in the room where the same value is received. For each scenario, the mobile receives RSSI information from a number of anchors, and for each grid of the map we will compute the likelihood for the mobile to be located at this position. Performance is computed as the localisation error for a given configuration. Our results show an expected increase in precision when the number of transmitters increase (Table I). The median error for 18 transmitters and a single receiver is 21 cm.

*Table I: Performance obtained with variable number of transmitters and a single receiver***.**

| Number of transmitters | 3 | 5 | 7 | 12 | 18 |
|---|---|---|---|---|---|
| Error (third quartile) | 356 cm | 300 cm | 267 cm | 145 cm | 73 cm |

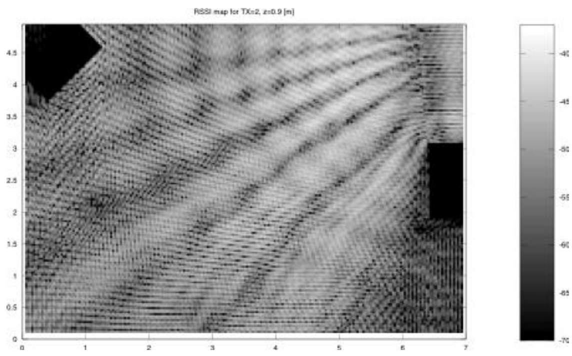

Fig. 2. Anchor in a corner, dipole slanted by 45°

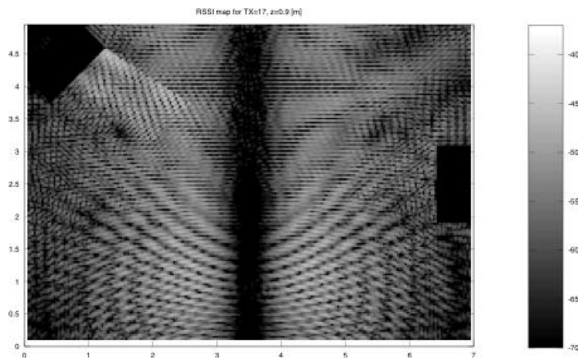

Fig. 3. Anchor in the centre of the room, horizontal dipole

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# Indoor Positioning Using Received Signal Strength of Iridium Satellites

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## 1 Summary

Iridium as one of Low Earth Orbiting (LEO) satellites emit high power signals which can easily pass into buildings. Therefore, one can receive its signals where no other signals can be reached. This paper tries to use signal strength of Iridium Satellites for indoor positioning.

The main idea in this paper is based on the determination of the user's position by measuring the signal power. At first the signal power pattern of iridium satellites in the building is simulated. Then, it is matched with the measured signal power in the receiver. Finally, the user's position is estimated with a specific level of precision. At the end, the self sufficiency of this method is discussed.

## 2 Introduction

Low Earth Orbiting (LEO) satellite signals can pass into high-rises and tall buildings. These signals pass through roof, walls, and windows to reach user's receiver and to transfer the information. However, the signal attenuation pattern is obviously different for each signal paths. But one can provide a specific signal power pattern inside a specific building.

From variety of LEO satellites, iridium satellites have been studied in this paper due to their high signal power and availability. Iridium satellites are orbiting the Earth at elevation of approximately 781 km. Moreover, the constellation has been designated to have excellent satellite visibility and service coverage at the North and South poles. These advantages make the iridium satellites useful for indoor positioning.

## 3 Methodology

In this paper, the signal strength or equivalently signal to noise ratio, is used for positioning. Furthermore, it is assumed that the map of the building is available for the user. The user can estimate the signal propagation pattern by using the map inside the building. Therefore, by matching the signal propagation pattern with the measured signal power, the user can be located with a specific level of precision.

In order to locate the user inside a building, there are some questions should be addressed. The first question is if the signal power pattern depends exclusively on the shape of building? In other words the question is if the position of satellite affects the pattern? The second question is if the signal power is different in different floors? If yes, then the user can be easily located within floors. Last but not least, the third question is about the level of precision with which the user can be located and if it is exclusively related to the shape of the building or not?

In order to answer these questions, this paper simulates the signal propagation inside the building. It is investigated whether the signal power pattern is the same by changing the satellite's position or not. Moreover, the signal power differences in different floors are also evaluated. It enables one to discriminate the specific floor the user is on. In addition, this simulation can provide a good insight about the expected precision of the estimated position based on the precision of the measured signal power at receiver.

Figure 1 shows the simulated signal power of iridium satellites in one floor building with a door and window.  It is assumed that the receiver is located at the centre of the building. This simulation presents the received signal power of iridium satellites in all directions.

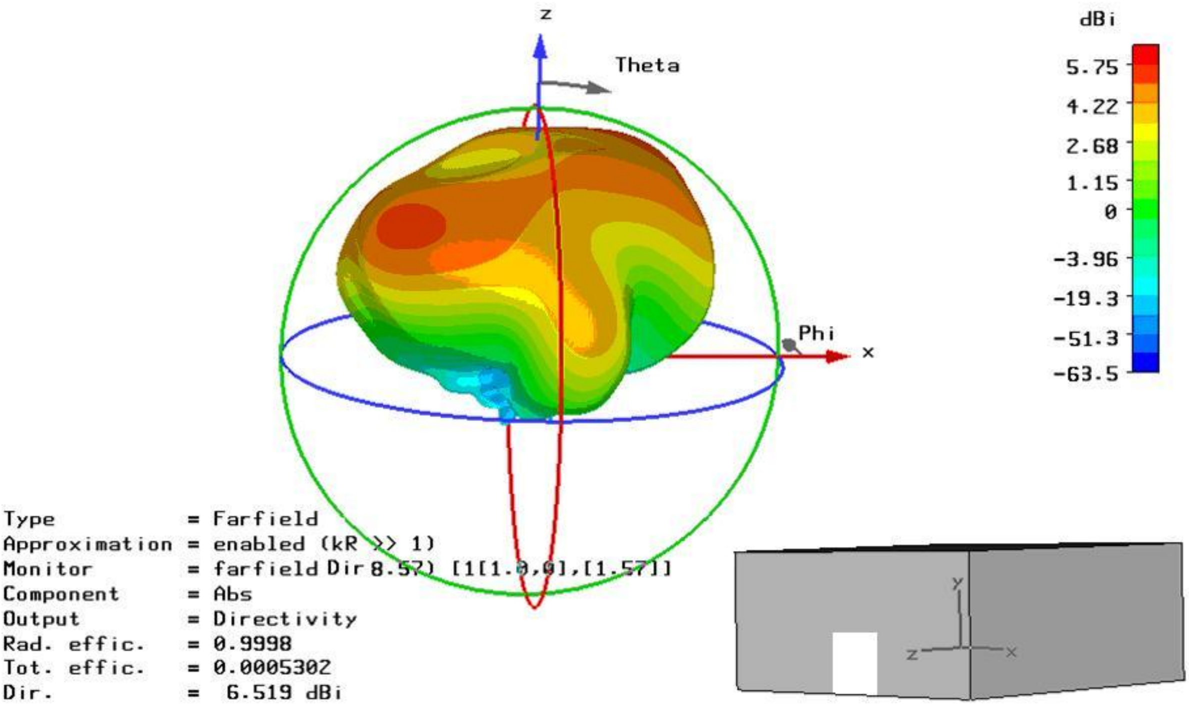


Figure 1: The received signal power of iridium satellites at the centre of a specific building.

## 4 Conclusions and Outlook

Last but not least, it is discussed if this method alone can estimate the user's location inside the building or it should be integrated with other methods.

**WLAN RSS (Signal Strength Based Methods), Fingerprinting**

Auditorium G7

Wednesday, September 15, 16:00 – 18:00

Thursday, September 16, 08:15 – 09:45 & 10:15 – 11:45

# RSSI-based Euclidean Distance Algorithm for Indoor Positioning adapted for the use in dynamically changing WLAN environments and multi-level buildings

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## 1 Summary

This paper presents a fingerprinting positioning algorithm for WLAN environments based on Euclidean Distance (EDA). The adapted algorithm can be used in large and dynamically changing environments and multi-level buildings. Evaluation results show a reduction of median location estimation error (LEE) from 12m using standard EDA to 2.12m when the adapted EDA is used. The discrete vertical z-coordinate could be estimated correctly in 97.45% of cases. Moreover, it is shown that the calibration effort can be reduced clearly by using larger calibration grids with an acceptable increase of LEE.

## 2 Introduction

For indoor localization in WLAN environments Received Signal Strength Index (RSSI) based methods may be used to determine the current position by fingerprinting and Euclidean distance algorithm ([5]). In large areas of measurement or in dynamically changing environments the basic Euclidean Distance algorithm shows large location estimation errors. This paper presents an adapted and improved algorithm for the use in dynamically changing environments.

## 3 Related Work

The RADAR System ([1]) uses EDA with affixed set of base stations (BS) together with a signal propagation model. A positioning system for industrial automation with automatic calibration was developed by Ivanov ([4]). This system is able to perform automatic measurement and model calibration so that no manual measurements are necessary. The Ekahau Positioning Engine ([2]) is a commercially available software using RSSI based WLAN indoor positioning. Another approach for getting reasonable accuracy in positioning as well as accurate continuous information about the current position on the z-axis is shown in Woodman and Harle ([6]). They use a foot-mounted inertial sensor combined with WLAN based RSSI algorithms.

## 4 Algorithm

Within permanent environments where all base stations can be received at all calibration points the number of received base stations *n* is constant. The basic Euclidean Distance algorithm can be used with a location estimation error of 2.33m ([3]). Within dynamically changing environments the basic EDA shows a drastically increased LEE. Dynamically changing environment means either sets of base stations varying from calibration phase to positioning phase for one specific calibration point or varying sets of received BS between neighbouring calibration points.

Within dynamically changing environments four specific problem cases are identified:

**Case 1**: A BS is measured in calibration phase but not in positioning phase,

**Case 2:** A BS is measured in positioning phase but not in calibration phase,

**Case 3**: Number of matching BS within calibration and positioning tuple too low,

**Case 4**: RSSI-values of positioning and calibration tuples too low.

The algorithm is adapted to handle these four different cases by not considering specific RSSI-values which either exceed specific threshold values or meet specific circumstances (e.g. BS measured in calibration phase but not in positioning phase). Therefore three different threshold values are introduced.

## 5 Evaluation and Results

Results from a series of measurements over three storeys in a building at University of Applied Sciences and Arts in Dortmund show that the number of matching BS (BS with valid value in calibration and positioning tuple) must be four or larger to receive adequate results. With lower numbers of matching BS estimation's quality worsens significantly.

The standard Euclidean distance algorithm shows very poor results with a median LEE of 12m. Using the adapted EDA leads to a decrease of median LEE to 2.12m.

The improved algorithm is evaluated using single position estimation values and with a moving median filter. With moving median the n last estimated positions are used to calculate a median from the position coordinates. The median LEE with single values and moving median are nearly identical (2.12 and 2.06m) with the advanced algorithm. The 90% value of LEE however decreases from 7.00m to 5.25m, the 95% LEE decreases from 9.25m to 7.00m. The maximum LEE shows the most dramatic changes. It decreases from 45.04m to 10.51m. The discrete vertical z-coordinate is estimated correctly in 97.45% of cases.

For the reduction of calibration effort different grid sizes are simulated using a subset of calibration points with basic 1m x 1m grid. When using a less dense calibration grid the median LEE increases from 2.12m (1m x 1m) to 3.35m (3m x 3m) and 3.64m (6m x 6m).

## 6 Conclusions

This paper shows that the presented adapted Euclidean distance algorithm can deal with dynamically changing WLAN environments and shows reasonable results. Three threshold parameters must be set correctly to receive reasonable results. This leads to additional calibration effort. It is shown that the calibration effort can be reduced clearly by using larger calibration grids with an acceptable increase of location estimation error.

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# Indoor Positioning Using WLAN Coverage Area Estimates

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Location fingerprinting is a positioning method that determines the location of a Mobile Terminal (MT) using a database of radio characteristics. Fingerprinting methods have been widely studied in indoor positioning and they have been reported to provide adequate accuracy for most location based services in indoor environments. The state of the art methods in indoor positioning collect WLAN Received Signal Strength Indicators (RSSI) at predefined locations and use Weighted K-Nearest Neighbor (WKNN) to estimate the position of MT. The fingerprints are collected during the calibration phase and each fingerprint consists of a list of heard WLAN Access Point (AP) Media Access Control (MAC) addresses, corresponding signal strengths and the coordinates of the fingerprint. The scheme is straightforward, but there are several difficulties. First, the calibration phase is very laborious, and large (in some cases extremely large) databases need to be constructed and processed. Secondly, these methods are based on variations of RSSI values as a function of position. However, WLAN chipset vendors use different RSSI definitions and the scales of different RSSI values vary from one chipset to another. As a result, RSSI values collected with different types of MTs are not comparable with each other. Thirdly, even small changes in the environment may have a huge effect on RSSI values, and the positioning performance degrades if the fingerprint database is not up-to-date. Finally, if the positioning calculations are carried out in MT, the amount of data transmitted between the network and MT might be too much even if the data is compressed using kernel approximations.

In this paper, the fingerprint data are compressed into coverage area estimates. In our approach, the collected fingerprints are divided into location reports by MAC addresses. For every MAC address there is a list of location reports, where the location reports are the coordinates at which an AP is hearable by MT. These location reports are used to estimate the coverage area of an AP. The coverage area estimates are assumed to be ellipse-shaped and only require the storage of five floating point numbers, and thus are easy to store in a database and to transmit to MT. The parameters of the coverage area are the location and shape parameters of the coverage area distribution and the parameters are assumed to be random variables. Location reports are assumed to follow a multivariate normal distribution, and the unknown parameters of the coverage area are found by calculating the posterior distribution of the parameters. The Bayesian approach is used because it allows fast recursive estimation and update of the coverage area estimates, and the use of a Bayesian prior, which models the subjective information about a typical coverage area. This information is especially important when there are only a few location reports from WLAN AP.

In the positioning phase the MT reports the MAC addresses of the heard APs and uses the coverage area estimates as measurements. The idea is to find the most probable location of MT given the detected APs. The distribution of the location can be derived using Bayes' rule. The distribution of the location follows a normal distribution, where the mean is a weighted average of the location parameters of the coverage areas and the weights are determined by the shape parameters of the coverage areas.

Integration of map information is one obvious way to enhance the positioning accuracy indoors. Digital floor plans are nowadays available for many significant buildings, such as hospitals, shopping malls and airports, and they can be easily used to improve the positioning accuracy indoors. It is known that map matching (i.e. projecting the positioning result to an indoor location) can be used to improve the performance of indoor positioning systems. The floor plan can also be used to restrict the location's probability distribution. The algorithms can utilize the outer walls of the buildings, or more detailed floor plan information can be used.

Positioning filters are applied in order to combine the new measurements with the past measurements and the motion model of MT. The Kalman Filter (KF) has been studied and applied extensively in positioning applications. KF assumes linear measurement function, Gaussian initial distribution, and mutually independent Gaussian measurement and motion model noises that are independent of the initial state. If these assumptions are met, KF offers a closed form solution for the posterior distribution of the state. If the distribution of position is restricted, the assumptions of KF are no longer valid and the posterior distribution of position cannot be calculated analytically. In situations like this, it is possible to use Particle Filters (PF), which use weighted particles to approximate the posterior distribution. PF usually produces a good estimate for the posterior distribution, but it requires a lot of computation compared to KF. One solution is to approximate the restricted posterior distribution with a Gaussian and use KF, or with a mixture of Gaussians and use Gaussian Mixture Filter (GMF).

This paper introduces different ways to use a floor plan in indoor navigation. Different methods are tested with real data collected from WLAN APs. The static location estimation method is compared with KF. We also investigate how the floor plan improves the position estimate and use PF and GMF for the position calculation. We also estimate the restricted posterior distribution of the state with Gaussian and use KF. This approach does not give as good estimate for the posterior as mixture of Gaussians, but it requires less computation than GMF and PF.

Results show that the location accuracy can be improved by limiting the number of heard access points during data collection and positioning. If only the strongest access points are taken into account during data collection, the coverage area estimates become smaller and lead to a more accurate position estimate. The filtering framework gives a more accurate position estimate than the static method. The floor plan also improves the positioning accuracy. The results indicate that PF gives the best positioning performance. KF and GMF, however, achieve almost the same accuracy as PF with smaller computational load. Altogether, the coverage area based positioning does not achieve the same accuracy as the traditional location fingerprinting. This method, however, compresses the fingerprint data into coverage area estimates. Thus the coverage area based method could also be used for large-scale solutions. Also, the Bayesian approach allows the use of recursive update formula of the coverage area estimates. Moreover, this coverage area based positioning method does not need RSSI values and thus it can be used with all types of MTs.

# Algorithmic Strategies for Adapting 802.11 Location Fingerprinting to Environmental Changes

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## 1 Summary

This paper studies novel algorithmic strategies that enable 802.11 location fingerprinting to adapt to environmental changes. A long-standing challenge in location fingerprinting has been that dynamic changes, such as people presence, opening/closing of doors, or changing humidity levels, may influence the 802.11 signal strengths to an extent where a static radio map is rendered useless. To counter this effect, related research efforts propose to install additional sensors in order to adapt a previously built radio map to the circumstances at a given time. Although effective, this is not a viable solution for ubiquitous positioning where localization is required in many different buildings. Instead, we propose algorithmic strategies for dealing with changing environmental dynamics. We have performed an evaluation of our algorithms on signal strength data collected over a two month period at Aalborg University. The results show a vast improvement over using traditional static radio maps.

## 2 Description

In recent years outdoor positioning and navigation systems have become household commodities due to continuously dropping costs of accurate GPS equipment. To facilitate an equally wide scale consumer adoption of positioning and navigation in indoor spaces, 802.11 (Wi-Fi) is an obvious technological choice due to the ubiquity of Wi-Fi infrastructures and the proliferation of Wi-Fi- (and GPS-) enabled mobile devices. Due to the somewhat unpredictable propagation patterns of Wi-Fi signals in indoor environments, the so-called *location fingerprinting* technique, which relies on empirically measured signal strengths, has yielded the best results in terms of obtainable positioning accuracy.

The main drawback of the technique, however, lies in the manual calibration effort needed to build the radio map. The problem is compounded by the fact that the collected signal strengths often have only limited temporal validity. Dynamic environmental changes, e.g., a varying number of people present, changing humidity levels, or the opening and closing of doors, means that signal strengths collected at one time may not accurately predict the signal strengths at other times. As a result, positioning accuracy decreases and the time and effort in building the radio map is essentially wasted. While the majority of research has assumed a static radio map, i.e., a radio map which is built once, Yin et al. [2005] and Chen et al. [2005] take the dynamic aspects into account by adding additional sensors to query the dynamics at a given time. While this approach does capture the signal strength changes, it is not well suited to ubiquitous positioning because only few buildings can be expected to accommodate the required, additional hardware.

The algorithms studied in this paper are part of the Streamspin system, a platform that supplies ubiquitous, user-driven indoor-outdoor positioning [Hansen et al. 2009]. The user-driven aspect of Streamspin refers to the fact that users upload fingerprints to an ever-evolving radio map with the aim of providing up-to-date signal strength information. We consider two distinct algorithms for adapting to different signal strengths caused by dynamic changes in the environment. To evaluate the accuracy of the algorithms, we apply them to signal-strength data collected over a two-month period at Aalborg University.

The algorithms are compared with two traditional approaches: a baseline approach that builds a radio map once (called Baseline-Single in Table 1) and a baseline approach that combines all received fingerprints into a single fingerprint (Baseline-Collected). Our first algorithm uses the notion of interval trees. Here, the fingerprints supplied by Streamspin users are sorted according to the time of day they were measured and split into several subtrees that capture the characteristics at different time periods. Our second algorithm does not explicitly consider the temporal aspect, but instead uses a divisive clustering technique with a single linkage criterion to group similar fingerprints together.

Table 1 outlines the main results. Scenario 1 depicts the case when there is little variation in the signal strengths. In this case, our two algorithms perform only marginally better than the Baseline-Collected approach. Using a single fingerprint results in the worst accuracy as the average positioning error is ca. 5 meters. A substantial difference is evident in Scenario 2 where signal strength variations occur. The accuracy of the Baseline-Single approach deteriorates by 1.5 meters, while the Baseline-Collected is affected particularly severely because it now contains widely differing signal strengths. In contrast, our two algorithms are more or less able to retain the accuracy. The very minor deterioration can be attributed to a loss of signal strength information as the information has been distributed in several clusters and interval tree nodes, respectively. These results demonstrate that the adverse effects of changing signal strengths have been avoided. Moreover, due to the algorithmic nature of our solutions, they are a perfect fit for systems that are meant to scale to several buildings without incurring any additional hardware costs.

Table 1: Average accuracy of the different algorithms in meters

| | Baseline-Single | Baseline-Collected | Interval Tree | Clustering |
|---|---|---|---|---|
| Scenario 1 | 5,16 | 1,48 | 1,13 | 1,42 |
| Scenario 2 | 6,68 | 9,99 | 1,30 | 1,71 |

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# Fault Tolerant Positioning using WLAN Signal Strength Fingerprints

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## 1 Summary

In this extended abstract we present our ongoing research on WLAN positioning. Our focus is on the fault tolerance of positioning methods, rather than the absolute accuracy in case of no faults. We introduce several fault models to capture the effect of AP malfunctions or malicious attacks during positioning and describe how these models can be applied in practice. We compare some well-known algorithms in terms of fault tolerance and present preliminary experimental results on their accuracy degradation as the percentage of faulty APs increases.

## 2 Fault Models for Positioning

A wide variety of fingerprint-based methods have been proposed that rely on Received Signal Strength (RSS) samples from available Access Points (AP). The focus of these methods so far has been on improving accuracy. In real world, however, APs can fail or exhibit erroneous behaviour, thus compromising the performance of these methods. For instance, RSS attack models are considered in [3] that perturb the original samples by an attenuation or amplification constant. Fault tolerance is an important issue that has not been addressed adequately. Our main contribution is to define realistic fault models, study the performance of positioning algorithms in the presence of faults and motivate future research in this direction.

First, we consider the case where several APs used in the training phase are not available during positioning. This can be caused by random AP failures, e.g. due to power outages, or when an adversary cuts off the power supply of some APs. Under this Fault Model, denoted as $FM_a$, we remove faulty APs from the original test data. Our second model ($FM_b$) captures the effect of relocating a set of APs and thus a faulty AP is detected inside an area that is different than the expected one. We simulate $FM_b$ by replacing the RSS readings of the corrupt AP in the test data with the values of a randomly selected AP. In another case, an AP may no longer be detected in some locations inside its original Region of Coverage (RoC), e.g. due to an obstacle that blocks the propagation path. Note that such an obstacle could be placed by an attacker in front of the AP antenna. This can be modelled by ignoring valid RSS readings for a set of APs in some test fingerprints ($FM_c$). Finally, an AP may be detected in locations outside its original RoC, e.g. by deliberately increasing the AP transmit power or by impersonating an existing AP. We model this by injecting random RSS values to some test fingerprints for a set of APs that would otherwise be undetected in those test points ($FM_d$).

## 3 Experimental Results and Conclusions

We used a typical 100x45m office setup with 31 APs installed in total and identified 107 reference points, while each point is covered by 9.7 APs on average. As a training set, we collected 30 fingerprints per reference point using a smart phone. We also recorded 192 fingerprints by walking on a path and sampled the same path 3 times, as test data. The reference points and the points inside the RoC of a single AP with the RSS levels are depicted in Fig. 1.

We compare the KNN algorithm [1], the probabilistic MMSE approach [2] and a KNN variant [3] that employs a median, instead of the Euclidean distance measure to alleviate the effect of faulty APs (medKNN). We also adapted the SNAP algorithm, presented in our previous work [4], to accommodate measurements of variable RSS levels, instead of binary data. Results are reported with respect to the mean positioning error ($m_e$) pertaining to the test data. When faults are injected the error is averaged over 100 runs using different sets of faulty APs.

In the fault-free case, $m_e$ is 3.8m, 2.7m, 2.5m and 3.3m for SNAP, KNN, MMSE and medKNN methods, respectively. In Fig. 2-5, $m_e$ is plotted as a function of the percentage of corrupt APs assuming the fault models discussed previously. The modified SNAP method is extremely robust when AP failures occur and has graceful accuracy degradation as the percentage of unavailable APs increases (Fig. 2). Results in Fig. 3 indicate that SNAP and medKNN methods have similar performance and are slightly better compared to KNN and MMSE. When $FM_c$ is used, SNAP performs better especially as the percentage of corrupt APs increases beyond 50%, followed by medKNN; see Fig. 4. If we consider $FM_d$, then the accuracy of both KNN and MMSE degrades rapidly, as seen in Fig. 5. On the other hand, $m_e$ remains relatively unchanged for SNAP, even when all APs are corrupted, and the latter outperforms medKNN method if more than 40% of the APs are faulty. In conclusion, the modified SNAP algorithm is a promising approach that we plan to study further. We will also work on modifications to other algorithms with the aim to improve their fault tolerance.

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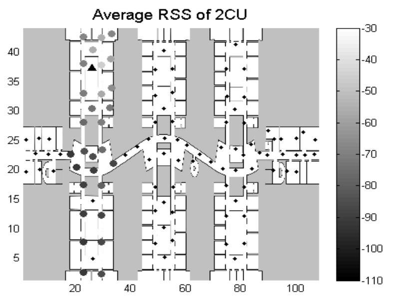


Fig. 1: Floorplan of the experimentation area.

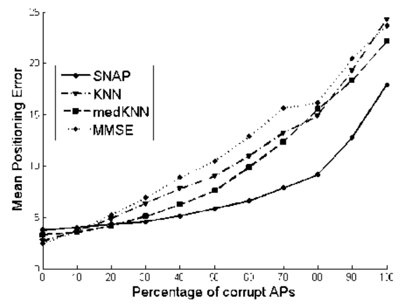


Fig. 2: Performance under $FM_a$.

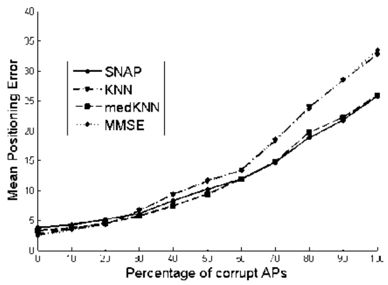


Fig. 3: Performance under $FM_b$.

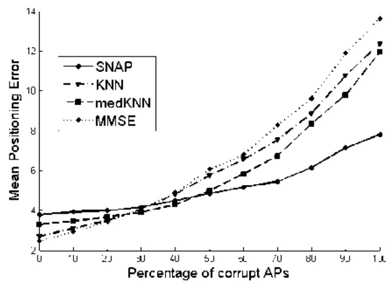


Fig. 4: Performance under $FM_c$.

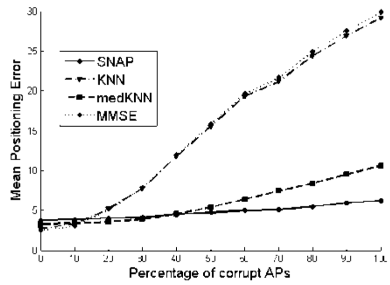


Fig. 5: Performance under $FM_d$.

# Implementation of Hyperbolic Location Estimation Using RSSI in WLANs

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## 1 Summary

As the deployment of Wireless Local Area Networks (WLAN) in dense-urban areas is growing rapidly, it can be a perfect supplement for providing location information of users in indoor environments and metropolitan areas, where other positioning techniques such as GPS, are not much effective. In this study, we propose a new WLAN positioning method that combines Received Signal Strength Indication (RSSI) fingerprinting and Time Difference-of-Arrival (TDOA) positioning techniques, which will provide reliable location accuracy and does not require any additional changes on actual WLAN infrastructure.

## 2 Proposed Algorithm

The RSSI-based indoor localization systems are growing in importance among other indoor positioning techniques, because of its availability on all existing WLAN equipments. The RSSI fingerprinting algorithm is normally organized by two steps: calibration and online tracking [1]. The calibration process builds RSSI fingerprint database of a target site in each location. During online tracking, the location of the mobile user is determined, by matching the RSSI value of the received signal to the closest fingerprint value.

In order to increase the location accuracy, we approached to online tracking phase differently, by applying TDOA positioning technique. Several studies have been proposed for applying TDOA positioning technique in WLANs [2]. Since the access points in IEEE 802.11 based WLANs do not provide timing information between user equipments, the implementation of TDOA needed changes on actual WLAN infrastructure to estimate the distances from access point (AP) to mobile station (MS). We approached the estimation of these distances by building RSSI fingerprint database and applying obtained values on one-slope prediction model (OSM) to calculate them with higher accuracy. The OSM assumes a linear dependence between path loss and logarithm of distance (*d*) from MS to AP [3] i.e.:

$$PL(d)[dB] = PL(d_0) + 10\gamma \log 10(d / d_0) \quad (1)$$

where, $PL(d)$ is the RSSI value at the mobile station and the $PL(d_0)$ is the closest reference point at distance $d_0$ (distance from AP to reference point) which we obtained during the calibration process. And, $\gamma$ specifies the path loss behaviour for a particular type of building [3]. From this equation we can derive the distance (*d*) between MS and AP:

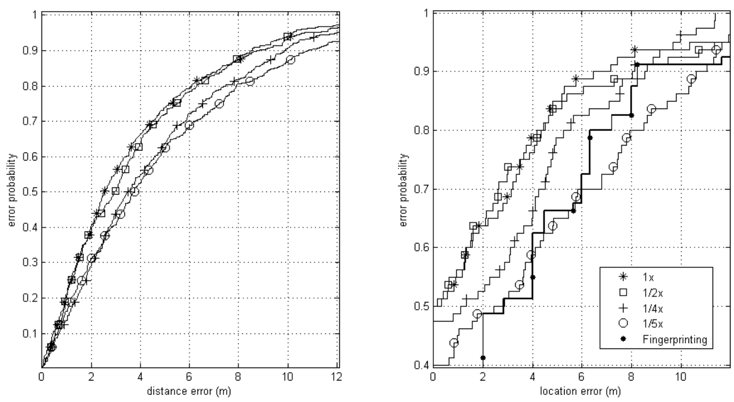
$$d = \left( 10 \frac{PL(d) \cdot PL(d_0)}{10\gamma} \right) \cdot d_0 \quad (2)$$

Since the $PL(d)$, $PL(d_0)$ and $d_0$ are known, we can use (2) to calculate the distances between *m* number of available APs and the MS. In general, distance estimation using OSM produces huge errors; however, we minimized the error by utilizing the data collected from target area.

After calculating all available distance information from each AP to MS, we make the *n* number of 3-AP combinations from all APs. Then, we apply Chan's three-sensor based hyperbolic location estimator [4] to each of these combinations and get *n* number of estimated location coordinates. On the final stage of our algorithm, we apply least median of squares (LMS) estimation technique [5] to select the best MS position from obtained set of coordinates.

## 3 Experimental Results

To evaluate our new algorithm, we built a test field at the Regional Innovation Centre (RIC) building of Yeungnam University (South Korea) with the total size of $1460m^2$. During the calibration process, we collected RSSI data every 2 meters of the test area and measured distances from APs to MS using this data (1x). Next, we calculated these distances with two, four and five times reduced number (1/2x, 1/4x, 1/5x) of reference points to compare the accuracy. Figure 1(a) shows the estimated distance accuracies from 5 selected APs to multiple MS positions located in the building. As we can see from this figure, the proposed algorithm can provide 4-6 meters accuracy within the 70% of time even with the reduced number of reference points. On the positioning phase of the algorithm, we used obtained distance information to locate mobile stations. Figure 1(b) displays the comparison of location accuracy of proposed algorithm and the original fingerprinting algorithm. It shows that, the proposed algorithm can provide a higher accuracy compared to the original fingerprinting method. On the other hand, it can also provide almost the same accuracy as conventional method, while reducing the number of reference points by 5 times. Thus, there is a trade-off between the number of reference points and the location estimation accuracy.




(a) Distance Accuracy (b) Location Accuracy

Figure 1. Field test results

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# A Perspective on Robustness and Deployment Complexity for RSS-based Indoor Positioning

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## 1 Summary

There are two major issues with practical deployment of RSS-based indoor positioning systems. These issues are coverage design (or equivalently reference node placement strategy) and development of the measurement-based radio-map. In this research, each problem is described and possible techniques that can simplify each problem are suggested. In the process, it shown that there is an elegant trade-off between these issues where simpler coverage design could lead to a higher complexity radio-map and vice versa. Various experiments and simulations are provided to demonstrate the results.

## 2 RSS-based Indoor Positioning Algorithms

Techniques based on the Received Signal Strength (RSS) have been extensively studied in the literature. These techniques, although, sometimes less accurate compared to more complex range-based techniques, are very simple to implement and offer low cost and effective alternatives for some applications. The core idea is to establish a relation between the received signal strengths from a few reference nodes and the current position of the mobile.

In order to provide location-based services with reasonable accuracy at indoor environments, the mobile needs to have the visibility of at least three reference nodes (i.e. anchor nodes) at all desired locations throughout the service area at all times. This is a much more complicated coverage design problem than its WLAN (i.e. data communication services) counterpart. This visibility must be maintained all throughout the service area. Since the building layout, construction material of the walls and other objects in the environment as well as maximum transmission power directly impact the coverage area of each node, reference nodes placement could have a great impact on the system performance. The placement strategy is a difficult coverage design problem, which currently does not have a straightforward or automated solution.

One solution to this problem is using reference nodes that are capable of acquiring multi-dimensional information from the received signal. This information could be RSS versus AoA (i.e. Angle of Arrival). For example, if the reference node can measure RSS from various directions, then the triple-coverage requirement problem can be avoided. This is achieved at the expense of a more complicated radio map generation process. Various simulations and experiments that show the accuracy and coverage effectiveness of this approach are presented.

Another drawback of most RSS-based techniques is the need for a measurement-based training phase, during which the radio map of the environment is created. These measurements need to be carried out prior to the normal operation of the system and are often necessary to be updated to compensate for changes in the environment. This radio map essentially contains the received signal strength from all reference nodes throughout the service area. The process to generate a radio map is not only labor-intensive and costly, but also very sensitive to possible sources of interference in the building. Therefore, there is a need for robust methodologies to eliminate this offline training phase that could be an obstacle in the practical implementation of these systems. Here, a novel idea that employs a model-based radio-map generation (based on ray-tracing) is presented and the performance of the proposed system (at NIST/ITL) is discussed.

## 3 Trade-off between Coverage Design and Radio-Map Development Complexity

Looking at the two issues discussed in the previous sections, there seems to be a trade-off between coverage design (or equivalently reference node placement complexity) and robustness against model-based radio map. Consider reference node density to be the average number of reference nodes per unit area. On one hand, it is desirable to have low reference node density to enable sufficient coverage for positioning services; while on the other hand, higher reference node density could provide a level of protection in the mobile signature that represents its position. This is analogous to the channel coding problem where redundancies are added to the raw information in order to combat adverse effect of the channel. By adding the redundancy, each codeword will be able to tolerate more channel impairment and as a result the system will exhibit lower average error.

Methodologies that can achieve high degree of robustness while maintaining low reference node density would be preferable candidates for easily deployable commercial applications. Although, our results show that simultaneous achievement of both objectives might not be possible, the methodologies presented in our research provide solutions that exhibit reasonable accuracies for low complexity indoor positioning services. Various results from experiments and simulations (with WLAN and Zigbee-based sensor networks) are provided to demonstrate the conclusions.

## 4 Conclusions and Outlook

Although, the requirements of a particular application could impact the choice of the architecture for a positioning system, for most commercial applications, it is desirable to have a system that is easily deployable and exhibits robustness against changes in the environments, interference and propagation model imperfections. Eliminating the offline measurement-based training phase is an essential step in providing robust methodologies that are implementable on low cost, low complexity infrastructure. This is an obstacle in practical implementation of positioning systems that are quickly deployable on commodity networks such as 802.11-based technology or sensor networks. Further research and studies need to be done before such systems can have widespread applications in our daily life.

# Wi-Fi Positioning: System Considerations and Device Calibration

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## 1 Summary

Due to the increasing number of public and private access points in indoor and urban environments, Wi-Fi® positioning becomes more and more attractive for pedestrian navigation. In the last ten years different approaches and solutions have been developed. In this article influences of the surrounding environment, the Wi-Fi infrastructure and hardware characteristics are presented and evaluated with a focus on the so called Wi-Fi fingerprinting technique for positioning. Based on this analysis a calibration approach for Wi-Fi devices is proposed and conclusions are drawn.

## 2 Wi-Fi Positioning and Testbed

Wi-Fi positioning is done by correlating received signal strength (RSS) measurements with entries of a fingerprinting database. The database is created by previously obtained RSS measurements and referenced with the coordinates of the position where they have been observed. As a testbed for positioning the metropolitan area of Nuremberg, Fürth and Erlangen is used. The comprehensive database contains about 50,000 fingerprints. About 60,000 unique access points have been observed.

## 3 Influences of Environment and Infrastructure

Each environment has characteristical signal propagation. The RSS at a specific position depends on the path loss, shadowing by objects and multipath propagation. The higher the density of shadowing objects, the higher is the accuracy of Wi-Fi positioning, as different fingerprints are less similar in signal space. Therefore, indoors Wi-Fi positioning works very well because of the building structure and furniture. Outdoors, especially on large squares the database correlation results in multiple ambiguities. Changes of the environment and moving shadowing objects, like cars, persons and the user, are not considered and therefore limit the accuracy and can lead to temporarily high positioning errors.

One advantage of Wi-Fi positioning in urban environments is that the infrastructure is already set up. Existing private and public access points can be used. Therefore, the infrastructure cannot be controlled. Positioning suffers from unobserved changes over time and the number of available access points varies from one place to another. To get meaningful positioning results at least three access points must have been observed. In areas with Wi-Fi coverage the average number of access points per fingerprint within the testbed is 12.6.

## 4 Characteristics of Mobile Wi-Fi Devices

Various Wi-Fi modules have found their way into many flavours of standard consumer hardware, like mobile phones, laptops, personal digital assistants and MP3 players. As Wi-Fi positioning relies on measured absolute RSS values, the characteristics of the different modules have to be considered. In Figure 1 the measured discrete RSS values of four mobile devices are depicted for one access point. The devices have been placed next to each other for several hours during night to exclude environmental changes. The measured RSS values differ significantly.

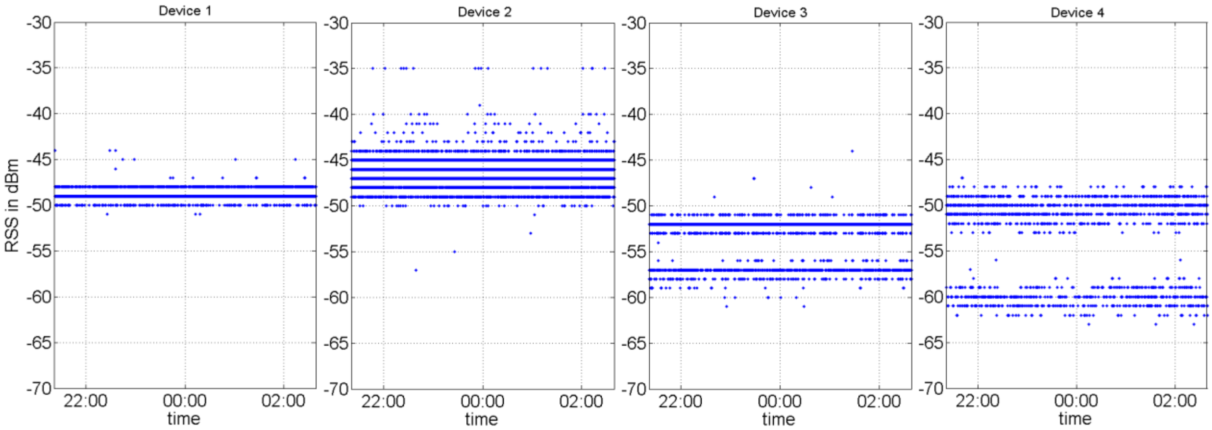


Figure 1: Stationary RSS measurements of one access point measured with different mobile devices

Differences in e.g. measured mean values, standard deviations, polling interval, number of received access points and percentage of incorrect measurements have been observed.

## 5 Calibration Approach for Mobile Wi-Fi Devices

In order to achieve similar positioning results with different mobile devices there is a need for classification of the hardware characteristics to enable calibration. A classification approach is depicted in Figure 2. Parameters like polling interval, ability to observe hidden access points, offset compared to a reference device and standard deviation can be determined and used for calibration. Re-calibration is necessary if there are changes in Wi-Fi drivers, firmware or hardware.

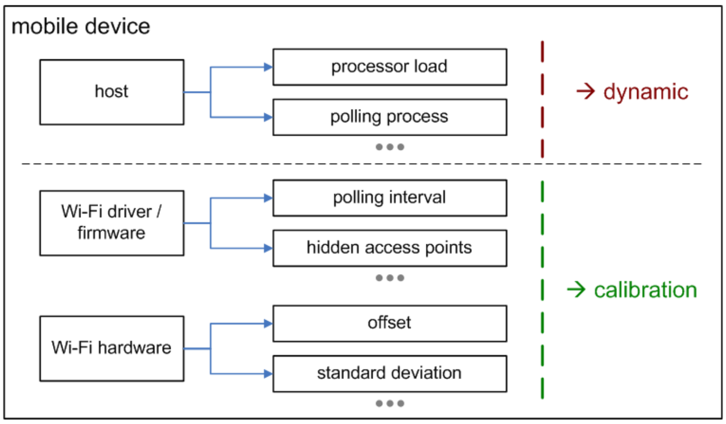


Figure 2: Classification of characteristics for mobile devices

## 6 Conclusions and Outlook

In this article influences on Wi-Fi positioning caused by the environment, the infrastructure and the measurement characteristics of different mobile Wi-Fi devices will be discussed. To improve positioning accuracy there is a need for calibration. Therefore, the measurement behaviour of Wi-Fi modules will be classified. A calibration approach will be presented. In order to validate the approach measurement results from the introduced testbed will be presented and discussed.

# An Indoor Location Based Service Using Access Points as Signal Strength Data Collectors

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**Summary**

WLAN location determination algorithms can be classified into client-based approach and infrastructure-based approach. Unlike the other infrastructure-based algorithms, we proposed a calibration-free infrastructure-based indoor location determination algorithm using access points as signal strength data collectors. In the proposed system, each access point runs OpenWrt, Kismet, and MySQL for collecting signal strength data from other access points and mobile devices. The location server builds a RSSI vs. Distance model based on inter-APs RSSI measurements and then predicts the location of mobile device based on the received signal strength measurements of all access points from the target mobile device. A location based service which provides timely class notes in a university environment is also presented in this paper to show the possible applications of the proposed technique.

**Introduction**

WLAN location determination algorithms can be classified into client-based approach and infrastructure-based approach. In client-based approach, the location determination process proceeds in two steps, off-line and real-time phases. In off-line phase, the radio map for the surveyed area is built. In real-time phase, a wireless client, which has a software installed for extracting the Received Signal Strength Indicator (RSSI) values, measures the RSSIs from APs and sends the RSSI vector to the location server for location prediction. This approach needs laborious work for calibration of RSSIs in the off-line phase, and it also requires the installation of a software for client readings of RSSIs from APs in range. To remedy these problems, the infrastructure-based approach was proposed.

The infrastructure-based approach is also called a calibration-free technique because the laborious off-line phase is not required. Depending on whether the RSSIs measured on wireless clients are needed, we can distinguish the infrastructure-based approach into client reading model and non-client reading model. As we mentioned before, the client reading model still needs the installation of RSSI measurement software in mobile device. For non-client reading model of infrastructure-based approach, the techniques of using special sniffers or emitters for collecting RSSIs from APs and mobile devices have been proposed in the literature.

***Proposed Method***

In this paper, we proposed a non-client reading model for infrastructure-based indoor location determination using access points as signal strength data collectors. In the proposed system, as shown in Figure 1, each access point runs OpenWrt, Kismet, and MySQL for collecting signal strength data from other access points and mobile devices. The location server builds a RSSI vs. Distance model based on inter-APs RSS measurements and then predicts the location of mobile device based on the received signal strength measurements of all access points from the target mobile device. A location based service which provides timely class notes in a university environment is also presented in this paper to show the possible applications of the proposed technique.

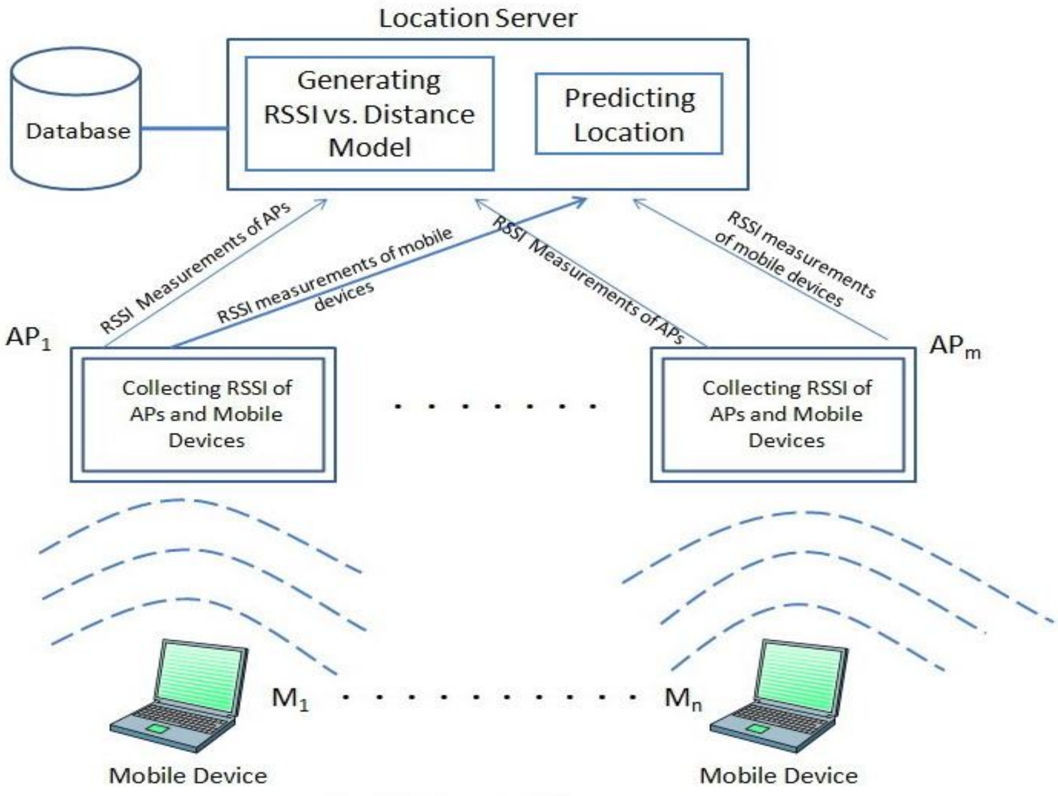


Figure 1. System Architecture of the Proposed Location Based Service

# Wi-Fi-Based Indoor Positioning: Basic Techniques, Hybrid Algorithms and Open Software Platform

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## 1 Summary

802.11 networks democratisation, combined with new mobility and needs, makes us interested in continuity of innovative services. The need for contextual knowledge grows, based on the availability of positioning services. It takes account of environmental dynamic changes and exploits Wi-Fi-based sensors from the market.

After state of the art reveals the need, considering characteristics of indoor and outdoor heterogeneous environment, we briefly introduce the initial system OWLPS-0.8 with the description of basic components, positioning algorithms and very first elements of expertise. We then present a set of new contributions from a topological model, a history memorisation algorithm derived from Viterbi and its implementation in positioning algorithms from the literature. We also propose a new design platform (OWLPS-1.0) addressing the dynamic changes in the environment and composing new algorithms to reduce the calibration and cartography cost as well as to minimise the distortion of signal strength dynamic variations in modern buildings.

## 2 State of the art

While outdoor positioning is widely treated and achieved by the GPS, indoor positioning is currently under development. Wi-Fi indoor positioning can be divided into two main families. One family is based on wave propagation and resorts on computing distances between mobile devices and points whose coordinates are known. The second family is based on mapping between signal strength measurements and geographical coordinates, called signal strength (SS) map. Locating a mobile device with a SS map consists in matching a measurement with some point of SS map. Measurements matching is either deterministic [Bahl00] or probabilistic [Ekahau02].

Propagation-based family is quick and easy to set up but lacks of accuracy. SS map family is accurate but is expensive to set up. Therefore, an efficient system would use both families strengths and suffer less drawbacks. In particular, propagation-based systems problems are bound to topology heterogeneity in buildings so a hybrid system has to address topology.

## 3 Base data

To build a hybrid, topology-aware, indoor positioning system, several base data are required:

– A minimal SS map, at least one point in each room. It allows a first, coarse, positioning of mobile device.
– A propagation model, for example FBCM. This model is calibrated and used locally, after coarse positioning based on SS map.
– A topology model, either discrete or continuous. Such model aims at refining positioning process with device tracking. It eliminates ambiguous locations based on past movements. A Viterbi-like algorithm performs elimination of all candidate points but one. It requires to store several candidate locations for each positioning iteration.

## 4 Algorithms

*Base algorithms*

Two base algorithms exist, above which complex techniques are developed. One performs search of *k* nearest points in a SS map, given a measurement. The other one, *Friis-Based Calibrated Model* (FBCM) [Lassabe09], consists in calibrating a propagation model with *a priori* measurements. Calibration determines which weight to give to transmitter-receiver distance in a Friis-like formula. It aims at computing accurately distances between mobile device and access points.

*Contributions*

From these base algorithms, we derive refinement techniques that combine a SS cartography, as in [Bahl00], and multilateration using FBCM. We called these techniques *FBCM and Reference-Based Hybrid Model* (FRBHM).

Furthermore, we can take into account the building topology. Describing precisely the room layout, we are then able to estimate the real distance between two points, instead of use a simple euclidean distance. Two variants of the FRBHM use the topology, combined with a Viterbi-like algorithm that uses the past positions of the mobile to compute the current position. The implementation of this Viterbi-like algorithm is an optimisation called *Fast Viterbi-Like*.

All these base and new algorithms are implemented in the *Open Wireless Positioning System* (OWLPS) [Cypriani09]. We are currently achieving a community version of the system, and plane to carry out new experiments within the next months, in order to confirm the previous results, better determine the accuracy in function of the SS map granularity and the radio environment alteration. We will also extend our experiments to new contexts and conditions such as the combination with other positioning services [Zirari10] at the periphery of buildings.

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# A sector-based campus-wide indoor positioning system

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Recently, the demand for Location Based Services (LBS) has grown exponentially, reflecting the increasing quality of mapping tools available to general users, such as Google Maps© or Google Earth©, and the rapid expansion of the smart phone market. Phones such as the Apple iPhone©, or HTC Dream©, are now small computer terminals with embed GPS (Global Positioning Systems), Wi-Fi (wireless fidelity), Bluetooth and 3G enabled chips, in addition of their basic mobile telephony capabilities. GPS is a reliable, generally available and comparatively accurate positioning technology, able to operate anywhere across the globe. However, it is also well known that GPS performance deteriorates very rapidly when the receiver loses view of the satellites, which typically occurs in indoor environments. In such environments, the majority of receivers do not function, and even the high sensitivity receivers have difficulties in providing coordinates with acceptable accuracies.

The general expectation of users of accurate positioning anywhere they go, and the inherent limitations of GPS availability and accuracy in indoor environments, have led researchers to investigate alternative technologies able to replicate GPS performance indoors. In this context, using Wi-Fi signals for positioning offers many advantages. First, the user doesn't need any additional hardware as most mobile phones are now equipped with Wi-Fi. Second, there is no need to deploy an extra dedicated network as Wi-Fi signals from at least a few access points (APs) can be detected in the majority of areas of interest, due to the proliferation of wireless networks, especially in areas where GPS is weak (indoors). Finally, Wi-Fi positioning technology can deliver room-level accuracy, which is usually good enough for a lot of applications, including asset tracking, location-based advertisement, location-based information for users, etc.

The purpose of this paper is to describe a campus-wide indoor and outdoor positioning system developed at the School of Surveying and Spatial Information Systems at the University of New South Wales, Australia. The system aims to provide students and staff with software able to guide them between any two locations on the university main campus, either indoors or outdoors, and, subsequently, to support other LBS applications. The development platform chosen is the Android©-powered HTC Dream© smart phone. This platform was chosen because the Dream© is equipped with Wi-Fi and GPS, the two technologies used for positioning, and because the Android© platform is open-source and provides an extensive API. The Wi-Fi positioning technique used is known as fingerprinting, described in numerous papers. This technique first requires the building up of a database of signal strengths (SS) from different APs taken at different points across the area of interest. Then, the user wishing to find his or her position scans the SS in the wireless network and sends the results to the database which will find the closest match in the database, and return the likeliest location of the smart phone.

The requirements for this system are: cost effectiveness, ease of deployment and maintenance, and room-level accuracy indoors. We believe that cost effectiveness and ease of use are very important issues any indoor-positioning system should try to address, in order for them to be more widely used. Ultra-wideband technology for instance, delivers centimetre-level accuracies but its very high-cost of initial implementation is a major drawback for its widespread development. Using Wi-Fi signals for trilateration suffers from poor accuracies, and needs the exact position of the access points to work, a piece of information not always easy to access. In this paper, we show that a relatively simple system, with minimal costs of deployment, delivers accuracies that would allow useful LBS to be developed for students and staff. The database generation and maintenance costs are the main disadvantages of the fingerprinting technique as they require time and labour, and when the environment changes significantly (for instance after a major building renovation), the database must be accordingly updated. For the system to be usable and used by students and staff, this issue has to be addressed. This paper investigates different approaches to database generation, and their impact on system performance. We show for instance that doing a quicker survey with fewer fingerprints does not impact performance as much as may have been expected. In such a survey, a five level university building was surveyed in less than one hour, keeping the projected database generation costs at an acceptable level.

This paper also investigates different algorithms used in the positioning phase, when the SS scan results sent by the user are matched to the database entries. The most basic one is the Nearest Neighbour (NN) algorithm, where the matching criterion is the distance in signal space between the scan result and each fingerprint entry in the database. We show that using more advanced algorithms can significantly improve performance, while keeping the computational cost at a reasonable level. For instance, while a simple NN algorithm returned the correct sector only 40% of the time, a more advanced algorithm returned the correct sector 60% of the time.

To conclude, our paper demonstrates the feasibility of a very cost-efficient Wi-Fi positioning system based on fingerprinting, with a minimal database generation cost, delivering accuracies which can be used to develop a large range of useful services for students and staff. Students could use this system to navigate through the campus of course, but also to locate friends for instance, or to gain access to information about the university’s facilities depending on their location. Location of critical staff members such as security guards, or facilities management staff could also be useful information for the university.

Multiple Wireless Technologies Fusion for Indoor Location Estimation

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**Summary**

Results from the analysis of electromagnetic signals are a possible source of information to feed the input of an indoor location system, as wireless communications are becoming more and more ubiquitous and widely available in consumer electronic devices. In this work a fingerprinting-based solution for indoor location that uses information from multiple communication technologies is presented. For testing and proof of concept purposes the authors used IEEE802.15.4 and IEEE802.11 as wireless communications technologies. When using multiple sources of information (technologies) to do location estimation two approaches can be used to integrate them: use each one separately, in layers, where each technology adds a detail level based on its coverage area, or, merge data collected from several technologies and thread them all together. In this work we use both approaches.

**Indoor Localization**

For indoor localisation using electromagnetic waves, the use of time properties to do location estimation can be very difficult, due to the fact that distances are very short and waves propagate at the speed of light. Therefore the use of techniques like TDoA (Time Difference of Arrival) or ToA (Time of Arrival) is very difficult and can be very expensive.

Another property of the signal that can be used for localisation purposes is the signal power at the receiver. It can be used to determine the signal attenuation over the radio link or it can be used for scene analysis. In the first case the distance between the mobile terminal and a set of references can be estimated using propagation models, and therefore, the location of the mobile terminal can be estimated. In the second case, the strength of the signal received from several references are compared against reference values stored in a database, searching for a match and trying to estimate the mobile terminal location.

In this work fingerprinting, which is a scene analysis technique is used. As communications technologies IEEE802.11 and IEEE802.15.4 were chosen to do the tests in our University Campus. The first was chosen due to its presence in almost the whole campus and the second due the fact that it is a very short range wireless technology and it is widely used in Wireless Sensors Networks (WSN). Another key factor for the choice of these two technologies is the fact that wireless reference nodes are easily discovered by other nodes and, in a very short time that in the worst case depends on the beaconing interval.

## Experimental Work

Experimental work was split into two phases: 1. The off-line phase that uses data from the existing scenario, recorded into a database. Each record consists in the RSSI (Received Signal Strength Indication) value, the location of the sampling point and the MAC (Medium Access Control) address of the wireless reference. 2. The on-line phase, where the localisation is made, it is based on data gathered in the previous phase and on the location where the algorithms (Nearest Neighbour, k-Nearest Neighbour and Weighted k Nearest Neighbour) were tested.

The present work is based on a multi-zone, multi-resolution approach that uses different range technologies to locate terminals in certain types of areas. Using wide range communications it is possible to locate the main zone where the terminal is, for example the building. This will enable a first estimation of the zone where the terminal is, and therefore we can eliminate all the references from the next analysis that do not belong to the zone. The number of layers in this approach depends on the number of different technologies used, and the zone size depends on the type of technology, geographical distribution or the type of the zones to be detected (e.g., Campus, building).

Experimental data was collected in two types of scenarios, the first using IEEE802.11 where the FM of the main hall of several buildings was built, in the second scenario the FM of a classroom (located near the main hall of one of the buildings) was built using both IEEE802.11 and IEEE802.15.4.

In the on-line phase of the experimental work the first step was to detect the building, which occurred without any problem. After detecting the building correctly, the next step was to determine the location inside that zone, in this case, inside a classroom. This was done by using both technologies. In the first test, using IEEE802.11 a precision of approximately 0,83 m and an accuracy of 77 % was achieved. When IEEE802.15.4 was used the obtained precision was approximately 0,72 m with an accuracy of 93 %.

To enhance the location several technologies can be combined and the search for the mobile terminal location is done using the fingerprint map information from more than one technology. Using both IEEE802.11 and IEEE802.15.4 a precision of about 0.46 m and a accuracy of 73 % was achieved. Although there is a degradation of the accuracy, the precision is much better.

## Conclusions

In this work we propose the use of multiple technologies to locate users and objects in an indoor environment, based on the fingerprinting technique. To eliminate possible error sources and even to reduce the computational time needed to correctly estimate the position, a multiphase/multilayer approach is presented. At each phase a different technology is used, starting with the wider coverage range technology and ending in the lower range technology. Shorter range of wireless technologies has better spatial resolution of it. So, a typical wireless communications network based on IEEE802.11 will achieve a worse spatial resolution than IEEE802.15.4, because the last solution needs more wireless nodes to achieve the same spatial coverage.

# Resolving the Fingerprinting Problem: Comparison of Propagation Modelling and Machine Learning Approach


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## 1 Summary


A major drawback of indoor localization based on RSS (Received Signal Strength) measurements is the necessity to generate a fingerprint. Generating a fingerprint database is an exhaustive, time consuming and cumbersome effort. Furthermore, a fingerprint is also bound to the indoor environment description and infrastructure at the time the fingerprint was generated.

Therefore, major changes in the environment (movement of large pieces of furniture or appliances, adding or removing walls) will render a current fingerprint inaccurate and require re-building of a new fingerprint. In other words, the current approach still has poor usability, judged from the effort that is needed to install and maintain it.

This disadvantage makes the indoor localization system inoperable as a localization system. This work explores two main approaches to overcome this problem: fingerprint prediction with a propagation model and fingerprint modelling with a machine learning approach.

The propagation model is used to predict the signal strength throughout the coverage area from access points to predict the fingerprint. There are two propagation models that can be used, namely the One Slope Model (OSM) and the Multi Wall Model (MWM). A particle filter is used as a filtering algorithm to estimate the user position.

The Support Vector Machine (SVM) is one of the machine learning algorithms that is used to model the complete fingerprint from few training data. As a pattern recognition algorithm, SVM will also be utilized to estimate the user position.

The evaluation among the fingerprinting approaches is conducted in a localization test-bed using WLAN technology. The fingerprinting prediction model with propagation and machine learning approach will be compared to the manual fingerprinting collection.


## 2 Propagation Model and Machine Learning Approach

Figure 1 shows an example of a fingerprint prediction with the OSM model. The signal loss in OSM is given by:

$$L = L_1 + 10n\log(d)$$

where $L$ is a signal loss, $L_1$ (dB) is a reference loss value of 1m distance, $n$ is a power decay factor (path loss exponent) defining slope, and $d$ is the distance in meters.

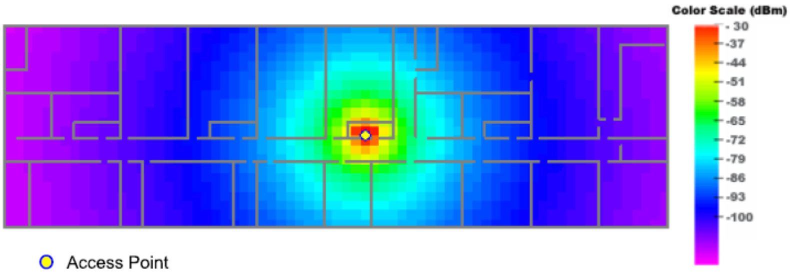


Figure 1 OSM Prediction of a Fingerprint

The principal advantage of fingerprint prediction is its speed in predicting the fingerprint. In the machine learning approach, a sizeable training database is collected and subsequently used to train the system to estimate the complete fingerprint database. SVM uses a fingerprint as its training data to build a classification model. During the training phase, SVM constructs a classifier termed as hyper-plane which in turn is used to estimate the target location.

## 3 Particle Filter

The Particle Filter is a non-parametric implementation of the Bayes' filter. It approximates the posterior probability by a finite number of discrete samples with associated weights, called particles. The Particle Filter is used as a filtering algorithm to estimate the user position. Figure 2 illustrates an example when the Particle Filter algorithm was used to estimate the user position.

Figure 2 The Particle Filter for state estimation

## 4 Results

The fingerprinting prediction with a propagation model and the machine learning approach will be compared to the manual fingerprinting collection. Table 1 shows an example of the localization error with manually collected fingerprints in the test-bed. It is based on the Kalman Filter (KF) and the Particle Filter (PF) as the localization algorithm. The localization error is the distance between the true position and the estimated location in the test-bed. It shows the average error ($\mu$) and standard deviation ($\sigma$) in metres.

Table 1: Localization Error (metres)

| **Fingerprinting** | **KF** | **PF** |
|---|---|---|
| Manual Fingerprint | $\mu$ =4.67 | $\mu$ = 3.25 |
| | $\sigma$ =3.84 | $\sigma$ =1.91 |

# Optimization Model for an Indoor WLAN-based Positioning System

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## 1 Summary

We propose an innovative approach where WLAN planning and positioning error reduction are modeled as an optimization problem and tackled together during the WLAN planning process.

## 2 Introduction

Positioning systems using Wireless Local Area Networks (WLANs) have been suggested as a viable alternative to provide location information for indoor areas. But, an increase of the density of Access Points (AP) can improve the system accuracy and precision, whereas the communication quality (due to frequency interferences) and the installation costs are increasing too. These are major drawbacks! This paper attempts to answer the relevant question: how can a WLAN be deployed in order to guarantee the requested Quality of Service (QoS) and meanwhile reducing the location error? Such a problem includes two aspects: WLAN planning and positioning error reduction. To provide users an optimal wireless access to their local network, WLAN planning not only consists of selecting a location for each transmitter and setting the parameters of all sites, but also of allocating one of the available frequencies to each selected AP. Once the Received Signal Strengths (RSSs) from all visible APs are measured and entered, the location is estimated and outputted using the RSS distribution and machine learning technique. We propose a new approach where WLAN planning and positioning error reduction are modeled as an optimization problem and tackled together during WLAN planning process.

## 3 Modeling and problem optimization

To find a feasible AP configuration satisfying QoS and positioning error constrains, we proposed a formal model which describes the whole problem parameters and which defines, in a precise way, an estimation of the costs, throughput of a network and the positioning accuracy.

1. **AP model:** Since different types of APs have different parameter values (azimuth, emitted power and frequency), we predefine a list of AP types for the users' choice. Furthermore, we predefine a finite set of candidate sites where an AP may be assigned.

2. **Received Signal Strength model:** RSS is the main parameter used for bit rate calculation and positioning estimation. We define three kinds of RSS thresholds corresponding to interference level, positioning level and communication level.

3. **Traffic and positioning model:** The traffic and positioning model of the network defines how to represent the demand for network load or positioning accuracy. The building is meshed, and the desired QoS and the desired accuracy are expressed by polygons covering service areas of the building. A pixel associated with QoS is called Test Point (TP) and a pixel associated with the accuracy is called Reference Point (RP).

Our optimization problem aims to determine the decision variables (site, transmission power, azimuth and frequency) in order to minimize positioning error and QoS lack under some constraints. To evaluate the accuracy and QoS, the proposed fitness consists of three terms. The first term is the network installation cost; the second term is the cost of unsatisfied demands on QoS and the third term is the cost of unsatisfied demands on positioning. The QoS is evaluated by the Signal to Interference plus the Noise Ratio (SINR) indicator. The positioning accuracy is estimated by a defined indicator called Refined Specific Error Ratio (RSER). Mathematically, the objective function is formulated by

$$\sum_{\mathrm{Site}} C_{\mathrm{Site}} + \sum_{TP} \beta \times \Delta_{rp} + \sum_{RP} \gamma \times \mathrm{E}_{rp} \ ,$$

where, CSite is the network installation cost of a site. β is the penalty coefficient assigned to the TP. $\Delta_{tp}$ is the deviation between the required bit rate and the real bit rate. γ is the penalty coefficient assigned to the RP. $E_{rp}$ is the magnitude of the positioning error. To solve this optimization problem, a Meta-Heuristic algorithm is implemented.

## 4 Experiments and performance analysis

To evaluate the performance of the location system, we carried out two experiments in the same experimental environment. The test scenario for performance evaluation took place at the first and the second floor of the library building in the UTBM campus. Each floor covers an experimental area of approximately 150 m x 40 m with more than 30 classrooms and offices of different sizes. We constrain that the maximum number of AP is 30 and the desired bit rate for each user is 500 kbps. The obtained results are shown in Figure 1.

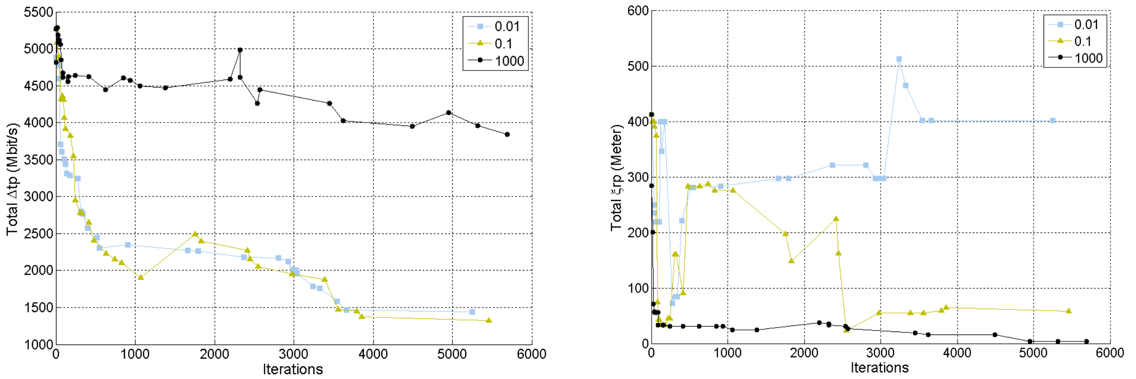


Figure.1: The variation of total $\Delta_{tp}$ and total $E_{rp}$ by different γ to β ratio in each improvement.

In Figure 1, we vary the γ to β ratio to study the relationship between QoS and the positioning accuracy. Figure 1 clearly shows that a high γ to β ratio of 1000 can guarantee a small positioning error while high total $\Delta_{tp}$. In the same way, a low γ to β ratio of 0.01 only guarantees a low total $\Delta_{tp}$. With an appropriate value of 0.1 for the γ to β ratio, our approach can find an AP configuration which can provide a good QoS demand and positioning accuracy.

## 5 Conclusions and Outlook

In this paper, we provide a solution where WLAN planning and positioning error reduction are dealt with simultaneously in form of an optimization problem. We have done the performance evaluation of our approach and the results indicate that our approach is able to achieve a WLAN planning which provides the required QoS demand and positioning accuracy. Further work will focus on multi-objective optimization.

# Effect of Environmental Changes on Accuracy of IEEE 802.11 Indoor Fingerprinting Positioning System WifiLOC

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## 1 Summary

The performance of our indoor positioning system based on IEEE 802.11 is evaluated for real environments. We call the system WifiLOC and it is implemented as a mobile assisted positioning system. The architecture and fundamental principles of the system are presented. The positioning system is based on the fingerprinting method, which utilizes signal strength information for position estimation. A lot of factors influence the propagation of radio signals in indoor environments. Therefore it is complicated to clearly model the properties of the signal propagation. This fact has also significant impact on particular properties of a RSSI based positioning system. In this paper, the impact of the positioning accuracy is presented taking into account various conditions such as moving objects in the observed area or the type of indoor environment, e.g. corridor, office and room. The influence of different conditions during the off-line and the on-line phase of fingerprinting positioning method on the positioning accuracy is also investigated. The observed facts are very important for successful implementation of location based services.

## 2 Motivation and Results

In the past, most attention was paid to research of positioning in outdoor environments. The utilization of GNSS (Global Navigation Satellite System) seems to be the best solution outdoors, but its limits become evident in urban canyons and especially in indoor environments. The increasing demand for indoor LBSs (Location Based Services) raised the interest of many research groups in indoor positioning. There are many typical examples of indoor LBSs: car navigation in garage buildings, patient position monitoring in a hospital or hospice. It could also be used in various shopping centres, galleries or airports for personal navigation. The purposes are different, but the user position should be known in all cases. Various positioning systems based on wireless platforms were proposed in [1 - 3]. We decided to propose our solution based on an IEEE 802.11 platform, because it is widespread. The basic idea results from the utilization of the platform apart from its main purpose, which is mainly to cover user data communication. Our approach adds value to the IEEE 802.11 communication platform by providing user positioning.

As mentioned above, our positioning solution is based on the IEEE 802.11 communication platform, is called "WifiLOC". WifiLOC was designed as part of global modular positioning system, which supports LBS everywhere. It means the localization is supported by various independent positioning systems in all environments, i.e. indoors and outdoors. Positioning system with the most suitable current conditions for positioning is used for final position estimation. It is based on a client - server architecture, which is shown in Figure 1.

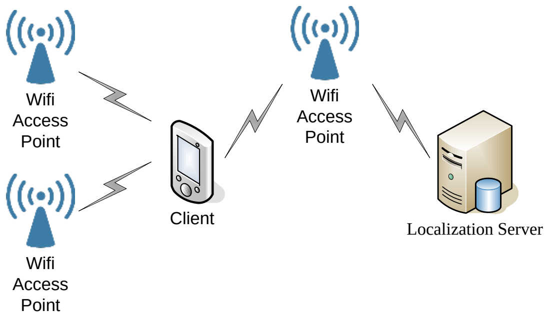


Figure 1: Architecture of WifiLOC.

The presented solution is based on the well known fingerprinting localization method. It utilizes the Received Signal Strength (RSS) from Access Points (APs) in range. It is not necessary to connect to particular AP for RSS measuring, therefore the APs of other network providers could also be used for positioning. It is new crucial benefit of the system, because it could be implemented almost without own infrastructure. The advantage of the RSS based system is its simplicity, because no synchronization is necessary, just the RSS is being measured by the "Client". The data measured by Client are sent to the Localization server for processing. All necessary computational operations are performed in the Localization server. The position information can be displayed in the client application in text form and graphical (by a global map, local map or even images of the current location). All these information are also available in Client and Localization server.

The properties of the described WifiLOC indoor positioning system are evaluated from various points of view. As mentioned above, WifiLOC is focuses on indoor positioning, therefore it has been tested in various indoor environments: corridors and rooms. Experiments have been implemented in the University of Zilina campus. The experiments were performed in several scenarios taking into account movable objects in the observed area. The impact of movable objects presence on the positioning accuracy during the off-line and the on-line phase of fingerprinting positioning method is investigated. The movable objects the RSS to fluctuate, therefore it is necessary to carry out measurements that define the limits of WifiLOC in various situations and environments, e.g. hospitals, offices, airport hall or parking house. The achieved experimental results are presented.

## 3 Acknowledgments

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# A Model – Based Approach for WLAN Localization in Indoor Parking Areas

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## 1 Summary

Wireless location of a User Equipment (UE) has received growing attention in recent years. The first step for the design of a wireless location system consists in choosing the system architecture and the localization algorithm that match the requirements of the working scenario. In this paper the area of interest is represented by an indoor parking lot, in which the presence of motor vehicles alters the electromagnetic field and causes large errors in vehicle location estimation. A possible strategy to deal with this problem is the use of a server-based architecture, that ensures a secure and scalable architecture and that allows the knowledge of system *state*, such as the number and the positions of the motor vehicles. Indeed this knowledge can be used to design suitable algorithm, based on simplified electromagnetic models, to improve the localization performance.

## 2 Server-based Localization Architecture

In this paper a server-based WLAN localization architecture is proposed, wihich exploits one of the existing WLAN systems in the widely diffused 802.11 class. The key element of this system is the Location Server (LS), that performs the following tasks.

a. LS collects the Received-Signal-Strength (RSS) measures from the UE's in the area under surveillance via a new specific protocol, the Location Information Protocol (LIP), that is an application layer protocol based on UDP.

b. LS performs the localization step via suitable algorithms.

This element is designed to interoperate both with an Home Network Authenticator and, by means of a WLAN Direct IP Access, with the AAA Server of a 3GPP Core Network, in order that only the correctly authenticated UE can have access to the Location Service. A sketch of the association and authentication procedure is depicted in Figure 1.

## 3 Knowledge-based Localization Algorithm

The adoption of a server-based philosophy is advantageous not only to deal with architectural issues, but also to access the existing information about the system *state* so as to improve the localization performance. The main idea is to use a standard technique, such as the RADAR one [1], properly modified for taking into account the environment state.

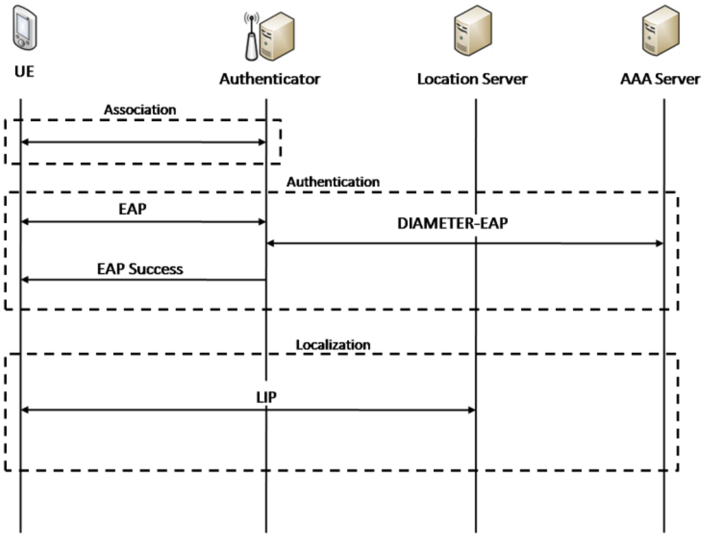


Figure 1: Association and authentication procedures.

In the challenging scenario of the parking lot, the main difficulties arise from the extreme variability of the propagation channel due to moving obstacles and reflection surfaces. In particular a single vehicle, depending on its position, can obstruct the Line-Of-Sight toward an Access Point, as well as it can introduce a newer path by reflecting the electromagnetic field. Accordingly, the purpose of this paper is to model the effect of the vehicles inside the lot and to propose the following consequent localization algorithm

a) the usual training phase is performed when the parking lot is *empty* in order to build a Radio Map [1];
b) when the first vehicle enters into the parking lot, it is localized in the standard way;
c) on the basis of the estimated vehicle position and by means of a proper electromagnetic *model* of the vehicle, the variations in the electromagnetic environment (due to diffraction and/or reflection) are predicted and the Radio Map is consequently *corrected*;
d) when another vehicle enters into the parking lot, it is localized by using the corrected Radio Map;
e) The steps c) and d) are performed for each vehicle that enters (new correction) or exits (remove the correction) from the parking lot.

The performance of this *model-based* approach is compared both with algorithms not accounting for the effects of entered vehicles and with some traditional adaptive methods (see e.g. [2]).

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# Fingerprinting Localization in Indoor Wi-Fi Networks Based on Received Signal Strength

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## 1 Summary

This paper considers the problem of fingerprinting localization in indoor Wi-Fi networks based on received signal strength. When a mobile device request services, a fingerprinting system compares the measurement with the values stored in a database to determine the location. This study investigates several factors impacting the location accuracy. First, we compare different fingerprinting algorithms, such as Bayesian, Support Vector Regression, and weighted-k-nearest-neighbor, to construct different relationships between the user's location and the measured RSS. Next, the compared positioning algorithms are performed on different transformed signal spaces to examine the performance by on-site experiments. The transformation is determined by different criteria, including principal component analysis (PCA), and multiple discriminate analysis (MDA). The former is known for preserving the most descriptive features while the latter is known for capturing the most discriminant ones after transformation. This study also examines the distribution of RSS, and the analyses of complexity.

## 2 Experimental Setup and Results

The proposed algorithm is evaluated on a realistic indoor environment. The measurements are collected on the fifth floor of BL building in NTU, as shown in Figure 1.

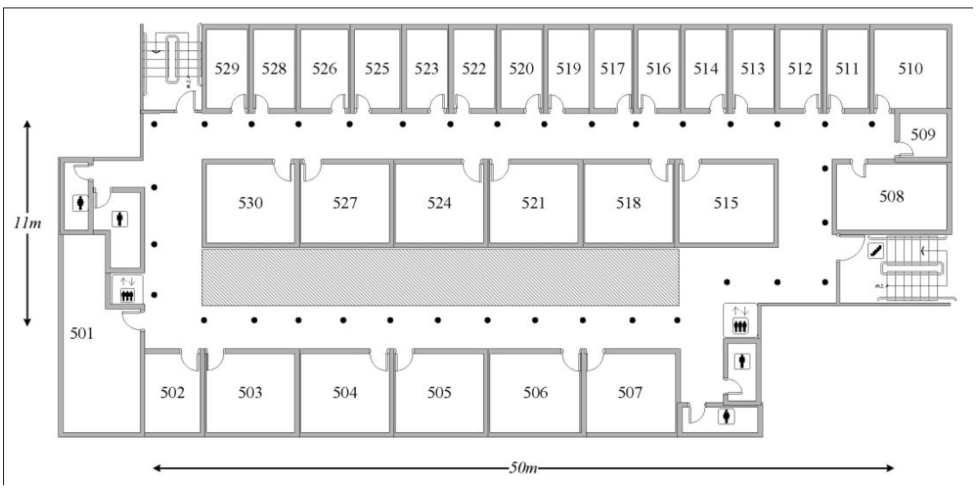


Figure 1: The fifth floor plane of the BL building, where we performed the experiments. The dots represent the reference locations.

We collect WiFi data in this area by a laptop with Windows XP operating system and NetStumbler network software. The dimensions of this test-bed are 52 m times 18 m. 35 reference locations are selected with a 3 m space. We collect 50 samples per location at different time periods for training and testing data, respectively. Our measurements show that over 30 APs can be detected in this floor. We select the most stable 15 APs for comparison. Finally, the positioning error is defined as the Euclidean distance between the estimated result and the true coordinate.

Figure 2 discusses the positioning performance under different signal spaces based on a probabilistic Bayesian approach. Due to the limited pages, the performance based on Support Vector Regression and weighted-k-nearest neighbour are not listed in this extended abstract. In Figure 2, accuracy versus computational complexity is drawn where the x-axis is the ratio of the used components and the y-axis is the percentage the estimated errors within 2 meters. This figure shows that the accuracy of RSS gradually rises to the peak as the complexity (the dimension) increases. In RSS space, the performance is saturated at about 46.67% complexity. The best performance of RSS space is in fact obtained by using only 10 APs and no longer improved while adding more APs. This result is consistent with the previous works. That is, using a subset of APs can produce a comparable or even better performance to full APs.

This figure also shows a significantly sharp increase in accuracy when transforming RSS into the projected space. Compared with the accuracy of RSS with full APs (60.91%), MDA only requires 20% computation and PCA needs 26.67% computation to provide an even better performance. Clearly, the slope of MDA is steeper than PCA. The main advantage of MDA over PCA is the reduction in complexity by 1 or 2 components. Under 20% complexity, MDA achieves 66.89% whereas PCA is only 53.83%. That means MDA has the advantage of using the littlest computation to achieve the same level accuracy. This figure demonstrates that the best performance is achieved at 20% complexity of RSS where the two transformations report a similar accuracy.

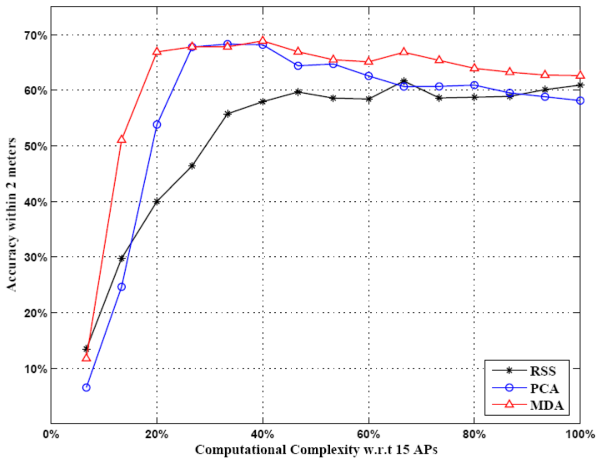


Figure 2: Accuracy (percentage of the estimated errors within 2 meters) versus the relative computational complexity in different signal spaces.

**TOF, TDOA based Localization**

Auditorium G7

Thursday, September 16, 13:15 – 15:00 & 15:30 – 16:45

# IEEE 802.11 Ranging and Multi-lateration for a Software-defined Positioning Receiver

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**Summary**

The implementation of a ranging exploitation method over the IEEE 802.11 signal standard for a software-defined radio architecture is presented. We propose the current wireless local access network (WLAN) as standard assistive infrastructure for ubiquitous localisation and positioning. The paper describes the architecture of a localisation receiver built around a FPGA. The described receiver can process GNSS signals, available for any number of satellites, together with IEEE 802.11 signals available from surrounding access points to infer its own position. The single ranging method, the hybrid GPS and IEEE 802.11 multi-lateration positioning calculation method and their implementation in a single software-defined receiver are discussed.

**Motivations and results**

Satellite-based navigation systems like GPS experience significant accuracy degradation when used indoors. Alternative wireless indoor localisation systems have been proposed to amend this [1]. The most popular wireless radio technologies include IEEE 802.11 WLAN, UWB and RFID systems.

Certain wireless radio localisation technologies are more suitable to be scaled up and employed for areas larger than a one-room space. Current state-of-the-art location methods for a building-floor area or a multi-floor environment use received signal strength indicators (RSSI) for ranging. [2] presents the first location method based on WLAN RSSI. Currently there are several commercial solutions based on this technology.

Location and tracking solutions based on wireless signal time of flight (TOF), similar to GPS, are considered superior to RSSI because such measurements scale linearly with the propagation distance and with better reliability. Recent works like [3,4] present interesting methods to implement TOF measurements over the RTS/CTS MAC layer of IEEE 802.11 signal standard. Furthermore [5] presents how such TOF ranging techniques could be implemented for a simple triangulation for localisation over an office space.

There is one aspect common to most of the literature on this topic: the effort to build methods, techniques and sometimes small hardware [4], that can allow standard WLAN hardware (WiFi communication cards) to infer the user's position within a standard WLAN network.

This paper takes a different angle and considers the implications of GNSS receivers being currently integrated into millions of mobile phones worldwide. The concept of a software-defined GNSS receiver capable of processing GNSS signals as well as IEEE 802.11 signal is presented. Via the use of a soft-core implementation, we present the idea of harvesting the large computational power of GNSS receivers to compute terrestrial signals like the IEEE 802.11 for indoor/outdoor localisation via a software-defined radio architecture [6,7].

The implementation of a WLAN single ranging method as well as a multi-lateration implementation suitable for a soft-core FPGA is presented. Simulations show how the proposed solution could provide a position with an accuracy of some metres over a large area like a university campus. Critical aspects like WLAN access point visibility (refer to Fig. 1) and expected global positioning accuracy (refer to Fig. 2) is studied via the implementation of a 802.11 positioning simulator.

The described localisation technique is simulated throughout the EPFL university campus, an area of approximately 1 square kilometre, where GPS satellite signals are very likely to drop out due to obstructions. Methods to combine GPS ranging together with IEEE 802.11 WLAN ranging are discussed. A prototype of a FPGA-based navigation receiver capable of both GPS and IEEE 802.11 ranging is presented. Key results of the effectiveness of such a multi-ranging implementation are presented.

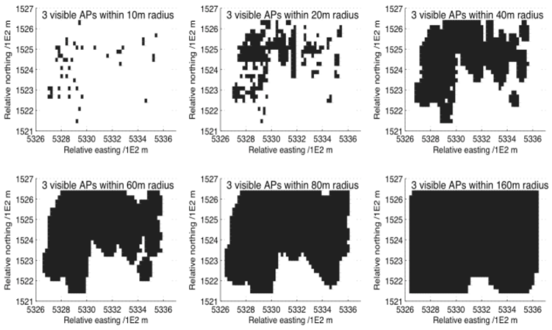


Fig.1: WiFi access point visibility for different values of radius.

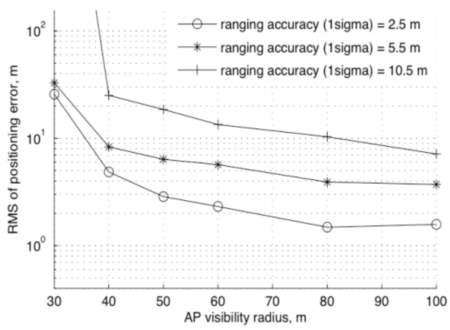


Fig.2: RMS of the positioning error vs WiFi access points radius visibility.

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# On the Minimization of Different Sources of Error for an RTT-Based Indoor Localization System without any Calibration Stage

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## 1 Extended Abstract

In previous essays, a system that measures the round-trip time (RTT) between a mobile user (MU) and several access points (AP) in an IEEE 802.11 wireless network was used to estimate the distance between them and obtain the MU's position by means of a trilateration technique [1]. However, different sources of error disturb the range estimates obtained previously to the trilateration process. As a consequence, the range accuracy, i.e. the degree of closeness to the actual distance, and the range precision, i.e. the variability of the range estimates, will be negatively affected. Moreover, after the trilateration stage, the estimation of the two-dimensional coordinates of the MU's position includes a random error that decreases the precision of this estimation. These sources of error appear whichever the technology and the environment selected, however, they acquire more importance in cluttered environments, such as indoor or dense urban scenarios, where the non-line-of-sight (NLOS) is more relevant.

The aim of this paper is to combine several error mitigation techniques in order to improve the final accuracy and precision of the RTT-based indoor localization system. The final accuracy is affected by systematic error, mainly due to the resolution of the measuring system and the number and distribution of the APs, whereas the precision is influenced by the random error, i.e. by experimental uncertainties such as electronic errors or multipath signal reflection. Furthermore, the NLOS error that characterizes the cluttered environment, introduces a bias in the RTT measurements that varies even for short periods of time, affecting not only the accuracy but also the precision.

The starting point is the RTT-based system depicted in [1], which first takes a set of RTT measurements between the MU and each AP in range, and then obtains the distance through a linear transformation of the Weibull's scale parameter taken from the RTT measurements [1]. The MU's position estimate is thus obtained by a trilateration technique based on the radical axis [1]. The next step is to mitigate the systematic error introduced by the NLOS in the range estimates prior to the trilateration stage. In order to do so, the prior NLOS measurements correction (PNMC) method, presented in [2], is implemented. In this way, NLOS is detected, quantified and reduced from the range estimates.

After subtracting the bias error, the random behavior remains on the range estimates, whose elimination entails a filtering problem. For this purpose, a linear-Gaussian motion model with a vector state which includes distance and velocity is considered. However, the error resulting from the PNMC stage leads to a non-Gaussian measurement model [1], thus, a simple Kalman filter (KF) is not adequate for this problem. Therefore, a better option is to use a particle filter (PF) to reduce the random error. The likelihood function for this filter has to be obtained from the set of RTT measurements at each MU's position instead of from a single bias-corrected range estimate, which is the output of the PNMC method. If the relationship between the distance and the RTT measurements were linear, the NLOS bias obtained by the PNMC method could be removed from each individual RTT and the likelihood could be derived from the bias-corrected RTT measurements. Although this is not the case of Weibull's scale parameter, in [3], the error in assuming this linear dependence was measured to be three orders of magnitude smaller than the resolution of the measuring system. Then, the PF can be applied by computing the likelihood function from the RTT distribution obtained after subtracting the NLOS bias from each individual measurement without loss of performance. Finally, after the trilateration process, the two coordinates of the position estimates present a random error which has been verified to be Gaussian by means of a Kolmogorov-Smirnov test. Being both motion and measurement models linear-Gaussian, a simple KF can be applied to the resulting position estimates.

The main contribution of this paper is that instead of applying a PF to the ranges estimates, and a KF to the position estimates, an RTT-only tracking filter which directly relates the position with the RTT measurements to each AP (after applying PNMC) is likewise proposed. Since in this case, the error in the measurement model is not Gaussian, a PF with a dynamic likelihood function is implemented. This filter will have the ability to handle the uncertain information in the process. This procedure has three main advantages compared to the previous scheme: first, soft decisions are made during the process and hard decisions are only made in the final position choice. Second, this filter has not to be restarted when any of the APs is not in range. And third, the processing time is reduced since distance estimation and trilateration steps are omitted and an only filter is needed, whereas, in the previous case, one PF per AP for range filtering and one KF for position tracking are implemented.

The root-mean-squared-error (RMSE) quantifies both the systematic (the bias) and random (the variance) errors. With the presented approach, based on soft decisions and RTT-only tracking, the RMSE, for a MU who covers a 40x15 m route in an indoor scenario with eight APs, is 3.86 m. This leads to a final reduction of 55% of the starting RMSE with no error reduction technique. Moreover, this result is the lowest error achieved with the different approaches discussed in this paper, and other common Kalman-based techniques with which it has been compared. It is worth mentioning that neither of these error mitigation steps nor the measuring system needs any calibration stage.

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# Maximum Likelihood 3-D Positioning with a Priori Knowledge of Nodes Topology for UWB Based Human Motion Tracking

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## 1 Summary

In this paper we analyze an ultra-wideband (UWB) based wearable human motion tracking system. A maximum likelihood (ML) estimator, which incorporates the UWB distance measurements and the a priori knowledge of nodes topology to localize a node, is presented. The result of measurement campaigns is compared with computer simulation results to evaluate the performance of the proposed scheme. Based on this performance evaluation, it is shown that taking into account a priori knowledge given by the topology of the nodes can improve localization accuracy in harsh environments (i.e. in the case of multipath propagation and when enough number of line-of-sight (LOS) distance measurements are not available to perform lateration). Moreover, it reduces the required number of anchors to localize a node.

## 2 Introduction

Human motion tracking is the process of estimating the position of different body parts in real time. It has many applications in the fields ranging from medicine to virtual reality [1]. In the field of medicine, it has been used to assist patients who undergo a stroke rehabilitation process; in sports science, motion tracking can be used to analyze athlete's training and exercise; in the entertainment industry, the motion of human actors and animals can be recorded to create an avatar animation.

Currently, there exist several commercial motion tracking systems which employ optical, inertial and magnetic sensing technologies (or a combination of them). Optical systems, even if they provide a reliable tracking, require dedicated laboratories, complex settings and highly skilled operators [2]. Inertial and magnetic systems, on the other hand, do not have LOS restriction but they are prone to drift errors and interferences from nearby ferromagnetic materials, respectively. In [3], a wearable full-body motion capture system with interconnected electronic sensors as an intrinsic part of a cloth is proposed as a low-cost and low-power solution.

It is known that at least four LOS distance measurements from anchors are required to localize a point in 3-D using lateration [3]. However, due to the anatomy of the human body, it is difficult to get so many LOS measurements when both the anchors and agents are located on the body (which is the case for wearable motion tracking systems). In this work, we analyze a scheme which utilizes the available LOS measurements along with a priori knowledge of nodes topology to improve positioning accuracy. An ML estimator which exploits the underlying geometric constraint is derived and its performance is evaluated. Note however that, even if we apply the approach to the human motion tracking problem, the proposed scheme is generic and can be readily applied to similar problems.

## 3 System Description

Figure 1-a shows an exemplary network of nodes which are attached on the human body to track the positions of the limbs. The position of the anchors is assumed to be known and

fixed. For brevity, in this abstract we will consider the problem of 2-D position estimation. The 3-D case will be discussed in the full paper.

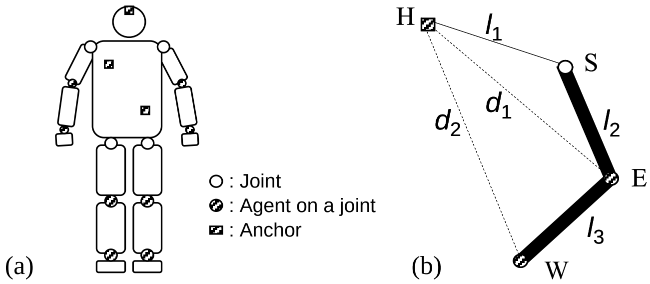


Figure 3. (a) Network of nodes for human motion tracking, (b) 2-D motion tracking of the arm.

If we consider the specific case of arm motion tracking, we will have a topology as shown in Figure 1-b. For a given person, the position of the node on the head (**H**), the position of the shoulder joint (**S**), and the distances $l_1$, $l_2$ and $l_3$ are known a priori. The distances $d_1$ and $d_2$ are estimated from ToA measurements using UWB signals. So, we have two triangles with a known side length. Hence, the position of the elbow (**E**) and wrist (**W**) joints can be calculated by applying the law of cosines. Note however that, since the ToA measurements are not perfect (so are the distance estimates) **W** and **E** have to be estimated from these noisy measurements under the given geometric constraint. So, for the ML estimate of **W**: ($w_x$, $w_y$), for example, we need to solve the following problem:

$$\begin{bmatrix} \hat{w}_x \\ \hat{w}_y \end{bmatrix} = \arg\max_{w_x, w_y} p\left( \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \middle| \begin{bmatrix} w_x \\ w_y \end{bmatrix}, \Theta \right) \text{, where } \Theta = \{\mathrm{H}, \mathrm{S}, l_2, l_3\}.$$

Figure 2 shows the root mean squared error (RMSE) curve for the ML estimate of **W** when the measured distances are corrupted by white Gaussian noise having zero mean and variance $\sigma^2$. From the figure, we note that an RMSE of less than 2 cm is achieved if the standard deviation of the noise is less than 10 times the true distance. Moreover, we note that only 2 distance measurements are required to localize **W** and **E** instead of 6, which would have been required by the classical trilateration method.

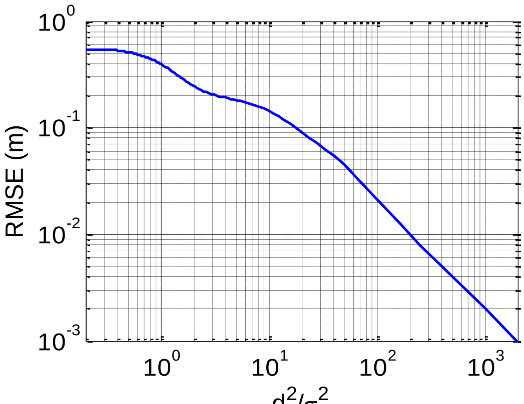


Figure 4. RMSE curve for the wrist joint.

In the full paper, a more realistic ranging error model will be considered and the ML estimation problem for the 3-D case will be discussed in detail. Moreover, a comparison of measurement and computer simulation results will be presented.

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# A Mathematical Model for a Polarisation Based Orientation Measurement Principle in Time of Arrival Radio Localisation Systems

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## 1 Introduction

There are different types of orientation measurement principles for localisation systems known in literature. In most cases sensors are used to measure the gravitation and magnetic field vectors of the earth [1]. From these two vectors the orientation of the object to be localised can be calculated. Without using sensors it is possible to measure the heading of an object as tangent to its route. But this method fails, if the localised object is stationary. Two or more receiver-lines are necessary in time of arrival (TOA) radio localisation systems to gain orientation information. The relative positions of the receive antennas have to be known. With two antennas only a direction vector can be calculated; for determination of orientation at least three antennas are necessary [2].

The rotation around the transmitter-receiver-axis can be measured by a suitable choice of the antennas at both sides. In GPS right-hand circularly polarised (RHCP) antennas are used for transmission and reception. Carrier phase measurements show both, changes in distance and direction, if the GPS-receiver is rotated around the aforementioned axis. Frequency drift, clock errors and atmospherics are assumed to be eliminated beforehand. To derive orientation information, the carrier phase measurements have to be decomposed into its components for changes in distance and orientation. This can be done by using the two GPS carrier frequencies L1 and L2 [3].

Another approach [4] uses one linearly polarised antenna at the transmitter and two in opposite direction circularly polarised antennas at the receiver, in order to measure rotations around the transmitter-receiver-axis simultaneously with changes in distance. It was shown that distance and rotation components of the measurements can be separated for a special case, for which only movements along or around the aforementioned axis are considered.

Based on this antenna configuration, a generic model will be given here, utilising the electro-magnetic field theory. In Section 2 the measurement principle and setup will be explained for completeness. The theoretical model will be given in Section 3.

## 2 Measurement Principle and Setup

Figure 5 shows the principle system setup, which is capable of measuring rotations around the transmitter-receiver-axis. A linearly polarised antenna is mounted on the transmitter at the left side of the figure. On the right-hand side a localisation receiver with two receiver lines is placed. One line is connected to a RHCP, the other line to a left-hand circularly polarised (LHCP) antenna. Both receiver lines are assumed to be synchronised with the transmitter. If carrier phase measurements are taken at both receiver lines, changes in distance alter the measured phase angles in the same way. If the transmitter, and therefore the polarisation vector, was rotated, the phase measurements change in opposite direction. Therefore, a distinction between translation and rotation is possible.

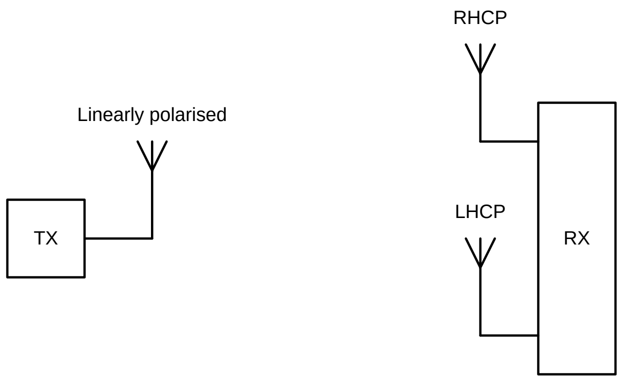


Figure 5: System setup

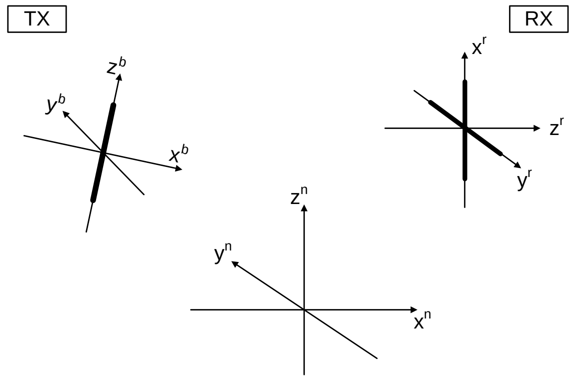


Figure 6: Antenna models and used coordinate systems

## 3 Electromagnetic Field Theory of the Transmission Chain

In this section, the general theoretical description of the complete transmission chain will be given. Starting point are the equations for the field of a short dipole. This dipole is depicted in Figure 6 on the left-hand side together with its associated coordinate system (body- or b-frame). These coordinate axis are moved and rotated with respect to the local navigation frame (n-frame) shown at the bottom of the figure. On the right-hand side, there are crossed dipoles serving as a model for a circularly polarised receiving antenna. This antenna can be shifted and rotated relative to the n-frame, too.

For this setup the complex vectorial electromagnetic field of the transmitter is calculated at the receiver side. Incorporating the orientation of the crossed dipole antenna, the induced currents in both dipole elements can be determined. Afterwards, the addition of the two currents can be carried out. At that point, the behaviour of the crossed dipoles as a RHCP or LHCP antenna has to be accounted for. The carrier phase measurements can now be extracted from the current of all receiving antenna elements.

## 4 Conclusions

The suggested model can be applied for simulation environments to synthesise localisation measurement data. With this approach, the behaviour of carrier phase measurements due to rotation and translation of the user equipment can be modelled. There is also the possibility of using the equations as a basis for an orientation measurement system.

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# Performance stability of software TOA-based ranging in WLAN

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**Introduction and background**

TOA-based ranging with off-the-shelf WLAN equipment enables cost-effective and accurate positioning. Authors reported in [1] first results on a software-only ranging technique employing the CPU clock of the client device to perform round-trip-time (RTT) measurements. The transmission and reception of standard IEEE 802.11 frames was time-stamped at the operating system (OS) level through the driver of the client's WLAN interface. Although the maximum accuracy reached in a real test-bed was better than in previous software proposals ([2, 3]), the WLAN interruption handling by the OS caused a high dispersion of the time measurements and therefore the performance stability was not as good as expected. This work proposes several enhancements to palliate this negative impact, taking as starting point the core design decisions proposed in [1], i.e. data-ACK frames for the RTT measurements and Linux OS with Madwifi WLAN driver for the client device.

**Proposed enhancements**

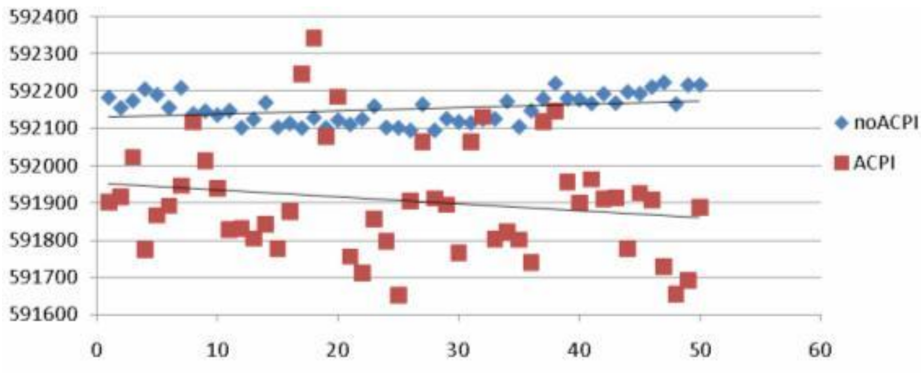
The first enhancement consists of anticipating the capture of the time-stamps in order to avoid the measurement of extra random delay caused by the interruption handling performed by the OS. The second enhancement is the correction of a bug in the Madwifi driver that did not allow setting a constant transmission rate at the physical level. The third and main improvement is provided by the use of a proper OS configuration in the client device.

Two significant and representative OS configurations have been considered for evaluation. The first is the default one: the one preferred by the end user to execute standard working and entertainment software. Since it is designed to optimize the general performance of the system, it presents more relaxed handling of the hardware interruptions and a possible lack of stability of the CPU clock signal. Therefore it can be disadvantageous to the performance of the RTT measurement mechanism. Patching the Linux kernel with real-time capability has been discarded based on previous performance tests. The second OS configuration is obtained by disabling the ACPI (Advanced Configuration and Power Interface) modules. ACPI allows the OS having complete and exclusive control of the power management of the hardware. When hardware and power are not managed via ACPI the performance parameters of the CPU and the other devices are expected to be constant, allowing higher stability of the time measurements. The main drawback of this configuration is the negative impact of disabling the ACPI on the usual operation of the device.

**Comparative evaluation of OS configurations and results**

The performance of the enhanced ranging method considering the different OS configurations is comparatively evaluated. The off-the-shelf employed hardware for the tests consists of the ranging client device (laptop with a 2 GHz CPU, an Atheros-based WLAN card, the modified Madwifi driver and the ranging software) and a Netgear D-Link AP. A large number of series of 1000 RTT measurements are carried out in multiple indoor and outdoor environments and distances, always with the same conditions for both configurations in order to guarantee a fair comparison. A first analysis of the measurements corroborates the bigger time dispersion for the measurements with the default configuration: around 800 CPU clock cycles for the no-ACPI configuration and around 5500 for the default one.

In order to assess the stability of the RTT statistical parameters, 50 series of measurements are repeated at different instants of time with the same conditions. The figure depicts the obtained average values in CPU clock cycles for each series of RTT measurements (i.e. series 1 to 50 in the abscissa axis). It can be observed that disabling the ACPI allows much better stability: the deviation of the 50 averages with no-ACPI is 38.869 CPU clock cycles, involving a maximum ranging error of only 2.59 m. can be caused by the system instability (four times smaller than with the default configuration). The complete report also demonstrates that the ranging accuracy is better with the no-ACPI configuration.




Obtained results show that the proposed enhancements employing a no-ACPI OS configuration allow overcoming the critical and inherent aspect of performance instability in TOA-based WLAN ranging at OS level. This result opens the challenge of achieving the same good performance but with the default OS configuration, in order to improve the practical applicability of the method. The researched approach to achieve this consists of mitigating the RTT measurement noise due to the ACPI operation, which is demonstrated to be feasible characterizing this noise by comparing the measurements of both configurations as first step.

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# Hardware Implementation of a Particle Filter for Location Estimation

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## 1 Summary

In this paper we present the hardware implementation of a particle filter for location estimation. Based on distance information to static network nodes, the filter estimates the three-dimensional position of a mobile network node. The design has been derived from a set of formal operation properties and synthesized for an FPGA prototype platform. Accessed through a serial interface, it can be used as a location estimation core from microcontrollers with low computational power. The implemented models for state transition and measurements can be re-parameterized during operation. Due to the chosen design approach these models can also easily be modified or exchanged in order to match the application needs. The correct functionality of the implementation has been shown using real time-of-flight based distance measurements. Therefore, the prototype platform has been integrated in an existing IEEE 802.15.4a compliant wireless network infrastructure.

## 2 Introduction

Location awareness is a more and more important issue in wireless networks. Without additional localization hardware, e.g. GPS receivers, the node's positions need to be inferred from network internal signal strength, time of flight or angular measurements. Because of the inherent uncertainty of such measurements, robust estimation techniques have to be applied. A common method for estimating a system's state from noisy observations are Bayes Filters, where both state and observations are considered as probabilistic functions. Kalman Filters are a very efficient and popular implementation of the Bayes filter algorithm, modelling state and observations as unimodal Gaussian distributions. As a drawback, they are limited to Gaussian errors and systems with linear state transition and observation models. Another implementation of Bayes filters are particle filters [1]. In contrast to Kalman Filters, arbitrary distributions can be approximated by a set of random state samples (particles). For reasons of approximation accuracy, the number of particles has to be large. The resulting computational effort and memory consumption is not feasible for low power microcontrollers that are commonly used in wireless sensor networks. In such cases it is desirable to have computational expensive parts as dedicated hardware components.

## 3 Filter Implementation

We present a hardware implementation of a particle filter for estimating the 3D position of a mobile node by incorporating distance information to reference points of known position (anchor points). The following update is cyclically performed by the filter:

1. Predict a hypothetical position for each particle based on its former position. This step involves an application specific motion model. In our implementation the mobile node is assumed to move without any favoured direction. This fact is considered by adding normal distributed noise with adjustable variance on the expected particle positions.

2. Calculate a weight for each particle involving a sensor specific measurement model. In our case, this model describes the probability of measuring a given distance at the particular particle position. We consider uncertainties relating to measurement noise and multipath effects under line-of-sight conditions using a quadratic decreasing weight function with separately adjustable slew rates for positive and negative distance errors.
3. Generate the final particle set through a low variance resampling procedure of the hypothetical set from step 1. The probability of drawing each particle is given by its corresponding weight. This step duplicates particles with large weights while less important particles are replaced. Thus, the resulting particle set is focused on regions with high probability.
4. Extract statistical parameters from the resulting particle set. Since we assume unimodal distributions, mean and covariance parameters over all particles are calculated.

The steps above represent the computational framework of the particle filter. The given models can be re-parameterized during operation and easily adapted to other application specific models. The design has been implemented using operation properties, an alternative, and in some application areas more convenient, design approach [2]. Our tool *vhisyn* derives a cycle-accurate register transfer model from a given specification based on a set of operation properties. The resulting VHDL design description has been synthesized and run on a Virtex-II Pro (xc2vp30) FPGA platform. The design is connected via the processor local bus to the embedded Power PC, which implements the serial user interface. The processor feeds the arriving distance measurements and reference positions into the weight calculation unit and reads the estimated position mean and covariance values from the design.

## 4 Results

The correct functionality of the implementation has been shown using real time-of-flight based distance measurements. Therefore the prototype platform has been integrated in an existing IEEE 802.15.4a compliant wireless network infrastructure. Distances between a mobile and several static network nodes of known position are cyclically measured and evaluated by the filter. The estimated position is read out and visualized using the 3D rendering library Panda3D. In our setup, we reach typical estimation accuracies of about 1m. The design runs at a maximum clock frequency of 25 MHz. With 8192 particles and 3 clock cycles processing delay per particle on average, a filter update is performed within less than 1 millisecond. In contrast, the comparable update performed by the reference software implementation on an ARM7 microcontroller needs 660 milliseconds. The design uses 6011 of 13696 slices, that is 43% of the FPGA resources.

## 5 Acknowledgements

This research work was supported in part by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung) in the project HERKULES under the contract number 01 M 3082 and the project InnoProfile under contract number 03 IP 505.

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# High Accuracy WLAN Positioning using Sparse Estimation Techniques

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## 1 Introduction

Positioning indoors is a requirement for a wide variety of applications. While significant research effort is ongoing to extend GPS indoors, real-time high accuracy positioning remains a challenge due to signal attenuation and blockage. Conversely, proprietary systems such as the Ultra Wideband-based Ubisense can provide cm-level (2σ) positioning accuracy but are limited by their high cost and small coverage areas [1]. The widespread use of WLAN has attracted substantial research to enable them to support low cost positioning. However, the current WLAN positioning capability is largely based on Received Signal Strength (RSS) fingerprinting which requires significant effort to build and maintain the currency of the relevant databases, and with positioning accuracy limited to 6m (95%) [1]. Conversely, time-based ranging could achieve high positioning accuracy but requires precise synchronisation and accurate time estimation. The latter is limited by factors such as bandwidth, multipath, non Line of Sight (LOS), Signal to Noise Ratio (SNR) and interference.

In this paper we develop a high accuracy positioning function for mobile devices based on the WLAN IEEE802.11g standard. A method that achieves time estimation in order to support sub-metre level (95%) ranging accuracy within a WLAN system is proposed. It is based on sparse estimation techniques and provides low complexity and fast extraction of measurements without compromising the achieved accuracy. The dependence of the time estimation process on the system bandwidth has been reduced by using high rate sampling clocks and then applying high resolution estimation techniques. Furthermore, in order to minimise the effect on the network data throughput, the extraction of measurements is based on the data frame preamble. The need for precise synchronisation has been removed by applying the Differential Time Difference of Arrival (DTDOA) technique. DTDOA is based on installing reference nodes with known ranges and LOS to a master node. The ranging process is depicted in Figure 1 where the short and long preambles of the WLAN IEEE802.11g frame are used for respective signal detection and sparse channel estimation.

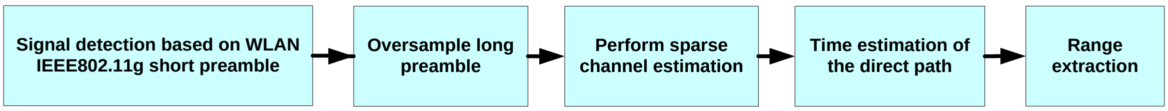


Figure 1: System-level block diagram for the proposed ranging method

The sparse estimation is enabled by the use of a high sampling rate as discussed in section 2 with the time estimation and corresponding ranging being covered in section 3.

## 2 The Use of Sparse Estimation for High Resolution Time Estimation in WLAN

Applying sparse estimation techniques is enabled by using high rate sampling at the receiver. This is based on modelling the received signal as:

$$Rx(t) = Tx(t) \otimes Ch(t) \otimes B(t) + v(t) = Tx_{BW}(t) \otimes Ch(t) + v(t) \qquad (1)$$

where $Tx(t)$, $Rx(t)$ the respective transmitted and received signals, $B(t)$ the system bandwidth, $Ch(t)$ the discrete channel impulse response with taps representing the delay and attenuation of multipath components, $\otimes$ denotes convolution, $v(t)$ the band-limited received Gaussian noise and $Tx_{BW}(t) = Tx(t) \otimes B(t)$ the band-limited transmitted signal which may be estimated *a priori* by observing $Rx(t)$ in a multipath-free channel. Equation (1) can be presented in vector format as ($\mathbf{Rx}$ = $\mathbf{A.Ch}$ + $\mathbf{v}$) where $\mathbf{A} \in R^{n \times m}$ is a toeplitz matrix with each column presenting a delayed version of the sampled band-limited transmitted signal $\mathbf{Tx_{BW}} \in R^{n \times 1}$, $\mathbf{Ch} \in R^{m \times 1}$ the discrete multipath channel. Increasing the sampling rate at the receiver leads to an increase in the size of $\mathbf{Rx}$ for the same observation period. This results in increasing the size of $\mathbf{Ch}$ by additional zeros since the number of multipath components is independent of the sampling rate. Hence, for a sufficiently high sampling rate, $\mathbf{Ch}$ can be treated as a sparse vector even when $\mathbf{Ch}$ represents a dense multipath channel.

In this paper, the regularised FOCal Underdetermined System Solver (FOCUSS) sparse estimation technique has been applied to estimate $\mathbf{Ch}$ due to its high-resolution performance and lower required processing power compared to other estimation techniques [2]. It is based on an iterative weighted minimum 2-norm approach.

## 3 Results

The performance of regularised FOCUSS is compared to the time-domain Multiple Signal Classification (MUSIC) and the de-convolution-based CLEAN algorithms in terms of achieved ranging error and required processing time (see Figure 2). Comparison is performed in a MATLAB platform and is based on sampling the WLAN received signal at 1GHz. Figure 2 demonstrates FOCUSS ability to provide better ranging compared to CLEAN and faster acquisition and better ranging at (>11dB) SNR values compared to MUSIC.

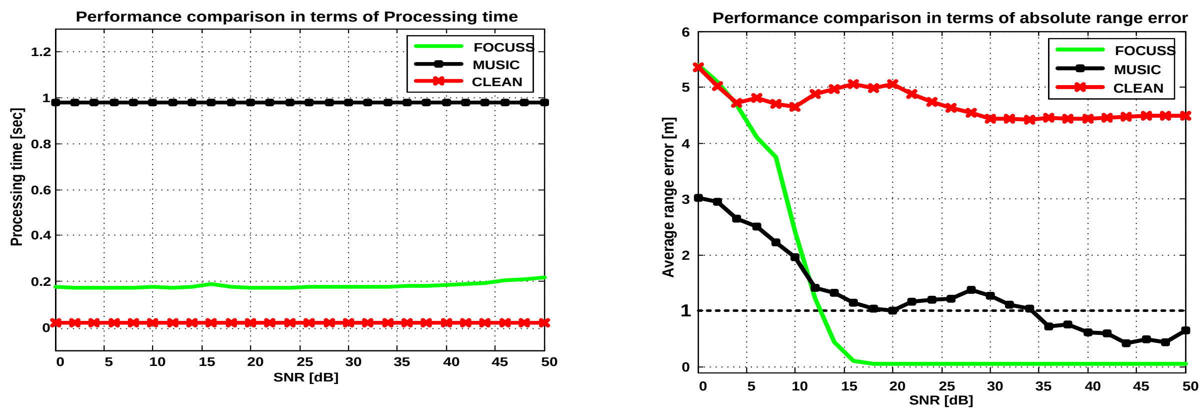


Figure 2: Comparison of FOCUS, MUSIC & CLEAN in terms of ranging error and processing time

## 4 Conclusion

This paper has proposed a low cost and high accuracy WLAN positioning system for mobile nodes in indoor environments. This is enabled by a fast acquisition and low complexity time estimation technique capable of addressing the bandwidth and multipath limitations under typical SNR scenarios. Further work is ongoing to evaluate its performance in real scenarios.

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# Ad hoc Indoor Peer-to-peer Tracking using Relative Location Estimation

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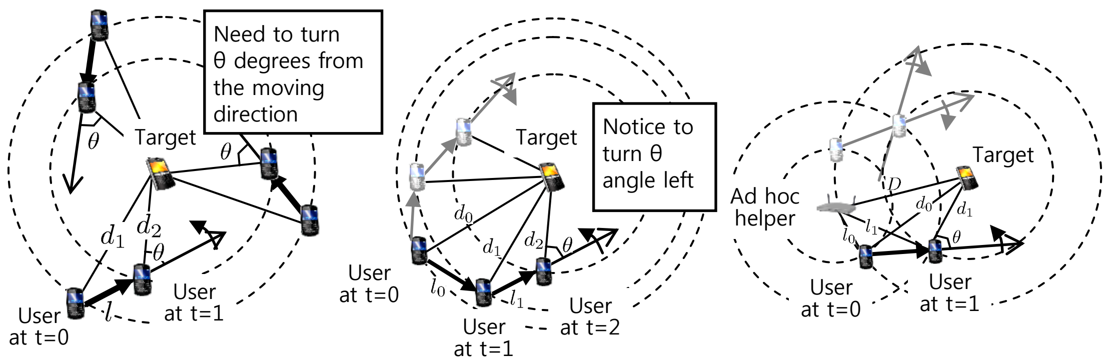
## 1 Introduction

An ad hoc indoor location-based service which finds and tracks location of a device is useful in many situations such as meeting friends, finding a child and looking for a lost device. In these situations, estimating absolute location of a target device is not suitable for the ad hoc indoor location service. Calculation and Notification of the absolute location require additional information such as maps and absolute locations of reference infra nodes, but it cannot be provided for every indoor environment.

We instead consider relative location, which is sufficient to help a user to move to the target. Relative location is determined by distance and direction from the user to the target. The distance to the target can be estimated reasonably in the indoor environments by measuring time of arrival (TOA) or received signal strength (RSS) of radio or acoustic signal. On the other hand, due to the non-line-of-sight (NLOS) environment, it is difficult to estimate the direction which is in general obtained by measuring direction of arrival (DOA).

When the user is moving, continuous measurements of the distance can be used to obtain relative direction to the target with reference to the moving direction. (See Figure 1(a), 1(b)) In this case, the devices should also have knowledge of their movement, which can be measured by, for example, inertial measurement units (IMU). If there is an ad hoc location-unknown helper node, such as a Wi-Fi access point, the user device can calculate the relative locations of the target device even without measuring the movement. (See Figure 1(c)) Detailed expressions for these cases will be given in the following section.

In this abstract, we only provide two examples as briefly described above. We will consider more examples, such as tracking a moving target and bi-directional tracking, in the full paper. We will also consider a generalized system which can support all the cases described.




(a) (b) (c)

Figure 1: (a) When $d_1$, $d_2$ and $l$ are known, the relative direction of the target can be calculated although the users do not know their absolute moving direction. (b) Relative location estimation with distance and movement measurements. (c) Relative location estimation with distance measurements and an ad hoc helper node. (Positions of gray devices are possible to be estimated but not actual.)

## 2 Motivational Examples

In this section, we assume no measurement errors in order to clearly explain the examples.

### a. Estimation with a fixed target, distance and movement measurements

Consider the situation in Figure 1(b) where the target is fixed, there are no helpers, and the user device can measure distance and its movement. Then, at time $t=2$, we see that the user device should turn $\theta = \cos^{-1}\frac{l_1^2 + d_2^2 - d_1^2}{2l_1 d_2}$ degrees. However, it does not know whether it should turn clockwise or counter-clockwise. This ambiguity can be removed if the user moves in a curve, as depicted in Figure 1(b). If $\theta$ estimated at $t=2$ is smaller than $\theta$ estimated at $t=1$, the user has turned to the correct direction at $t=1$.

### b. Estimation with fixed target and helper, and distance measurement

Consider the case in Figure 1(c) where the target is fixed, there is an ad hoc helper, and the devices can measure the distance between devices. In this case, the target device should send the value of measured distance $D$ to the user device. Then the user should turn $\theta = \pm\cos^{-1}\frac{D^2 + d_0^2 - l_0^2}{2Dd_0} \pm \tan^{-1}\frac{(l_1^2 - l_0^2) - (d_1^2 - d_0^2)}{\sqrt{4l_0^2 D - (l_0^2 + D^2 - d_0^2)^2}}$ degrees. There are 4 possible outcomes of $\theta$ depending on the signs of the two terms in the above equation. As in Section 2.1 mentioned, this ambiguity can be removed if the user moves in a curve and the device can measure how many degrees it has turned.

## 3 Evaluation

We simulated a user moving to its target. The scenarios in Sections 2.1 and 2.2 are adopted. We see in Figure 3 that the user moves well to the target. In the full paper, we also use a sequential Monte Carlo method, which is easily adaptable to various cases such as the capability of movement measurement or the existence of a helper node. We will provide the detailed algorithm in the full paper. In the full paper, we also evaluate the approach for other cases such as tracking a moving target and bi-directional tracking.

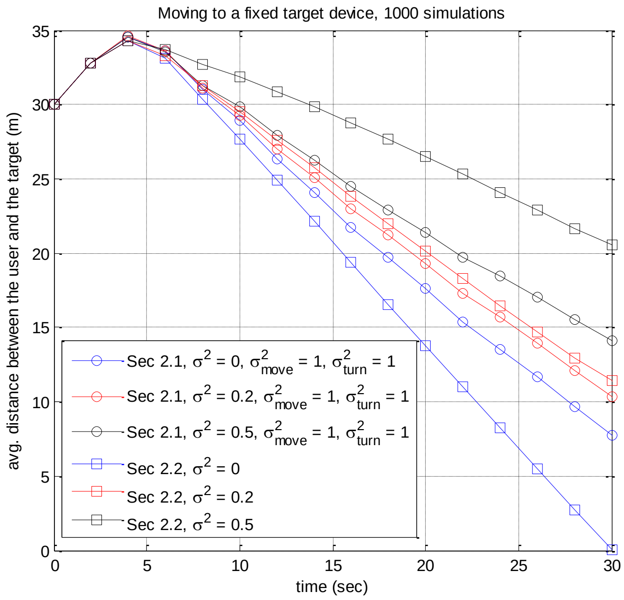



Figure 3: Simulation results for the situations in Sections 2.1 and 2.2. Every 2 seconds, the user walking with 5km/h checks the relative location of the target and heads to the target (turns maximally 60°). The plot is the average distance between the devices over time for 1000 simulations with Gaussian distance measurement error $N(0,\sigma^2)$, movement measurement error $N(0,\sigma_{move}^2)$, and rotation measurement error $N(0,\sigma_{turn}^2)$.

# Direction Estimation for Cellular Enhanced Cell-ID Positioning Using Multiple Sector Observations

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## 1 Summary

In this paper, we propose a method that improves the accuracy of the direction of User Equipment (UE) for Enhanced Cell-ID (ECID) positioning of mobile phones. The proposed method estimates the direction of UE by the use of different reception sectors. The evaluation of the direction accuracy and positioning accuracy are presented via computer simulations. The improvement in the direction accuracy is approximately 65% for the Rayleigh fading environment under the assumption that the number of observations is 10 and the width of the sector is 60°. The RTT (Round Trip Time) positioning accuracy is improved by about 50% using the proposed method when the RTT measurement error is 156 m and the cell spacing is 4 km.

## 2 Background and Conventional RTT Positioning

ECID positioning of cellular systems utilizes information of the reception Node B (NB) which is equivalent to the BTS (Base Transceiver Station). It is frequently used when GPS positioning cannot be applied [1] [2]. As shown in Figure 1, the conventional RTT positioning method [3], which is known as one of the ECID positioning methods, estimates UE position by using the distance and direction of the UE. The distance can be calculated based on the measured RTT of the radio signal between the UE and NB. The direction of the sector is used as the direction of UE. The error of the estimated direction degrades the position accuracy of the RTT positioning method when the sector is wide or has large cell spacing. Therefore, it is important to improve the accuracy by estimating the direction of the UE. So we propose a novel method to estimating the direction of UE more accurately to enhance the RTT positioning as shown in Figure 1.

## 3 Proposed Method

In a Diversity Handover (DHO) situation, signals from multiple sectors can be received by the UE. We call such received sectors observed sectors. In the proposed method, the UE repeats the sector observation multiple times at a specific interval. The number of observed sectors is counted and added under the sector ID. Then, we choose the two most observed sectors and estimate the average received signal power ratio using their observation times. Finally, the direction of UE can be calculated by using the estimated average received signal power ratio and the sector's antenna pattern.

In a W-CDMA (Wideband-Code Division Multiple Access) network, the RNC (Radio Network Controller) always has the DHO information of each UE. Therefore, we propose a method that can estimate the direction of UE without an extra report from the UE. This should be increase the effectiveness in order to decrease network traffic.

## 4 Simulation Results

The direction accuracy of the proposed method is evaluated based on a computer simulation. Figure 2 and 3 show the Cumulative Distribution Function (CDF) of the direction accuracy and the position accuracy where the cell spacing is 4 km, the number of sectors in each cell is 6 and the average RTT measurement error is 156 m. The wireless channel is assumed to be the Rayleigh fading. Compared to the conventional RTT positioning, the improvement in the direction accuracy is approximately 11° at 67% CDF when the number of observations is 10. Furthermore, by increasing the observations to 50 or more, the direction accuracy of the proposed method becomes even better. By using 10 observations, the proposed method exhibits an improvement in the positioning accuracy of approximately 150 m at 67% CDF compared to the conventional RTT positioning. Moreover, there is almost no observed deterioration compared to the limit of the RTT positioning accuracy that estimates the UE direction using the measured received signal power ratio.

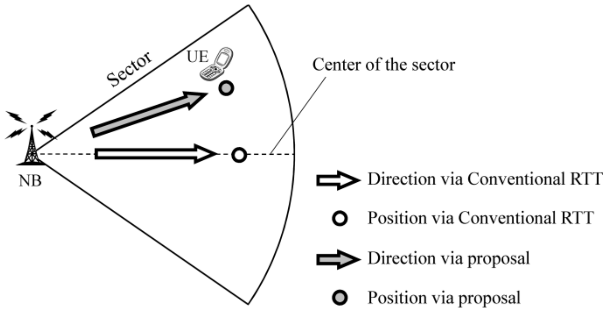


Figure 7: RTT positioning method

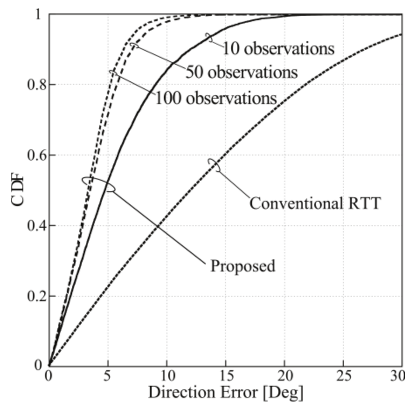


Figure 2: Direction accuracy

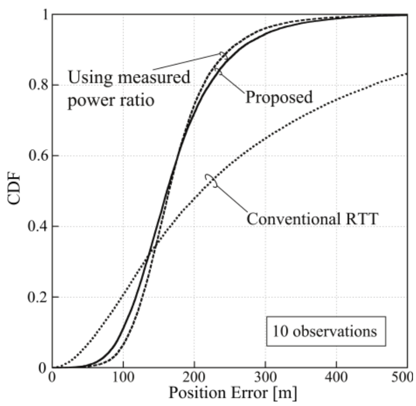


Figure 3: Position accuracy

## 5 Conclusions

We propose a method for estimating the direction of the UE by exploiting the sector of arrival. The evaluation results show that the direction accuracy can be greatly improved by using the proposed method compared to the conventional RTT positioning method.

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## Localization, Algorithms for WSN

Auditorium G7

Friday, September 17, 08:15 – 09:45 & 10:15 – 12:00

Beschreibung

# A comparison of multidimensional scaling and non-linear regression for positioning applications.

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For locating a set of stationary devices, algorithms such as MDS-MAP have been favoured by the sensor network community [4,5] because of their low computational complexity. Whilst comparisons for complexity and performance have been done for other algorithms, non-linear regression has been neglected. The authors find that it is not much more expensive, and can yield significantly better accuracy for sensor network localisation.

**Algorithms**. MDS-MAP [4] takes a block of measurements and calculates the *NxN* matrix of dissimilarities, which is the distances between each pair of devices. Those which are missing (i.e. which are not available via direct sensor measurement) are then filled in using a shortest-path algorithm, such as Floyd-Warshall. Once the dissimilarity matrix is complete, multidimensional scaling is performed which reduces the *NxN* matrix into a *2xN* coordinate space using a form of isotonic regression.

Non-linear regression is a model-based fitting algorithm which takes the given measurements by a device and then, using a minimisation function such as Levenburg-Marquardt [3], performs non-linear least squares to produce a solution which best fits the model. This works by iteratively regressing the solution until the residual squared error is lower than a given threshold. For our localisation scenarios we have found the number of iterations to be between 3 and 7.

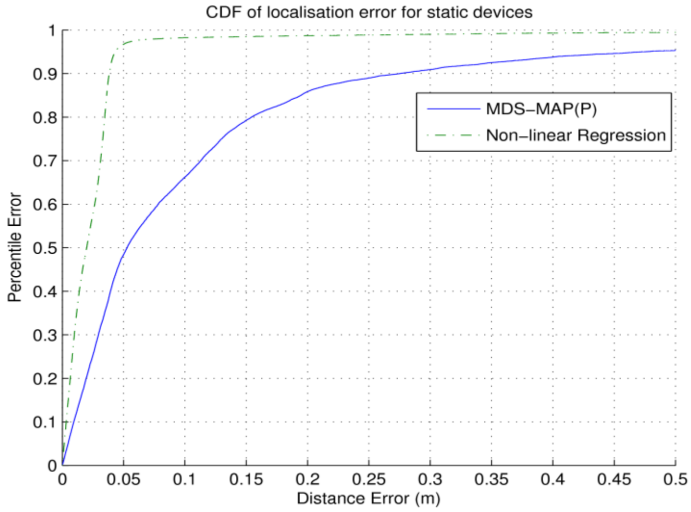
**Complexity**. MDS-MAP requires two main operations: computing shortest paths, and multidimensional scaling. If we take $k$ as the number of devices in a neighbourhood, the complexity of the Floyd-Warshall shortest path algorithm is $2k^3 + 6k^2 + 6k + 2$. Multidimensional scaling has a time complexity of $36k^3 + 110k^2 + 114k + 39$, mostly stemming from eigenvalue decomposition. This brings the overall time complexity of MDS-MAP to $38k^3 + 116k^2 + 120k + 41$ as found by Bischoff *et al* [1]□ .

Non-linear regression using Levenburg-Marquardt can be implemented efficiently using well-known algorithms, such as those outlined in *Numerical Recipes in C.* Using code analysis, the time complexity was found to be $276k^3 – 460k^2 + 756k – 287$, where $k$ is the number of nodes in the neighbourhood.

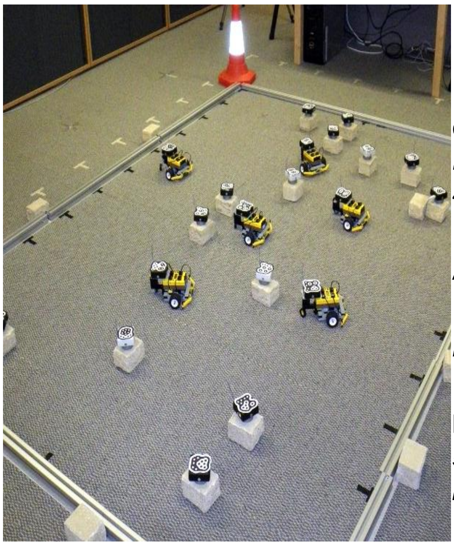
From the above comparison it is easy to see that non-linear regression is almost 8 times more expensive than MDS-MAP, in terms of the total number of operations required. But it is worth noting that MDS-MAP is limited to distance measures only. Non-linear regression uses parametric modelling and as such can use any mixture of metrics, such as range (time difference of arrival), pseudorange (time of arrival), and bearing (angle of arrival), to augment its solution.

**Empirical comparison from sensor node data.** Using data gathered from experiments using our custom ultrasonic devices [1]. Operating in round-robin fashion, each node transmits an ultrasonic pulse, while the other nodes measure and report the estimated range. MDS-MAP and non-linear regression algorithms were executed and their results compared. Measurements were taken in a 2.75 x 2.00 m arena (below, left) with a camera-based ground truth capture system (accurate to several millimetres) in place. The graph (below, right) is the cumulative localisation error distribution of a five nodes, placed in five randomly generated spatial layouts.

As the graph shows, the ninetieth percentile error of MDS-MAP is 27.5 cm with a median error of 5 cm, whilst non-linear regression has a ninetieth percentile error of 3.8 cm with a median error of 1.9 cm. An interesting point of note is the “long tail” of the distribution for MDS-MAP. The ninetieth percentile error of non-linear regression is better than the median of MDS-MAP, and the ninety-fifth percentile error of MDS-MAP is about half a metre.




With a much finer grain accuracy, non-linear regression seems a more flexible choice, especially with its support for many different measurement types—our platform can also supply bearing measurements. Depending on the application, the poorer accuracy of MDS-MAP may not be worth its one-eighth computational complexity.

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# Cooperative Indoor Position Location

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## 1 Summary

Indoor positioning has become a hot research topic due to a plethora of interesting applications ranging from emergency responder tracking to location-based services. In this work we focus on the problem of *network localization* also sometimes called *collaborative localization* where a network of nodes is to be localized using both connections to anchors (when they exist) and connections between unlocalized nodes [1]. Although several algorithms have been investigated in the literature (e.g., [2]), most have assumed line-of-sight (LOS) propagation which is uncommon in most indoor environments. Although the impact of non-LOS (NLOS) propagation has been considered in the literature (e.g., [3,4]), this has typically been limited to traditional single-node localization such as cellular location estimation. Specifically, we propose a technique designed for NLOS propagation for collaborative position location and demonstrate the performance improvement possible.

## 2 Problem Statement

A group of *N* nodes are attempting to determine their positions in an indoor area by performing ranging measurements to all other nodes within range. A portion of the connections between nodes are LOS, while the rest are assumed to be NLOS. Unlike most investigations, we assume that the NLOS measurements are more frequent. For example, consider a typical indoor office environment pictured in Figure 1(a). With random node placement, most of the connections are NLOS, especially as the communication range grows. For the pictured environment, the probability of a LOS connection given the communication range is plotted in Figure 1(b). Specifically, in this example we can see that if all of the links are 10m or less (i.e., the communication range is 10m), the probability of a link being LOS is only 20%. Thus, any algorithm must be able to effectively handle NLOS propagation. In this work we assume that LOS links result in an unbiased range measurement with Gaussian error. On the other hand, NLOS links result in a positively biased range measurement (the bias is uniformly distributed between $b_{min}$ and $b_{max}$ ) with Gaussian error.

## 3 The Proposed Algorithm

The proposed algorithm is a distributed approach based on projection onto convex sets. The original algorithm was designed for LOS links [5] but has been adapted specifically to handle NLOS propagation. The algorithm can work with various levels of *a priori* information including (but not limited to) NLOS identification, minimum bias knowledge, maximum bias knowledge, and mean bias knowledge.

## 4 Example Results

Figure 2 provides example performance results for the algorithm as compared to a state-of-the-art technique based on semi-definite programming (SDP) [2]. Specifically, the plots show the performance in a uniform network with 40 nodes and 13 anchors in a 100m x 100m area. A majority of the links (80%) are assumed to be NLOS with a 1m bias. The proposed technique effectively handles NLOS propagation improving mean localization error. In the final paper we will provide comprehensive results including 3D scenarios. Additionally we will address the ranging technique which is based on round-trip-delay.


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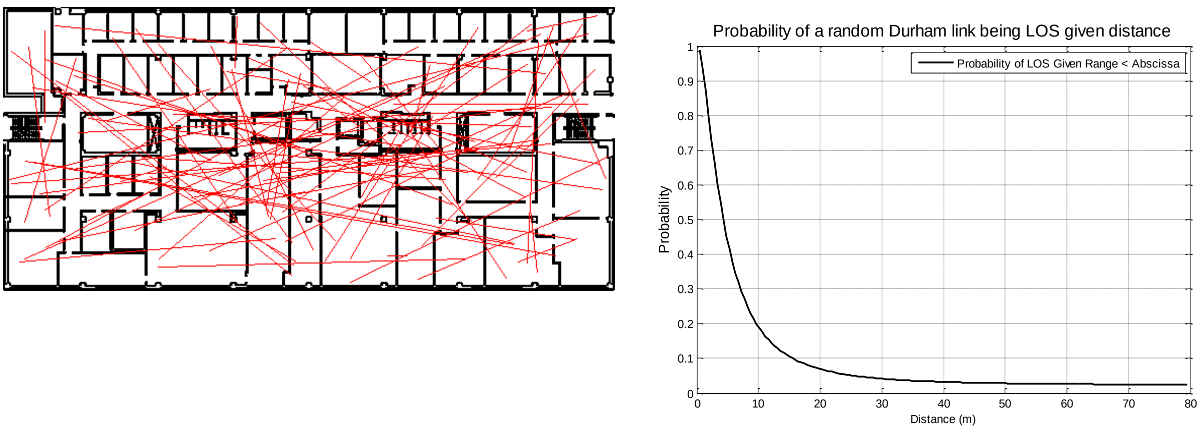
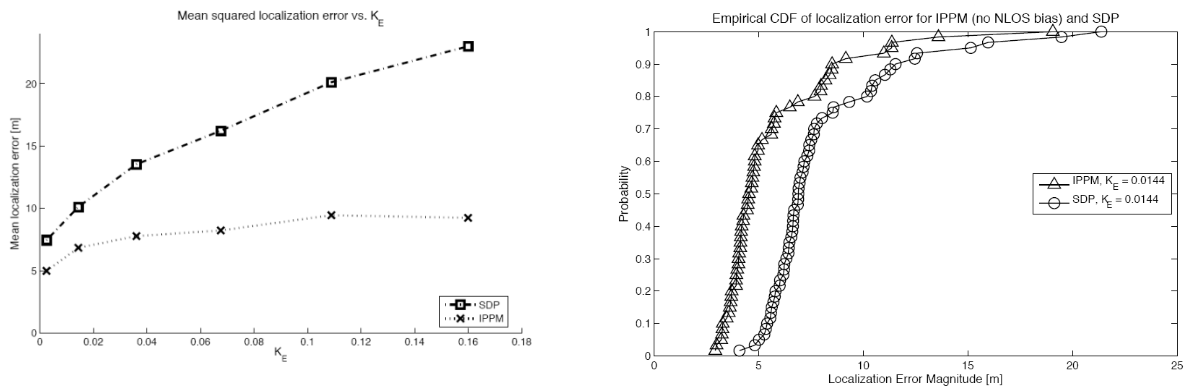



(a) (b)

Figure 1 – Example of Indoor Connectivity between Nodes in Typical Indoor Environment (a) and the Resulting Probability of LOS Propagation (b)




(a) (b)

Figure 2 – Performance of Proposed Algorithm (IPPM) as Compared to Semi-Definite Programming (SDP) (a) Mean Square Localization Error vs. Noise Power; (b) Example Empirical Cumulative Distribution of Localization Error

# Hybrid RSS-RTT Localization Scheme for Wireless Networks

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**Extended Abstract**

The purpose of localization schemes is to find the unknown position of a mobile station (MS) given a set of measurements. As the received signals coming from the global navigation satellite system (GNSS) technology are too weak to provide an accurate location in indoor environments, it may be practical to use information coming from the wireless access points (APs) that are currently deployed in many buildings (shopping malls, museums, hospitals, airports, etc.). Once the localization metrics between the MS that is going to be located and the APs are collected, these metrics are processed through a positioning algorithm to estimate the MS position. As the metrics become less reliable, the complexity of the positioning algorithm has to be increased. However, the possibility of obtaining different localization metrics at the MS encourages us to combine them and exploit their complementary behavior in order to develop a hybrid scheme improving the accuracy and without necessarily increasing the complexity of the algorithm. The aim of this paper is to provide a new hybrid strength-delay RF-based localization method to tackle indoor environments. This method takes advantage of easily available received signal strength (RSS) and time delay information. The latter is taken in terms of round-trip time (RTT) measurements thanks to the printed circuit board (PCB) proposed in [1], so as the time synchronization wireless network is not needed. Both, RSS and RTT measurements were carried out at the MS that is going to be located.

The hybrid localization scheme is based on a dynamic RSS ranging technique that uses RTT ranging estimates as range constraints. RSS ranging is based on the principle that says that the greater the distance between two wireless nodes, the weaker their relative RSS measurements are. However, the relationship between the RSS values and the MS position depends to a great extent on the propagation environment present between the MS and each AP, being very difficult to know which propagation models are the most suitable to describe such a relationship in an indoor environment. As changes in the indoor environment diminish any calibration effort, in this paper the RSS ranging technique proposed in [2] was used since it does not need any calibration stage. In [2] we proposed a technique that dynamically estimates the models that best fit the wireless channel present between the MS that is going to be located and each AP, using only the actual RSS values. Basically, these models depend on the path-loss, -the attenuation caused by the distance between the MS and the AP- which are inversely proportional to the distance raised to a certain exponent. Consequently, the RSS ranging technique consists in obtaining at each time step the path-loss exponents that maximize an objective function which quantifies the compatibility of the distances between the MS and each AP. However, the objective function does not have to be maximized for any value but, for a set of path-loss exponents belonging to a feasible set of solutions. In [2] a feasible set of path-loss exponents was derived using heuristic constraints. Nevertheless, the advantage to be exploited in this paper is the fact that a simple device, such as the PCB proposed in [1], can gather both RSS and RTT information from the

APs. Therefore, RTT-based range estimates [3] can be used as constraints, since RTT-based ranging estimates correlate closely to the actual distance. Finally, once the path-loss exponents are accurately estimated, the range estimates are obtained by using the models that relate the distance to the path-loss.

After having estimated the distances between the MS and the APs, the MS location can be found by means of multilateration, a common and well-known operation to find the MS location by using its range estimates to three or more APs whose positions are previously known. Fortunately, additional capabilities can be included into multilateration methods to find the MS position more accurately. Since measurement outliers naturally occur in an indoor environment due to the complex propagation of the transmitted signal between the MS and the APs, this paper proposes a new multilateration technique based on a robust least-squared method with the aim of accurately finding the MS position from both RTT and RSS-range estimates.

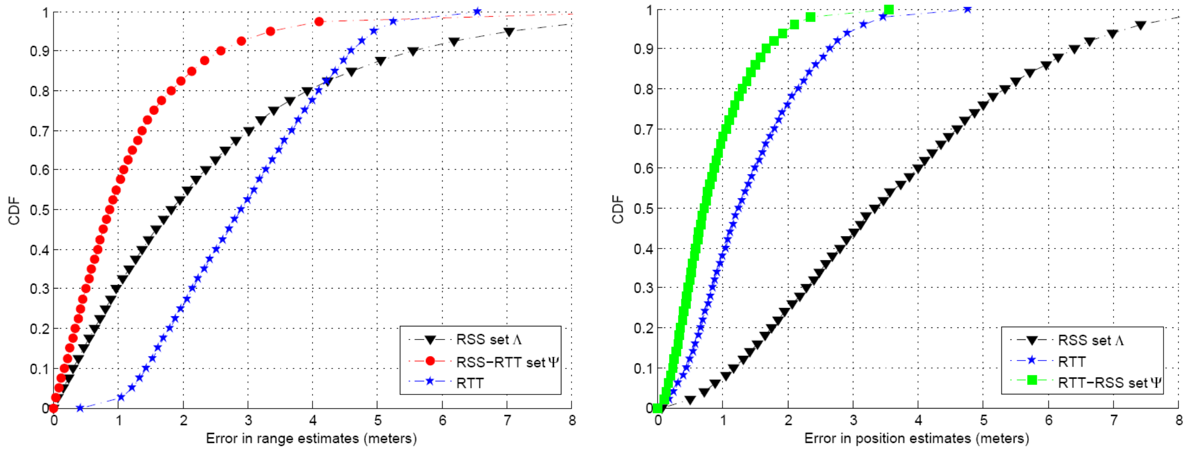


Figure 1: Performance of the hybrid RSS-RTT localization scheme. (a) Error in range estimates. (b) Error in position estimates.

Figure 1 represents the performance of the hybrid RSS-RTT localization scheme compared to the RSS-based and RTT-based schemes, where Λ represents the set of heuristic constraints and Ψ represents the previous set of constraints together with the constraints derived from RTT-based range estimates. Figure 1(a) represents the cumulative distribution function (CDF) of the errors in range estimates, while Figure 1(b) represents the CDF of the errors in position estimates. These errors are defined as the difference between the estimated range or position and the actual ones. The hybrid localization scheme coupled with simulations and real measurements in an indoor environment demonstrates that it outperforms the previous RSS-based and RTT-based indoor localization schemes. Finally, it is important to point out that the performance shown is achieved without using either a filtering technique or a previous calibration stage of the environment that would surely improve the performance even more.

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# pVoted: A Progressive On-Line Algorithm for Robust Real-Time Localization and Tracking in spite of Faulty Distance Information

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## 1 Summary

We present a progressive 3D localization algorithm for obtaining fairly precise position estimations in spite of highly imprecise and error-prone distance measurements from low cost hardware. At the same time, we achieve a high localization frequency, reduce energy for wireless data aggregation and require very little memory. We also provide a quality and trust classifier for each estimation. The low CPU load also facilitates its use on weak devices, e.g. within wireless sensor/actor networks (WSAN). For real-time tracking applications, a short position history further improves performance and precision.

## 2 Motivation, Measurements and Goals

While implementing our real-world indoor localization and tracking system SNoWBat [1], we observed several problems concerning signal detection and distance measurements via TDoA of radio and ultrasound. Beside strong distance and angle dependencies, we encountered significant influences of the system's reactivity and timestamping reliability for related actions, events or IRQs. This was particularly obvious upon concurrent execution of several software components/tasks. By using a lightweight DSP procedure and the preemptive SmartOS operating system [2], we achieved an almost constellation independent and temperature compensated error characteristic despite of node mobility (Fig. 1). In addition to the shown *central errors* ($e_c \sim N(0)$, $e_c = \pm\varepsilon$) and *side errors* ($e_s \sim N(\pm\lambda)$), the probability for sporadic gross errors (up to 10cm) was ~0.1%. Nevertheless, the goal was to reliably achieve an absolute 3D position error $e \leq \delta = 2\varepsilon \cdot \sqrt{3} < \lambda$ and a high localization frequency $f$ despite of only few (≈60%) "good" values.

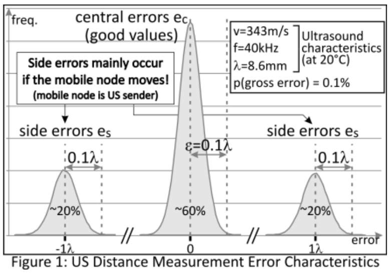


Figure 1: US Distance Measurement Error Characteristics

## 3 The pVoted Algorithm for Position Estimation

pVoted is a centralized five stage algorithm (Fig. 2) running on mobile nodes. Starting with a position ***P**rediction* $p_{pred}$ from just the most trustworthy historic values, it computes the position dependent number $m$ of required distance vectors (DVs toward static anchors) for the next estimation. Then it configures a self-organizing radio protocol [3] to efficiently receive this data by a collision free TDMA scheme with tightly packed slots. After invocation of any ***R**anging* process, the ***A**ggregation* stage successively collects the DVs $d$ from the anchors and ***G**enerates* potential location points (LP) $p$ from each consistent DV triplet, i.e. if the corresponding spheres (centers at the anchors, radii=distances) intersect in ≥1 point. For each new $p_n$, the *score* $s(d)$ of each involved DV $d$ is incremented. Using a heuristic, $p_n$ receives a *precision trust* $t_p(p_n) \in [0,1]$ inverse to its probability for an error due to inconvenient anchor constellations. Then, similar to many ranking algorithms, $p_n$ is voted against any available former $p_f$: If $\|p_n,p_f\|=s \leq \delta$ these LPs "vote" for each other. Then, the *overall precision* $P(p_n) \mathrel{+}= t_p(p_f) \cdot 1/s$ is updated and vice versa for $p_f$. The *consistencies* $\varsigma(p_n)$, $\varsigma(p_f)$

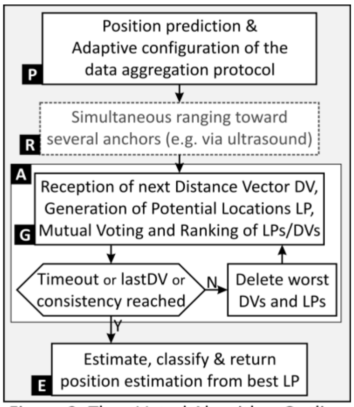


Figure 2: The pVoted Algorithm Outline

are incremented by $1/s$ reflecting the weighted number of mutual voters. In parallel, the *best location so far* $p_B$ is updated (by $\max \varsigma(p)$, initially $p_B := p_{pred}$). Then, the worst LPs ($\min \varsigma(p)$) as well as the worst DVs ($\min s(d)$) are deleted to limit the memory usage and computation time for further iterations. The aggregation stage stops as soon as either an adjustable threshold for $\varsigma(p_B)$ or a timeout is reached or if the radio protocol signals the reception of the last data packet. Then, based on $p_B$ the final ***E**stimation* $E$ is computed by Weighted Centroid Localization over all LPs which voted for $p_B$. The individual weight equals the precision trust these points imposed on $p_B$. Among other metrics, a final cross classifier $X(E)$ considers $p_B$'s reached precision and consistency compared to an expected value $X_{exp}$ which depends on the number of received DVs and the measurement error characteristics. The algorithm computes $X(E) \in [0,½)$ for less and $X(E) \in [½,1]$ for more reliable estimations. Commonly, in case of sufficient DVs, $X(E) \sim 1/\text{absoluteError}$. While this information is an advantage for many applications, the next prediction also relies on it to avoid the use of weak estimations and to define its impact on the next localization.

## 4 Performance Analysis Overview

For a short overview, a mobile node was tracked along four traces within an industrial hall of 30x20x7m (Fig. 3a). The anchors at the ceiling granted a 99% chance for ≥4 good measurements ($\varepsilon$=±0.86mm) for each estimation. For some algorithms (see [4] for Eckert's with Kalman filtering), Fig. 3b/c show the RMSE and the number of estimations within the requested accuracy $e \leq \delta$=±2.98mm. For comparison, the Multilateration marked with "*" was fed with good values only. While producing better results than this, pVoted can reliably distinguish its own good and bad estimations at runtime (Fig. 3d). Since we run the *A*/*G*/*E* stages in parallel to the *P*/*R* stages of the next iteration, a localization frequency of $f \approx 2.9\text{Hz}$ was achieved within our setup ($m_{max}$=9) based on MSP430 CPUs at 8MHz. Note, that *R*+*A* already take 337ms (CPU independent) while *G*+*E*+*P* just fill CPU idle times.

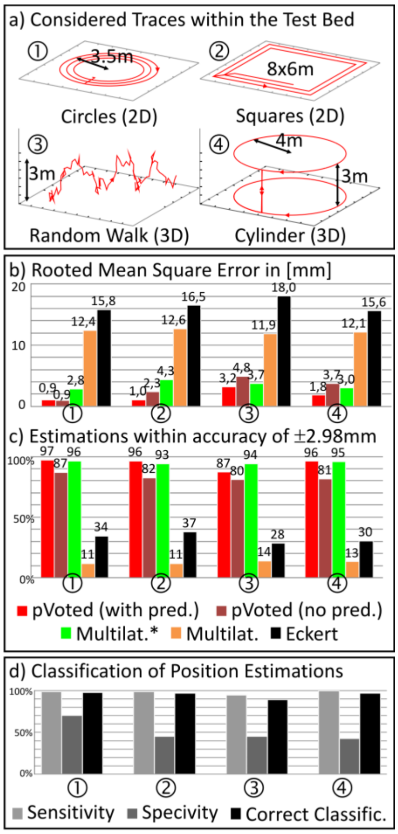


Figure 3: pVoted Performance Analysis

## 5 Conclusion and Outlook

Beside this very brief overview, further work considers the adaptive configuration of the radio protocol and the classification/estimation scheme. Both significantly reduce time and memory consumption (precise bounds can be shown) and even allow the detection of faulty sensors. We also compared more sophisticated algorithms and address anchor installation and self-calibration. Therefore, we currently research an extended pVoted scheme for SNoW Bat to observe its real-world performance when deploying setups of 50 anchors and concurrently operating mobile nodes.

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# Localization Services in Hybrid Self-organizing Networks

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## 1 Summary

In this paper we present a localization technique for self-organizing hybrid networks, where both indoor and outdoor scenarios coexist. In the proposed framework, outdoor anchor nodes act as reference nodes for estimating the position of mobile nodes which are moving in an indoor scenario. The reference nodes are equipped with both IEEE 802.16e and GPS network interface cards. The mobile nodes share some location information for estimating their own position by using flooding communication scheme. The accuracy of localization measurement is assessed in terms of Dilution of Precision, which is strictly depending on nodes topology. To minimize position and speed estimation errors of each node, an Extended Kalman Filtering technique is adopted. Simulation results demonstrate the effectiveness of the proposed approach, in terms of position and speed uncertainty.

## 2 Introduction

Localization information sharing is an essential task to support mobility in new generation networks. Mobile Ad-hoc NETworks (MANETs) are peer to peer self-configuring wireless ad-hoc networks, composed by mobile nodes placed in an arbitrary topology. Traditional MANET applications are in the military field, as well as in disaster recovery (*i.e*. emergency operations, flooding, earthquakes, and so forth). To assure end-to-end communications, due to lack of existing infrastructure, in self-organizing mobile networks it is necessary to estimate and monitor nodes' positions.

The emerging class of services –Location Based Services– allows the tracking and the navigation of a user in a location-aided environment, configured as point-to-multipoint, mesh, or ad hoc network. Several methods have been proposed in literature for estimating indoor position, *i.e.* Time of Arrivals, Time Difference of Arrivals, or the Direction of Arrival. Moreover, in indoor scenario where a drastic reduction in signal penetration and multipath occur, most of the location techniques fail to provide a sufficiently accurate position. As a consequence our vision is to introduce outdoor environment to support, and enhance indoor local positioning.

In this paper we extend the localization technique proposed in [1], used for traditional IEEE 802.11 indoor networks, to hybrid environments (*i.e.* both indoor, and outdoor networks), where a set of outdoor Reference Nodes (RNs) work to track and localize indoor Mobile Nodes (MNs). RNs are GPS-assisted, so that temporal synchronization is solved according to ranging mechanism as proposed in [1]. In our approach the positioning estimation is optimized by adopting an Extended Kalman Filtering (EKF) technique. Dilution of Position (DOP) factor has been evaluated as position accuracy monitoring during simulations for dynamical node configurations, both in a mesh topology and centralized architecture.

## 3 Proposed technique and main results

The proposed scheme is based on a recursive EKF approach, starting from an accurate initial position estimation to obtain high accuracy at the end of simulation period. We considered both centralized, and mesh topology. In both cases, a MN can get its own position by (*i*) three RNs, (*ii*) two RNs and one neighbouring MN, and (*iii*) MNs only. Notice that the choice of particular RNs depends on Geometric DOP value. Figure 1 depicts the hybrid scenario we considered.

Our algorithm can be summarized in four main steps: (*a*) each MN sends a Localization Service Request (LSR) packet to a master node, acting as Point of Coordination (PoC); (*b*) when the PoC receives the LSR, it collects the identifications of all the MNs in the network, and sends back to the MNs an LSR reception notification; (*c*) each MN can calculate RNs' positions, and obtain its position by triangulation of Time of Arrival (TOA) measurements; (*d*) MN's position is sent to the PoC, to optimize this information by EKF technique.

Simulation have been performed for three RNs (*i.e.* $RN_1$, $RN_2$ and $RN_3$), and four MNs. Each MN obtains its position by three TOA measurements (*e.g.* $MN_1$ by $RN_1$, $RN_2$, and $RN_3$). In the simulated scenario the MNs move uniformly at 5m/s, plus a random contribution; location updating period is set at 0.5s, and standard deviations of distance error are set in the range [0.01, 0.5] m. Position uncertainty is shown in Figure 2 (*left*). As can be noticed, after few iterations positioning error is minimized. As the same, in Figure 2 (*right*) we estimated speed uncertainty of four MNs. Notice that just after 8 iterations the uncertainty is strongly reduced.

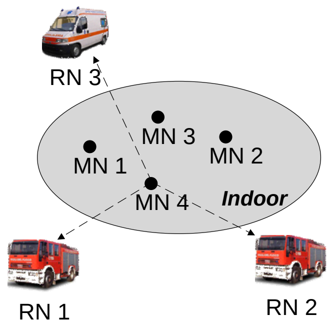


Figure 1: Hybrid network environment, composed by indoor MNs, and outdoor RNs.

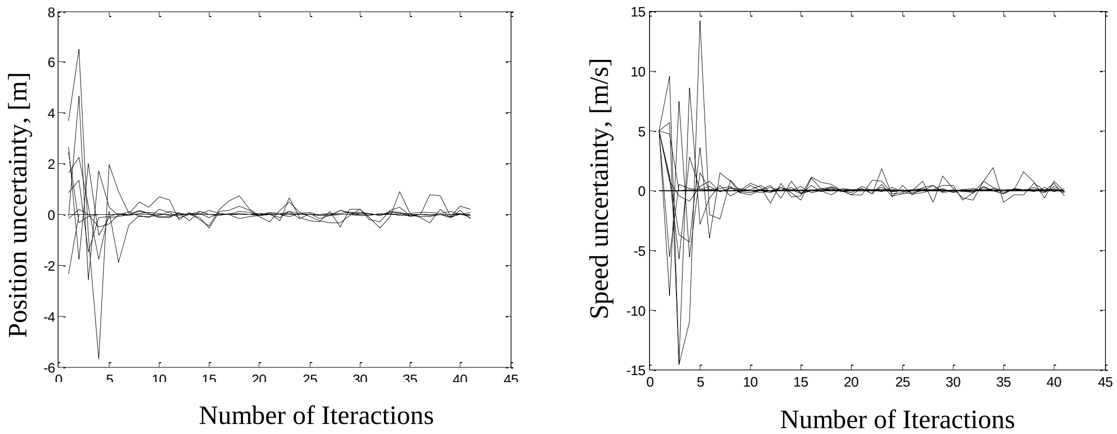


Figure 2: (*left*) Position, and (*right*) speed uncertainty, respectively.

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# On Distance Estimation based on Radio Propagation Models and Outlier Detection for Indoor Localization in Wireless Geosensor Networks

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## 1 Summary

The determination of a precise position in wireless geosensor networks requires the use of e.g. distance measurements. These distance observations derived by Received Signal Strength (RSS) measurements are inherently inaccurate. Furthermore, in general, the distance observations using RSS do not take obstacles into account. In this paper we present a new approach for indoor positioning to correct erroneous RSS measurements affected by obstacles. This technique is combined with the known "Anomaly Correction in Localization" (ACL) algorithm where sensor measurements are used to detect and eliminate outliers and therefore to improve the determined highly energy limited sensor node positions.

## 2 Background and Algorithm Description

In Reichenbach et al. the "Anomaly Correction in Localization" algorithm (ACL) was proposed [1]. This algorithm uses spatial information inherent in sensor measurements. The principal idea used is as follows: Usually a sensor network contains redundant beacons. Using simple trilateration, to reduce the energy consumption of the sensor nodes for localization, different positions can be estimated followed by the determination and elimination of outliers. For this elimination, the object of interest will be subdivided into sensor intervals where these intervals represent the physical parameter to be monitored. The expected range of sensor values will be modeled based on *a priori* information on the basis of e.g. floor plans and stored as a footprint map on the sensor nodes. During the localization process, the determined position will be adopted one-to-one into the footprint map. The sensor then measures the physical parameter and compares the measured value with the expected one on the footprint map for the calculated position. If the position on the map matches the sensor measurement it will be marked as valid and used for the final localization. If not it will be marked and deleted as an outlier. Here, only raw distances are used. There are many factors affecting the distance estimation. One of the major problems is the signal propagation through the medium between the emitting and the receiving node and accordingly the attenuation of the signal. Several models exist in literature to take these problems into account [2]. In our approach we investigate different models mainly based on the "Shadowing Model" [2]. Common models are based on deterministic functions and presume an ideal transmission range. The "Attenuation Factor Model" takes signal fading caused by obstacles into account and is therefore more realistic. In first simulations we used the "Attenuation Factor Model" which approximates obstacles by extending the "Shadowing Model" by a material characteristic factor. In our approach this algorithm will be extended by a method which corrects deviations caused by obstacles in the signal path. For this, the footprint map is extended by additional geographical information such as walls and possible obstacles (closets, desks, etc.) including their characteristic material factor. After the sensor node detects an outlier using ACL, the corresponding distances will be evaluated by comparing with obstacles marked in the footprint map. If the distance is obstructed, the corresponding attenuation factor will be added to the distance equation and the calculation repeated. After the calculation the newly derived position will again be tested by ACL.

## 3 Results

For the simulation five Beacons have been deployed covering three rooms of different static temperature. That is, ten possible trilaterations have been carried out, each repeated 10000 times to overcome empirical influences. First simulations show that the material of an obstacle has a large impact on the received signal strength. RSS measurement is highly inaccurate by itself. Due to the log-normal distribution, small errors have large influences when determining distances from RSS. By using ACL it was possible to detect and to eliminate a large number of outliers. However, since it does not take obstacles into account, ACL falsely detected valid measurements as outliers. This also has an impact on the remaining observations used for trilateration. By applying eACL the falsely determined observations could be largely corrected. Here, the material has a large impact on the number of outliers. Depending on the material, eACL improved the number of valid points by factor ten (see Table 1). For the scenario where attenuation caused by the walls is lower, the improvement was only of factor two. This has also an influence on the achieved accuracy. For more highly attenuating material, the precision of eACL increases also by factor 10 whereas the accuracy for the other material stays in the same ranges.

Table 1: Simulation Results using the Attenuation Factor Model

| ***Material*** | ***Valid Positions after ACL[%]*** | ***Valid Position after eACL[%]*** | ***Deviation in Position ACL [m]*** | ***Deviation in Position eACL [m]*** |
|---|---|---|---|---|
| Concrete Wall | 2.18 | 10.76 | 0.78 | 0.25 |
| Concrete Block Wall | 1.11 | 10.14 | 1.10 | 0.19 |
| Wooden wall | 6.04 | 11.40 | 0.57 | 0.53 |
| Brick wall | 3.96 | 10.93 | 0.67 | 0.35 |

## 4 Conclusion and Outlook

In this extended abstract we proposed the “extended Anomaly Correction in Localization” algorithm (eACL) in which we have extended the existing ACL by radio propagation models for distances derived by RSS measurements. Valid points falsely marked as outliers have been detected and distances corrected for subsequent trilateration. In first simulations it was possible to increase the number of valid positions by about factor 10 depending on the material. The resulting localization error was reduced by factor 3 to 10 in some scenarios. The eACL algorithm can be considered as an efficient additional method for localization. Even with relatively few preconditions it is possible to improve the localization. In particular in combination with approximate algorithms it is possible to obtain good results, but also with exact positioning where large distance errors are present then the eACL is of benefit.

The presented approach only uses damping factors of different materials to model the path loss of the transmitted signal while passing an obstacle in the line of sight. Current work is the investigation and implementation of additional signal propagation models. Moreover, the application of eACL in a sensor network to test real measurements is planned.

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# Theoretical Analysis and Validation Experiments of the Localization-by-Superposing-Beats Procedure

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## 1 Summary

Many everyday life activities require precise localization information. Navigation by means of global positioning system (GPS) is a well-known example, but this localization method cannot be utilized in all application areas. Logistics, factory and laboratory automation, as well as warehouse management, for example, require a low-cost localization of various objects with precision of few centimetres, particularly in indoor environments. For this application domain, this paper proposes a new procedure, called the Localization-by-Superposing-Beats (LSB) Procedure, to measures the relative distance of a receiver between two points, i.e., the transmitters. The LSB procedure is based on the superposition of particularly parametrized beats, and is characterized by very low resources demands. This paper presents a description of the procedure, a preliminary theoretical analysis, as well as some laboratory experiments.

## 2 Introduction

The Localization-by-Superposing-Beats (LSB) procedure detects the phase-shift of two high-frequency radio signals from one received signal through the evaluation of a low-frequency radio signal. Even though the high-frequency transmission signals might assume some MHz or even GHz, the analysis can be done on a signal that has only a few Hz. The high-frequency radio signals determine the resolution of a measurement that can be as small as a few centimeter. But since the evaluation has to be done on a few periods of the low-frequency signal, a detector can be realized in a low-cost implementation.

## 3 The Procedure: Description and Analysis

The LSB procedure is based on the superposition of simple beats. A beat arises through the superposition of two signals $s_{1/2} = \sin(2\pi f_{1/2} t)$ with similar frequencies $f_1 \approx f_2$. A receiver will be reading the beat $r(t) = s_1(t) + s_2(t)$. The beat $r(t)$ is enveloped with the low-frequency $f_{low}=(f_1-f_2)/2$. If in this very same configuration, i.e., both transmitter remain at fixed locations, the receiver is moved by $\Delta x$, a (theoretical) phase-shift $\Delta\varphi$ occurs between the envelopes with respect to the original position. This phase-shift can be used to derive the distance $\Delta x$ of the first and second receiver position. However, in order to make use of this phase-shift, the receiver would require some global timing information to calculate the phase-shift by two independent measurements. With respect to the realization of a proper measurement system, it might be useful to note that the phase-shift can be directly derived at the low-frequency enveloped signal. The LSB procedure assumes the same physical setup as already described, but the transmitters emit beats of the form $b_k(t) = \sin(2\pi f_k t)\cos(2\pi f_m t)$ with slightly varying carrier frequencies $f_k$ but identical envelopes $\cos(2\pi f_m t)$. The major effect of properly configured beats is that its superposition leads to an interference signal, $r(t) = b_a(t) + b_b(t)$, with a shape that uniquely depends on receiver's position.

Figure 1 sketches the shapes of the envelope of the interferences that occur at various differences $\Delta x$. The information of the relative distance difference is located in the different

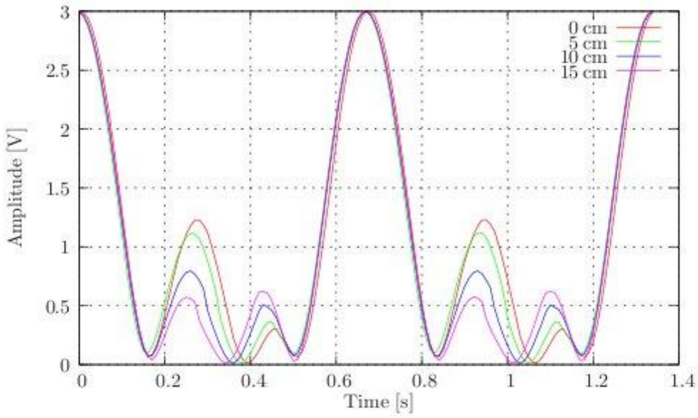


Figure 8: The envelops at four different locations $\Delta x$.

characteristics of the antinodes amplitudes. By evaluating the shape of this location-dependent envelope signal, a receiver is able to derive its relative distances to the two transmitters on its own. The envelopes in Figure 1 can be approximately described by the fitting function $r(t) \approx |2\cos(2\pi f_m t)\cos(2\pi \Delta f t - 2\pi f_g \Delta t)|$ with the following parameters: carrier frequency $f_g$, modulation frequency $f_m$, beat frequency $\Delta f$, and the constraint $f_m = \Delta f/k$ with $k \in Q$ and $k \neq 1$. The resolution of the distance measurement depends on the carrier frequency. By a detectable phase-shift of about 1°, a precision of 1cm can be measured with a 84MHz carrier frequency.

## 4 Laboratory Experiments

The laboratory experiments have validated the described principle of the LSB procedure. The experiments have used a wire-based setup with two transmitters and one receiver. The wires were realized by two line-stretchers for adjusting various relative distance differences between the two transmitters and the receiver. As the envelope detector, the AD8361 TruPwr Detection RFIC was used. The transmission signals were generated by the AD9959 DDS-Chip. With this setup and carrier frequencies of 50, 100 and 150MHz, a precision of about ±1cm was achieved; the beat frequency was set to 2.98Hz, and the parameter k was set to k=[0.25, 0.5, 2, 4].

## 5 Detection Algorithm

The recorded envelops were evaluated by a matching pattern detection algorithm. The recorded envelop was correlated with pre-calculated patterns and the lowest correlation value indicated the best matching pattern, which represents the receiver's location $\Delta x$.

## 6 Conclusions and Outlook

The laboratory experiments have demonstrated the principle utility of the LSB procedure for measuring the relative distance difference between two transmitters and one receiver with an acceptable maximum error for the used carrier frequencies. Future research will be devoted to the development of a detection algorithm that derives the phase shifts from a fast-fourier-transformation. Furthermore, future experiments will include a wireless setup. But for this step, some main noise influences, such as the near field problem of antennas and multi-path propagation, have to be solved.

# A Cross-layer Design of an Anycast-based Routing Protocol for Fast Indoor Localization

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## 1 Summary

This abstract presents a cross-layer design of an anycast routing protocol for Indoor Positioning Systems (IPSs). The main function of the IPS is to track the movement of individual emergency responders who carry out search and rescue operations in disaster zones. The proposed protocol is tightly coupled to the positioning application and the MAC protocols. In the next section, we present an overview of the IPS. Section 3 describes the design principles of the anycast-based routing protocol, and Section 4 evaluates the performance of the protocol. Finally, conclusions are drawn in Section 5.

## 2 Indoor Positioning System (IPS)

The considered IPS [1], which is a mobile wireless sensor network, consists of four types of nodes (see Figure 1): a Control Unit (CU), a Base Unit (BU), a Dropped Unit (DU), and a Mobile Unit (MU). The MU is a sensor that is worn by every emergency responder. The MU has the capability to calculate its position which is in turn delivered to the CU. The BUs are located outside and around the incident area. The DUs are strategically placed in the incident area by emergency responders to serve as relay nodes once the MUs lose wireless connectivity with the BUs. Like the MUs, the DUs can determine their positions and relay them to the CU. The CU provides the main visual display to the rescue coordinators, showing the current position and direction of movement of individual emergency responders with respect to the incident area topology, e.g. a building. As shown in Figure 1, the IPS is composed of a UWB subnetwork and a non-UWB subnetwork. The reason for two separate subnetworks is that the CU is not involved in the localization process. Thus, more radio resources are available for the UWB subnetwork, in particular, when the number of MUs increases.

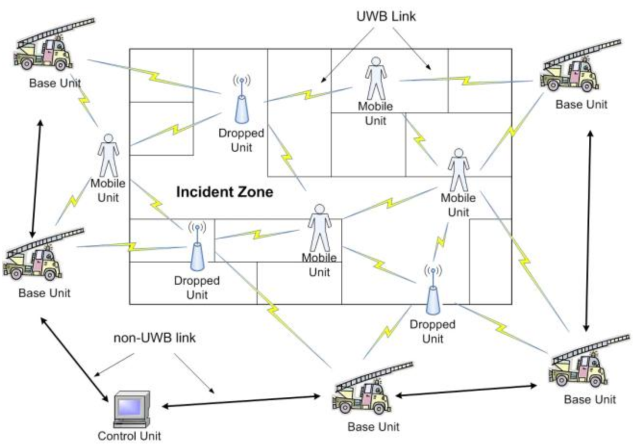


Figure 1: Indoor Positioning System

## 3 An IPS Anycast-based Routing Protocol (IAR)

In the design of the IAR, we assume the BUs are connected as a ring. The MUs/DUs are located in the area encircled by the ring. Packets (e.g. position data) originated from the MUs/DUs, which are destined for the CU, are first delivered to anyone of the BUs. Then the packets are forwarded to the CU by the BU. The CU can be co-located with one of the BUs or a separate entity. Since the location of the CU is implementation-dependent, routing between the CU and the BUs is not taken into consideration by IAR. IAR only concerns with the routing between the BUs, the DUs and the MUs. It exploits the positioning characteristic of the BU, the DU and the MU in order to achieve a highly bandwidth-efficient and very low overheads routing protocol. As a result, no dedicated routing packets are defined for IAR. Dissemination of route information relies on the positioning packets broadcast during positioning. Route information is embedded in network header of the positioning packets. The IAR defines two route information fields, namely hop count and congestion level. Hop count indicates the distance of a unit (in terms of the number of hops) to a reference unit that initializes the hop count. It increases monotonically at each hop. Congestion level is used to indicate the buffer occupancy of a unit. Route establishment is initiated by each BU since its position is known in advance. The MUs/DUs just listen to the BU broadcasts since they need to determine their positions. Once the MUs/DUs have determined their positions, they also broadcast their positions and include the routing information. In the route establishment process, each unit only maintains the next-hop routing information of the broadcaster. Since the positioning is a repeated process in order to maintain up-to-date position information, consequently all the routes maintained by the MUs/DUs are updated automatically. Therefore, no specific route maintenance functions are required to update routes.

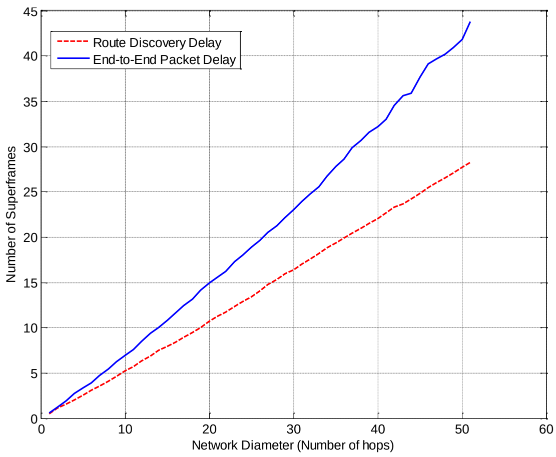


Figure 2: Route Discovery and End-to-End Packet Delays

## 4 Simulation Results

The route discovery and end-to-end packet delays were evaluated using the OMNeT++ simulator [2] and the mobility framework. A chain topology was used. Figure 2 shows that both the route discovery and the end-to-end packet delays are linearly proportional to the number of hops. Therefore, both delays are bonded by $O(h)$, where $h$ is the number of hops.

## 5 Conclusions

The abstract described a cross-layer design of an anycast-based routing protocol for indoor localization of emergency responders. The proposed protocol is tightly coupled to the positioning application and the MAC. As a result of the cross-layer design, the protocol is highly bandwidth-efficient, which consumes less than 1% of the channel capacity. Furthermore, routes are automatically established and maintenance without the need for dedicated routing packets. Simulation results show that the protocol is highly scalable.

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# The Impact of Location Errors on Geographic Routing in Realistic WSNs

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## 1 Introduction

Geographic routing (aka location/position-based routing) has recently received extensive research effort and emerged as one of the most efficient and scalable routing solutions for wireless sensor networks (WSNs). This operation can be an efficient, low overhead method of data delivery if it is reasonable to assume: 1) high link reliability; 2) accurate localization. Unfortunately, neither of these assumptions is valid in reality. Previous studies have shown that in real sensor network deployments, wireless links vary over space and time and can be highly unreliable. Moreover, the inevitable location errors also lead to a substantial degradation in the performance of geographic routing on both energy consumption and packet reception ratio (PRR). In this paper, we study the geographic routing under a more realistic WSN. By "more realistic", we mean that both a realistic packet loss model and localization inaccuracy will be considered. The PRR and energy performance of geographic routing is our main focus in this study. We believe this work, as the first study which takes into consideration both crucial factors in realistic WSNs, exposes new findings and problems which have not been previously discovered or have been misunderstood before due to too simplistic and unrealistic network models.

## 2 Analysis of the impact of location errors

The insufficient study of geographic routing in realistic WSNs motivates us to investigate these problems. Assume the spatial distribution of the nodes on a plain follows a two-dimensional Poisson distribution with the average density $\lambda$. The area of the forwarding region is the area of the lens formed by the intersection of two circles with source node *i* and destination node *d* as the centre, respectively (shaded area in Fig. 1). Hence, the probability of finding *k* nodes within the forwarding region *A* is:

$$\text{Prob}(k) = e^{-N}\frac{\lambda^N}{k!}, k \geq 0$$

where $N = \lambda \times A$ is the average number of nodes in the forwarding region. Thus, we have

$$\text{Prob}\{\text{there is at least one node within } A\} = 1 - \text{Prob}(k=0) = 1 - e^{-N}$$

Given the error model in [1], the probability that the measured location is within the forwarding region is:

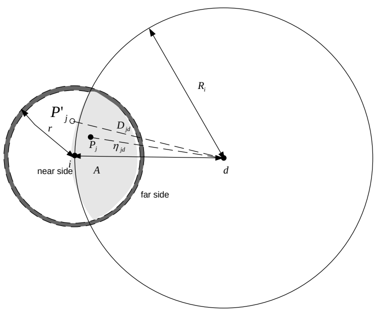


Fig.1 Impact of location errors on geographic forwarding

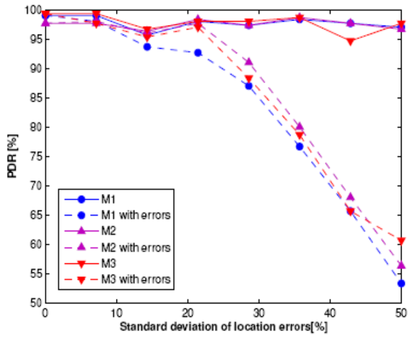


Fig.2 PDR versus the stand standard deviation of location

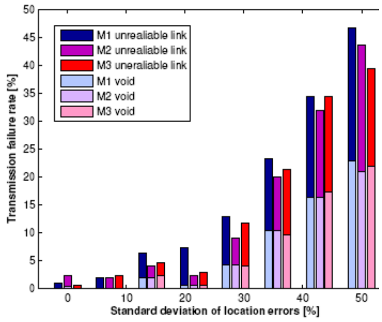


Fig. 3 Transmission failure rate versus the standard deviation of location errors.

$$\begin{aligned}&\text{Prob}\{\text{measured location is within the region } A\}\\&=1-\text{Prob}\{\text{measured location is out of the region } A\}=1-\text{Prob}\{D_{dj}>R\}\\&=1-\int_R^{\infty} f(D_{dj})dD=1-\int_R^{\infty}\frac{D_{dj}e^{-(D^2{}_{dj}+\eta^2{}_{dj})/2\sigma_{dj}{}^2}}{\sigma_{dj}{}^2}I_0\left(\frac{D_{dj}\eta_{dj}}{\sigma^2{}_{dj}}\right)dD=1-Q_1\left(\frac{\eta_{dj}}{\sigma_{dj}},\frac{R}{\sigma_{dj}}\right),\end{aligned}$$

where $D_{dj}$ is the measured distance between destination node *d* and neighbour node *j*. $\sigma_{dj}$ is the standard deviation of $D_{dj}$, $\eta_{dj}$ is the real distance between destination node *d* and neighbour node *j*, and $Q_1$ is Marcum's *Q* function with *m* = 1. Hence, the end-to-end packet delivery rate (PDR) for a path length of *N* hops is:

$$\begin{aligned}PDR=\prod&(\text{Prob}\{\text{there is at least one node within } A\}\bullet\text{Prob}\{\text{measured location is within the region } A\}\\&\bullet\text{Prob}\{\text{packet reception rate}\})\approx\prod_{i=0,j=1}^{N_{hops}-1,N_{hops}}((1-e^{-\lambda A})\bullet(1-Q_1(\frac{\eta_{dj}}{\sigma_{dj}},\frac{R}{\sigma_{dj}}))\bullet prr_{ij})\end{aligned}$$

## 3 Conclusions

In this paper, we studied geographic routing under a more realistic WSN scenario. Both, localization accuracy and a realistic packet loss have been considered in this study. A log-normal shadowing model was used to obtain the relationship between distance and PRR. Three cases of the location error have been discussed realistically regarding the packet delivery rate and energy performance of geographic routing. From the established mathematical model, we found the transmission failure caused by location errors is not significant when its deviation is less than 20% of the transmission range. Network voids and unreliable links that both contribute to transmission failure have also been compared via simulation and found that network void is not as serious as unreliable links when the location error is less than 20%. Extensive simulation results also confirmed these findings in more realistic scenarios.

## 4 Reference

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# Survivability of Mobile Sensor Network using Security Adaptation Reference Monitor (SARM)

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## 1 Summary

Wireless Sensor Network (WSN) should be capable of fulfilling its mission in hostile milieu such as in sinkhole attacks environment. Moreover, one of the main challenges of Mobile WSN (MWSN) is to save the limited energy in order to ensure long lifespan of the network. Some protocols like MIX are working well when all sensors cooperate. Therefore, we have applied to MWSN our generic Security Adaptation Reference Monitor (SARM) that has been developed to deal with extremely dynamic security conditions. SARM is based on an autonomic computing security looped system, which fine-tunes security means based on the monitoring of the context including the user environment and energy consumption aspects. We evaluate SARM on top of MIX protocol in the context of MWSN under sinkhole attacks through a simulation tool. The results show that SARM is efficient in terms of overall network utilization and power consumption.

## 2 Motivation for our Framework and Analysis

The sensors usually forward their messages to a base station (Internet gateway) in a hop-by-hop fashion because they are resource-constrained in terms of energy; the spending of energy dramatically increases with the range of transmission. It is quite easy for an attacker to defeat the WSN purpose by dropping messages when received rather than forwarding them or run out of energy other sensors by asking them to send information. Many solutions have been proposed for non-mobile WSN but there is a lack of literature for MWSN. Indeed, it is harder to deal with mobile attackers. We propose SARM as a compelling solution for this problem, because it was developed especially for highly dynamic wireless network. Our framework is run on top of MIX algorithm which is a gradient based routing protocol.

We would like with SARM to fine-tune security means as best as possible taking into account the risk of the current user environment of each sensor in a distributed manner and the performance of overall system, mainly regarding the optimization of its energy consumption. Thereby, our system differs from others by its:

1. Autonomic computing security looped system
2. Dynamic and evolving security mechanisms related to mobile sensor context-monitoring
3. Explicit energy consumption management

We have depicted in Fig. 1 the different components of SARM and their interconnections. We split SARM into two units looped as a servo control system model to fine tune the adequate security measures/means. One unit called management or monitor unit is for monitoring the context by evaluating and analyzing risks, performances and energy consumption, which are significative for detecting attacks and tuning the adequate security means using the second module called functional unit. Light SARM2 is the particular use of our framework in MWSN.

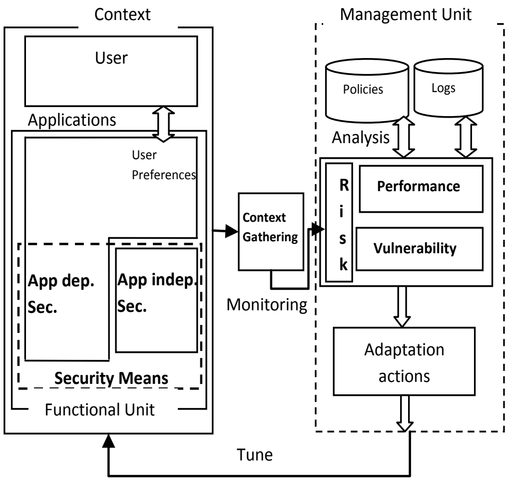


Fig. 1 SARM Components High-Level View

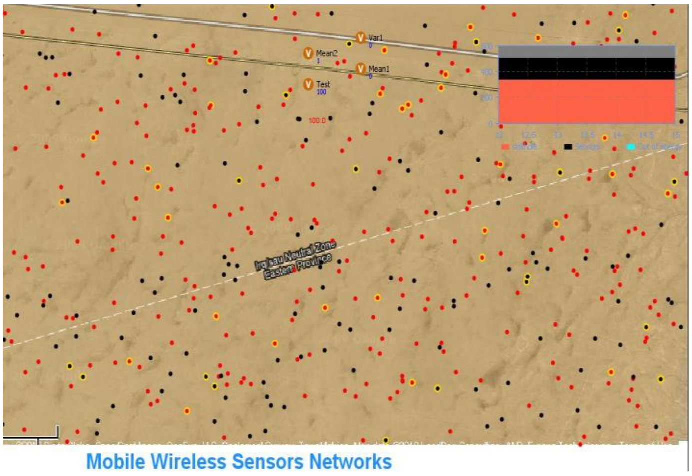


Fig. 2 Animation interface and results

## 3 Validation and results

We have implemented Light SARM2 and validated it in a MWSN simulation developed with AnyLogic, which is a simulation tool that supports all different simulation methodologies. In our experiments, we have validated our proposed solution and analyzed the extended performance under a range of various mobility scenarios. All sensors are moving over rectangular topography, and operating over one day of simulation time. In our simulations, each mobile sensor was configured to have a reference communication range equal to 30 meters and the base station has a fixed position and his energy is not limited. We assume that each sensor know its own position to a sink/base station and to his neighbours as well as their energy. Thus we estimated the impact of our solution for a network depending on the security and energy consumption aspect. The movement pattern of mobile sensors was totally randomized, in order to comply with a real WSN application. To achieve this, we used the Random WayPoint mobility model with pause time equal to the time of network access and data transfer. Three scenarios were tested 10, 25 and 50% of sensor attackers half of them are mobile sensors. We find that we are largely better in all cases than normal MIX protocol. Fig. 2 shows the animation and interface of simulation using Anylogic. Light SARM2 is making the best choice in accordance with the policy and User Preferences. Indeed, Light SARM2 constitutes a good trade-off for all studied cases, because it allows simultaneously a high overall utilization and a lower energy wasting, which means a long lifespan of the network. Therefore, it shows that our Framework is efficient in this context and is making the best trade-off between security and performance.

## 4 Conclusions and Outlook

We have applied our Security Adaptation Reference Monitor (SARM) based on the Reference Monitor concept and the Autonomic Computing Security pattern to deal with sinkhole mobile attackers. We present the validation of SARM in MWSN that we called Light SARM2. The results show that our solution is better than simple MIX protocol and copes with a dynamic security changing environment and is efficiently tuning the adequate security means whilst preserving lifespan of the network. Our future work will focus on evaluating SARM under other sensors attacks.

# Hybrid active and passive localization for small targets

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## 1 Summary

The abstract summarizes a particular approach we investigate for improving the trade-off between energy consumption and performance in localization tracking process. The scenario of application is common: a set of fixed beacons is used for tracking positions of one or more targets that are moving in a limited environment. The technology considered in the study is Ultra-wide band (UWB). The principle behind the proposed approach is relatively simple: tracking of a small target device in a limited indoor environment is realized by mixing *active* signal transmissions that allow using usual techniques for deriving distances and locations as well as *passive* signal receptions that exploit reflections caused by an object during signal propagation. The tracking process exploits the combination of these two types of transmissions with the advantage of possibly saving energy in the target device.

## 2 System Model

Let $N_B$ UWB fixed transceivers (beacons) with coordinates $(x_{Bi}, y_{Bi})$ be deployed in a room (Fig. 1). The transceivers are equipped with matched filter front ends followed by chip-spaced samplers and the -3 dB system bandwidth is 512 MHz. We also assume that UWB transceivers transmit ranging data to a central processing station in which the localization and tracking algorithms are performed. A transceiver pair is formed if two transceivers are within communication range of each other. As in [1], we assume that known signal waveforms are exchanged among unsynchronized transceiver pairs. An estimate of the channel impulse response between each pair of transceivers can therefore be obtained from the cross-correlation between the noisy received signal and a known signal template. A number of UWB devices with known reception-transmission delay moves in the room. Based on a sequence of signals at the beacons, we aim to track the position of moving objects.

## 3 Localization Algorithm Overview

The principle exploited in the process is simple: the target device alternates phases in which it acts as an active transmitter with signal regeneration (namely it transmit a specific packet to the beacons for allowing estimation of times of arrival and distances as a Fig. 1-a) to phases without signal regeneration in which it acts as a simple relay or even a passive scatterer (Fig. 1-b). The difference between these two phases at the beacons is the following: in regenerative phases the beacons exploit the signal received from the target for estimating the corresponding distance while, in the non regenerative phases, the beacons derive measures on the total reflected paths between each couple of beacons (Fig. 1-a and 1-b). From the target perspective the regenerative and non regenerative phases differ in the energy consumption and this aspect can be interesting in a series of applications where small, inexpensive devices should benefit from energy savings also at the expense of performance reductions. The localization algorithm incorporates two key components, ranging in regenerative and non-regenerative phases and tracking, operated by a bank of Extended Kalman Filters (EKFs):

1. Ranging: when the target is in the regenerative state, the *i*-th beacon estimates the direct distance $d_i$ to the target. On the other hand, when the target is in the non-regenerative phase, each couple of beacons, *i* and *j*, is interested by the measure of the reflected path, $d_i + d_j$. If a soft algorithm is used [1], several distances associated to their likelihoods can be collected for each sampling time.
2. Tracking: a bank of EKFs is used for updating the mobile target(s) locations. The bank is necessary when tracking more targets or/and when managing multiple measures and likelihoods associated to a single distance; in this latter case a metric is built and updated for selecting the most likely trajectories in a hypothesis tree [2]. Obviously the measures coming from regenerative and non-regenerative steps are subject to different update steps implemented into the EKFs, which realize a fusion of the measures.

## 3 Numerical simulations

In the system we exploit ranging algorithms based on times of arrival and characterized by *soft* detection techniques that have demonstrated performance advantages w.r.t. other approaches [1] [2]. Numerical results will be focused on the trade-off between mean squared error (MSE) and the ratio λ between the number of measures derived by non-regenerative and regenerative phases.

## 4 Conclusions

In this work [(°)], we study the trade-off between localization performance and the ratio between regenerative and non regenerative steps in the signal processing of a tracking application. This simple principle is developed for obtaining energy savings in indoor localization.

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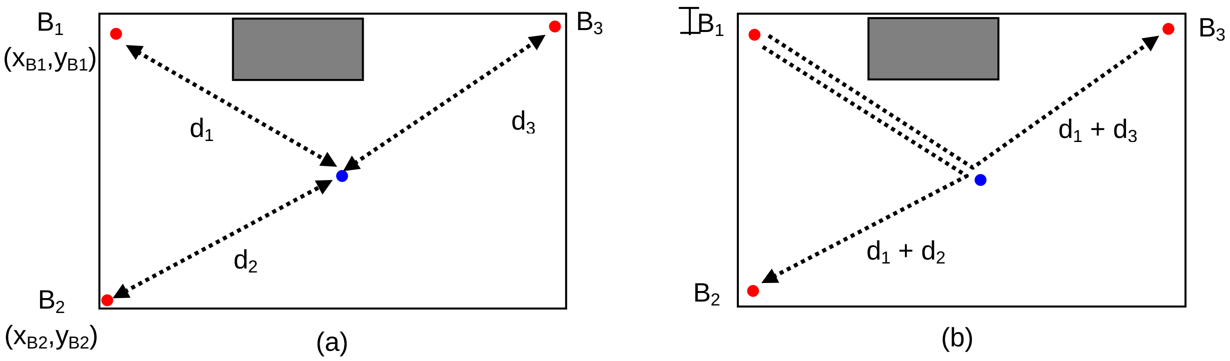


Figure 1: Combination of regenerative (a) and non regenerative (b) measures.


(°) This work was supported by the European Commission within FP7 Network of Excellence in Wireless COMmunications NEWCOM++ (contract no. 216715).

# Linear Antenna Array, Ranging and Accelerometer for 3D GPS-Less Localization of Wireless Sensors

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## 1 Introduction

Localization capability is required in many applications of wireless sensor networks (WSN). For example, monitoring WSN of any type requires node location awareness in order to stamp the measurements with the location (and also with timestamp), otherwise the measurement is of no meaning for the infrastructure owner. A particularly interesting indoor localization scenario is node positioning for automated building monitoring. The goal here is to greatly reduce the human-generated mistakes and errors, and the overhead of manual work during deployment by automatising the localization process. Nodes should set up the network automatically, including positioning of the nodes.

There are several challenges for localization in WSNs that monitor structures. Firstly, the network is installed in an unknown environment. The network is therefore most probably multi-hop and the reference nodes may not be globally available to all other nodes in the network. Secondly, the connectivity (that is the number of neighbours) may become relatively low locally in some passages in the structure. We propose a localization algorithm which is multi-hop, scalable and robust. Our algorithm uses the hardware that is capable of ranging and elevation-type Angle-Of-Arrival (AOA) which are backed up with earth gravity direction awareness.

Literature covers a variety of possible localization algorithms. Some algorithms use only one type of measurements, like ranging alone (lateration based algorithms, e.g. Cricket) or AOA only. However, one can obtain more robust results by using more than just one source of information, such as the combination of ranging and AOA.

In our previous work we proposed a localization algorithm which was using ranging, accelerometer (for earth gravity direction) and 3-D AOA. 3-D AOA requires at least a 4-element antenna array (or 3-element antenna array if we have the means to deal with the ambiguity problem). Such complex hardware returns a complete position vector to the observed sensor and enables localization of every single node that is connected (e.g. when a wireless node has as little as one neighbour). However, this antenna hardware may also be expensive and may require more electric power than simpler antenna solutions while power is an issue in WSNs. We found a way of using the reduced number of antenna elements effectively and keeping the AOA functional. In this work we present the localization system which uses ranging, an accelerometer and a 2-element antenna array.

## 2 Position calculations

All wireless sensors in the network are equipped with the ranging device, accelerometer and linear antenna array (comprising of 2 antenna elements). (The antenna elements can also be just switched antennas with programmable phase shifter connected serially with one of the elements. This is a simple beam former.)

The localization algorithm will be formulated here as an optimization problem.

– Input values.
  $\mathbf{P}_0$ - node's given position (reference node or node which acquired this knowledge),
  $d_i$, $\phi_i$ - measured values: distance to *i*-th node and elevation-type angle to *i*-th node,
  $\hat{\mathbf{n}}$ - the direction of $\phi_i = 0$ dependent on the orientation of the antenna elements.

– Calculated parameters needed for the final problem formulation.
  $\hat{\mathbf{u}}$ - unitary vector s.t. If $\hat{\mathbf{n}} \cdot \hat{\mathbf{x}} < 1 - \varepsilon$ then $\hat{\mathbf{u}} = \hat{\mathbf{n}} \times \hat{\mathbf{x}} \times \hat{\mathbf{n}}$ else $\hat{\mathbf{u}} = \hat{\mathbf{n}} \times \hat{\mathbf{y}} \times \hat{\mathbf{n}}$. In other words, $\hat{\mathbf{u}}$ is an arbitrary but unconstrained (any) vector which is $\perp$ to $\hat{\mathbf{n}}$.
  $\hat{\mathbf{v}} = \hat{\mathbf{n}} \times \hat{\mathbf{u}}$ - a vector perpendicular to $\hat{\mathbf{n}}$ and to $\hat{\mathbf{u}}$,
  $r_i = d_i \sin(\phi_i)$ - distance of *i*-th node to the axis that comprises $\hat{\mathbf{n}}$,
  $\mathbf{C}_i = \mathbf{P}_0 + \hat{\mathbf{n}} d_i \cos(\phi_i)$ - a projection of a position of an unknown node on $\hat{\mathbf{n}}$-axis.

– Final formulation of a parametric equation of position of an observed node.
  $\mathbf{P}_i = \mathbf{C}_i + r_i \cos(\alpha_i^0)\hat{\mathbf{u}} + r_i \sin(\alpha_i^0)\hat{\mathbf{v}}$, where $\alpha_i^0$ is an unknown parameter.

– Optimization problem.
  For $n$ viewpoints $i \in \{1..n\}$ one can compose the set of $n$ equations, where the parameter $\alpha_i^0$ solves the *i*-th equation.
  $\min \sum \left(\overline{\mathbf{P}} - \mathbf{P}_i\right)^2$, where $\overline{\mathbf{P}}$ is an average of all $\mathbf{P}_i$'s.

## 3 Main results

In this chapter we summarize some of the results obtained from the research of the proposed localization algorithm.

1. Minimum connectivity required. This result tells how many nodes that are location aware are needed in order to transform one unknown node which is their neighbour into a localized node. We have found that the problem formulated in chapter 2 (4.) can be solved for as little as 2 independent viewpoints (2 reference nodes connected to an unknown node) if $\hat{\mathbf{n}}$ vector of one node is non-parallel to this of the other node. Generally 3 viewpoints suffice.

2. Simulation scenario where all nodes were located on a plane. We have found that for certain arrangement of nodes the advantage of having the AOA capability becomes insignificant. This occurs when $\hat{\mathbf{n}}$ vector of each node is perpendicular to the plane where all nodes of WSN are placed. This case can be solved using 2-D equally accurately as using trilateration with the assumption that the plane with which nodes coincide is known. In real scenarios this plane may sometimes be easily determinable in large one-storey buildings as e.g. floor.

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## Hybrid IMU Pedestrian Navigation 1

Auditorium G3

Wednesday, September 15, 10:30 – 11:45 & 13:15 – 16:00

# A Modular and Mobile System for Indoor Localization

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**Summary**

The work presents a system for sensor data and complementary information fusion for localization in indoor environments. The system is based on modular sensor units, which can be attached to a person and contains various sensors, such as range sensors, inertial and magnetic sensors, a GPS receiver and a barometer. The measurements are processed using Bayesian Recursive Estimation algorithms and combined with available a priori knowledge such as map information or human motion models and constraints. The processing can be done locally, since all necessary data is available on the mobile unit. This system provides a platform for implementation, combination and evaluation of various localization principles and can be used for a variety of applications, such as indoor and outdoor pedestrian navigation, localization of other objects such as vehicles as well as robotics applications.

## 1 Motivation

There are numerous localization methods and techniques, including inertial navigation, multilateration or multiangulation based on radio or acoustic signals and optical methods, such as computer vision or laser range scanning. Most of these methods, when used stand alone, are able to provide sufficient performance only for special types of applications within controlled or restricted environments. Especially radio based methods usually suffer from significant errors induced by multipath wave propagation in indoor environments. We follow the approach that a robust and usable indoor localization system combines various complementary sensor data and any other information available to provide a reliable position estimate. Therefore a wearable, modular and extendible sensor system was developed, which enables simultaneous usage of different sensing modalities.

## 2 System Description

The basic concept of the proposed system is shown in Fig. 1 (left). Several PCBs, each designed to fulfill a certain task (e.g. providing power, enabling wireless communication, data processing, input/output capability) or to contain a specific sensor group (e.g. inertial sensors, GPS, ultrasound sensors), are stacked together to form a setup best fitting the requirements of a particular application. Fig. 1 (middle) shows the subset of the system, which is used in our current experiments on indoor localization. It contains a radio ranging module for distance measurements and data communication between the mobile node and fixed anchor nodes (Fig. 1 right) and inertial as well as magnetic field sensors.

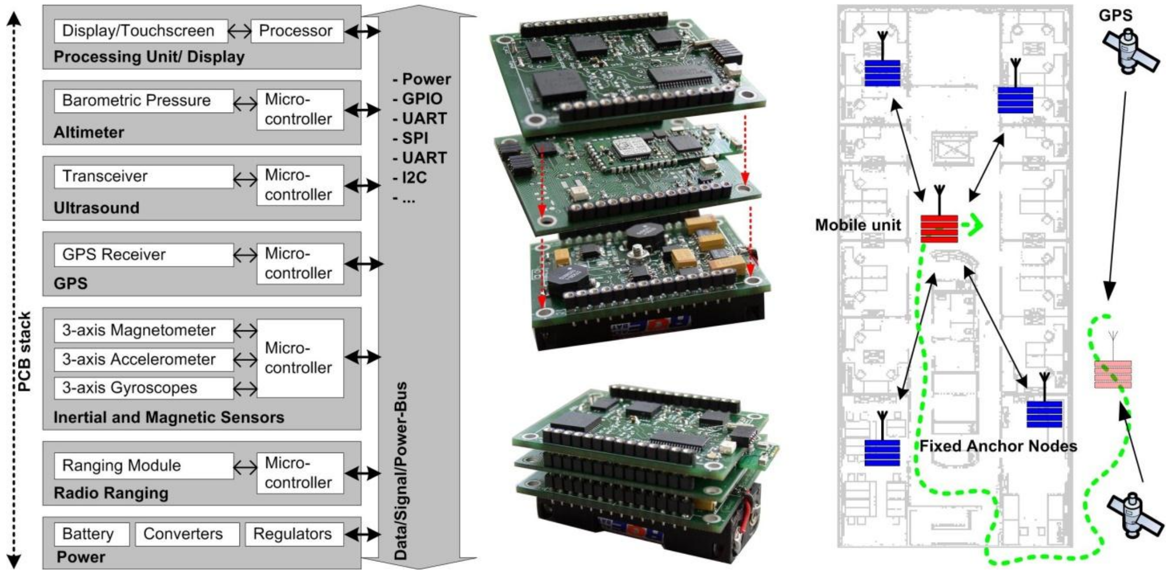


Figure 9: System concept (left), current hardware (middle), setup for indoor/outdoor localization (right).

The estimation algorithm framework also follows a modular approach (Fig.2 left). A particle filter is implemented, where different measurements are processed either in the prediction or the correction step of the algorithm to estimate the position of a person. A priori knowledge, such as indoor maps and motion constraints is also processed to increase the localization performance. Fig.2 (right) shows an example measurement in an office environment using radio range measurements, inertial sensors and an indoor map.

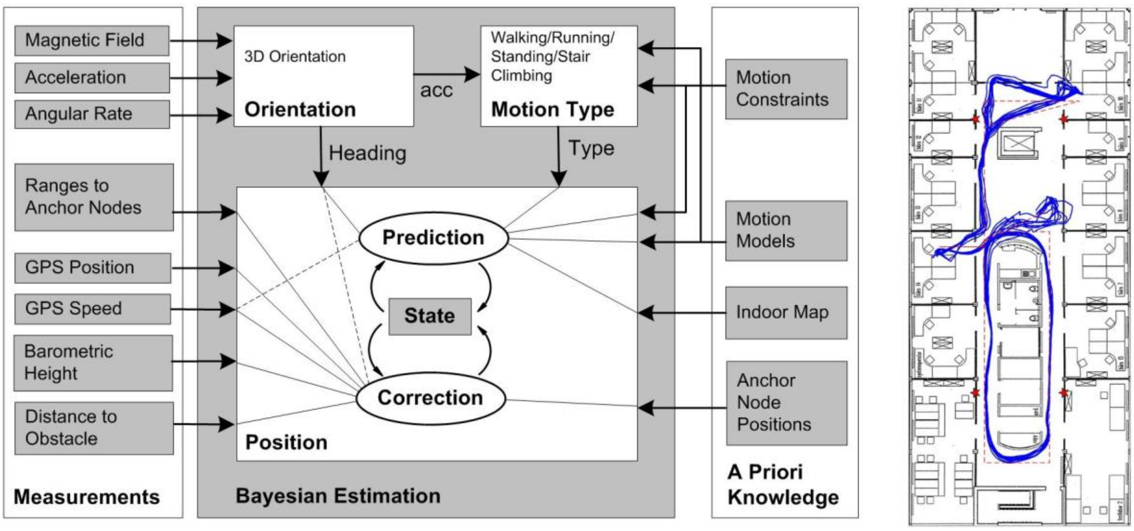


Figure 10: Algorithm concept (left), path estimation based on the current system setup (right).

## 3 Outlook

This abstract presents a short overview of the concept and the current state of the system. The full version of the paper will contain a detailed description of the algorithms and a systematic performance evaluation, as well as measurements containing new sensor modalities, such as GPS, ultrasound or barometers.

# Self-Contained Indoor Positioning on off-the-shelf mobile Devices

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## 1 Introduction

From pedestrian navigation and innovative location based services to medical studies, rescue or E-911 services, the knowledge of human displacements through space has many applications. For this reason we introduce a self-contained seamless positioning system for indoor and outdoor environments, based on off-the-shelf mobile devices. Position information is deduced from a combination of GNSS where available, combined with Dead Reckoning (DR) utilizing inertial measurements and context-aware activity based map-matching. In remaining independent from any external infrastructure, accurate localization is also possible in environments, where the installation and maintenance of such infrastructure does not make sense or is simply not affordable – e.g. in large parking garages to guide a user to an exit or back to his car.

Typical personal positioning strategies rely on the combination of GNSS with either map-matching (outdoor) or an INS/PDR approach (indoor, ubiquitous positioning). One of the first projects within the scope of inertial dead reckoning were the Personal Dead Reckoning Module (DRM) from the Point Research Corporation [1] and the Pedestrian Navigation Module (PNM) from the Laboratoire de Topometrie at the Ecole Polytechnique Fédérale de Lausanne (EPFL) [5]. Other projects like the NAVIO [7] or the $UCP_{NAVI}$ [6] project developed at the Vienna University of Technology extend investigations to route guidance strategies or the integration of additional positioning technologies based on RFID beacons or WLAN.

## 2 Inertial Position Sensing

The availability of GPS, acceleration sensors and an electronic compass in actual smartphones like for example the Nokia N97 or the iPhone 3GS establishes a powerful basis for inertial positioning. The proposed Pedestrian Dead Reckoning approach heavily exploits the kinematics of human movement by detecting steps, estimating each step's length and propagating a relative position using a heading measurement (fig. 1), while being comparatively robust against inaccurate measurements and disturbances as well as flexible regarding the exact placement and attitude of the device.

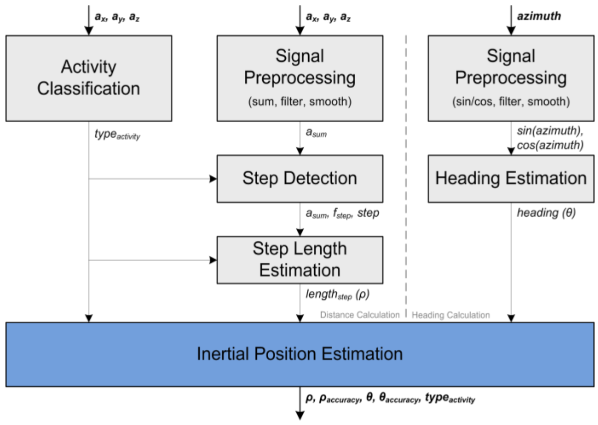


Figure 1: DR based inertial position estimation model processing acceleration sensor and compass readings.

Estimation of the travelled distance is realized using the tri-axial acceleration signal of the device measured at a rate of 20 Hz. To improve the results of step detection and step length estimation according to the status of actual movement pattern, we introduced an activity classification procedure to differentiate between eight patterns. Step detection is implemented based upon a slightly modified version of a sliding window peak detection algorithm as proposed by Sun et al. [8]. Concerning the length calculation of a detected step, which is more or less a time-varying process and approximated as a function of several parameters like the acceleration signal variance, the step frequency and some scale factors computed by linear regression with respect to the actual movement pattern, we rely on the results of investigations by Ladetto [3], Ladetto et al. [4] and Kim et al. [2]. Since the raw sensor measurements from the accelerometer cannot be used directly for the algorithms above, the signal has to be preprocessed to remove possible disturbances, high frequency components and gravitational influences. This is done using a 6th order Butterworth bandpass filter with different cutoff frequencies in relation to the different types of movement.

The heading is calculated using the azimuth readings of the device's leveled compass provided at a rate of 10 Hz. To prevent discontinuities during the calculation at 0/360 degree crossovers, the sine and cosine of the azimuth measurements are used. Possible signal drifts arising from magnetic interferences or other disturbances are reduced through a moving average filter of variable order with respect to the different movement patterns.

## 3 Multi-layer Position Integration

In addition to the inertial position sensing unit (IPU) which allocates relative position information with respect to a known starting point, our proposed system also incorporates a GPS based GNSS positioning Unit (GPU) and a map positioning unit (MPU) providing an absolute position in terms of real world coordinates (fig. 2). While the GPU preprocesses satellite based position information to reduce negative effects arising from signal degradation and multipath effects, the MPU implements a context-aware activity based map-matching strategy on detailed micro maps incorporating the current movement pattern – if for example the movement pattern is estimated as ascending stairs, the position can be projected to the closest stairs in the subject's proximity. Both IPU and GPU as well as the MPU are integrated through a loosely coupled integration scheme using an Extended Kalman Filter (EKF), whereby absolute position measurements from GPU and MPU are used to amend and recalibrate the inertial prediction model of the IPU. Regarding the initialization of the seamless positioning system, the initial position could be received either from the GPU itself or directly from a car, providing its actual position (for example in a parking garage or a dense urban scenario).

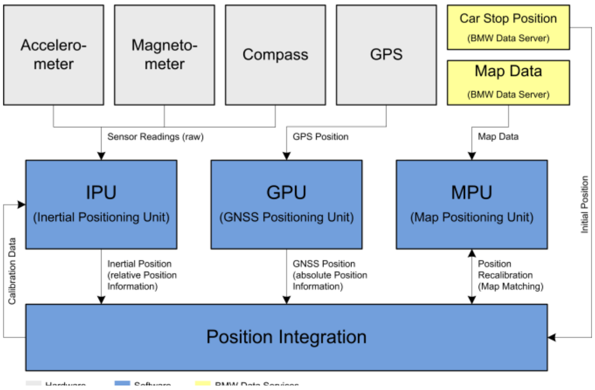

Figure 2: Schematic overview of the implemented seamless positioning system.

## 4 Results and Conclusion

We introduced a novel seamless positioning solution predicated on the integration of inertial, satellite and map-matching based position information sources and well suited for off-the-shelf mobile devices and implemented it on a Nokia N97. Due to the absence of appropriate gyroscope or barometric sensors in present devices the proposed system is limited to some extent. Nonetheless we could show that given an initial position with accuracy of a single parking spot a user can be guided from his parked car to the next exit of large parking garages like the P7 at the Munich Airport.

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# Pedestrian Smartphone-Based Indoor Navigation Using Ultra Portable Sensory Equipment

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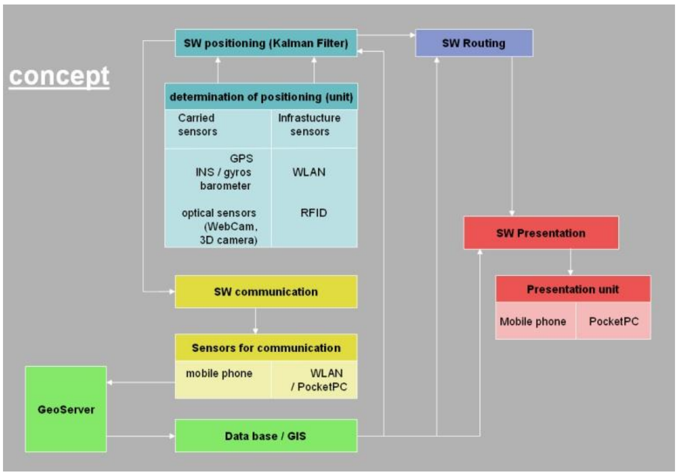
## 1 Introduction

Current portable navigation devices usually rely solely on satellite navigation infrastructure. However, they will seize to function, once the satellite signal becomes unavailable. Other navigation systems are based on inertial navigation systems (INS) to provide a continuous navigation solution. However, the INS solution is inherently inaccurate during longer measurement periods, due to error accumulation. Hence INS systems rely on external support information, usually provided in the form of GPS fixes. Prevalent pure indoor navigation systems are almost always depending on a complex and hence costly setup of infrastructure components such as radio beacons or other dedicated equipment.

The presented concept constitutes a low-cost and ultra portable mobile indoor navigation device which does not depend on complex external sensory equipment. Its central sensing element is a highly integrated inertial measurement unit (IMU) providing a continuous inertial navigation solution. This solution is supported by additional internal and optional external sensory inputs.




This work is based on the preliminary analysis of a portable low-cost INS/GPS navigation system regarding indoor navigation performance. [1]

## 2 Sensor Equipment

The initial effort presented in [1] is based on the Xsens MTi-G INS/GPS navigation system. This unit constitutes a portable, low-cost navigation system, integrating a GPS receiver, accelerometer, gyroscopes, temperature and barometric pressure sensors. Its built-in firmware allows for different navigation scenarios and is fitted with several Kalman filters for sensor fusion.

Figure 11: Xsens MTi-G

Current research is based on a highly integrated IMU.

MEMS sensors measure barometric pressure, temperature, three-axis acceleration and three-axis turn rates. Sensor fusion algorithms on both the IMU (inertial strapdown algorithm [2]) and the hosting smart phone (filtering and user interface) will handle the data streams.

The development platform used is a state-of-the-art smart phone that runs a Linux-based open mobile operating system. It is fitted with camera, tilt sensors, GPS receiver, WLAN and Bluetooth modules and magnetometers. The aim is to provide a navigation application that may be used on many Linux-based smart phones, provided the IMU hardware is connected to it.

## 3 Mobile Handheld Indoor Navigation

Based on [2,3], the provided sensor information is used to compute an inertial navigation solution. This processing is done by the DSP on the IMU. The calculated position update is then transmitted to the smart phone. On the smart phone, the current position is updated by the INS position increment and improved by available additional internal and external sensor information received by the smart phone sensory hardware. Potential additional sensor information sources are listed in Table 1.

| **Sensor** | **Provides** |
|---|---|
| Magnetometer | Magnetic Heading |
| GPS Receiver | GPS fix |
| Camera | Optical Input (Markers) |
| WLAN Module | WLAN Range Information |
| Bluetooth Module | Bluetooth Range |

Table 1: Additional Sensors

One objective is to improve the inertial navigation solution provided by the underlying strapdown system that integrates gyroscope and accelerometer information. Furthermore, the sensor fusion methods, usually implemented as Kalman filters are optimized and alternative filtering concepts evaluated. Finally, the optimal external sensor combination is being determined. Focus here is placed on assessing data quality and selecting the optimal combination to support the INS solution.

The thus determined position is then combined with previously downloaded information about the building currently being navigated. Visualization efforts and user interface development are being undertaken by members of the *DigitalCity Research Group at HCU Hamburg.*

The discussed system therefore presents a novel approach to indoor pedestrian navigation, as it is independent of specialized external sensors such as step counters or radio beacons and integrates additional information to improve on the position estimate as they become available.

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# A low cost navigation unit for position estimation of personnel after loss of GPS position

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Norwegian Defence Research Establishment[2]

## 1 Summary

We have built a test unit containing a GPS, an IMU, magnetometers and a barometer. When the GPS looses its signals, the other sensors are used to keep track of the position. Unscented Kalman filters have been used to test the performance of different aid sensor configurations. There was no indication that any particular configuration was better, but the measurements showed significant improvements by using aid sensors. In order to quantify the error sources the inertial navigation system has been simulated using Monte Carlo simulations. This simulation shows that noise from the gyroscopes is the main error source. The simulation of an IMU yielded a standard deviation of the position of 9 m after 30 seconds. Eight different sensor configurations have been tested with real data collected by the test unit. These tests show that there are significant benefits by using aid sensors.

## 2 Introduction

The objective of the project was to develop a multipurpose navigation unit that can be used by military personnel, vehicles and other equipment in areas with difficult satellite signal conditions such as inside buildings. If all personnel and vehicles shall be equipped with such a unit it must be of low cost, small size and low power consumption. The test unit uses an IMU which contains three accelerometers, three gyroscopes and three magnetometers. In addition we use a barometer and a GPS module. The test unit, Figure 1, also contains a microcontroller and a SD memory card for storing data.

## 3 Modelling of sensors and navigation equations

For modelling the earth the WGS-84 model was used. The navigation equations are found in [1], except that quaternions were used instead of a matrix differential equation. The error model coefficients for all sensors have been estimated except for the magnetometer, because of a lack of calibration equipment. To estimate the position the Unscented Kalman Filter was used and the filter was initialized with the last position from the GPS. We assume that the sensor is stationary and initializes the filter with zero velocity and uses the QUEST [2] algorithm to find the initial attitude by comparing the measurements from the accelerometer and magnetometer to an earth gravitation model and the IGRF model. The measurement update for the barometer converts the height to pressure and the measurement update for the magnetometer is given in [3].

## 4 Simulation and measurements

The performance of the navigation system without aiding sensors has been simulated using Monte Carlo simulation in order to quantify the error sources. The main error sources are the noise from the gyroscopes ($Q_{gy}$), and the initial attitude given by the QUEST algorithm ($P_{q,0}$). The simulation result, Figure 2, shows that the total error is below 9 m after 30 seconds. If the gyro noise could be reduced by a factor of 10 the total error would be reduced to 3.5 m.


Figure 1: Picture of the test unit

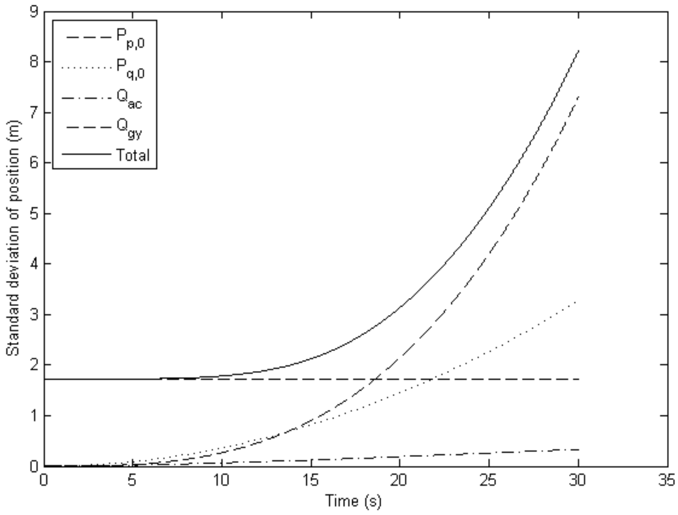


Figure 2: Simulation result. The standard deviation of the position has been averaged over 30 simulations

Several tests have been performed with the system. The tests show that the system has significant errors, but also that there are large benefits to include magnetometers and barometer as aid sensors. We have used eight different combinations, with and without filtered gyroscope output and different aiding sensors. From the test results the best configuration cannot be significantly determined, but they clearly show that there are large benefits from having aid sensors. Based on the test results and the calibrations results it is very likely that the magnetometer creates a larger error in the initial attitude than those found in the simulation because of the magnetic disturbance in the surroundings. A field calibration technique is required to reduce this error. The Kalman filters that uses both magnetometer and barometer updates has an artificially low covariance on the attitude because of the magnetometer update. This causes the Kalman filter to weight the magnetometer measurements too high compared to the barometer measurements.

## 5 Conclusions

The simulation does not take into account magnetic disturbance, errors in the pressure measurements that have not been modelled, and the fact that the magnetometer is not calibrated accurately. These errors cause the position error for the real system to be larger than in the simulations. A better magnetometer update method that does not create an artificially low attitude covariance is required. The main error source is probably caused by the calculation of the initial attitude. Therefore the magnetometer needs to be calibrated and a method for compensating for the magnetic disturbance is required. A navigation unit based on cheap and small devices is feasible if these problems are addressed.

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# A GPS/INS-based architecture for rescue team monitoring

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## 1 Summary

The present work shows the obtained results using a low-cost pedestrian system made up of a GPS receiver and an inertial platform. This positioning system can be used by rescue teams to locate hazard zones and escape routes. Our study shows how multiple sensors can be used in a non-traditional way: the inertial platform is used as an odometer (step counter) in which the magnetometers allow the estimation of gyroscope drifts. The GPS receiver, however, is used to correct the bias when the GPS observables are sufficiently reliable.

Particular focus will be given to the estimation of sensor errors and the reliability of the entire system, which is a critical problem of these equipments.

## 2 Introduction

The aim of the our study is to achieve a low cost pedestrian positioning system, that is based on a metrical reliability and accuracy and suitable for particularly difficult environments such as burning buildings, devastated villages, etc.

The positioning system is based on the integration of an inertial sensor (XSens MTi), that includes accelerometers, gyros and magnetometers, and a high sensitivity GPS receiver (u-blox 5H), specifically designed for indoor positioning applications.

Due to compact size and low weight, all the used sensors are particularly suitable to become an integral part of rescue teams' equipment, for example by mounting the GPS antenna on the top of a rescuers' helmet and the inertial sensor near to the barycentre of the body.

## 3 The realized pedestrian navigation system

A low-cost pedestrian navigation system requires a proper positioning algorithm that must be specifically developed and calibrated with respect to the quality of the involved sensors and to the final applications. Using the traditional algorithms concerning the GPS/INS integration, indeed, the solution can be inaccurate and often unreliable. The problems are in particular related to the accelerometer and gyro drifts, to the high inertial measurement noise and to the high noise and multipath of the received GPS signal.

For these reasons, the proposed solution relies on using the inertial sensor measurements like a "step odometer", not directly measuring the travelled distance but the time when a well-known distance (e.g., the step length) is accomplished, and the attitude (e.g., the heading angle) of the body at the same time. This approach, well known in pedestrian applications, is therefore solved using the information collected by all the sensors included into the IMU platform.

The inertial positioning solution is coupled with the data of the GPS receiver, after a careful data filtering based on a previous analysis of the GPS signal in indoor environments.

The advantages of this positioning solution are:

- the easiness of the step identification process, observing the total acceleration pattern;
- the calibrating facilities of the step length starting from data measured by accelerometers;
- the possibility of estimating motion direction due to gyroscopes and magnetometers information.

## 4 Preliminary findings and conclusions

A positioning example of the developed system is shown in the Figure 1. The trajectories demonstrate how the odometer-like use of INS data allows detecting the travelled trajectory with sufficient accuracy, even if a drift angle, which propagates in time, is still evident. In addition, the inertial-based trajectory is upgraded by applying to the heading angle, during the position estimation, a drift value estimated by static measuring, contributing to a remarkable improvement of the navigation solution.

Generally, if an operator is moving into an indoor environment any GPS solution provides bad positioning accuracy. Actually, the use of GPS data is justified only for outdoor environments, even if further tests will be done in order to improve the GPS indoor positioning reliability.

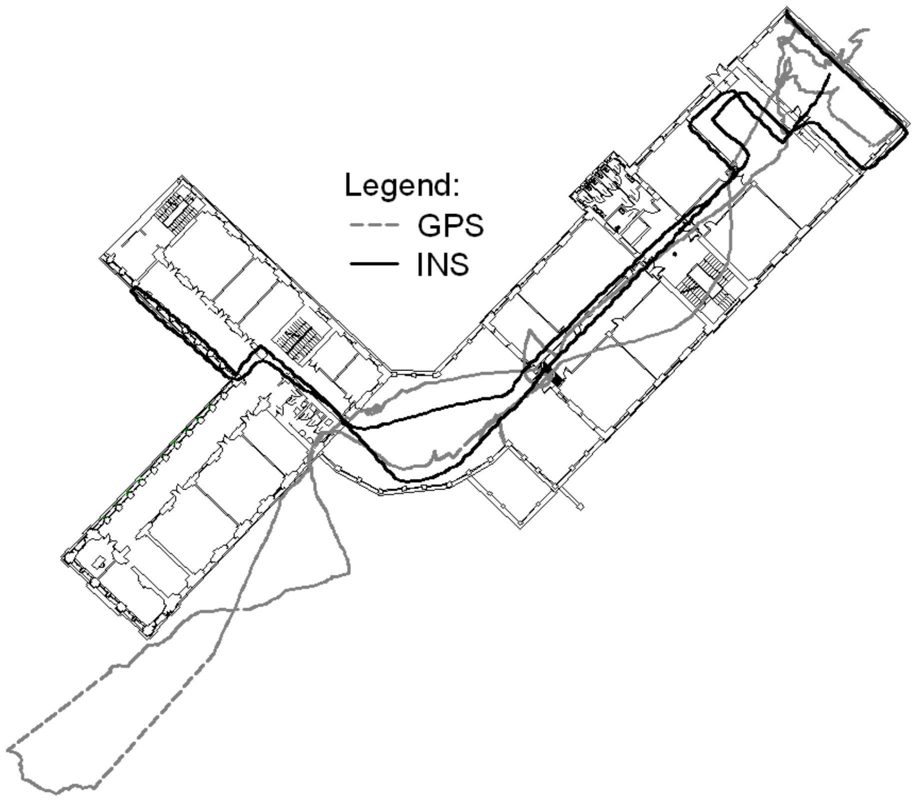


Figure 1: trajectory computed processing the GPS (dashed gray line) and the INS (continuous black line) data after the gyroscope drift compensation

# Hybrid positioning system combining angle-based localization, pedestrian dead reckoning, and map-filtering

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[2)] *Nokia Research Center, Helsinki, Finland*

## 1 Summary

We present a hybrid indoor positioning solution combining angle-based localization, pedestrian dead reckoning, and map-filtering. The angle-based localization system provides absolute location fixes in large, open indoor areas. While the main purpose of these location fixes is to update the user location, they are also used to adjust the parameters of a pedestrian dead reckoning (PDR) module that estimates the relative movement of the user i.e. shape and length of the traversed route. In areas covered by the angle-based localization system, the user location is a combination of absolute location fixes, PDR estimates, and map information, which is used to limit the possible movement trajectories of the user within the building. In other areas, the user location is based on only the PDR estimates and map information. The hybrid positioning system is evaluated in a trial that is carried out in an office building that consists of large open areas, office rooms, and connecting corridors.

## 2 Hybrid positioning system

The Global Positioning System (GPS) provides reliable positioning and navigation to worldwide users in outdoor environments, but satellite based positioning will not be a realistic solution for deep indoor spaces due to increasing signal attenuation through building structures and signal degradation due to multipath propagation. While accurate, commercial solutions for indoor positioning already exist, they often involve costly and time-consuming setup phase or require a complex installation of expensive infrastructure.

In this paper, we present a hybrid indoor positioning solution combining location information from various sources. Absolute positioning estimates are obtained from a novel angle-based localization system covering a large, open indoor area by using only two transmitters. Relative positioning information is obtained from a pedestrian dead reckoning (PDR) module utilizing inertial sensors. In addition, map information (floor plan) is used to limit the possible movement of a pedestrian within the building.

The angle-of-departure of a communication packet from the transmitter is resolved at the receiver using the information of antenna array geometry and calibrations. Data received from a single transmitter is already enough to determine the receiver's 2D location when the height of the receiver is known. In practice the height of the transmitter is assumed to be around 1.2−1.4m, that is, the height where most people hold their mobile phones. Concurrent data from several multi-antenna transmitters yield naturally a more accurate location estimate.

The implemented PDR method uses step detection and step length estimation to approximate travelled distance. Step detection is based on peak detection of total linear acceleration (total acceleration minus gravity), and step length estimation is based on assumption that there exists a relation between time elapsed between two consecutive steps, and step length. Changes in the movement direction are estimated by integrating the horizontal angular velocity over time with the help of gyroscope and accelerometer data.

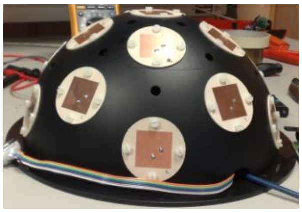
The user location is estimated using a particle filter that fuses the relative PDR information, and absolute positioning fixes from the angle-based system. Always after propagating the particles according to the PDR updates, map filtering is deployed to see if some of the particles have moved to restricted area or crossed some of the walls. Finally, user location is calculated as the average of particle locations weighted by the normalized particle weights.

## 3 Field trial

A positioning trial is carried out in an office building that consists of a 21m tall main lobby, cafeteria, corridors, and office rooms. The positioning infrastructure in the trial building comprises of two multi-antenna transmitters (see Figure 12a) attached to the ceiling of the main lobby.

The test platform representing the mobile terminal to be positioned is depicted in Figure 12b. It comprises of three main components: an inertial measurement unit (IMU), a direction-based positioning unit, and a computing platform running the hybrid positioning algorithm. The Bluetooth Low Energy (BLE) receiver and the IMU are connected to the laptop via USB.

a)



b)

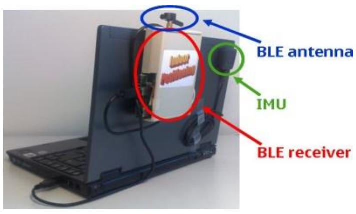



Figure 12. a) One of the two multi-antenna transmitters attached to the ceiling of the building main lobby. b) The test platform representing the mobile terminal to be positioned.

As shown in Figure 13, the fusion of absolute position estimates with PDR data and map information yields more accurate trajectory of the user location than using only the angle-based localization. Moreover, the user can be tracked outside the operational area of the angle-based localization system.

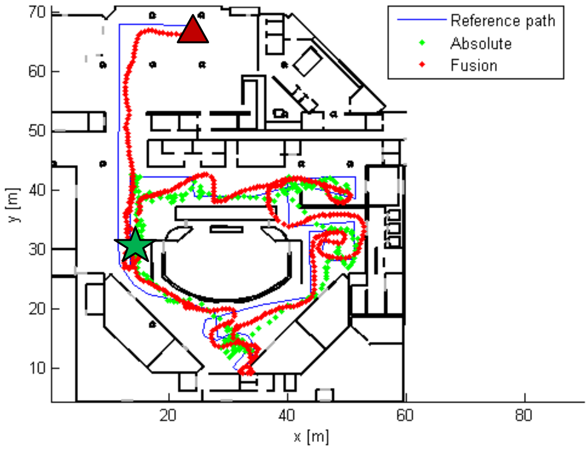



Figure 13. A test route in an office building is marked with the blue line. The route starts at the green star and ends at the red triangle. Absolute estimates are depicted with green dots and fusion estimates with red dots.

# Indoor Localization in Multi-story Buildings Using a Human Operated Backpack System

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Automated 3D modelling of building interiors is useful in applications such as virtual reality and entertainment. Using a human-operated backpack system equipped with 2D laser scanners and inertial measurement units, we use scan-matching-based algorithms to localize the backpack in complex indoor environments such as a T-shaped corridor intersection, and two indoor hallways from two separate floors connected by a staircase. The localization results are used to (a) generate textured 3D scene models, and (b) enable image based rendering of indoor environments.

We mount orthogonally positioned 2D laser scanners and two inertial measurement units (IMU's) on a backpack, as shown in Figure 1. Orthogonal placement of the laser scanners allows us to run scan matching to recover five backpack pose parameters over time. One IMU is a navigation grade Honeywell HG9900, which provides highly accurate measurements of all six pose parameters and serves as our ground truth. The other IMU is an InterSense InertiaCube3, which provides orientation parameters. We use the laser scanners and the InterSense IMU to localize the backpack.

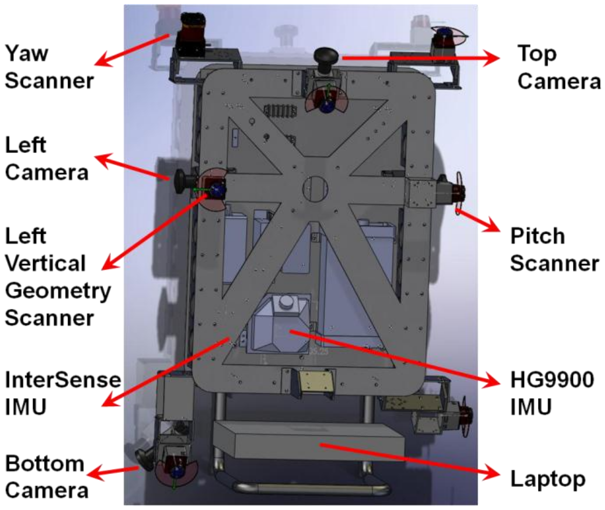



Figure 1: CAD model of backpack system

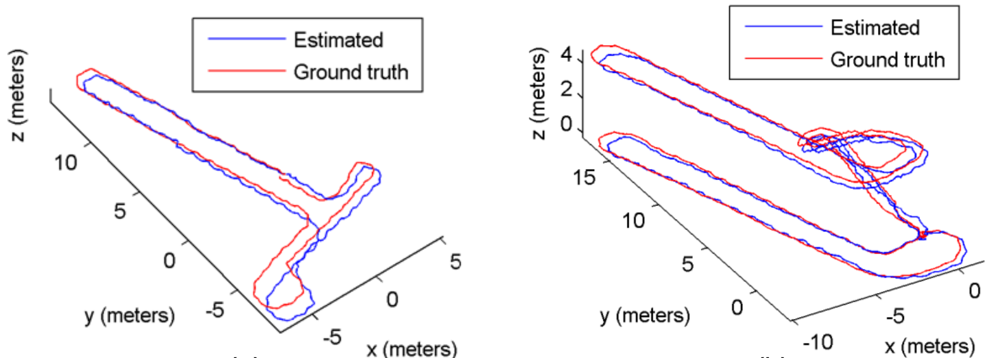
When the backpack is worn by a human operator, the direction of forward motion is x, leftward motion is y, and upward motion is z. Roll, pitch, and, yaw are defined as rotations around the x, y, and z axes respectively. We use the yaw scanner to estimate x, y, and yaw, and the pitch scanner to estimate z of the backpack pose via scan matching [1]. Lastly, we use the InterSense IMU to estimate roll and pitch. We enforce loop closure by applying the Tree-based Network Optimizer by Grisetti et al [2] to globally optimize our estimated poses, accounting for locations revisited and making use of scan matching and sensor uncertainty.

We test our localization algorithm on two datasets: a T-shaped corridor intersection (set 1), and two indoor hallways from two separate floors connected by a staircase (set 2). Estimated trajectories and associated error characteristics are shown in Figures 2 and 3 respectively. Figure 4 shows a snapshot of the textured 3D model resulting from set 3. In generating this model, we used the vertical scanner on the left side of the backpack to capture geometry, and three cameras to generate texture for the resulting geometry.

We use the localization results to enable virtual walkthroughs using an image based renderer. The renderer uses a three-step process to determine which image to display. First, it locates an initial set of neighbouring camera positions relative to that of the viewer. A dot product between the viewer and camera's orientation vectors provides a threshold to eliminate image planes facing the wrong direction. The renderer chooses the final image from the nearest neighbouring camera. Then the RANSAC algorithm is used on SIFT features from neighbouring images to find an optimal homography to stitch images for an increased field of view. In addition, the localization algorithms can generate plane fitted models for occlusion detection within the renderer. If an intersection with a plane occurs between two camera positions, the images are occluded and no longer considered to be neighbours. This filters both the initial set of neighbouring images and the set for stitching images together. The image-based renderer performs at 25 frames per second (fps) when one image is rendered and at 5 fps when 4 images are stitched per frame on an unstructured set of 800 images.

[1] G. Chen, J. Kua, S. Shum, N. Naikal, M. Carlberg, and A. Zakhor. “Indoor Localization Algorithms for a Human-Operated Backpack System,” to be presented at 3D Data Processing, Visualization, and Transmission 2010, Paris, France, May 2010.

[2] G. Grisetti, C. Stachniss, and W. Burgard. “Non-linear Constraint Network Optimization for Efficient Map Learning,” IEEE Transactions on Intelligent Transportation Systems, Volume 10, Issue 3, Pages 428-439, 2009.




(a) (b)

Figure 2: Estimated trajectory vs. ground truth for: (a) set1 and (b) set 2

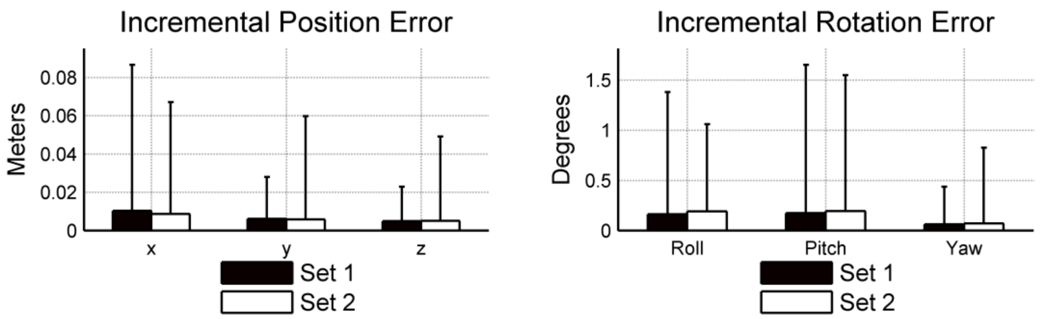



Figure 3: RMS error for estimated poses (lines above bars denote peak errors)

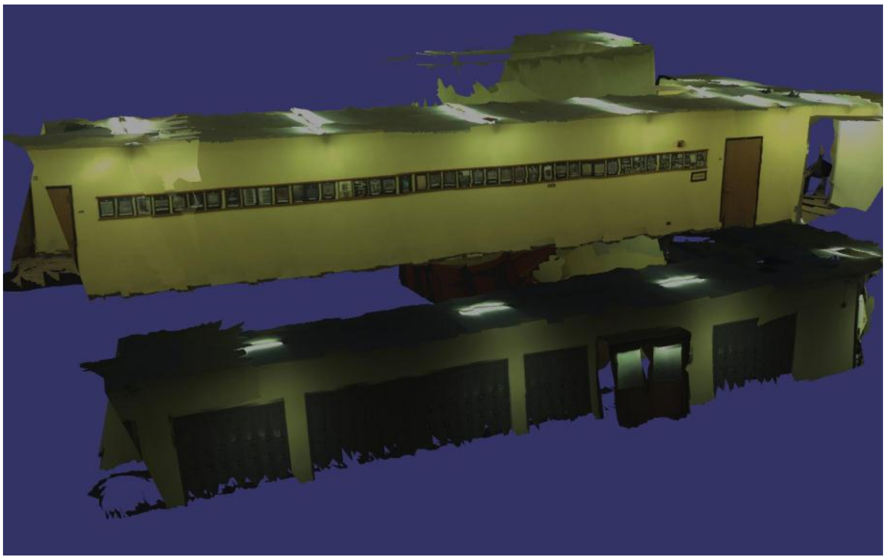


Figure 4: Snapshot of the textured model for set 2

# Hybrid Indoor/Outdoor Positioning Using Particle Filters and Multiple Sensors on a Personal Transporter

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## 1 Summary

Modern navigation systems can successfully help people navigate in outdoor scenarios, but once the user arrives outside the destination building, navigation cannot be continued, leaving the precise destination localization inside the building to the user. In order to provide complete door-to-door navigation assistance, we propose combining a variety of sensors (GPS, WLAN, a laser range finder and odometry) on an enhanced Segway Personal Transporter to guide the user outdoors as well as indoors, all the way to the desired destination room inside the building. By combining the sensor measurements using a particle filter, the system is highly flexible and remains open to adding further sensors. The multitude of sensors enhances the robustness and the precision: Combining WLAN, GPS, odometry and environment models allows robust outdoor positioning, while the laser range finder enables precise indoor positioning that is further improved by incorporating WLAN measurements.

## 2 Using the Segway Platform for Hybrid Indoor/Outdoor Navigation Assistance

The Segway Personal Transporter is an ideal testbed for hybrid indoor/outdoor positioning and navigation assistance as it can be driven outdoors as well as indoors. We have enhanced a Segway platform using, among other sensors, a laser range finder, a GPS receiver, a WLAN interface, and wheel encoder information for odometry calculation.

Figure 1: Left: modified Segway platform enhanced with various sensors for navigation assistance. Right: Hokuyo URG-30LX range finder installed on the Segway base.

## 3 Indoor Positioning

While indoor position tracking by aligning a planar laser scan with a 2D map can be considered fairly straightforward, our scenario requires a 3D environment model due to uneven floors and ramps and the fact that the Segway transporter tilts forward and backward in order to balance and move. The sensor model compares the real scan to the expected scan as seen from each particle's position. Given the fixed position of the rangefinder with respect to the Segway's base, positioning is effectively constrained to four degrees of freedom (*x, y, pitch, yaw*), making the particle filter approach computationally feasible.

None of the available sensors can deliver a unique, precise indoor position from a single measurement. We must therefore perform *global localization* in indoor environments by estimating the correct position over time from multiple ambiguous measurements. The particle filter is particularly suited to handling multiple initial hypotheses. However, a uniform a-priori particle distribution would require too many particles. In order to achieve a more precise a-priori distribution, two techniques are used: First, a number of simple features are extracted from the scan such as the swept area of the scan and the first and second moments of the point clouds (Martínez 2010). They are then compared to the indoor environment model in order to quickly eliminate implausible hypotheses. Second, WLAN-based localization constrains the initial distribution. Here, the particles' expected RSSI measurements are calculated from a grid-based interpolation of previously recorded fingerprints (Howard et al. 2006).


Figure 2: A view of the lab corridor and its 3D environment model.

## 4 Indoor/Outdoor Transitions

When moving outdoors, GPS measurements become available and are integrated into the particle filter. The sensor model then determines the particle weights according to a normal distribution based on the reported GPS location and precision as well as its proximity to known buildings (in order to counter Urban Canyon effects). By specifying traversable areas outdoors as well as indoors, the motion is further constrained to increase precision. Since a building can only be entered and left at very specific positions, the last known indoor position provides a basis for outdoor positioning. Conversely, outdoor localization uniquely identifies the entrance taken when approaching a building, and thereby provides a good initial estimate for indoor positioning.

## 5 Conclusions and Outlook

The aim of this effort is to show that a particle filter provides the necessary flexibility to combine a rich set of diverse sensors for location determination, and that sufficient positioning performance can thus be attained both indoors and outdoors. Current work focuses on extensive testing and the possibilities of integrating further sensors for improved precision.

## 6 References

Howard, A., Siddiqi, S., and Sukhatme, G.S. (2006). An Experimental Study of Localization Using Wireless Ethernet. Springer Tracts in Advanced Robotics, volume 24, pp. 145–153.

Martínez Mozos, O. Semantic Labeling of Places with Mobile Robots. Springer Tracts in Advanced Robotics, volume 61.

# Improved Vehicle Positioning for Indoor Navigation in Parking Garages Through Commercially Available Maps

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## 1 Introduction

Large parking garages are often a challenge for drivers as orientation in complex environments is especially difficult. Consequently, appropriate guidance is needed to assist the driver in tasks such as finding an individual parking spot or guidance to the right exit. In this context, precise positioning is essential. Accurate vehicle positioning is also a starting point for seamlessly continued navigation, e.g. with pedestrian navigation devices.

Conventional vehicle navigation devices typically use a cascaded filter algorithm (e.g. Retscher [1]). In a first step, an Extended Kalman-Filter (EKF) fuses data from dead reckoning (DR) based on inertial sensors with measurements from a Global Navigation Satellite System (GNSS). The resulting position estimate is then matched to a digital map. In absence of GNSS measurements, however, sensor bias and drift cause the fidelity of the estimation to decrease quickly.

Therefore, we present a method that allows precise vehicle positioning independent of GNSS and instead using DR and a digital map of the parking garage. No additional hardware or infrastructure is needed, since the used inertial sensors and odometry are available in current premium series vehicles. Only additional map data for parking garages is required, which can be gathered with current technology available at map companies.

## 2 Map Data and Map Matching

The map data used was based on the standard NAVTEQ core map in RDF format and was extended with data for the parking garages. This data was gathered in part by NAVTEQ with IMU equipped vehicles with relative accuracy below 5m and some was generated from building plans and transferred into RDF format with relative accuracy below 1m.

The used map matching algorithm uses a position estimate to determine the most likely map segment by calculating a matching probability measure for each segment in range, based on position, heading, speed, link connectivity and basic traffic rules. It yields a projection of the position estimate onto the segment as well as additional information, e.g. the probability measure and the distance to the closest intersection.

## 3 Data Fusion

The key idea in our approach is to use the matched position as an additional measurement, similar to a GNSS measurement. Thus, high positioning precision is maintained even where GNSS signals are unavailable. An overview of the filter is shown in Fig. 1. In a first step, data from odometry and inertial sensors is processed in an EKF using an extended single-track vehicle model and sensor bias compensation. The central EKF fuses the resulting position updates with map-matched positions from previous estimates and optionally with GNSS data.

Additionally, a ramp detection module based on inertial sensors allows the map matcher to operate in multi-story parking garages with many overlaid levels.

The refeeding of map-matched positions has been successfully demonstrated on similar applications: e.g. Najjar [2] uses the concept to improve a road-matching algorithm. In our work we improve the precision of the position estimate, with a focus on parking garages and intersections that are captured improperly by digital maps.

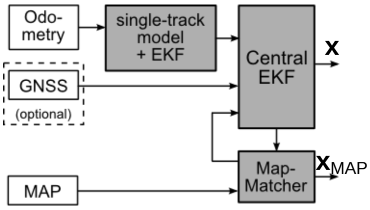


Fig. 1: Cascaded Filter Structure

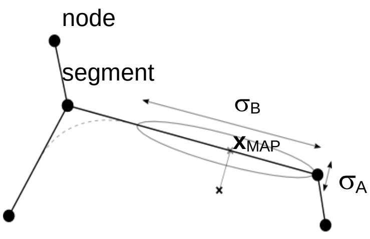


Fig. 2: Error Ellipse for Map-Measurement $\mathbf{x}_{MAP}$

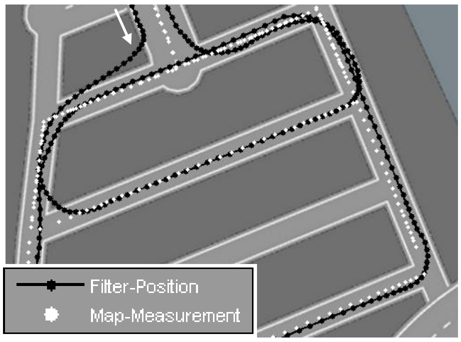


Fig. 3: Position-Traces on a rendered garage map

A key issue in the operation of an EKF are accurate error statistics, i.e. variances, of the input signals – in this case the assignment of a Helmert error ellipse to a map-measurement $\mathbf{x}_{MAP}$. Since $\mathbf{x}_{MAP}$ is an orthogonal projection onto a map segment, it yields the error perpendicular to the straight segment. As depicted in Fig. 2, the error ellipse is streched along the segment with $\sigma_A$ dependent on the lane width and $\sigma_B$ related to the segment length. Because of this dependency on the lane heading, frequent turns are needed for corrections in all directions. Parking garages typically feature many rectangular turns and thereby ensure overall positioning integrity.

Sharp curves and perpendicular intersections, common in parking garages, result in sharp angles in digital maps. Typical trajectories, however, follow smoother paths as shown in the filter-position trace in Fig. 3. Therefore, a term is introduced to increase the variance of $\mathbf{x}_{MAP}$ based on the distance to the closest intersection, the angle between corresponding segments and the probability measure to account for ambiguous matches.

## 4 Evaluation and Conclusion

We introduced an indoor vehicle positioning system for parking garages. It is operational in real-time on a test vehicle. Given accurate map data (relative accuracy below 1m) it allows for robust and stable vehicle positioning to individual parking spots, even in large multi-story garages as P7 at Munich Airport, without additional hardware or infrastructure. The orthogonal lane patterns in parking garages proved especially suitable for the proposed filtering strategy.

## 5 References


[1] *G. Retscher, E. Mok:* Integration of mobile phone location services into intelligent GPS vehicle navigation systems, *3rd Workshop on Mobile Mapping Technology, 2001*

[2] *M. Najjar, Ph. Bonnifait:* A Road-Matching Method for Precise Vehicle Localization using Belief Theory and Kalman Filtering, *Automomous Robots,* 19(2):173-191, 2005

# Tracking Persons with an Autarkic Radio-Based Multi-Sensor System

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## 1 Summary

The combination of different sensors from different areas of technology, including software analysis and parameterisation led to an innovative indoor tracking system based on a wireless sensor network. The new hardware platform represents the outcome of sensor fusion with three-dimensional motion vector pattern recognition. The measured data of the individual sensors is evaluated in respect to the physical quantities and additionally to their weighted quality indicators. This quality assessment reduces the influence of external environmental parameters on the motion vector and is used for an enhanced position estimation. In addition to the motion-sensor data, the information from the radio transceiver is exploited for the recognition of the environment. This enables gradual reconstruction of the environmental scenario. The fusion of all the information obtained using hardware and software minimises the relative average deviation to about ± 2 m for a spatial coverage of 100 m.

## 2 The BodyGuard System

The research of wireless sensor networks often focuses on algorithms and simulation. Our system focuses on the accuracy of the gathered sensor data and the robustness of the sensor network.

Table 1: Components

| Name/Manufacturer | Function | Application |
|---|---|---|
| MSP430F2618 / TI | Microcontroller | Processing and pattern recognition of sensor data |
| PAN2355 / Panasonic, TI | Transceiver, CC1101 | Wireless Data Communications / Building Reconstruction |
| MMA7260 / Freescale | Triple Axis Accelerometer | Transaction Data |
| EMC-03RC / Murata | Gyroscopes | Rotation data |
| FSA03 / Falcom, u-Blox | GPS-Receiver, UBX-G5010 | Absolute position determination (Outdoor) |
| HMC6352 / Honeywell | Two Axis Compass | Absolute angle determination |
| MS5540 / Intersema | Barometer | Altitude change / environment condition |
| SHT15 / Sensirion | Humidity & Temp Sensor | Environmental condition |
| RMCM01 / Polar | Heart Rate Receiver | Vital signs |

1. The design objectives for the newly developed hardware platform were the miniaturization of the 3D sensor and the interaction and combination of each other. The hardware platform consists of a microcontroller from the MSP430 series (Texas

Instruments) and a number of individual sensors (see Table 1). Complete processing of all data is performed on the BodyGuard Node.

2. The measurement data of the analog sensors is sampled with a rate of 1 kHz and 12 bit precision. For each channel the data is averaged in intervals of 100 ms. In addition, characteristic features of the trace are determined and used for pattern recognition. The digital sensors operate in a frequency of 10 Hz and linked to the analog data.
3. The merged data is then transmitted via radio using CC1101 at a data rate of 400 Kbit or via USB to a remote station or computer. The data can be transmitted via single-hop or via multi-hop. Due to data fusion in multi-hop networks the redundant data could be used to achieve more precise environment recognition especially in buildings.
4. For the visualization of the data two software versions have been developed: an evaluation version for the experimental validation of the sensors, pattern recognition and sensor-specific data analysis as well as a second version for visualization of the position with integrated pattern recognition in a Google Earth based interface.

## 3 Processing module for measured data

Figure 1 shows the software engineering process of the data from data acquisition to visualization.

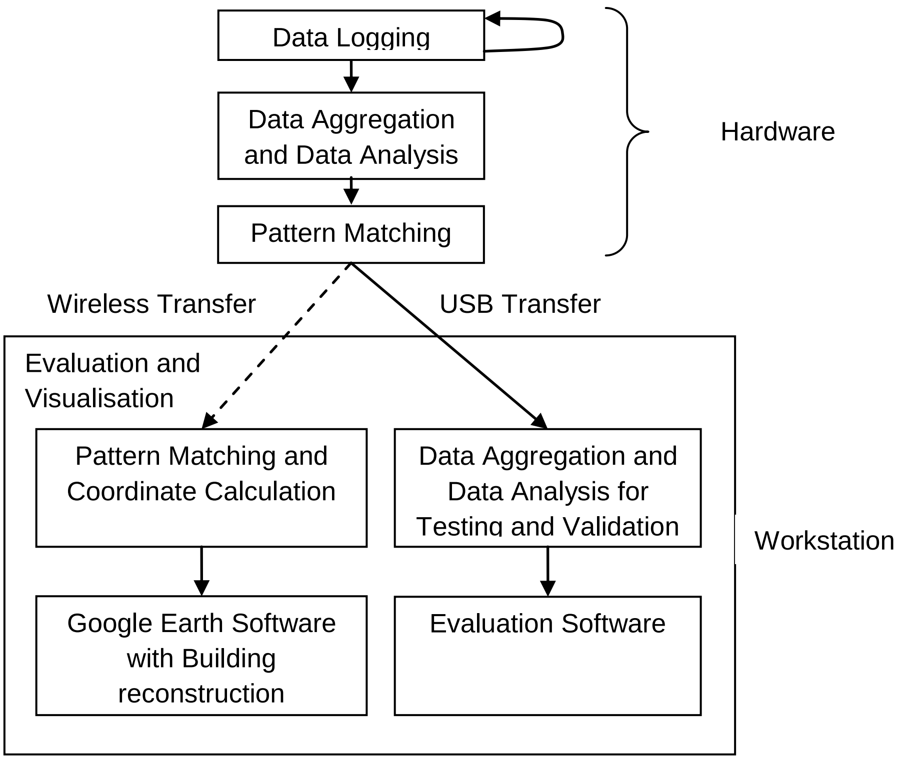


Figure 1: Processing module.

## 4 Conclusions and Outlook

In order to increase the accuracy of the rotation and height, more accurate sensors could be used in the next stage of development. The orientation dependence of the used compass could be eliminated by the use of a new three-axis magnetic field sensor. The gyroscopes and the air pressure sensor could be replaced with more accurate sensors which are currently used.

# Set-Up of a Combined Indoor and Outdoor Positioning Solution and Experimental Results

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## 1 Introduction

Within an European research project, our main task is the development of a combined indoor and outdoor positioning solution. The objective of this hybrid system is to improve the safety of workers on construction sites. Therefore it is important to know the position of workers at all times without latency in a central coordination office. The aim is to develop a robust methodology which covers indoor and outdoor scenarios, where the current 3D position of every worker is available for himself and in a central risk management office.

## 2 Requirements for the Positioning Solution

The developed system can be applied in all industrial environments. Construction sites are most challenging, as the buildings are raised up or demolished, walls will be mounted or removed. Signal propagation in such an environment makes the positioning to a challenging task. Construction sites can be subdivided into indoor, outdoor and boundary areas (Figure 1).

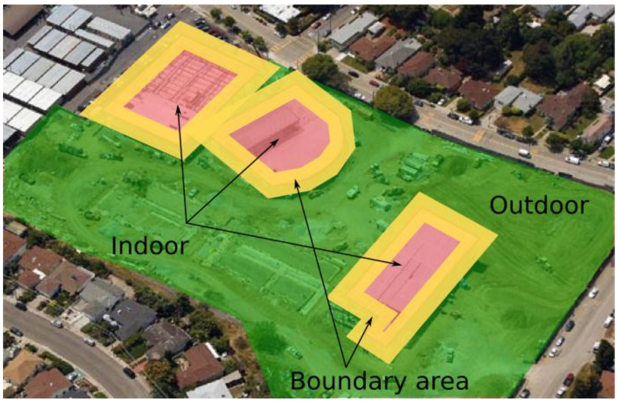


Figure 1: Indoor, outdoor and boundary areas on a construction site. Photo by Dave Piper (CC)

The requirements are: accuracy up to 0.5 m, position update rate 2 Hz or higher, reliability and robustness: close to 100%, to be carried at working clothes: small and light components and multi-directional data communication. A good compromise between costs and workers safety must be found.

## 3 Proposed System

Our approach is a hybrid system, consisting of an UWB and RFID system mainly for indoor and a DGNSS used for outdoor environments, see Table 2. The positioning system may be supported by additional hardware like barometric sensors and Inertial Measurement Units (IMU). ZigBee communication nodes in mesh configuration will be used for data transfer, because they are designed for low power consumption and therefore advantageous for integration.

Table 2: Overview of the proposed positioning systems. Characteristics may be out of date due to system improvements.

| Technology | Signal / Technique | Accuracy / Update rate / Weight | Costs | Notes / Limits |
|---|---|---|---|---|
| UWB | radio impulse / TDoA, AoA | 15 cm / ~10 Hz / low | Expensive hardware (Dev. kit ~50 x 50 m: 4 readers, 10 tags, software) ~13'000 € | Power cables (e.g. PoE), synchronisation cables |
| RFID (active) | radio frequency / signal strength | ~3 m / > 1 Hz / low | Tag ~25 €, reader ~85 € | low-current |
| DGNSS, RTK | radio frequency / ToA, lateration | mm – m / 20 Hz / low to moderate | receiver ~1200 €, needs data link to reference station | for outdoor only |

The DGNSS system with own reference station makes the positioning task independent from technical troubles of service providers but possible troubles of the satellite system itself remains. This concept makes our solution available in nearly every place all over the world. For our system the AsteRx1 from Septentrio has been chosen. The selected Ubisense 7000 system allows accurate positioning indoors. This system reaches accuracies up to 15 cm (line-of-sight). The set-up of this system needs to build up a costly and complex infrastructure. Only areas with high requirements on accuracy will be equipped with this system. RFID based systems need less installation effort and are much cheaper than the UWB system. Placing RFID-Tags in doorways allows room wide determination of workers' location. By combining this information with typical characteristics of the worker and the surrounding environment, an increase in the position accuracy and availability is possible.

## 4 Experiments

First results on experiments in different environments will show the achieved status of this development. Within this paper we will describe the set-up of this hybrid system including the communication solution.

## 5 Conclusions and Future Prospects

The combination of satellite-, Ultra-Wide-Band (UWB) and RFID based positioning systems is a good solution for reliable localisation purposes, which is independent from the environment.

By this innovative positioning and communication solution a significant reduction of risks for workers in industrial environments is possible. Some specific items, as the growing set-up of the positioning system corresponding to different phases of a construction process, are applicable to all other industrial branches as well.

## Hybrid IMU Pedestrian Navigation 2

Auditorium G3

Wednesday, September 15, 16:00 – 18:00

# Infrastructure-independent person localization with IEEE 802.15.4 WSN

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## 1 Summary and system concept

In this paper, a new concept for infrastructure independent person localization by means of a wireless sensor network (WSN) in combination with a pedestrian dead reckoning device (PDR) is proposed. In an arbitrary in- and outdoor environment, each nodes position estimation is initialized upon its deployment by means of a MEMS based PDR device if no GPS signal is available at the deployment position and time (anchor node deployment). Every anchor node broadcasts its (estimated) position as well as an uncertainty parameter in regular intervals, and mobile nodes without inertial navigation capabilities (carried on the body of moving persons in the area of interest, on-body nodes) estimate their positions based on the received signal strength (RSS) and uncertainty information of all received packets. Additionally, a GPS-equipped subset of the anchor nodes allows for an improvement of the position estimation as soon as a GPS fix can be obtained at the deployment position. The uncertain position estimation of the networked nodes is enhanced during runtime based on the RSS values of packets received from neighbouring nodes within one hop communication range.

## 2 Motivation and state of the art

A system that allows the localization of mobile persons and that can be used in both in- and outdoor environments and does not require advance knowledge of the surroundings of the area of interest, could be applied in a variety of different fields. The tracking of fire-fighters that enter a burning building or a complex of buildings, the coordination of a police operation or also the supervision of Alzheimer patients in the compounds of a retirement facility are some example applications in which an ad-hoc localization system could be of significant help. The considered requirements of such a system include scalability in terms of number nodes and covered area (which necessitates a low-cost implementation of the nodes), robustness against changing influences in varying environments and accuracy in the range of several meters. The combination of a pedestrian inertial navigation unit with a WSN seems to be an interesting approach to these exigencies.

There has been some work on integration of an IMU with WSN technology [1] for localization purposes and some approaches to the simultaneous localization and map building (SLAM) problem within the field of robotics seem to be comparable to a certain degree [2], but to our knowledge there are currently no comparable approaches to ad-hoc person localization.

## 3 System aspects overview

Three main areas of interest are explored within the project and further explained in the paper:

- **PDR: combination of sensor node and inertial measurement unit (IMU):** the PDR consists of a combination of a commercially available IMU with a proprietary sensor node. This node can thus use pre-processed alignment information (data-fusion of 3 gyros, 3 accelerometers and a 3-axial magnetometer, processed in a digital signal processor), to establish information about the movement direction of the person carrying the node. The covered distance is then estimated from a step counter (acceleration sensor) in combination with the available information from other sensor nodes within communication range (data fusion).

- **ZigBee-based ad-hoc network deployment:** the use of the ZigBee protocol stack for the development of the required network and communication infrastructure allows a quick implementation of the desired functionality. The current system provides a robust localization and implements the mentioned functionalities.
- **Received signal strength (RSS) position estimation:** the position estimation algorithm for on-body nodes has to be computable on the limited resources of a low-cost microcontroller (MCU) and has to be robust against RSS fluctuations and systematic errors caused by the changing environment and position of the on-body node. A very simple localization approach to cope with these impediments has been designed and seems to allow reasonable accurate position estimation.

## 4 Current development status and outlook

So far, the implementation of the outlined network and localization functions and the development of the required hardware components (cheap and extensible sensor nodes, connection platform for inertial measurement unit) have been completed. First experiments with the developed RSS-based localization system show promising results for the localization of on-body nodes in an outdoor environment if the anchor nodes have known positions.

At the moment, further in- and outdoor experiments are carried out to collect a comprehensive real-world database for the development and test of localization algorithms that provide a robust functionality independent of the environment. Based on this database, the simulation model will then be tuned and a numeric optimization of localization with estimated (inaccurate) anchor node positions can be started. The next steps include the development of the described PDR and the implementation of the node deployment process.

## 5 Conclusions and paper topic

The proposed system seems to be a promising approach to infrastructure independent ad-hoc person localization in WSN. The paper includes a detailed description of the outlined system and the current state of the development.

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## RSSI-based Indoor Positioning using Diversity and Inertial Navigation

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### 1 Summary

A substantial criterion with the use of wireless communication is the missing location information of the mobile participants. RSSI (Received Signal Strength Indicator)-based localization techniques are an easy and well known method to predict the position of an unknown node in indoor environments whereas additional methods are required for a sufficient accuracy. The distance-pending path loss is affected by strong variations, especially appearing as frequency specific signal dropouts. A diversity concept with redundant data transmission in different frequency bands can reduce the dropout probability. Not only the availability of the communication and the positioning, but also the accuracy of the localization can be increased with the diversity concept. Another improvement can be reached by a sensor fusion of RSSI-based position data with an Inertial Navigation System. First experimental results with miniaturized transceiver prototypes show that a good performance for precision and availability can also be reached with low infrastructural costs.

### 2 System Architecture

Our indoor localization system (MotionLoc) uses a Kalman Filter for the sensor fusion of two separate position estimation techniques. An RSSI-based radio localization system (RSSILoc) and an Inertial Navigation System (INS) are combined in the localization process. The infrastructure of MotionLoc consists of the Blind node (BN) which should be located and several Reference Nodes (RNs) with fixed positions (cf. Figure 1).

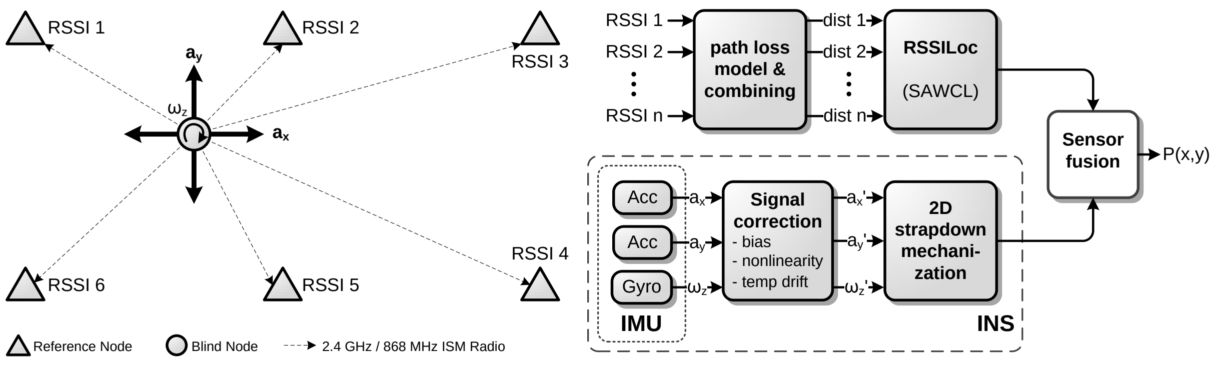


Figure 1: Infrastructure components (left) and localization techniques (right) of the MotionLoc system

The RSSI-based localization uses the Log-distance path loss model to calculate the distances between the BN and the RNs. The position of the BN is then computed with the weighted centroid of the RN’s fixed positions (SAWCL, Selective Adaptive Weighted Centroid Localization). The Inertial Navigation System uses a two-dimensional strapdown Inertial Measurement Unit (IMU) to have a constant update of the BN’s position.

The essential criterion of the RSSI-based localization system is the use of a diversity transceiver with two proprietary RF modules operating at 2.4 GHz ISM and two additional proprietary RF modules operating at 868 MHz ISM. We have carried out many measurements to search out the influence of different antenna adjustments with our first prototype (“Multichannel Prototype”) using rod antennas. Our new transceiver prototype (“Multichannel Mini”) is much smaller and uses chip antennas (cf. Figure 2).

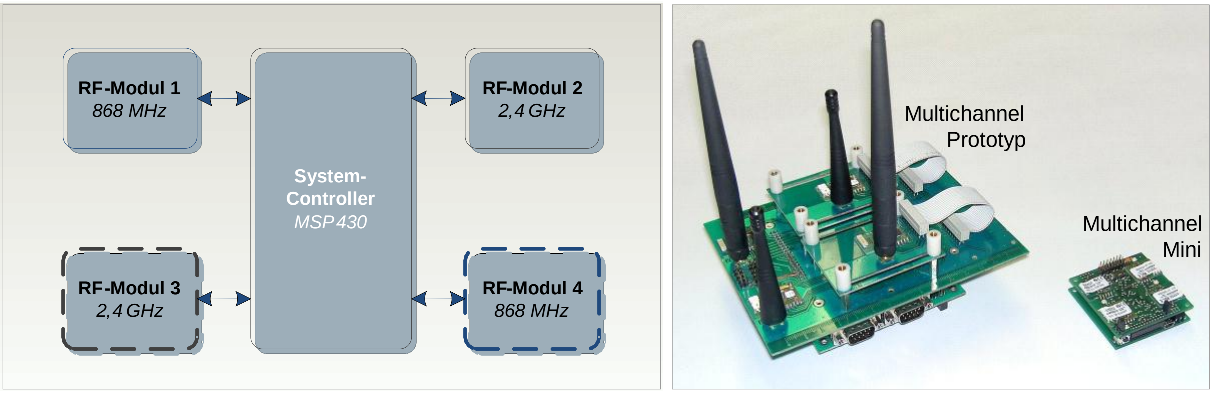


Figure 2: Redundant transceiver module – system architecture (left) and prototypes (right)

The low-cost IMU on the BN consists of the LIS3LV (ST Microelectronic) 2g three-axis acceleration sensor and a LY530ALH (ST Microelectronics) +-300°/s gyroscopic sensor to measure the horizontal attitude of the device. The IMU sensors are strapped directly to the BN’s body and located on a different PCB underneath the transceiver board.

## 3 System Evaluation

The test bed is a PC pool at our institute with a footprint of approximately 11m x 7m and a quantity of macroscopic objects. We use a Java application to visualize and analyze the localization (cf. Figure 3).

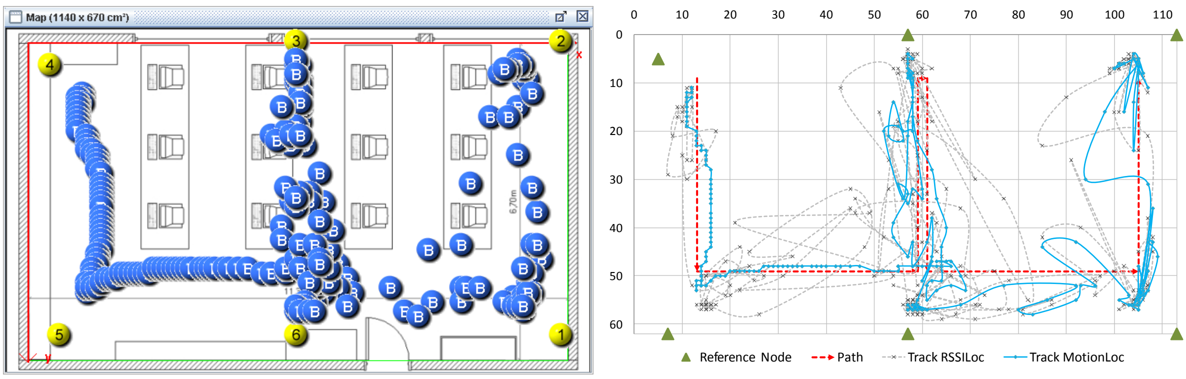


Figure 3: Visualization of a tracking measurement in an obstructed test bed

The trajectories for the RSSILoc and the MotionLoc system in Figure 3 were collected with our first prototype and a former type of sensor fusion (plausibility filtering of RSSILoc position according to the INS motion vector). At the moment we carry out measurements with our new miniaturized prototype and the improved sensor fusion algorithm. We expect similar results for the availability of the communication / localization but a more accurate position estimation and we are looking forward to present the enhanced system in the final paper.

# Calibration of the Accelerometer Triad of an Inertial Measurement Unit, Maximum Likelihood Estimation and Cramér-Rao Bound

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## 1 Summary

In this paper, a simple method to calibrate the accelerometer cluster of an inertial measurement unit (IMU) is proposed. The proposed method does not rely on using a mechanical calibration platform that rotates the IMU into different precisely controlled orientations. Although the IMU is rotated in different orientations, these orientations do not need to be known.

Assuming that the IMU is stationary at each orientation, the norm of the input is considered equal to the gravity acceleration. As the orientations of the IMU are unknown, the calibration of the accelerometer cluster is stated as blind system identification problem where only the norm of the input to the system is known.

Under the assumption that the sensor noises have white Gaussian distribution the system identification problem is solved using the maximum likelihood estimation method. The accuracy of the proposed calibration method is compared with the Cramér-Rao bound for the considered calibration problem.

## 2 Introduction

Traditionally the calibration of an IMU has been done using a mechanical platform that turns the IMU into several precisely controlled orientations. At each orientation, the outputs of the accelerometer cluster and the gyroscope cluster are observed and compared with pre-calculated gravity force vector and rotational velocities, respectively. However, many times the cost of a mechanical calibration platform exceeds the cost of developing a low-cost IMU. Therefore, different calibration methods have been proposed that do not require a mechanical platform. Most of these calibration methods utilize the fact that for an ideal (noise free) IMU, the norm of the measured output of the accelerometer should be equal to the magnitude of the gravity force vector. However, using such an assumption, the optimization of the corresponding criterion function typically leads to a biased estimate of the calibration parameters.

To avoid this, we solve the system identification problem using maximum likelihood estimation (MLE) framework. This leads to an unbiased estimator that is asymptotically minimum variance. Then the performance of the calibration algorithm is compared with the Cramér-Rao bound. This bound sets the lower limit for the variance of the estimation error for all unbiased estimators.

## 3 The Proposed Method

A nine-parameter sensor model of the accelerometer cluster is considered; the three scale factors, the three misalignment angles, and three biases. To estimate the nine unknown calibration parameters, the IMU requires to be rotated in different orientations. Each time the IMU is placed in a new orientation two new unknown rotational angles that need to be simultaneously estimated together with calibration parameters are introduced. The uncertainty in the rotational angles which appears in the input force of the system makes our calibration problem a blind identification problem.

Assuming that the sensor measurements are disturbed by additive white Gaussian noise, the observed data has a multivariate Gaussian distribution and the mean vector contains all the unknown parameters to be estimated. As we are interested to derive an unbiased estimator, we use the MLE method which is asymptotically unbiased. Finding a closed form one step solution for maximizing the likelihood function is difficult in this case and we propose to use an iterative approach. In our method, the unknown parameters are clustered into two groups, the rotational angles and the calibration parameters. The optimization is done by maximizing the likelihood function with respect to one group of parameters at a time while keeping the remaining parameters fixed at their current values.

## 4 Results

The proposed calibration approach has been evaluated by Monte-Carlo simulations. In the presented simulation, the IMU was rotated into nine unknown orientations and the accelerometer noise variance was set to 0.01[m/s$^2$]. In Figure 1, the empirical mean square errors of the estimated scale-factors are shown along with the corresponding Cramér-Rao bounds. The simulation results show that the square-root of empirical mean square error (EMSE) of the estimated parameters converges to the square-root of the Cramér-Rao bound already after a few numbers of measurements.

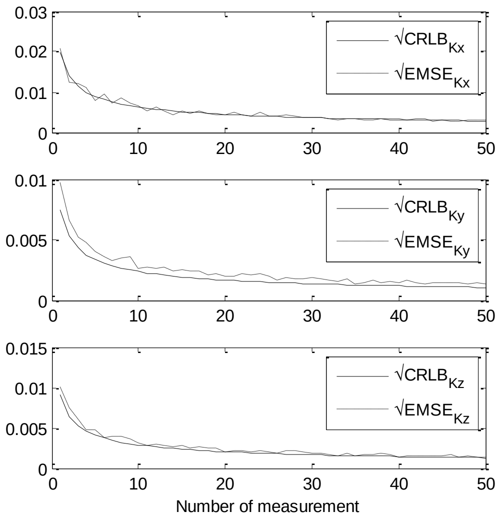


Figure 1: Square-root of the empirical mean square errors of the estimated scale-factors and the square-root of the Cramér-Rao bounds (CRLB), versus the number of samples at each orientation.

## 5 Conclusion

An approach for calibrating the accelerometer cluster of the IMUs has been proposed. The method does not require any expensive mechanical calibration platform. Instead, the proposed calibration method is based on a maximum likelihood estimator that jointly estimates the orientations of the IMU and the calibration parameters of interest. The simulation results show that the EMSE of the sensor parameters estimated using the proposed calibration method converges to the Cramér-Rao bound after only a few measurements.

# Joint calibration of an inertial measurement unit and coordinate transformation parameters using a monocular camera

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## 1 Summary

An estimation procedure for calibration of a low-cost inertial measurement unit (IMU), using a rigidly mounted monocular camera, is presented. The parameters of a sensor model that captures misalignments, scale and offset errors are estimated jointly with the IMU-camera coordinate transformation parameters using a recursive Sigma-Point Kalman Filter. The method requires only a simple visual calibration pattern and moreover provides figures of merit of the estimates. A simulation study indicates the filter's ability to reach subcentimeter and subdegree accuracy.

## 2 Introduction

Developments in micro-electro-mechanical systems (MEMS) have enabled the use of low-cost inertial measurement units in applications ranging from navigation to augmented reality. Many of these are highly dependent on the accuracy of the inertial sensors, hence the need for calibration. Cost factors motivate calibration procedures that do not require mechanical platforms and rotation tables. The proposed method uses a monocular camera, which is inexpensive and can be rigidly mounted to a 6 DOF IMU with relative ease, along with a simple visual calibration pattern. This amounts to a joint sensor model and IMU-camera parameter estimation problem where the latter parameters are in themselves useful for applications that fuse visual and inertial information [1,2].

## 3 Sensor model

An inertial sensor that provides a digitized measurement of specific force or angular velocity is subject to errors that arise from unmodeled nonlinearities, manufacturing imperfections, quantization noise, etc. Ideally a cluster of three accelerometer sensitivity axes should be mutually orthogonal and their outputs of equal scale. Similarly, the cluster of gyroscopes should be orthogonal and placed in relation to the accelerometer cluster. We let an affine mapping between the sensor output and the sought physical quantity capture misalignments; scale errors; offset error; and random noise arising from quantization [3].

## 4 Estimation framework

The estimation framework exploits the inertial navigation system (INS) equations in a feedback approach to estimate the IMU sensor model parameters as well as the transformation parameters between the inertial and camera coordinate frames. A simple calibration pattern, normally used to calibrate the internal camera parameters, is placed on a horizontal plane perpendicular to the gravitational field. The observed feature points of the pattern are pixel measurements on the image plane, fed into a recursive Sigma-Point Kalman Filter that estimates the sought parameters. The diagonal elements of the square root error covariance matrix provide figures of merit of the estimates.

## 5 Results and conclusions

An evaluation of the proposed estimation procedure was performed by means of Monte Carlo simulations [4]: A trajectory of an IMU, with a rigidly mounted monocular camera, was generated moving above and facing a 12x12 cm calibration pattern which consisted of an array of 4x4 feature points. These were projected using a pinhole camera model and subject to measurement noise with a standard deviation of 2 pixels.

The IMU-camera transformation parameters were estimated to subdegree and subcentimeter accuracy. The misalignments of the accelerometer and gyroscope clusters were estimated to subdegree precision, and the scale factors differed by at most 0.1 percentage points. The accuracy, quality and rate of convergence of the estimates are dependent on exciting sufficient motion of the system. The results suggest an inexpensive procedure for calibrating low-cost IMUs without the need for mechanical platforms.

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# DCM based Attitude Estimation Using Low-cost IMU Aided by Distributed Accelerometers and Magnetometers

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## 1 Summary

In this paper, we describe the development and analyze the performance of a low-cost attitude and heading reference system (AHRS) realized through micro electrical mechanical system (MEMS) inertial sensors and magnetometers. Due to the poor performance of low-cost MEMS gyros and accelerometers, we aid a traditional inertial measurement unit (IMU) with low-cost distributed accelerometers. By doing so, we get two achievements: the first is an improvement in the angular rate knowledge because of the angular information computed from distributed accelerometers. The second improvement is in the acceleration knowledge as a result of the redundancy of accelerometers. Two cascaded filters will be used to estimate the attitude. The first filter fuses the angular information coming from the distributed accelerometers and the gyros and returns the angular rate. The second filter fuses the angular rate, specific force and magnetometer measurements and returns the estimated elements of the direction cosine matrix (DCM). Simulation results and real time experiments will be used to verify the efficiency of our approach.

## 2 Structure of AHRS and traditional IMU

The AHRS is a device that provides attitude and heading information for many applications. Nowadays, we have a wide range of applications that require knowledge of attitude information such as navigation, aerospace and robotics. The advantage of inertial navigation systems (INS) over other navigation systems is that they are self-contained and hence do not require any interaction with the external environment in order to operate. An IMU consists of three mutually orthogonal accelerometers and gyroscopes. For the static case, a set of low-cost accelerometer triad can provide the accurate tilt angles (roll and pitch) while the remaining heading angle can be found using a magnetometer triad. Tilt angles are found by measuring the projection of the local gravity vector, which should be exactly known, on the body frame axis using three mounted accelerometers. For the dynamic case, the angular rates from the gyros are integrated over time to update attitude. Since magnetometer and accelerometers allow for direct measurement of the attitude, Kalman filtering methods can be used to correct the accumulating errors due to the integration of gyros' outputs.

## 3 Angular information from distributed accelerometer triads

Generally, accelerometers are less costly, less weight and less power consuming than comparable gyros which have typically the disadvantage of complicated manufacturing techniques, high cost, high power consumption, large weight, large volume, and limited dynamic range. Hence, research efforts are conducted on the use of accelerometers in order to infer the angular motion. Using certain configurations that consist of twelve separate mono-axial accelerometers produces an angular information vector (AIV) that consists of a 3D angular acceleration vector and six quadratic terms of angular velocities [1]. Distributed accelerometers can be used to form a gyro free inertial measurement unit (GF-IMU) or they can be aided by low-cost gyros. Gyro's aid might be needed to solve the sign indeterminacy problem resulting from having the quadratic terms of angular velocity in the AIV. In our design, we aid a standard IMU with three distributed accelerometers triads besides the magnetometer triad aid as shown in Figure 1.

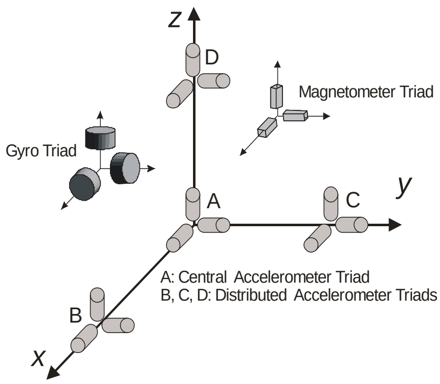


Fig.1 Inertial measurement unit aided by distributed accelerometers and magnetometers

## 4 DCM based attitude estimation algorithm

The purpose of the attitude filter is to estimate the attitude through optimal fusion of angular rate, specific force and magnetometer measurements. There are three common attitude representations that can be used for the fusion filter implementation, namely Euler angles, quaternion and DCM. We developed a novel DCM based attitude estimation algorithm to estimate DCM elements. To minimize the computational effort, we estimate only six elements of the DCM and the remaining three elements are determined by DCM orthogonalization. The advantage of using a DCM based model is having a linear process model for the DCM update and a linear measurement model for accelerometers and magnetometers measurements and hence avoiding linearization errors and reducing computations.

## 5 Evaluation of the performance

We analyzed the improvement in the IMU performance through simulations and experiments. For experimental evaluation, we mounted two IMUs of on a platform: one has an accurate output and the other is our developed unit. The accurate IMU serves as a reference for performance assessment of our developed IMU. The benefits of the aid using distributed accelerometers and the fusion utilizing the DCM based attitude algorithm were evident.

## 6 Conclusion

A reliable attitude is achieved by the use of a standard IMU aided by distributed accelerometers and magnetometers and fused with a novel DCM based attitude estimation algorithm.

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# UWB/IMU Tracking Validation using an Optical System

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## 1 Abstract

In this paper we report the results of a validation study of a 6DOF tracking system combining Ultra-Wideband measurements with low-cost MEMS inertial measurements. The tightly coupled system estimates position as well as orientation of the sensor unit. The comparison with the results from an optical system show robust and continuous tracking in a realistic indoor positioning scenario.

## 2 Introduction

Commercially available Ultra-Wideband (UWB) systems typically consist of a network of synchronized UWB receivers which track a large number of small, battery powered and inexpensive UWB transmitters. Reported indoor position accuracies lie in the order of decimetres, but suffer from multipath effects and non-line-of-sight (NLOS) conditions. These effects are most prominent while tracking moving objects or persons and give rise to distorted and bumpy trajectories. Although the obtained performance is often sufficient for the aforementioned applications, many potential application areas have higher performance requirements.

To improve the tracking performance (especially the positioning accuracy) we propose to combine UWB with a low-cost micro electro mechanical system (MEMS) inertial measurement unit (IMU) consisting of a 3D rate gyroscope and a 3D accelerometer. The main justification for adding an IMU — providing accurate position tracking for short periods of time, but drift prone for longer timescales — is to obtain a robust system, capable of detecting and rejecting multipath effects and NLOS situations. Additional benefits of adding an IMU include improved tracking results, especially for dynamic quantities like velocity, and that the orientation becomes observable as well. This results in a system providing a 6 degrees of freedom (DOF) general purpose tracking solution for indoor applications.

In our previous work [1] we reported a full 6DOF tracker estimating both position and orientation based on tightly coupled fusion of UWB and inertial sensors. In this paper we present the results of a comparison with an optical system.

## 3 Results

The UWB/IMU tracking system setup has been used in a room of 8 x 8 x 3 m in size, in which also an optical tracking system (Vicon) is present. The UWB setup consisted of a total of 10 receivers; 5 are placed on the floor and 5 are mounted to the ceiling. The inertial sensor with integrated UWB transmitter has been equipped with an optical cluster. Hence the

[1] J. D. Hol, F. Dijkstra, H. Luinge, and T. B. Schön. Tightly coupled UWB/IMU pose estimation. In *Proceedings of IEEE International Conference on Ultra-Wideband*, pages 688-692, Vancouver, Canada, Sept. 2009

estimated position and orientation trajectories can (after time synchronization and alignment) be compared to those of the optical system.

Figure 1 shows the tracking results for a 60 s trial where the sensor has been moved through the (limited) optical tracking volume at moderate speeds. It shows that the two systems agree very well, with a RMSE of 0.6 degrees in orientation and 5 cm in position.

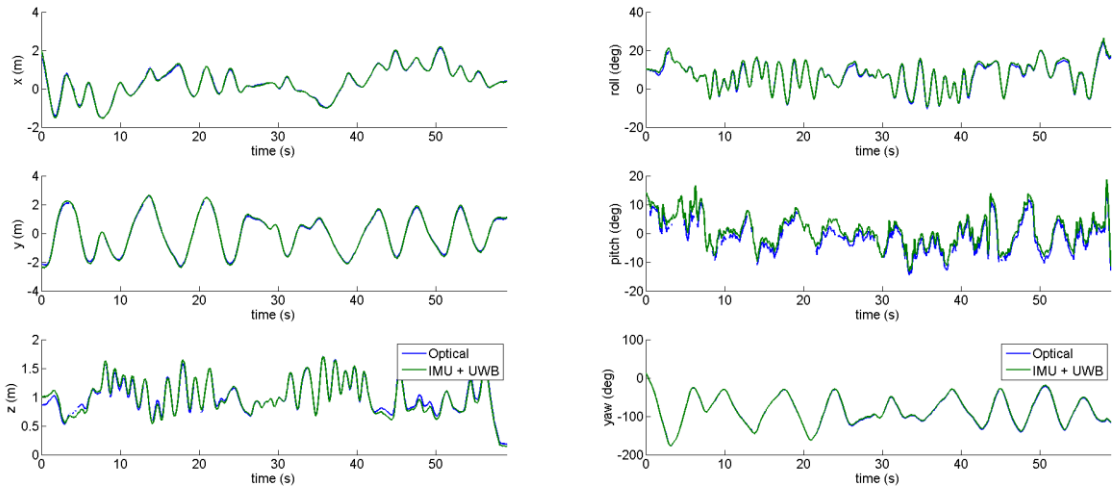


Figure 1: Position and orientation trajectories from UWB/IMU and

## 4 Conclusions

In this paper a 6DOF tracking algorithm estimating both position and orientation based on tightly coupled fusion of UWB and inertial sensors is compared against an optical system. Experiments show that a robust and accurate system is obtained.

# Performance Evaluation of an Hybrid RSSI-Inertial Localization Algorithm in IEEE 802.15.4 Wireless Sensor Networks

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## 1 Summary

In this work we present an evaluation of the performance of a range-based hybrid localization algorithm based on the Received Signal Strength Indicator (RSSI) and inertial data applied in a real world WSN. As can be found in literature, RSSI-based localization algorithms exhibit low accuracy due to the variability of the radio signal. Adding inertial information, such as accelerations values obtained by an Inertial Measurement Unit (IMU), in combination with an implementation of a dedicated data-fusion algorithm, it can provide a higher level of accuracy. In order to evaluate the accuracy gain, we compared the results obtained in the field using only RSSI data against the values provided with a hybrid localization system in the same environment.

## 2 Localization Algorithm

Many techniques might be used for the estimation of the position of an unknown target node in a WSN, such as a Global Positioning System, a laser, infrared or acoustic waves, but all these methods are not energy efficient due the need of external hardware [1]. To overcome this limitation, the RSSI index – that can be read without any external hardware – is often used to estimate the distance between the target and the references, followed by a computation of the position of the target with appropriate algorithms [2]. Some of the well known algorithms are based on geometric considerations, such as Multilateration or Min-Max, while others rely on statistical considerations such as the Maximum Likelihood method. Due to the small computational power of WSNs nodes, we decided to use the Min-Max algorithm for our tests.

On the other hand, inertial data have been used to estimate the position of a target node starting from the acceleration value obtained by the accelerometers, and performing a double numerical integration. Unfortunately, such readings are affected by noise – and by the double integration, the error grows quadratically over time. To bound this error, the integration is usually calculated over small amount of time only. The position provided by the IMU is then fused with the position from the RSSI estimation by an appropriate filter that is able to keep track of the past positions measured by the target node for the estimation of the subsequent position. In order to perform the data fusion we implemented a simple, steady state Kalman filter [3], where the position estimated by RSSI measurements is used to correct the position that is computed with those obtained by the IMU. Due to the low amount of energy disposable in a sensor node, we decided to use a MEMS IMU that is low power demanding, small, cheap and sufficiently accurate for this purpose.

## 3 Experimental Results

The nodes of the WSN deployed for our tests are based on the Arduino Diecimila development board, the Digi's XBee IEEE 802.15.4 compliant transceiver; the IMU uses the ADXL330 triaxial MEMS accelerometer. The WSN has been deployed in an indoor scenario, where 6 anchor nodes with known positions and a target node with unknown position have been placed. The target node has been moved on a straight line in the middle of the room and the performances of the implemented algorithm have been evaluated in 8, fixed positions along the target path.

First, we tried to perform localization in our environment using only RSSI information: to perform channel characterization, we acquired many RSSI values in specific positions and discarded outlier values larger than three times the standard deviation from the dataset in order to improve the accuracy of the estimation. In this case we found that the target position was estimated with accuracy values that may be acceptable only for non-critical applications such as people localization at the room level in a museum. In fact, the mean error was around 2 m.

Then, we performed localization using both RSSI and inertial information, implementing a dedicated Kalman filter in order to perform data fusion and obtain estimations of the target position that take into account the data coming from both sensors. This way, we obtained an effective improvement in the localization of the target position, with up to 0.4 m estimation accuracy. The results of the performed localization are shown in Table 1.

Table 1: MSE of the two compared localization algorithms.

| **Real Position (x, y) [m]** | **RSSI localization (x, y) [m]** | **MSE RSSI Localization [m$^2$]** | **Hybrid localization (x, y) [m]** | **MSE Hybrid Localization [m$^2$]** |
|---|---|---|---|---|
| 1.35, 0 | 0.12, 1.54 | 3.88 | 1.27, 1.38 | 1.91 |
| 1.35, 1 | 0.32, 0.47 | 1.34 | 1.65, 1.53 | 0.37 |
| 1.35, 2 | 0.11, 1.16 | 2.24 | 1.24, 2.41 | 0.18 |
| 1.35, 3 | 0.98, 3.92 | 0.98 | 1.32, 3.62 | 0.39 |
| 1.35, 4 | 0.02, 1.2 | 9.61 | 1.48, 3.92 | 0.02 |
| 1.35, 5 | 2.25, 3.54 | 2.94 | 1.54, 4.28 | 0.55 |
| 1.35, 6 | 1.01, 4.47 | 1.70 | 1.36, 4.92 | 1.17 |
| 1.35, 7 | 0.98, 4.47 | 6.69 | 1.27, 6.01 | 0.99 |
| **Average MSE Value** | | 3.67 | | 0.70 |

## 4 Conclusions and Outlook

In this work, we presented a comparison of the performances of two possible localization methods that can be used in wireless sensor networks to find the unknown position of a target node. In particular we have shown the performances of an RSSI-based localization algorithm, and then we added a simple MEMS IMU to the target node performing data-fusion with the two sources through a dedicated steady state Kalman filter.

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## Foot Mounted Pedestrian Navigation

Auditorium G3

Thursday, September 16, 08:15 – 09:45 & 10:15 – 11:45

# A High Precision Reference Data Set for Pedestrian Navigation using Foot-Mounted Inertial Sensors

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## 1 Summary

In this paper we will describe a data collection methodology and reference data set that can be used by the indoor navigation community to verify and improve algorithms based on foot mounted inertial sensors. The data set is collected using a high precision optical reference system that is traditionally used in the film industry for human motion capturing or in specialist applications such as analysis of human motion in sports and medical rehabilitation. The data provides synchronous 6 degrees of freedom inertial measurement sensor readings from a foot mounted MEMS sensor array as well as the high resolution data from the optical tracking system providing location and orientation ground truth. We will also provide the results of algorithms that identify the rest phase during the human gait cycle which is an essential part of pedestrian dead reckoning systems for positioning.

## 2 Motivation and Description of the Data Collection Process

Recent years have seen many advances in pedestrian localisation in GPS denied environments [1-4]. In particular, work has focussed on the sensor fusion approach drawing on sensor data such as inertial sensor data (IMUs), barometers, and magnetometers in conjunction with non linear estimation techniques such as particle filtering. An important building block is so-called human odometry or dead reckoning which tries to estimate the individual steps of a pedestrian while he or she is walking in the environment. Estimates of the steps which are obtained in a relative coordinate system are then combined with other sensor data such as wireless positioning or information such as the building floor plans [2-4]. Foxlin pioneered the use of a Kalman filter and Zero Velocity Updates (ZUPTs) to estimate the step vector from step to step with a very high degree of accuracy, especially in the distance travelled [1, 5]. Critical is the correct identification of the rest phase of the foot from the IMU raw data (accelerometers and giros). During a ZUPT the integration of the inertial navigation system (INS) is reset and the Kalman filter operating in the INS error domain can estimate some of the IMU error states, significantly reducing the error build up over time.

However, practical experience has shown that the ZUPT is dependent on circumstances such as the composition of the floor material (e.g. soft carpets vs. hard surfaces), the shoes worn by the pedestrian, as well as the kind of motion (e.g. walking, running, unusual movement). Furthermore, it is difficult to verify the performance of human odometry at the macro scale where one compares the ground truth of the user’s location with perhaps 0.5 m accuracy against the algorithm output. This is compounded by the fact that the sensors are not necessarily co-located on the user’s body. To address this we propose to use an optical reference system that can provide extremely high accuracy reference information about the position and orientation of the actual sensor array.

Our measurement setup consists of eight infrared (IR) cameras and IR strobe lamps that provide a full and redundant coverage of a volume of space (room sized) within which the experiments are conducted. The user equipment (i.e. the foot mounted IMU) is tracked with the aid of a number of firmly attached small IR reflectors. The measurement computer processes the camera signals and provides highly accurate measurements of the marked user equipment in terms of its location and orientation at a rate of about 200 Hz.

## 3 Experimental Scenarios

The resulting reference data is very simple to describe and to use. It consists of time-stamped ground truth data as well as the readings from the IMU and the co-located 3 axis magnetometer. A video will accompany each data set. To provide a rich data set we will document human steps under different conditions:

1. Different floor surfaces such as firm and soft carpets and hard floors.
2. Different shoes worn by different peoples from different age groups and of different gender.
3. A variety of walking modes, such as slow and fast walking, turns, walking backwards, running, and transitions.

We believe that reference data on short segments of motion that are possible within a room are sufficient to evaluate different algorithms, because the ground truth is so accurate. In this way researchers can concentrate on how their algorithms detect individual phase of the human stride as well as the errors that occur during INS processing. For some of the data sets we will also provide evaluations of our own simple ZUPT algorithms and Kalman filter position estimates for comparison purposes.

The resulting data set and our evaluations will be available for free download.

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# Evaluation of Zero-Velocity Detectors for Foot-Mounted Inertial Navigation Systems

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## 1 Summary

An experimental study of the performance of four different zero-velocity detectors for a foot-mounted inertial sensor based pedestrian navigation system is presented. The four detectors in the study are the *(i)* acceleration moving variance detector, *(ii)* the acceleration magnitude detector, *(iii)* the angular rate energy detector, and *(iv)* a generalized likelihood ratio detector. The performance of each detector is assessed by the accuracy of the position solution provided by the navigation system employing the detector to perform zero-velocity updates. The results show that for leveled ground, forward gait, at a speed of 5 km/h, all detectors yields the same position accuracy. Moreover, the results also show that for the generalized likelihood ratio detector the threshold that yield the highest position accuracy, and the position accuracy at this threshold, is independent of the data window size of the detector.

## 2 Introduction

Pedestrian indoor navigation systems constructed around foot-mounted inertial measurement units have shown promising results; refer to e.g. [1]. These navigation systems are commonly implemented as a zero-velocity update aided inertial navigation system and use the fact that the foot on a regular base is stationary during ordinary gait to reduce the position error growth of the system. The use of zero-velocity updates requires identification of the time epochs when the inertial measurement unit is stationary. Thus, a range of detectors that from the output of the accelerometers or gyroscopes tries to detect when the inertial measurement unit is stationary have been proposed in the literature, see e.g. [2]. However, the proposed detectors are generally derived in an ad-hoc manner and the literature lacks a study on their characteristics and performance. Therefore, in [3] the zero-velocity detection problem was formalized as a hypothesis-testing problem and analyzed by applying results from statistical detection theory. It was shown that the acceleration moving variance (MV), the acceleration magnitude (MAG), and the angular rate energy (ARE) detectors are all special cases of a more general detector. Further, a novel generalized likelihood ratio test (GLRT) for the zero-velocity detection problem was proposed.

## 3 Problem Formulation

In this study, we extend the work in [3] by seeking the answer to the following two questions. First, how does the choice of detector affect the accuracy of the position solution provided by navigation system? Secondly, how does the accuracy of the position solution depend on detector parameters such as the data window size and the detection threshold?

Several parameters affect the performance of a foot-mounted zero-velocity aided inertial navigation system. Since we are interested in quantifying the contribution of the choice of zero-velocity detector and the detector parameters to the position error of the navigation system, all other system parameters are first tuned using an external reference zero-velocity detector; the reference detector is constructed around three switches mounted beneath the user's shoe. Then, given the system parameters that yield the smallest position error in the system with the external zero-velocity detector, we evaluate the performance of the system when employing the MV, MAG, ARE, and GLRT detector.

## 4 Preliminary Results and Conclusions

Table 14: Minimum empirical RMS position error for the four detectors after 80 m of levelled ground, forward gait, at a speed of 5 km/h.

| Detector | Empirical RMS Pos. Error |
|---|---|
| GLRT | 19 cm |
| ARE | 16 cm |
| MV | 23 cm |
| MAG | 22 cm |

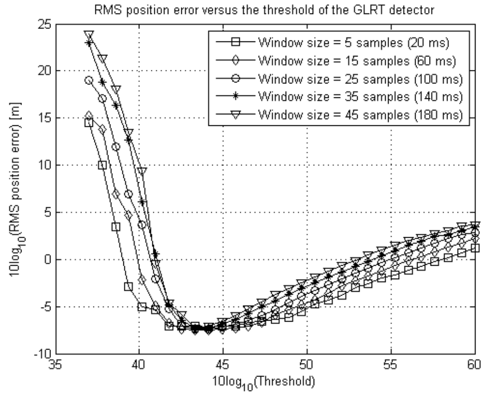


Figure 1: The accuracy of the position estimate versus the threshold of the GLRT detector.

Table 1 shows the minimum (with respect to the parameters of the detectors) empirical root mean square (RMS) position errors after 80 m of levelled ground, forward gait at a speed of 5 km/h, obtained with the considered detectors. From the numbers in Table 1, it is clear that for levelled ground, forward gait, at a speed of 5 km/h, all detectors yields approximately the same position accuracy. Fig. 1 shows the empirical RMS position error as a function of the threshold of the GLRT detector. From Fig. 1, we can read out three facts. First, the detection threshold that yields the smallest position error is independent of the window size. Second, at that threshold the performance of the detector is independent of the window size. Third, for all other thresholds the position error increases as the window size of the detector increases.

To summarize, for forward gait at a speed of 5 km/h, the results shows that all four detectors gives the same position accuracy – although they utilize different sensor information. Further, for the GLRT detector the threshold that yields the highest position accuracy, and the position accuracy at this detection threshold, is independent of the window size of the detector. The results are believed to important for robust design of detectors, because of the shown trade-off between design parameters and performance as shown in Fig 1.

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# Comparison and Evaluation of Acceleration Based Step Length Estimators for Handheld Devices

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## 1 Summary

The growing market of mobile phones equipped with accelerometers leads to new opportunities for personal navigation solutions. In this work we investigate current step length estimation algorithms regarding their performance using measurement data of handheld devices. The requirements for step length estimation with handheld devices differ from regular approaches which are usually based on known sensor poses. We compare mathematically four step length estimators and evaluate them with real data. The goal is to characterize the estimators and to determine which offers the best performance at different walking speeds and for all sensor poses.

## 2 Compared Algorithms

The chosen step length estimators range from well known mechanisations like the inverse pendulum estimator, which relies on the sensor position and mounting, to more modern estimators which are optimized for handheld devices.

Table 2: Comparison of investigated step length estimation algorithms

| Step Length Estimator | Motion-Model | Specific Characteristics |
|---|---|---|
| $S = K\sqrt{2lh - h^2}$ <br> $S = K\sqrt[4]{a_M - a_m}$ | Kneeless biped | Designed for hip mounted sensors; Defined sensor orientation needed |
| $S = 0.1\sqrt[2.7]{\frac{\sum_{i=1}^{N}\|a_i\|}{N}}\sqrt{\frac{k}{\sqrt{\Delta t \cdot a_{peak,diff}}}}$ | Empirical relationship between step frequency, mean norm of acceleration vector and step length | Sensor could be placed in trouser pocket; Rough guess of sensor orientation needed |
| $S = 0.98 \cdot \sqrt[3]{\frac{\sum_{i=1}^{N}\|a_{z,i}\|}{N}}$ | Empirical relationship between mean norm of vertical acceleration and step length | Designed for foot mounted sensors; Defined sensor orientation needed |

The estimators can be separated into two groups. One group is based on the underlying biomechanical model of the kneeless biped. This approach relies on accurate acceleration measurements and prior knowledge, e.g. length of leg. The other group is based on empirical relations between frequency, acceleration pattern and step length. Every estimator has the ability to be calibrated to the individual gait of the user by choosing an appropriate correction parameter. Depending on the estimator this affects the result in a linear or nonlinear way.

## 3 Comparison Methods

The algorithms were compared in two ways: First, a theoretical view of the error propagation and the theoretical achievable accuracy is presented. Second, the performance of the algorithms using real measurement data was evaluated. The measurements were taken from a group of six adult men and six adult women in the age of 21-32 years. Each of them walked a distance of 212 m at three different walking speeds: slow, normal and fast. We gathered measurement data at the center of mass (COM), on the feet and at the hand. Main aspects in our comparison are usability of the algorithms considering different sensor poses, their performance at all three walking speeds and robustness against misguessed correction parameters. Figure 1 shows measured accelerations of four accelerometers during four steps. While the accelerations measured at the hip still show a typical walking pattern, the signal at the hand is heavy damped and distorted due to the multistage spring-mass-dampener-system between hip and hand.

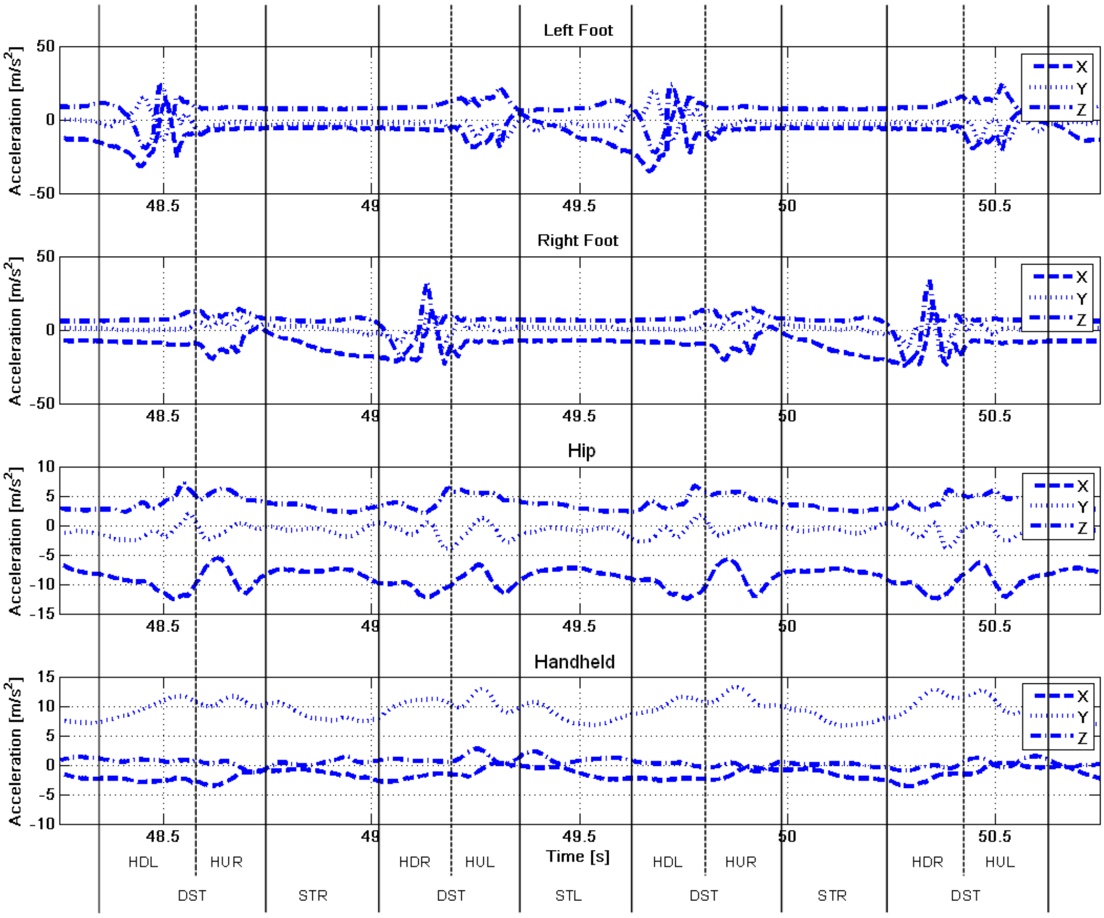


Figure 15: Measured accelerations during four steps; sensors mounted at left foot, right foot, hip and carried in hand

## 4 Conclusions and Outlook

In this article different step length estimators from current literature were compared and evaluated for the use with handheld devices. The propagation of errors and the accuracy were theoretically investigated and confronted with real measurement results. Due to the distortion of the signal at the handheld position it is necessary to use more complex biomechanical models or to exploit empirical relations between measurements and step lengths.

# An improved shoe-mounted inertial navigation system

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## 1 Summary

This paper proposes an improved shoe-mounted inertial navigation system for pedestrian tracking. The improvements consist of a fuzzy logic (FL) procedure for better foot stance phase detection and an indirect Kalman filter (IKF) for drift correction based on the typical zero-updating (ZUPT) measurement and our proposed angular updating (AUPT) pseudo-measurement. We illustrate our findings using a real time implementation of the proposed approach.

## 2 Angular Updating (AUPT) pseudo-measurement

Typically, shoe-mounted inertial navigation systems estimate and correct drift errors in position, velocity and orientation via an assisted zero-velocity updating indirect Kalman filter (IKF). The procedure consists in detecting the foot stance phase in order to build a zero-velocity-based pseudo-measurement which is delivered to the IKF to estimate drift errors [1,2]. Following this idea, and since the inertial measurement unit (IMU) is rigidly attached to the shoe in a known space configuration (see [1]), we propose to built an attitude pseudo-measurement at the foot stance phase. In what follows the symbols used are consistent with those of [1]. Thus, let suppose that the attitude's pseudo-measurement model may be written as

$$y_\Theta = \Theta + n_\Theta \quad (1)$$

where $\Theta = [\phi \quad \theta \quad \psi]^T$ is the vector containing the true IMU's roll $\phi$, pitch $\theta$ and yaw $\psi$ and $n_\Theta \sim N(0, Q_\Theta)$ with $Q_\Theta = diag(\sigma_\phi^2, \sigma_\theta^2, \sigma_\psi^2)$. Since in this paper the attitude is represented as a unit quaternion we must establish a quaternion pseudo-measurement instead. Hence, using eq. (1) and the equations relating $\Theta$ to unit quaternions i.e. non-linear equations of the form $\overline{q} = f(\Theta)$, we can write after a Taylor series expansion and some algebraic manipulations the quaternion pseudo-measurement $y_q$ as

$$y_q = L(\hat{\overline{q}})\delta\overline{q} + J(\Theta)n_\Theta \quad (2)$$

where $\hat{\overline{q}}$ is the IMU's attitude computed by the strapdown inertial computer, $\delta\overline{q}$ is the error quaternion, $J(\Theta)$ is the Jacobian $\partial f / \partial\Theta$ and $L(\cdot)$ is an operator letting to express a quaternion product into a matrix product. Finally, using the error quaternion definition $\delta\overline{q} = L(\hat{\overline{q}})^{-1}\overline{q}$ and $\delta\overline{q} \approx [1 \quad \delta q]^T$, where $\overline{q}$ is the true IMU's attitude, we may write the IKF AUPT measurement model as

$$z_{\delta q} = \delta q + w_\Theta \quad (3) \quad \text{where } w_\Theta \sim N(0, R_{\delta q})$$

with $R_{\delta q} = H_q L(\hat{\bar{q}})^{-1} J(\Theta) Q_\Theta J(\Theta)^T L(\hat{\bar{q}})^{-T} H_q^T$ and $H_q = [0 \quad I_{3x3}]$. In practice, we can use a consistent estimate of $\Theta$ computed from the IMU's acceleration measurements at the foot stance phase during the initialization procedure. This allows us to compute roll and pitch only. Yaw may be considered to be that one computed by the strapdown inertial computer.

## 3 Fuzzy logic (FL) step detector

As stated in pedestrian navigation literature the accurate detection of the walking motion's stance phase is crucial since it indicates the IKF the right time to apply ZUPTs and AUPTs to estimate and correct drift errors. Therefore, in order to detect the stance phase we propose to use a fuzzy logic-based procedure whose membership function is defined as $\mu_a = 1 - \min(|y_a|/s_a, 1)$, where $|y_a|$ ($|y_g|$) represents the vector norm for the IMU's acceleration (rotation speed) measurement and $s_a$ ($s_g$) is the associated stance phase threshold. To account for both grades of membership ($\mu_a$ and $\mu_g$) we take $\mu_s = \min(\mu_a, \mu_g)$, and finally we decide if $\mu_s \le s_s$, where $s_s$ is the stance threshold, that the foot is moving. See figure 1.

## 4 Experimental results and comments

A real time application of the shoe-mounted inertial navigation system was developed in C++. It consists of a strapdow inertial computer, the FL step detector and an assisted AUPT - ZUPT Indirect Kalman filter. Several experiments were carried out; two of them are shown in figures 2 and 3 for two different walking scenarios composed of straight line walks, turns and down stairs. The system exhibits an improved accuracy for short term navigation using the IMU's acceleration and rotation speed only. Moreover, the system can be further improved using additional sensors and/or using maps.

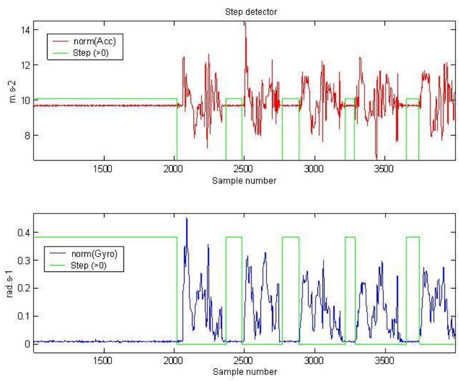


Figure 1: Step detector

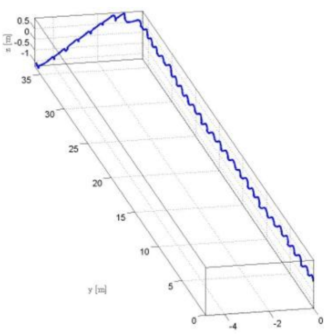

Figure 2: Scenario 1

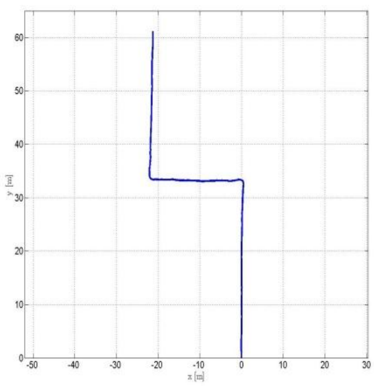

Figure 3: Scenario 2

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# Context-Adaptive Algorithms to Improve Indoor Positioning with Inertial Sensors

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## 1 Summary

Body-mounted inertial systems for indoor positioning and pedestrian guidance have some major advantages against other technologies. They do not require any preinstalled facilities, i.e. they can run completely autonomous and all the necessary components are standard equipment of a modern smart phone. The quick availability and autonomy is a special advantage in fields of application such as first responders and military, while the integration of all system components in an everyday life gadget makes it especially attractive for the consumer market. But in both cases there is a severe problem to solve: The positioning accuracy is very weak, if only a simple double integration of the accelerations is performed. In the following two context-adaptive algorithms to improve indoor positioning with inertial sensors are presented and the achieved results are discussed. The first algorithm enhances the detection of zero-velocity updates; the other method improves positioning by map matching.

## 2 Introduction

The Institute for Building Informatics at Graz University of Technology concentrates its research efforts on answering safety questions in case of extraordinary situations, mainly on the management of disasters in urban environments. The framework project CADMS (Computer Aided Disaster Management System) covers several research projects; the most ambitious being the IPS (Indoor Positioning System) project. The developed application allows for the self-contained positioning of rescue teams within buildings and underground structures, as well as their tracking by a command centre. Some components of the system have also been implemented on smart phones to be used for pedestrian navigation.

Various inertial sensor systems have been tested. It has been shown by these tests that during a longer period of tracking the accuracy is unsatisfactory due to various reasons (disturbed terrestrial magnetic field, drift, noise, etc). It is necessary to correct the deviances from the true position either constantly or periodically. Bearing this in mind, a couple of new context-sensitive algorithms have been designed to recognise the movement patterns and to improve the positioning by an automatic interaction of the inertial sensor with a building model.

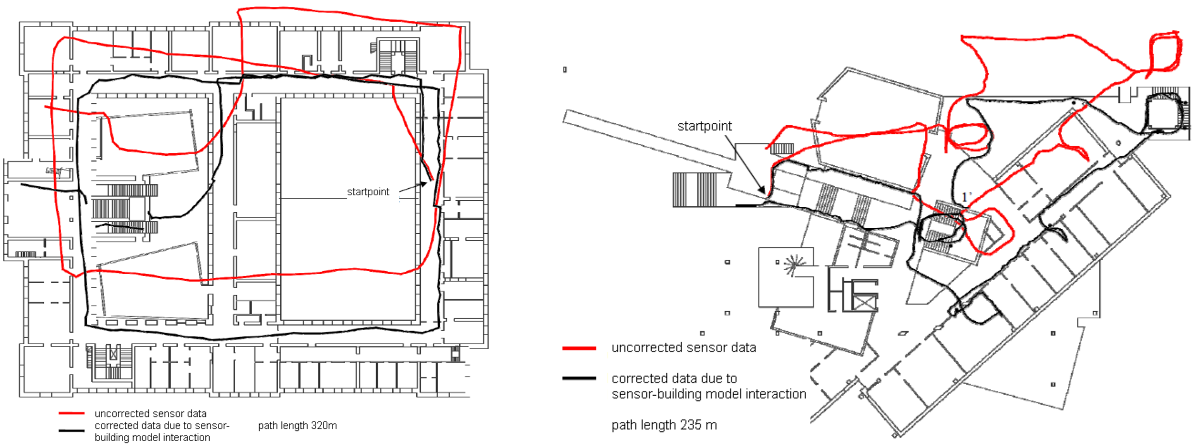
## 3 Enhanced zero-velocity updates

As it is well known, the best, drift-free results are achieved when the integration period for the accelerations and velocities is short (1 – 3 seconds) and the velocity regularly becomes zero to allow for a periodic velocity reset. One can achieve these short breaks e.g. when the sensor is mounted on the user's foot. During the foot strike, the speed should be close to zero for a short time. It is very important to detect this certain moment, but it is difficult, because it is dependent on the movement type of the person, its velocity, the type of the ground, the measuring accuracy and where the sensor is mounted. Time (between zero velocity updates, ZUPT) and velocity dependent algorithms have been developed for foot mounted sensors, as well as for body mounted systems where ZUPTs are replaced by a drift control. They will be presented in detail in the full paper and during the conference.

## 4 Sensor – Building Model Interaction

Though the improvement of the position calculation by better integration algorithms is considerable it can't compensate systematic errors, like deviations of the terrestrial magnetic field, e.g. by electrical installations or steel structures.

For this reason a newly developed building map-sensor interaction has been implemented. This core element of the IPS continually analyses the plausibility of the position provided by the sensor algorithms by exploiting the information of the building model. Depending on the deviation of the derived position, the location presented to the user is adapted and shifted towards the most likely position. Typical types of inaccuracy include the pedestrian's route intersecting a wall or the missing of doors and stair cases. The corrections have to take into account the current local situation within the building (Fig. 1).




*Results obtained with the context adaptive position correction*

The algorithms have been evaluated intensively. Test runs with an overall travelled distance of more than 6 km have been carried out. This involved buildings with various construction styles and occupancies, numerous test persons and different test equipment and ways of moving (walking, running, crawling, ascending stairs, etc.). The statistical evaluation yields an accuracy of 1 – 2 metres for over 95 % of the covered path inside the buildings. This complies with the demands for indoor navigation in the field of application for first responders.

## 5 Conclusions and Outlook

The development of CADMS has been supported by civil first responder organisations, the Swiss and Austrian Armies and well-known companies from the security industry. The practical implementation in some of these organisations is planned at the end of 2010. Meanwhile research is going on, especially in the field of user interfaces for such a system and in the wireless networking of a greater number of systems during the deployment.

# Dual IMU Indoor Navigation with Particle Filter based Map-Matching on a Smartphone

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## 1 Summary

In this paper an Indoor Navigation System with map-matching capabilities in real-time on a smart phone is presented. The basis of the system is an in-house developed Integrated Pedestrian Navigation System, based on 2 low-cost IMUs, an electronic compass and an altimeter with a slightly drifting navigation solution. Combining this system with an additional laser ranger and SLAM algorithms, we are able to build accurate maps from office buildings for already visited rooms in post processing.

This paper presents a map matching algorithm based on a new reduced particle filter in order to use these maps later for real-time applications without an expensive laser ranger but relying only on the dual inertial system.. It can be used with both, pre-processed SLAM maps or with already available maps. Finally to smooth the resulting trajectory after particle filtering we propose the use of a new “balanced bubble band smoother” allowing the trajectory to optimally match to both, map and recorded IMU data. This new approach makes it possible to do map matching online on a smart phone.

## 2 Motivation

Localization and navigation in indoor environments is a core issue for fire fighters, police task forces and first responders but also for the blind. In general it is necessary to provide navigation without any knowledge of the building when the emergency responders get in; knowledge of the building is often not available. But if a building plan is available, it is helpful to make use of the building information. Also a map that is created with laser or vision sensors and provided via internet could be used from another user in the same scenario. In any of the applications, aiding with maps would be desirable where available. In combination with an inertial based pedestrian navigation system, this will increase localization performance, navigation robustness and long-term stability. To make this system operable for mobile operators, it should be running on a small hand held device.

## 3 Dual IMU System

The sensor basis for the approach is an in-house developed Dual IMU System, which takes advantage of Zero Velocity Updates from the foot mounted IMU and records the dynamics from a second, torso mounted IMU, normally combined with a laser or a camera sensor. Due to the Dual IMU concept, a tight coupled data fusion is possible. This allows constructing building maps based on laser sensor data and determined by SLAM algorithms. During the application the laser or vision aiding sensors may temporarily not be available. We nevertheless we require the calculated position is within the previously estimated map without using vision or laser sensors but based on inertial sensors only.

## 4 Map matching on a Smart Phone

Processing the building information to solve the multi-modal problem of map-matching requires high computational effort. Therefore, particle filters are used that on the other hand cause high computational burden due to a drifting navigation solution. However, a portable system on a smart phone has not enough computational power to solve the problem with standard map matching algorithms based on particle filters.

## 5 Particle filter & Balanced Bubble Band Smoother

Therefore we propose a simplified map-matching particle filter which is running on a Linux based phone using the compass aided navigation solution of the dual IMU system. With our approach, it is possible to match the slightly drifting Dual IMU based solution to a known map. On the left side of Figure 1, three clusters of particles represent 3 possible areas where the user can be after having walked about 15 meters. After continuing on a unique path, the position algorithm will converge and the actual position of the user can be estimated without knowledge of his starting point, see Figure 1.

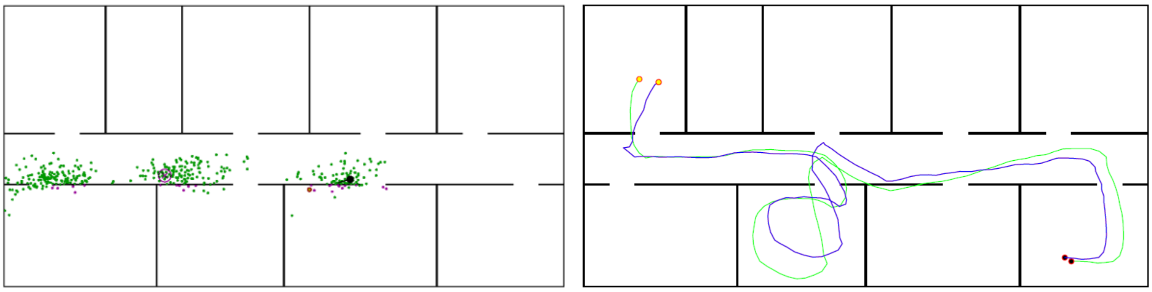

Figure 1: *Left: Position p*robability distribution after 15 m walk. *Right: Inertial drifting solution* (green) and the PF result (blue). The starting point also was found automatically.

This provides a long-term stable drift-less estimation of the walked path, which can be calculated and shown on the smart phone display. In addition, it can also be used for guidance. Figure 2 shows results in detail from a particle filter solution with artefacts from the nonlinear filtering. For further smoothing of this result, we propose the use of a new "balanced bubble band algorithm" which uses the smoothing force of a bubble band but also holds the "balance" with the IMU solution to optimal match both, map and IMU data without contracting loops as visualized in a more difficult scenario in Figure 2:

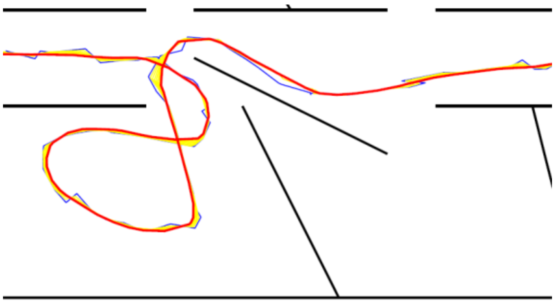

Figure 2: More difficult scenario. Particle filter results with many artefacts in detail after processing (blue) and "balanced bubble band smoothing": see iterations (yellow) and the final balanced solution (red). The bubble band does not contract the loop due to the balance with estimated inertial IMU trajectory

## 6 Conclusions and Outlook

This paper shows that a standard particle filter based map-matching algorithm can be adapted and simplified in order to be applicable on a smart phone. Online calculated results prove the efficiency of our approach. In the future we want to extend this approach for multi-floor building plans, which requires handling staircase walks.

# Design choices, filter parameter tuning, and calibration of zero-velocity update aided inertial navigation systems for pedestrian navigation

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## 1 Summary

Inertial navigation systems (INSs) placed on the foot of the carrier together with a zero-velocity detector providing so-called zero-velocity-updates (ZUPTs) is a promising technique for infrastructure free, pedestrian indoor navigation. The ZUPTs aid the INS to limit its error growth; without the ZUPTs the errors growth is such that the system becomes useless after only a few seconds. When implementing the ZUPT-aided INS numerous design choices have to be made and multiple parameters tuned. This together with the high dynamic and frequency component ranges of the motion of the foot makes the system hard to optimize.

In this study, we look at what design choices and tuning parameters of a ZUPT-aided INS there are. A heuristic approach to handling the large number of design choices and parameters is suggested. Based on analysis and experimental data we argue how the design choice should be made and the parameters set. The parameter settings are in clear contrast to many of the one found in the literature. Correct settings are shown to give a significant performance gain.

## 2 Introduction

A popular sensor type for indoor pedestrian navigation is micro-electro-mechanical system (MEMS) inertial measurement units (IMUs), which together with navigation equations make up an INS. Unfortunately, due to its integrative nature, a standalone INS based on a MEMS IMU can only be used during a few seconds before the position errors is in the order of several meters. Hence, additional information about the systems motion is needed to limit the error growth of the INS. Such additional information can be acquired from additional sensors or from models of the motion and the environment. Building an accurate and general model for the full motion of a person on foot is difficult. However, placing the IMU on the foot let us use a simple but general model of the motion; the foot is either stationary or in motion. Various detectors working on the inertial measurements can then be used to determine when the system is stationary. Via standard techniques of aided INS, these ZUPTs together with an extended Kalman filter (EKF) can be used to estimate the errors in the navigation solution of the INS. The estimated errors are then used to correct the navigation solution of the INS and limit the error growth rate of the system. A large number of recent publications of such systems exist in the literature; refer to e.g. [1] [2].

In the construction of a ZUPT-aided INS there are many design choices to be made and parameters to tune. Changing between design choices is typically too laborious and the parameters are too many for it to be feasible to make a global search for the optimal design choice and parameter values. Moreover, the optimal design choice and parameter values will depend on the conditions under which the system is intended to work.

## 3 Contribution

In this paper, we look at what the design choices and tuning parameters of a ZUPT-aided INS are and suggest a way of dividing them into subsets. We then look closer at two out of three subsets, namely (1) *the design choices connected to hardware setup*, e.g., sensor placement and sensor specifications and (2) *the design choices and calibration parameters connected to the EKF*, e.g., what errors to estimate, how to model the ZUPT, and filter noise parameters. Hardware design choices are made and motivated, and carried over to a ZUPT-aided INS implementation. Cost functions are constructed and used in the tuning process of the system. Remaining design choices are analyzed and set. This and the tuning are done with the support of a large number of independent data sets recorded under specified conditions. To facilitate the construction of a marginal cost function of the filter parameters an independent zero-velocity detector based on pressure sensors is constructed and described. Finally, statistical performance figures of the tuned system are given. The third subset of the suggested division, the design choices and parameters of the detector, is studied in a companion paper.

## 4 Preliminary results

A marginal cost function for the first subset of parameters can be constructed based on measures on the raw data in time and frequency domain. Experimental data show that the needed dynamic range of the IMU is higher than that of many standard units on the market and that the preferable placement of the sensor is below the foot. Analysis of the second parameter set show that, in contrast to many publications and systems featuring aided INS, accelerometer biases should not be modeled. Tuning with experimental data, together with the pressure sensor zero-velocity detector, show that the accelerometer process noise should have a standard deviation of 0.1-1m/s$^2$ and that the gyroscope process noise should have a standard deviation of 0.1-0.01°/s. Finally, calibration results show that the tuned system has a mean-square position error of 0.1-1% of the travelled distance depending on operational conditions. This can be put in relation to reported errors of 0.3-15% in the literature [1].

## 5 Conclusion

The optimizations of a ZUPT-aided INS system for pedestrian navigation can be handled approximately by heuristically dividing the parameters into three subsets and then optimizing the performance with respect to one parameter set at the time. The performance gain of carful design choices and parameter settings is substantial and a systematic treatment of them is advisable.

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Pedestrian Indoor Navigation by aiding a Foot-mounted IMU with RFID Signal Strength Measurements

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## 1 Summary

We present a method to accurately locate persons indoors using an Inertial Navigation System (INS) with a foot-mounted IMU, aided by the Received Signal Strenght (RSS) of some active RFID tags. Other authors [Renaudin2007, Zhang2008] have already integrated IMUs with RFID tags in "loose" Kalman Filter (KF)-based solutions. They feed the KF with the residuals between inertial- and RFID-calculated positions; no Zero Velocity Updates (ZUPT) are employed. In this paper, we present a "tight" KF-based [Retscher2007] INS/RFID integration method using the residual between the INS-predicted range to tag, and the range derived from a generic RSS model. Our approach also includes ZUPTs at detected foot stances, and heading drift reduction using magnetometers. A 15-element error state Extended KF [Foxlin2005, Jiménez 2010] compensates positioning, velocity and attitude errors of the INS solution, as well as IMU biases. This methodology is valid for any kind of motion (lateral/backwards walk, running), and does not require a specific off-line calibration, nor for the user gait, neither for the location-dependent RSS fading in the building.

## 2 The Integrated INS+ZUPT+RFID Pedestrian Localization Methodology

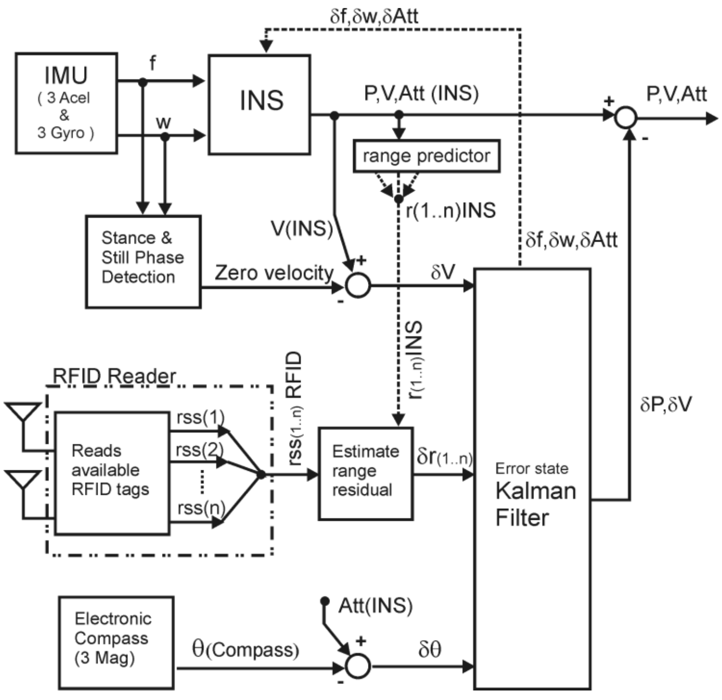


Figure 1: RFID/ZUPT/Compass-aided INS for pedestrian position estimation.

The implemented RFID-aided INS indoor pedestrian navigator is depicted in figure 1. It uses a classical INS mechanization that is corrected by an EKF, which has as observations: 1) zero velocity updates (δV) [Foxlin2005], 2) range residuals estimated from RFID-received signal strength (δr), and 3) Heading corrections from other components such as magnetometers (δθ) [Jimenez 2010]. The range residuals, essential to aid the INS, are estimated with a non-linear function of the received signal strengths, $rss_{(1..n)RFID}$, and the INS-predicted range, $r_{(1..n)INS}$. The methodology estimates and feeds back the IMU biases and heading errors, to accurately calculate the person's position even with few RFID tags.

## 3 Indoor Tests

Estimated positions, with and without RFID aiding, are plotted in figure 2. Several tags are placed in the building, some at strategic positions such as doorways in order to maximize the signal strength (RSS), and consequently the ranging certainty. Typical positioning accuracies are about 2 m from the true trajectory, and the step-by-step estimation is 5 cm accurate.

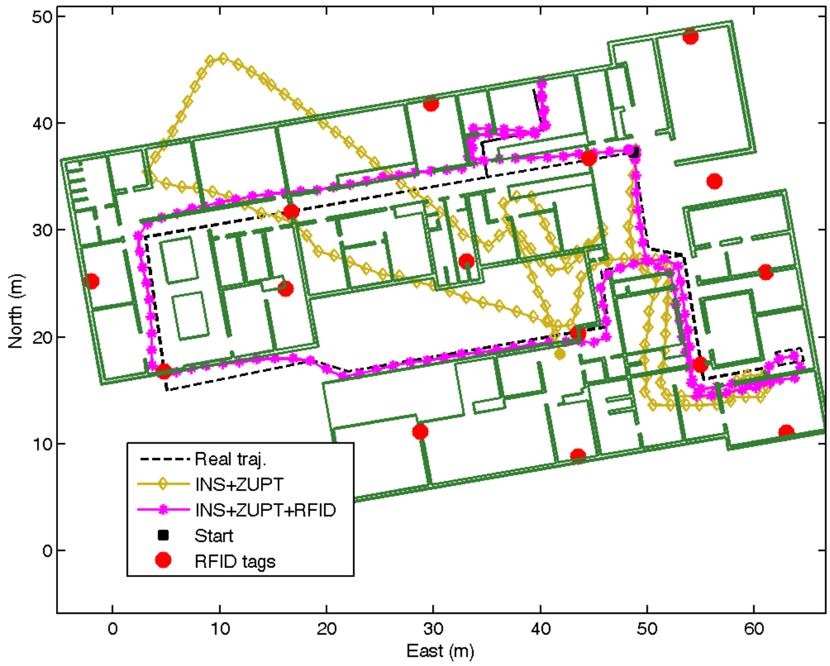


Figure 2: Indoor positioning test with a total path length of 200 meters. A person is walking at normal pace in CW direction along the main corridor. Diamonds and asterisks mark detected foot stances.

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# On the use of foot-mounted INS, UWB-ranging and opportunistic cooperation in high-accuracy indoor positioning systems

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## 1 Summary

In order to achieve an accurate, robust indoor localization system it is anticipated that a multi-sensor system approach is required. High-sensitivity GPS (HSGPS) receivers, inertial sensors, and local radio-based ranging are natural choices. These sensors may need to be complemented with e.g. barometric altimeters, magnetometers ultra-sonic sensors or soft information such as (full or partial) building floor-plans. In this paper we focus on examining the performance of a sub-set of the full system, namely foot-mounted inertial measurement units (IMUs) in combination with ultra-wideband impulse-radio (IR-UWB) ranging between cooperating soldiers. Experimental data is collected with two persons moving inside a building, where each individual is equipped with foot-mounted IMUs and UWB-ranging devices. In conjunction to ranging, the UWB-units are used to convey position and error estimates, which are used to improve the position accuracy. The increased accuracy obtained through cooperation will be evaluated for different movement scenarios.

## 2 Introduction

An accurate, reliable indoor positioning system can significantly increase the safety of military personnel and first responders. A soldier and first responder positioning system should be light-weight, small, inexpensive and power efficient, and still provide metre-level accuracy during extended indoor operations. The main technical challenge lies in creating a system that yields metre-level accuracies in GPS-denied environments.

In order to achieve an accurate, robust indoor localization system it is anticipated that a multi-sensor system approach is required. High sensitivity GPS (HSGPS) receivers, inertial sensors, and local radio-based ranging are natural choices. These sensors may need to be complemented with barometric altimeters, magnetometers and possibly also ultra-sonic sensors. Furthermore, imaging sensors may increase localization accuracy in indoor scenarios, as well as providing an estimate of the building layout to the command and control system [1]. Finally, if up-to-date accurate building floor-plans, or even just partial map-information, are available the positioning accuracy can be significantly improved.

In this paper we focus on examining the performance of foot-mounted inertial measurement units (IMUs) in combination with ultra-wideband impulse-radio (IR-UWB) ranging between cooperating soldiers. Through inter-nodal ranging and transfer of position estimates and error covariances, as shown in Figure 1, it is possible to significantly improve the positioning accuracy.

## 3 Scope

We are currently performing measurements on the performance of the cooperative positioning approach examined in [2]. In that work, the potential benefits of cooperation was clearly shown, as illustrated in Figure 3. Two units are equipped with foot-mounted

MicroStrain 3DM-GX3 IMUs, and UWB-ranging is performed with the TimeDomain PulsOn 220. We will show the performance of the foot-mounted inertial navigation utilizing ZUPT and statistical stance-phase detection algorithms. However, the main focus of the paper is on evaluating the effects of introducing opportunistic cooperation under different scenarios.

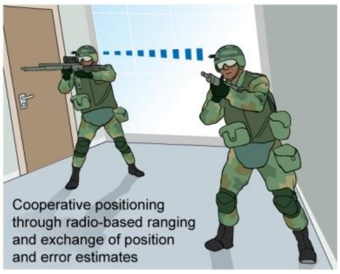


Figure 1: Illustration of opportunistic cooperative positioning between units equipped with locally-worn positioning sensors.


Figure 2: Illustration of cooperative positioning as an integral part of a soldier positioning system. Radio-based ranging is combined with transfer of position and error estimates, between units moving inside building as well as out to vehicle-mounted transceivers outside.

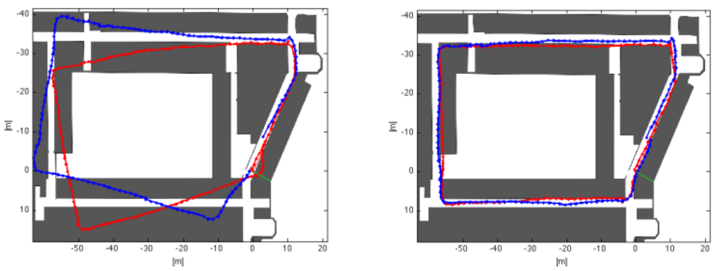

Figure 3: Left: Foot-mounted INS with ZUPT but without use of cooperative navigation. Heading errors are affecting the position solution. Right: Cooperative navigation is able to improve the end result as well as the whole trajectory significantly.

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**Frameworks for Hybrid Positioning**

Auditorium G3

Thursday, September 16, 13:15 – 15:00

# Tracking Framework for Heterogeneous Sensor Sources

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## 1 Summary

We describe a scale-independent (space and time) tracking framework for moving items (objects, animals, humans). Different sizes and characteristics of the items are considered as well as different tracking environments / contexts. This work enables the integration and processing of spatial temporal data obtained by heterogeneous sensor sources. The framework does not rely upon one tracking / positioning technology but instead considers the combination of several technologies to calculate the best positioning result. The data is processed in a core and provided by different internal and external interfaces. The framework consists of different applications. One application is used for visualization of the context and tracked items. Other applications analyze large amounts of data e.g. via machine learning techniques. Two different use cases (laboratory mice / service technicians) were used to develop the framework.

## 2 Introduction

Tracking and localization technologies are used to gather spatial temporal data of moving items to obtain information about behavior or to support them with location-based information. Problem: Tracked items and/or their environments are equipped with sensors to get spatial temporal data. Depending upon the tracked items, tracking environments and the project in question, many different technologies may be in use simultaneously. This leads to a variety of sensors and spatial temporal data without a standardized format, processing or analysis.
Motivation: To enable the integration and combination of heterogeneous tracking data so that a useful synthesis of the information involved can be obtained. Prototypical industrial applications include assisting in work flows and providing information. Furthermore, this work enables interdisciplinary scientific tools for the support of experimental scientists by allowing them to collect and process large quantities of moving item data.
Background: The idea is based on the tracking of laboratory mice [6] (1st use case) via RFID-technology, weight scale and camera. The aim is to find movement and behavior patterns. In the second use case, service technicians are tracked indoor in an industrial environment via RFID, UWB (Ubisense[2]), WiFi fingerprints and keystroke sensors to support them in their maintenance work.

## 3 Related Work

Many applications focus on tracking and localization [3]: AAMPL [7] or Redpin [2] combine different technologies in mobile devices to get precise locations. Opportunistic localization using smart phones with WiFi, GSM, GPS and accelerometers has been developed [8]. The StarTrack framework provides a set of operations to ease the development and deployment of track-based applications [1]. The EnTracked system is based on estimation and prediction of system conditions and mobility to minimize energy consumption and optimize robustness [5]. The location stack is a 6-layer design framework that establishes clearly defined abstractions, building from data to context aware computing [4]. Problems of scalability to large environments and uncertainty due to environmental symmetry have also been considered [9].

[2] Ubisense homepage latest update 2010-06-02: http://www.ubisense.net/en

## 4 Implementation

The concept behind the framework is divided into 4 parts, 3 of them are already implemented: Architecture of the tracking framework: The architecture of the framework consists of four different levels: sensor sources, databases, a processing core and various applications. The framework and its modules have different well-defined internal and external interfaces for the import and export of data. This architecture allows for the integration of different applications.
Modeling of the environment: It is possible to display 3D models of the environment with integrated sensors as one application. The required attributes for a scale invariant 3D modeling of sensors have been taken into consideration. They are used for the extension of a scene graph model with sensor nodes (VRML and Java 3D) and to provide context information. The software allows for the positioning of sensors integrated in the environment to be changed, added or deleted by users. A tracking component allows the display of moving items in the environment.
Sensor fusion: Different levels of instrumentation of the environment and of the tracked items are taken into consideration. The modeling of heterogeneous data sources is necessary, as well as a standardized data model for the gathered data. This enables the framework to integrate various data sources (in this work RFID, UWB (Ubisense), WiFi fingerprinting and keystroke sensors are in use) into the application. The generalized data model determines which data is gathered and stored for positioning and tracking. The data model is easily extensible for more sensor sources. A database schema for the storage of the data has been designed as well as a schema for metadata of tracking technologies. Information about tracked objects can be obtained, and a format has been defined in which data are delivered for further analysis.

## 5 Conclusions and Outlook

This abstract proposes a tracking framework for moving items based upon heterogeneous data sources. A modular architecture and well defined interfaces make it possible to integrate different applications. In the future, different analysis modules will be established to obtain information: Machine learning will classify patterns without domain knowledge. An expert can add meaning to the patterns and they can be verified in the data. Similarity matching of attribute-labeled related graphs can be used to find predefined patterns (template graphs) in collected data (data graph). Template graphs (designed by a domain expert) can be used to define certain patterns. The aims are to find patterns in movement and behavior, classify observed items and to learn about individual items for the prediction of future behavior.

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# A Fusion Component for location management in mobile devices

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## 1. Summary and objetives

When indoors, several positioning technologies and systems may coexist (e.g. WiFi, Bluetooth, ZigBee, HF-RFID or bidi codes serving as beacons, cellular networks, etc.); each of them delivering its location estimates with a given accuracy at a given computational cost. In this paper, we describe a Mobile Fusion Component (MFC) -prepared to run in a mobile device- which aims at optimizing the selection of the available positioning systems by handling Quality-of-Location (QoL). The objective of the MFC is to offer the (best) location estimation which fulfills the consumer applications' QoL needs, at the same time that minimizes resource consumption in the mobile device. Additionally, the MFC will provide seamless hand-off among location technologies and allow the user to establish his own privacy level for location data sharing. The MFC is part of a service-oriented mobile framework which offers 'Context Acquisition Services anD Reasoning Algorithms' (*CASanDRA Mobile*) to accelerate the development of context-aware applications.

## 2. A fusion algorithm for the MFC

The fusion algorithm for the MFC handles a Quality-of-Location [1] tuple which gathers information about the accuracy, availability and freshness of the location estimation provided by the available localization systems. 'Accuracy' refers to the mean error in the location estimate; 'availability' includes data from the electromagnetic visibility of relevant components of the localization infrastructure (e.g. number of available access points); finally, 'freshness' gathers the age of the estimate.

The MFC is dynamically configured to adjust its output to the consumer application's requirements in terms of QoL. It compares the available location estimates from different sources, provides the application with the estimate that better fits its needs, and initiates or stops sensors to optimize resource consumption. The QoL tuple is provided by the available location systems, together with the location estimate. When different technologies are available, the MFC prioritizes those offering better accuracy whenever the 'availability' in terms of visible infrastructure is enough and the estimation is recent enough ('freshness') to fulfill the application's needs.

In order to prototype our MFC, we consider that GPS and Cell-ID positioning are available when outdoors, and the latter also when indoors. Additionally, in closed environments (such as our laboratory), we assume that a deployment of WiFi and Bluetooth access points may be used to locate a mobile device [2] [3]. Moreover, some HF RFID tags will be situated in waypoints to be read from a mobile device. Each of these location systems may offer a given QoL, being the RFID method the most accurate (cms) but offering non-continuous location (event-based) (the full paper will describe the information flow to make the estimator's choice). Another important issue to consider for the MFC is how to handle hand-offs between localization systems, always guaranteeing seamless transfer and resource consumption optimization. The 'availability' information in the QoL parameter is used to start additional sensors and to adjust periodic wake-up of slept sensors.

## 3. The Fusion Component as part of CASanDRA Mobile architecture.

The Mobile Fusion Component has been designed to work in the architecture of CASanDRA Mobile (Fig.1) [4], to be offered as a standard feature for the framework. In brief, CASanDRA Mobile is composed by three building blocks - Acquisition Layer, Context Inference Layer and Core System. To implement the MFC, the Acquisition Layer needs to contain five sensors gathering data from communication interfaces (WiFi, Bluetooth, RFID, cellular networks and GPS), while the Context-Inference Layer will host six enablers which process raw data from sensors (localization algorithms). The Fusion Component's intelligence is bundled in the Location Fusion Enabler (LFE). Additionally, the Core System will provide standard features for development, such as discovery and registry management of new elements. Both 'sensors' and 'enablers' publish their output data in the middleware through an event manager. Applications run on top of CASanDRA Mobile middleware.

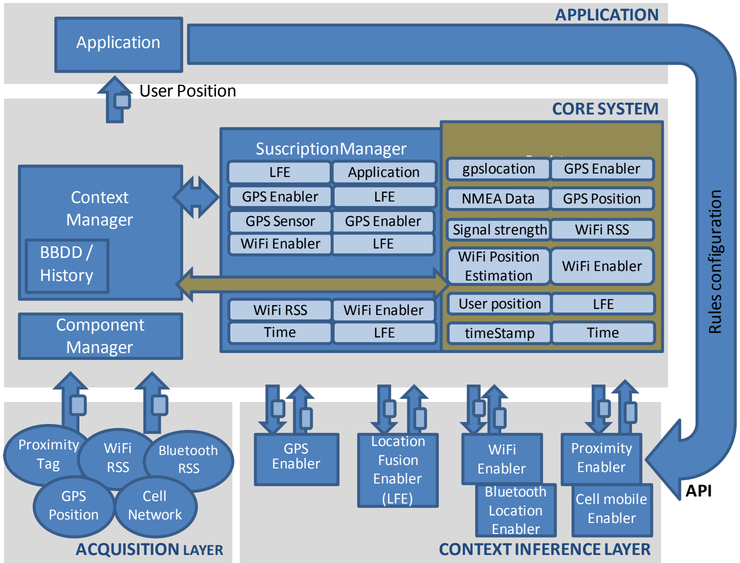


Figure 1. CASanDRA Mobile Middleware prototype is implemented on Windows Mobile 6.1 OS. The middleware is based on the Equinox OSGi platform.

## 4. Full paper contents

The full paper will go depth in the QoL concept, explaining the relevance of all its elements from the state-of-the-art. The fusion algorithm will be exemplified with cases of use, and the scalability feature will be clearly demonstrated. The performance of the component will be evaluated in terms of energy and memory consumption. Moreover, the full paper will include a detailed description of the MFC in CASanDRA Mobile.

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# Detecting Visibility in Heterogeneous Simulated Environments for Positioning Purposes

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## Introduction

In previous research, we elaborated positioning systems based on heterogeneous data, such as GNSS and Wi-Fi, in order to calculate a 3D geographical position of mobile equipments. The results were quite interesting and encouraged us to study a more automatic positioning system with a transparent migration between different environments and equipments, without implementing any additional infrastructure. The aim of the paper is to describe the simulation system through the following steps:

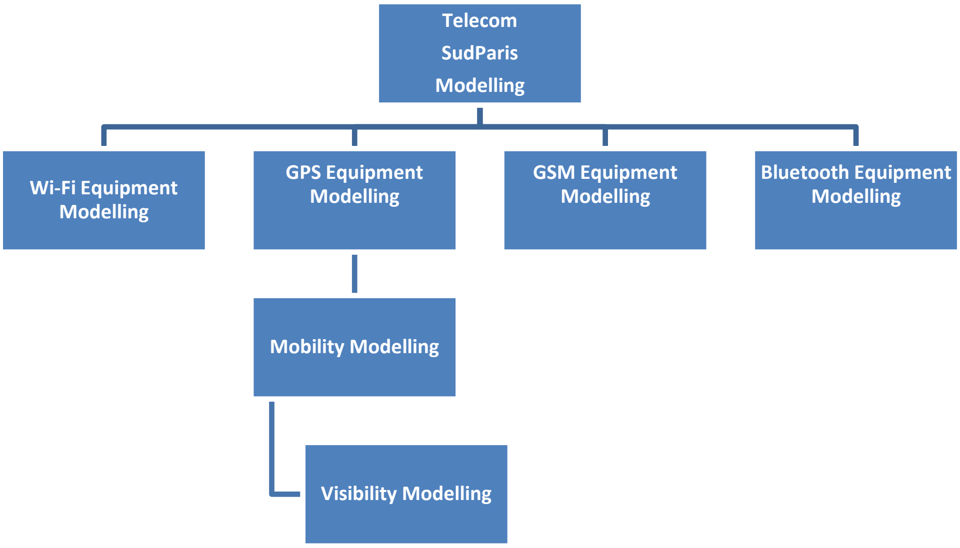
- Simulating a 3D environment with equipments using different technologies of mobile communication.
- Elaborating mobility models towards these environments with a transparent transition between indoors and outdoors.
- Developing and studying the concept of visibility of the equipments using different mathematical and physical methods.
- Applying the previous steps towards a global positioning model taking advantage of telecommunication networks.

## Approaches and methods

The term “visibility” means “detection of equipments for a given technology” in our approaches. The visibility is thus defined by different types of methods. For instance, the visibility of two equipments is achieved

- if they are in radio range. The coverage area could differ, according to the real environment.
- if the distance between them is lower than a given distance. This distance is calculated using the Friis Formula, depending on the environment.
- if the signal strength received is inferior to a predetermined threshold.
- by studying the time of signal arrival.
- if the number of hops between them is inferior to a threshold.

Today, equipments include multiple sensors, enabling them connections to different kinds of networks (the IPhone is a typical example). Our approach aims at evaluating the possibility to use these multiple data for positioning purposes. The proposed system was simulated with “Matlab”. The paper also gives details on the 3D description of our building and its environment. Then, we developed simulating modules for the different technologies: GPS, Wi-Fi, GSM and Bluetooth. These modules simulate the interactions between networks. The figure below presents the organization chart of the system.




In addition, we implemented different types of mobility models. Several 3D trajectories were designed in order to provide possible realistic situations of mobility. Three of them are described in the paper, using three mobility models: Gaussian, Sinusoidal and Parabolic. Note that the most common model is the Gaussian mobility one. However, it does not take into consideration the 3D changes. For our purposes, we thus elaborated an enhanced 3D Gaussian Mobility Model, fully described in the paper. This step also requires the preparation of different possible paths within buildings and the outdoor environment, simulating user mobility.

Then, we studied the detection of equipments along the paths previously described. Mobile terminals wishing to estimate their positions must then establish a "visibility data collection". This collection is in the form of a database including all the equipments "seen" by the mobile terminal, as well as their attributes. The collection of the data is carried out for all the equipments. The final database is composed by all these data. This step is needed in order to establish a 3D representation of the geographic relations between equipments.

### Results and future works

Simulation results are provided showing the impact of both the visibility pattern and the mobility model chosen on the global connectivity of a mobile terminal. This connectivity will be the foundation of the next step of the complete positioning model under development. Our future works are thus oriented towards the design of this second step of an automatic system, consisting in carrying out positioning algorithms and computations. Note that experimental data are also provided in order to discuss the validity of the various models (visibility and mobility).

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# Indoor Navigation Integration Platform for Firefighting Purposes

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## 1 Summary

In Germany about eighteen fire fighters loose their lives and more than 16.000 accidents happen on duty every year. One of the main problems is the orientation inside of complex buildings during operations especially if rooms are full of smoke. Route cards (printed on paper) to find fire detectors in buildings, are means, which often do not meet all requirements with regard to orientation and up-to-datedness. The aim of the presented research project "Context Sensitive Indoor-Emergency-Navigation-System for Complex Buildings" is to develop a solution for response and recovery to support rescuers in finding the shortest way within a complex building. Existing Building Information Models (BIM) are exported and used for displaying plans on mobile devices and for routing purposes. The Indoor Navigation is based on Wireless LAN, Ultra-Wide-Band and Radio Frequency Identification (RFID).

## 2 Introduction

Within the presented research project – which is funded by the German Federal Ministry of Transport, Building and Urban Affairs – a system using mobile devices and Real-Time Location Systems (RTLS) is developed. Graphs for route calculation generated from BIM-data (Building Information Model) guide fire fighters to the triggered fire detector. Additionally, important information, e. g., about sprinkler systems and dangerous goods, is displayed according to the position of the fire fighter within the building.

Related work in the area of Indoor-Navigation for fire fighters is done by [1], [2], [3] and [4]. These Projects focus mainly on one technology for Position sensing in emergency cases or on communication platforms. The approach presented in this abstract is based on the integration of different existing RTLS, integrating them in a Multi-method-Approach (MMA) and using BIM-Data to generate route graphs to guide fire fighters in buildings.

## 3 Claimed content in detail

Complex buildings like airports have many different environments and one single indoor positioning system does not work for all environments [5]. Due to this reason three systems have been chosen (see Figure 1). The MMA uses most of the existing technical infrastructure and requires additional navigation infrastructure only where necessary.

Ultra Wide Band (UWB) is appropriate for position sensing in halls. UWB is less influenced by metals and high humidity than other radio communication technologies and is therefore chosen for passenger and baggage halls.

Existing Wireless LAN networks can be used for position sensing in office areas. Wireless LAN is capable of being influenced by human beings walking by or by structural measures. On this account active RFID-tags are added.

Cellars and underground parkings are equipped with active RFID-Tags using the UHF-band (868 MHz). These tags are planned to be placed at central points. As bar antennas of active RFID-tags are small they are suitable for easy handling with mobile devices.

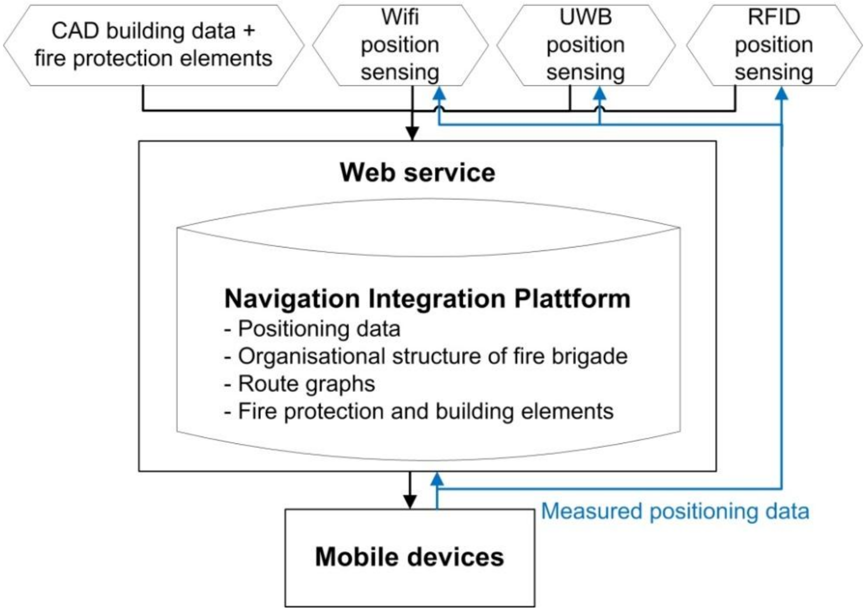


Figure 1: System architecture.

The Navigation Integration Platform administrates the actual positions of the fire fighters, the organizational structure including work schedules, route graphs for navigation and information on fire protection and building elements. The communication between the mobile devices and a web service of the Navigation Integration Platform can be established by WLAN, GPRS, UMTS or other possibilities for internet access.

## 4 Conclusion and remarks

A prototype of this system has been tested at the Institute of Numerical Methods and Informatics in Civil Engineering and at the Frankfurt Airport fire brigade training center. The results suggest a distinct improvement of orientation especially in smoke filled areas.

Tests of the different positioning systems (e. g. the Positioning Engine of Ekahau Inc.) showed that the accuracy is satisfactory for a detection of room accuracy. Experiments with active RFID-Tags from Identec Solutions showed that the signal-strength for calculation of distances is not precise enough. For this reason a new system from Identec Solutions (IntelliFind RTLS), which is based on time measurements of signal dispersion, is evaluated for different types of rooms at the moment. The results will be presented in the paper.

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# Combined Indoor and Outdoor DOP Criteria helpful to Position and Dimension

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## 1 Summary

The democratization of wireless networks, combined with the emergence of increasingly autonomous and efficient mobile devices, leads to new services. Positioning services become pervasive. The accuracy is the main criterion applied in the assessment of positioning systems. But high accuracy cannot be guaranteed because it depends on the environment where the user is located and on the positioning systems used (GNSS, GSM or Wi-Fi). To overcome this disadvantage, hybridization or combination is the best solution. In this paper, we first introduce the hybrid dilution of precision criteria that allows the free choice of the system for positioning in indoor and outdoor environments. Secondly and finally, we present an algorithm for combined positioning.

## 2 Introduction

Recently positioning has become an essential and integral feature of any system of mobility. Indeed, with the appearance of positioning capabilities, applications have emerged and multiplied. Mobile tracking and games are only two of many markets that can benefit from getting positioning information. The bulk supply of positioning is provided by wireless systems such as Global Navigation Satellite System (GNSS), GSM, Wi-Fi, sensors, etc. and their combinations.

Navigation satellite systems can guarantee an overall accuracy of about three meters when the user is in an open area or when the visibility of satellites provides good reception of more than four direct signals with the minimal noise. As soon as we move to a closed environment like an alley or building, the accuracy can decrease significantly. Environments that are well managed by networks, such as Wi-Fi that now prevail in the positioning indoor market, or GSM that has become a repository for assistance applications.

The characteristics and the performances of positioning technologies are defined by the three main dimensions: accuracy, coverage and cost.

The control of those criteria allows increasing the accuracy of the location, ensuring continuity of service and providing better quality of service. Indeed, we need a coefficient that quantifies the quality of these three criteria.

In this paper we first propose different dilution of precision criteria to estimate the accuracy of various positioning systems. Secondly we propose an algorithm for a combined positioning system based on GPS/Galileo and Wi-Fi. Finally, we use an evolutionary algorithm to optimise the combined DOP using the best terrestrial access point positions.

## 3 Contribution

In order to estimate the accuracy and the coverage in the GNSS domain we tend to use the *Geometric Dilution Of Precision* (GDOP) to measure the contribution of satellite's geometry to positioning accuracy. With the emergence of other positioning systems such as GSM, researchers tried to adapt the GDOP to those systems extending it to a more Combined Dilution Of Precision. *Gondran et al.* provide a geometric indicator for WLAN planning which is based on the study of the covered area by a Basic Service Set (BSS), where a cell relative to an antenna is a set of pixels associated to a given base station.

The first factor we propose is dedicated to WLAN based on signal strength, the number of visible access points and their disposal to assess the accuracy of the computed position.

The second dilution of precision criterion that we present is dedicated to combined positioning systems (indoors and outdoors), which use visible satellites, access points and the visible BTS as indicators. The criterion is differing for hybrid positioning systems.

Unfortunately there is no efficient positioning solution for all situations and environments. For this reason, hybridization or combination appears to be the best solution to overcome the problems of service discontinuity or the lack of positioning in some environments.

Finally, we present a combined positioning system based on GPS and Wi-Fi. We propose to complement the GPS equation system using pseudorange measurements with Signal Strength measurements from 802.11 networks.

## 4 Results and conclusion

The results of experiments show that the GPS by itself does not guarantee good accuracy regardless of time and environment. Indeed, the values of the indicator reach infinite values when the receiver does not intercept non-noisy signals from GPS, while the contribution of additional data for this indicator leads to better values.

Where the mobile moves from an environment with perfect visibility of the satellites to another with no visible satellites, as it is the case when entering a building (assuming there is at least one visible access point), the hybrid/combined dilution of precision criterion, follows the environmental changes and allows estimating the quality of positioning in both, indoors and outdoors.

The other simulation with a combined positioning system, shows that the combination is more suitable for a positioning system with a high accuracy.

In this paper, we illustrate the trade-off that is to be made by choosing the proper positioning system and the features. First, we introduce the equivalent dilution of precision criterion for each system. Then, we present an algorithm for combined positioning. Finally, we analyse the results obtained from the simulation and the emulation of various scenarios.

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# Generic architectural framework for hybrid positioning

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## 1 Introduction

A myriad of positioning algorithms [1] have been developed in the last few years. A standalone solution generally does not offer sufficient accuracy in different environments (indoor/outdoor, different type of buildings…). We propose an easy-to-use generic positioning framework, which allows users to plug in a single or multiple positioning algorithms. Multiple algorithms can be active at the same time. A reasoner is used to select the algorithm giving the most accurate position or to intelligently combine the results of multiple algorithms into a more accurate position. Different wireless technologies can be used with this framework. We illustrate the usability of the framework by discussing a hybrid positioning solution.

## 2 Framework Architecture

The framework is developed in Java and consists of three parts: the positioning server, the web server and the client application.

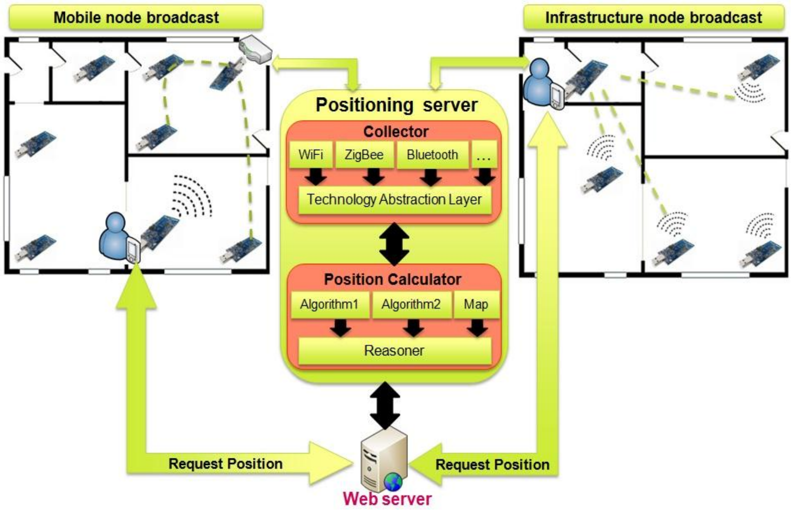



*Figure 1: Framework architecture*

1. Positioning Server - The **positioning server** has two functional blocks. The **collector** is responsible for the retrieval of positioning information gathered by the network infrastructure or mobile unit that is being located. The collector further incorporates an abstraction layer which hides the underlying technology (ZigBee, Wi-Fi, Bluetooth …) from the positioning server. In *figure 1*, two different approaches for positioning in wireless sensor networks are shown. On the left side, a mobile device broadcasts positioning beacons and the sink node of the WSN forwards the beacons to the **collector**. On the right side, the infrastructure nodes broadcast beacons and the mobile unit collects and forwards the beacons to the **collector**. The **collector** further passes the positioning information to the position calculator, which consists of pluggable **positioning algorithms**. Multiple **positioning algorithms** can be active at the same time. A **reasoner** is used to select the algorithm giving the most accurate position or to intelligently combine the results of multiple algorithms into a more accurate (hybrid) position. **Map** info can also be taken into account when calculating the position.
2. Web server - The **web server** can poll the **positioning server** for the user's position.

3. Client - The **client** application can either run on a PDA or a central monitoring station. The client communicates with the **web server** through e.g. Wi-Fi or Ethernet.
   Some advantages of the framework:
   - Existing PDA applications can use position information by implementing a simple interface allowing the application to request a user's position from the **web server**.
   - Conversion of relative coordinates to GPS notation is possible. This implies that **client** applications developed to work outdoor (GPS), can easily use this framework.
   - The user of the **client** application can pinpoint his correct location on the floor plan (for testing purposes). The application then calculates the difference between the estimated and the real position, thus allowing the user to evaluate the algorithm.

## 3 Positioning Solution

We've implemented two positioning algorithms, which are described below. The reasoner decides how the results of the different algorithms are combined. The decision making process of the reasoner can also be influenced by other sorts of input, e.g. **map** information of the building. Finally, we present a hybrid positioning solution.

- Proximity based solution (figure 2): The proximity solution requires a mobile device with a limited wireless range. The resulting position is the **centroid** of all infrastructure nodes within range of the mobile unit.
- Weighted-RSSI solution: In this RSSI-based approach, weights (based on RSSI) are calculated between infrastructure nodes [2]. Using these weights, the **position calculator** computes the target's position based on the distance from the target to 3 infrastructure nodes. Triangulation is used to determine the position of the mobile target.
- Hybrid solution (figure 3): The **reasoner** allows the position calculator to combine the results of different algorithms and other available information. In our hybrid solution information about walls, rooms and doors is used to influence the position estimate.

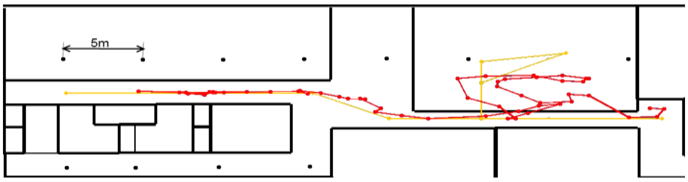
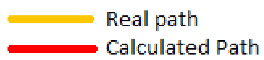



*Figure 2: Proximity solution (max. error 2.5m)*



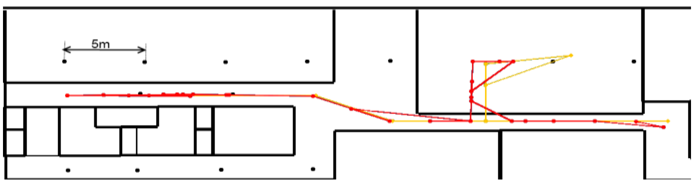




*Figure 3: Hybrid solution (max. error 2.5m + room accuracy guarantee)*

## 4 Conclusion

This framework should significantly reduce the time spent on testing and debugging new positioning algorithms. The proposed hybrid solution has been tested in different real life environments (office, arts center, care home) and results in an average error of 2 meters, with room accuracy guaranteed.

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# A Localization Framework for Wireless Mesh Networks

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## 1 Summary

Indoor localization is a service that could be provided by many already deployed IEEE 802.11 wireless networks and enable to find people, printers, or rooms in large office buildings without any additional costs. For this, we developed a framework for the study of various localization algorithms in a testbed environment. The *Anchor-Free Distributed Localization-Algorithm* (AFL) [1] was implemented as a proof of concept. We discuss several problems that arose when an algorithms that has been previously studied only in simulation environments is transferred into a real world scenario. An initial experiment series was run in the DES-Testbed [2], a multi-transceiver mesh network and highlighted many issues due to under-specification or problems that do not arise with abstract models in simulations.

## 2 Motivation

Localization algorithms can be classified based on many properties. One particular classification considers how many nodes in the network know their physical location. Either all nodes are position-aware, a subset (for example log(n) nodes) knows their coordinates, or in the most extreme case none of them. The last class is known as anchor-free algorithms and is particular interesting for indoor localization using common network devices without specialized hardware; an application scenario where GPS is not available. Although it is only possible to create a relative coordinate system with no relation to geographic positions, several applications already benefit from this. The localization of people, devices, or rooms as well as firefighters and paramedics searching for victims are possible.

For applications in *wireless mesh networks* (WMNs) there is currently limited support available. We implemented the *Localisation Framework for Testbeds* (DES-LOFT) that enables the configuration, execution, visualization, and evaluation of experiments. We focus on scenarios where a precision of about 1 to 2 “normal sized" rooms is sufficient. In contrast to some *wireless sensor networks* or specialized localization systems, we assume that only IEEE 802.11 WLAN transceivers are available and the nodes are sparsely deployed creating a random network with varying node degree.

## 3 Localization Framework

The *Localisation Framework for Testbeds* (DES-LOFT) consists of three major parts. The *Node Agent* is a daemon that runs on the mesh routers that enables the communication between the nodes, network-wide configuration and probing of the current state. A *Proxy* is run on a gateway node that provides access to all nodes in the network and caches data for subsequent queries to take load off the nodes. As last and depicted in Figure 1, a GUI provides a management interface with a 3D view of the network showing two different locations of the mesh routers: real and localized position. Currently experiments are mostly run in an interactive-way using the GUI to allow fine granular control. The user can make crucial important decisions for the algorithms under study if a deterministic behavior has to be forced. Fully distributed and autonomous experiments are also possible.

## 4 The AFL Algorithm in the DES-Testbed

*Anchor-Free Distributed Localization-Algorithm* (AFL) [1] distinguishes two separate phases: initial fold-free graph embedding and mass-spring based optimization. In the first phase, a coordinate sytem for the network is created. Hop-count is applied as metric to select particular nodes that create the axis. All nodes are then asigned initial positions based on their location in the network topology. In the second phase, the nodes are considered to be connected by springs which apply forces to them. The power of these forces depend on the difference between the measured distances to the neighbors and the distances based on the positions in the coordinate system. The mass-spring algorithm “pushes and pulls” the nodes in the coordinate system to minimize the network-wide force.

We encountered several issues during the implementation based on DES-LOFT. For example, AFL is actually not fully distributed as phase one requires a network coordinator using some election process. Further on, the original coordinate system algorithm can create a distorted coordinate system in some situations which results in poor performance in phase two. In general, a full routing protocol is required as provider of topology information and to achieve a distributed localization. Side-effects of the additional overhead and used link metric have to be considered. We provide modifications to the original AFL specification and propose solutions for open questions that are due to under-specification.

## 5 Conclusions and Outlook

An initial experiment series in the *Distributed Embedded Systems* (DES) testbed [2] at the *Freie Universität Berlin* using three IEEE 802.11 tranceivers per node showed that our modifcations can improve the overall performance of AFL. 16 different configurations were considered and evaluated using three metrics. We are certain that by further extension of AFL a sophisticated indoor localization system for common WMN deployments can be provided. DES-LOFT has proved to be a mature basis for the research of localization algorithms in our testbed scenario and other algorithms will be implemented subsequently.

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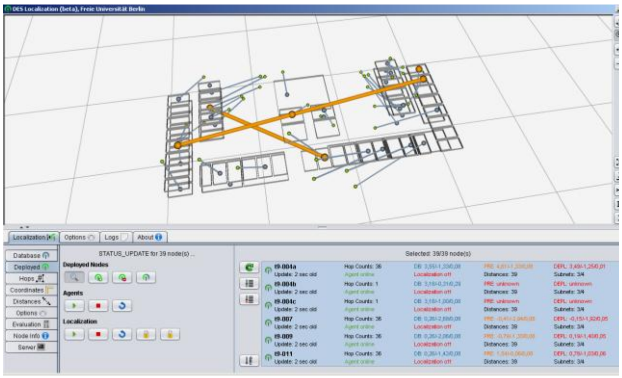

Figure 1: DES-LOFT user interface for the execution and visualization of experiments. A sample experiment using nodes in one building is shown.

## Industrial Metrology & Geodetic Systems, iGPS (Nikon)

Auditorium G3

Friday, September 17, 08:15 – 09:45 & 10:15 – 12:00

# Performance Evaluation of iGPS for Industrial Applications

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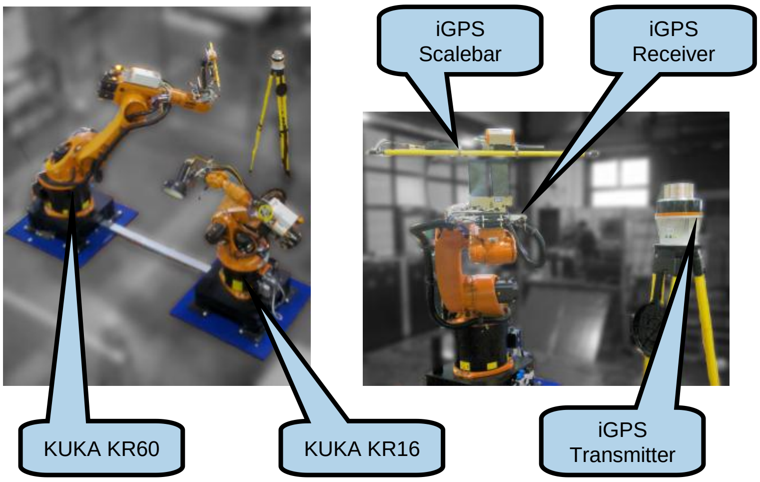
## 1 Summary

Precise measurements in large volumes will be a key technology in tomorrow’s industrial applications. The iGPS system of Nikon Metrology is a measuring system, which represents a suitable compromise for measurement uncertainty, scalable work area and potential number of measuring points. This advantage is used at WZL to show the use of iGPS in industrial applications with two cooperating robots to allow absolutely precise movements.

The measurement uncertainty of the iGPS-System influences its possible applications. Already performed analyses show an uneven distribution of the measurement uncertainty. The objective of these analyses is the definition of areas with minimized measurement uncertainty and building up a basis for the robot control. Currently a basic control loop is implemented to identify and roadmap further development topics. The control loops extend the Adaptive Robot Control (ARC) delivered by Nikon Metrology and show the possibility to use them in dynamic industrial applications.




## 2 Large-Volume metrology in production environments

The term „Large-Volume Metrology“ summarizes a whole class of mobile, optical measuring systems, which particularly meet requirements of very large or only heavily to handle work pieces [1,2]. iGPS is a measuring system, which represents a suitable compromise for measurement uncertainty, scalable work area and potential number of measuring points. The main advantages of the system are the possibility to have as many receivers in the iGPS as needed and a superior scaling capability. This advantage is used at WZL in a robotic cell with two cooperating robots to allow precise absolute movements of the robots needed to use them for directly performed offline programs, cooperating tasks or measurement applications.

## 3 Performance Evaluation of iGPS

The measurement uncertainty of the iGPS-System influences importantly its possible applications. Already performed analyses based on comparative measurements with laser tracking interferometer have showed an uneven distribution of the measurement uncertainty in the volume of the iGPS measuring system [3]. Especially, there is a strong dependence between the position of the Transmitter and the measurement uncertainty [4]. The iGPS setup at the WZL is analysed concerning local measurement errors. Therefore, comparative measurements with tracking interferometer are performed. The reflector for the tracking interferometer is fixed on the robot, as well as the Sensors of iGPS system, with known offset. The measured coordinates from the iGPS in the movement volume of the robots are compared with the results of the tracking interferometer measurements. Results are a 3D-matrix of local measurement errors in the volume of the iGPS system. By repeating measurements under different environmental conditions a variance of local errors is detectable. The objective of these analyses is the definition of areas with minimized measurement uncertainty independent of environmental caused variances building up a basis for the robot control.

## 4 Absolutely precise robot movements

iGPS may be used for the calibration and control of robots. Currently a basic control loop is implemented to identify and roadmap further research topics. The control loops extend the Adaptive Robot Control (ARC) delivered by Nikon Metrology. This system is able to statically correct positioning of robots within 0.4 millimetres independent of working piece weight or other external influences. Control gains have to be kept low in order to avoid instability mainly caused by high latency and noise of the iGPS. The control parameters therefore limit the system dynamics of the iGPS-controlled robots and will lead to further research topics.

## 5 Conclusions and Outlook

The influence of Large-Volume metrology systems is going to be stronger due to the rising complexity and flexibility of future production systems. iGPS provides synchronized measurement data in a globally aligned coordinate system, making it a possible candidate for this purpose. Current evaluations show the strength and weaknesses of iGPS and may be used to address further research topics to broaden the suitability for industrial applications.

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# Indoor navigation of machines and measuring devices with iGPS

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## Introduction

Depending on the application in the industrial measurement segment, the requirements for appropriate large volume metrology systems are often very challenging. Fast, reliable and accurate measurements of points and geometric features or positioning of moving parts in real-time are required. iGPS, a measurement system developed by Nikon Metrology, can handle these requirements more flexible than many other metrology systems. The research project "USOFI – Untersuchung und Systemoptimierung für iGPS" and other research projects investigate the capabilities of this promising technology for further optimization of hardware and software. In this paper the focus will be on two case studies that have contradictory requirements and therefore demonstrate some of the versatility of iGPS.

## Concept of iGPS

Static transmitters send infrared signals into the local workspace that can be received by multiple sensors in line of sight. The horizontal and vertical angle from sensor to transmitter is determined based on the arrival time of the transmitter signals that can also be used to synchronize all sensors. Any sensor position with angle measurements to at least two transmitters can be determined along the concept of triangulation. The transmitter positions have to be determined beforehand by bundle adjustment using known reference points or at least one scale bar. Measurements with multiple synchronized sensors also allow the determination of orientations or deformations of work pieces in real-time. Standard deviations of approx. 0.1 mm per 10 m diameter of the working area can be expected for three-dimensional point determination of typical iGPS configurations with four transmitters in a controlled environment.

## Feature inspection with a laser scanner integrated into iGPS

Many tasks especially in quality management, involve the determination of geometric features. These measurements often can be performed in a static mode, but require high accuracy, full automation, and a very short measurement period. Instead of investigating the iGPS capabilities on feature inspection itself, a laser scanner was set up, providing more information especially when measuring free form surfaces. If the size of a work piece exceeds the scanners working area, it has to be repositioned several times, while each of the scans requires an overlapping scan area with distinctive features or additional identification marks, either on the work piece itself or on a fixed frame. Even if there are only some small areas of interest on a large object, more scans have to be taken to relate the isolated scans to each other. With iGPS providing a higher-level coordinate frame, it is possible to determine the position and orientation of the scanner itself in the iGPS coordinate system (Figure 1). The goal is to provide a method with combined three dimensional point accuracy of the scanner and iGPS that matches the accuracy of relating scans to each other by best-fitting, but is more flexible and faster.

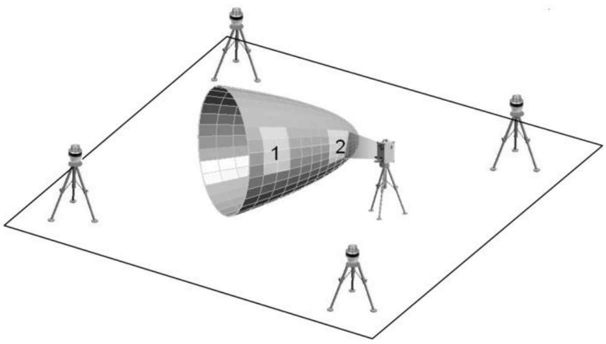


Figure 1: Scanner operating in iGPS provided measurement cell

Therefore a rigid structure was created that can be fixed on the scanner and includes four or six iGPS sensors. The position and orientation of the iGPS sensors on the structure is known through calibration. Each time, the scanner is repositioned, its position and orientation is determined to transform the scans directly into the iGPS coordinate frame.

### Kinematic measurements in tunnel navigation of road headers

In comparison to the first application, the accuracy needed in navigation of tunneling machines is lower, but the requirements are different. Apart from difficult environmental conditions, for example dust and vibrations, the road header can move very fast. Furthermore the concept of navigating a tunneling machine with iGPS has to compensate for the small range of up to 55 m of the transmitters in this scope of application. Transmitters have to be repositioned every 20 m due to the security distance to the road header that is at least 20 m. This half-automated repositioning (leap frog) of the transmitters uses additional sensors on the tunnel wall, which are measured before and after the leap frog, so that all transmitters can be transformed into a common coordinate system. With each leap frog additional errors arise that can sum up rapidly. Simulations that evaluate the combined accuracy of multiple leap frogs and kinematic measurements at different ranges support the feasibility of the navigation concept. Depending on measurement conditions more than seven leap frogs (equivalent to 140 m tunneling) can be performed until 10 mm accuracy level is reached. Studies in cooperation with VMT GmbH under real tunnel conditions support the simulation results. Based on the Server-Client-Structure of the iGPS software, a client was developed and integrated in VMT's navigation software for tunnel excavation. This client software simplifies the setup, leap frog and measurements with iGPS, and communicates the iGPS measurements to the tunnel navigation software SLS.

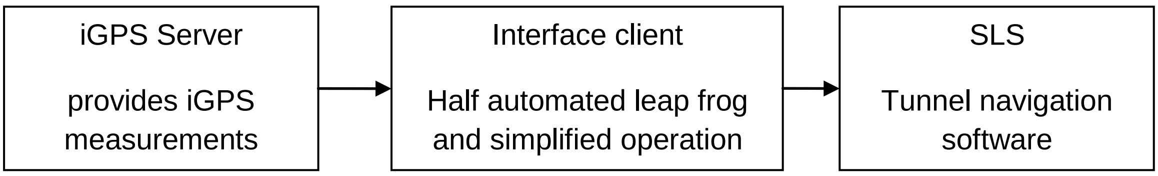


Figure 2: Data flow of the Server-Client-Structure

### Conclusion and Outlook

Examinations of iGPS promise good accuracy and reliability in controlled environment and under difficult conditions, though the two applications have to be proven in practice currently. With further developments of software and hardware, iGPS can be integrated in many applications where high flexibility, high accuracy and the possibility to track multiple sensors or the orientation of objects are required.

# Path Tracking with iGPS

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## 1 Summary

iGPS technology is a laser-based indoor system with optical sensors and transmitters to determine the 3D position of static or moving objects. The technology is based on internal time measurements related to spatial rays that intersect at sensors in the measuring volume. Due to the measurement principle of iGPS, tracking measurements can cause a delay time which will lead to deviations in spatiotemporal positioning. Utilizing the new Digital Input Module it is possible to analyze the kinematic performance of the iGPS metrology system with the time-referenced 4D test and calibration system. By using the latest equipment and Surveyor software it was possible to show that the iGPS system has made significant improvement in tracking capability. In this experimental set-up, the system could collect and process data up to object velocities of 3 m/s. At this high velocity, the tracking deviations for the 3D position were less than 0.3 mm and the 4D tracking deviations were less than 1.5 mm.

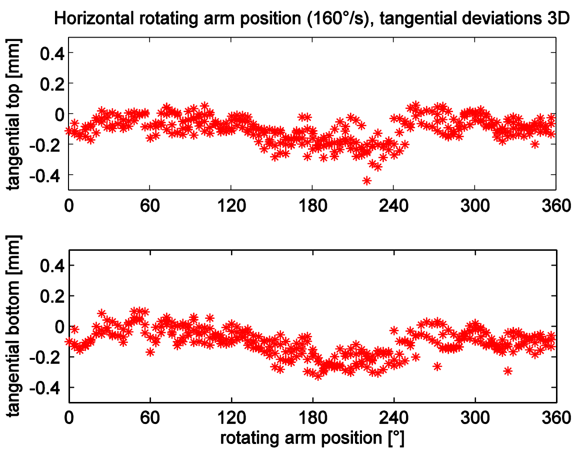
## 2 Path Tracking with iGPS

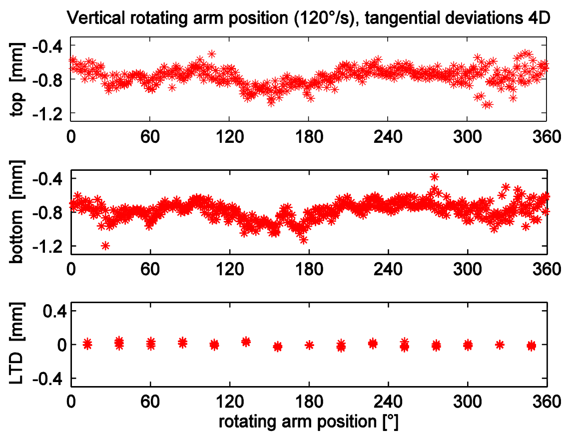
The typical components of an iGPS network are at least two transmitters, a mini-vector bar with two sensors, an amplifier as analog-digital converter and the position calculation engine (PCE) that measures the arrival time of each signal with an internal clock and manages the communication with the host PC. Each iGPS transmitter emits two different types of signals, the strobe signal and two fan-shaped beams which are projected from the rotating head of the transmitter. Each sensor in the working volume receives signals from each visible transmitter and the arrival time is measured. Based on these time measurements and the fan beam's geometry, the angle values (azimuth, elevation) from transmitter to sensor are determined. The location of the sensor may be calculated using the process of triangulation in an analogous manner to a theodolite network. iGPS can be used for static or kinematic measurements. With the new PCE Digital Input Module (DIM) it is possible to synchronize an external digital input signal with iGPS data. To analyze the 4D kinematic performance of iGPS time-referenced measurements are strictly necessary. For tracking optical measuring systems of any kind a time-referenced 4D test and calibration system was developed at the Geodetic Institute at Karlsruhe Institute of Technology (KIT). This system consists of a tiltable rotating arm with a length of 2 m. A rotary direct drive is used as primary mover of the rotating arm and a real-time multi-axis servo motion controller is used for position and velocity control of the direct drive.

The kinematic measurements were executed in July 2009 in the Geodetic Laboratory of KIT. Four iGPS transmitters were arranged around the rotating arm and a 1 m scale bar was used for bundling (system calibration). A mini-vector bar was fixed on one end of the rotating arm. A frequency generator delivered the input for the DIM and the test equipment. The iGPS Surveyor software version 1.2.30 was used. For independent measurements a Leica laser tracker LTD 500 was employed, which was triggered also by the frequency generator. The rotating arm was placed in three different positions: horizontal, slant and vertical. Each time new transmitter network positions were calculated through a bundling calibration procedure. For the coordinate transformation a static reference measurement with both systems – iGPS and laser tracker – was carried out. Within the kinematic mode the laser tracker could only follow at vertical rotating arm position, because of the visibility of the CCR. In the kinematic mode angular velocities up to 160°/s (2.9 m/s) could be reached.

For every revolution of the rotating arm a 3D circle fitting was calculated using the least-squares method. The results were shown as planar deviations (perpendicular to the circle plane) and radial deviations. Tangential deviations were calculated after a coordinate transformation. The static measurement of the horizontal rotating arm position showed for the planar, radial and tangential deviations nearly the same deviations < ±50 µm for iGPS sensors and laser tracker. For the kinematic measuring with a velocity of 160°/s the planar deviations are nearly in the same order and the radial deviations are less than ±0.15 mm for iGPS for 3D path tracking. For the tangential deviations, spatial (3D) and spatiotemporal (4D) deviations must be distinguished. “Spatial” refers to the 3D position only, which can be expressed as path tracking. “Spatiotemporal” refers to position and time (4D), which means that the sensor has to be at the correct position at a specific time. In that way the result has to be split up into 3D and 4D deviations. The spatiotemporal tangential deviations show that there is a time offset of about 0.3 ms and it seems that the sensor is "running ahead". In order to show what happens with the 3D position, this time offset is considered for new calculations. The left figure shows the tangential deviations (after correction, top and bottom sensor iGPS) with a horizontal rotating arm position at an angular velocity of 160°/s for 4 revolutions of the rotating arm. The vertical rotating arm position has the advantage that both systems – iGPS and laser tracker – can be used simultaneously, but it should be noted that in this special experimental set-up the iGPS transmitter network configuration was regarded as poor and at the limits of the hardware functionality. The right figure shows the 4D tangential deviations (top and bottom sensor iGPS and LTD500) at an angular velocity of 120°/s for 4 revolutions of the rotating arm. The 3D tangential deviations (iGPS) are nearly in the same order as the deviations of the horizontal rotating arm position.

The sum of these findings shows that the development of the latest iGPS system has been successful in reducing the theoretical delay time. For path tracking (3D) up to velocities of 3 m/s the deviations are less than 0.3 mm. If spatiotemporal positions (4D) are required then there is a time offset about 0.3 ms and the deviations increase with the sensor velocity. Approximately 1 mm at 3 m/s was observed. iGPS can be used as a static or kinematic measuring system and due to the flexible measuring performance it provides an interesting range of applications.



# Locata: A new high accuracy indoor positioning system

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The Global Positioning System (GPS) is a reliable, versatile, generally available and comparatively accurate positioning technology, able to operate anywhere across the globe. GPS is, in fact, the most effective general-purpose navigation tool ever developed because of its ability to address a wide variety of applications: air, sea, land, and space navigation; precise timing; geodesy; surveying and mapping; machine guidance/control; military and emergency services operations; hiking and other leisure activities; personal location; and location-based services. These varied applications use different and appropriate receiver instrumentation, operational procedures, and data processing techniques. But all require signal availability from a minimum of four GPS satellites for three-dimensional fixes.

In the coming decade a number of other Global Navigation Satellite Systems (GNSS), and regional systems and augmentations, will be launched. The number of satellites and transmitted signals suitable for centimetre-level accuracy positioning will at least triple. However, the most severe limitation of GPS performance will still remain; the accuracy of positioning deteriorates very rapidly when the user receiver loses direct view of the satellites, which typically occurs indoors or in severely obstructed urban environments. In such environments, the majority of receivers do not function at all, and even the high-sensitivity receivers have difficulty in providing coordinates with sub-dekametre level accuracies.

Accurate indoor positioning is required for a variety of commercial applications, including warehouse automation, asset tracking, emergency first-responders, and others. In fact, the general expectation of users today is for “GPS-like” positioning performance anywhere they go. The inherent limitations of GPS signal availability indoors and in satellite-occluded environments, however, has forced researchers to investigate alternative technologies which may be able to replicate GPS/GNSS performance indoors. Inertial navigation systems (INS) are useful but no panacea because positioning accuracy degrades rapidly with time due to the drift errors of the gyroscopes and accelerometers. Laser or optical-based systems suffer from line-of-sight restrictions, whereas traditional radionavigation-based systems are affected by multipath and time synchronisation challenges.

The University of New South Wales, with a number of academic partners including the University of Nottingham, has conducted pseudolite research for many years in an effort to overcome problems found in GPS-occluded or denied environments. Experiments have included pseudolites in non-synchronous and synchronised modes for a variety of applications, using both the GPS L1 frequency as well as the 2.4GHz ISM band. (A "pseudolite" is a GPS-like signal transmitted by a ground-based transmitter, or "pseudo-satellite"). The extensive research directed at addressing these GPS challenges has concluded that pseudolites have fundamental technical problems that, even in a controlled or lab environment, are extremely difficult to overcome. In the real world the challenges of optimally siting pseudolites, controlling transmission power levels, trying to ensure extremely high levels of synchronisation, configuring special antennas, and designing the "field of operations" such that GNSS and pseudolites can work together (or at least not interfere with each other) have been largely insurmountable.

A new terrestrial RF-based distance measurement technology, trademarked "**Locata**", has overcome the enormous technical challenges required to create "a localised autonomous terrestrial replica of GNSS". Locata requires ground-based transceivers - called LocataLites - that cover an area with strong time-synchronised ranging signals to form "a LocataNet". It should be noted that a LocataLite is not a pseudolite in the traditional sense – it is true that both transmit signals on the ground but beyond this similarity the underlying synchronisation technology (which is vital for positioning) is fundamentally different. When a receiver uses four or more Locata ranging signals it computes high-accuracy carrier phase-based positions entirely independent of GNSS or INS. In relatively open outdoor environments such as open-cut mining, construction sites, ports, etc, LocataNets are providing real-time stand-alone kinematic positioning (*without* differential base stations) at centimetre-level accuracy (equivalent to RTK or survey-grade GPS).

Locata has developed many advanced features over a period of almost 15 years, through several technology generations. They include the LocataNet time-synchronised positioning network, network propagation to many LocataLites, improved signal penetration, changes of transmitting frequency or signal structure, and spatial and frequency diversity. However, the most difficult technical challenge for high-accuracy positioning indoors is multipath. Throughout the history of radiopositioning this problem has been the nemesis and the bane of accurate and reliable results. Locata has therefore worked for over 8 years on the development of a completely new type of antenna which would allow industrial-grade, cm-level positioning indoors. The result of this extensive development – the Small **TimeTenna** – is now approaching commercial release.

This technical paper describes indoor positioning results with the latest generation of Locata positioning devices incorporating the new TimeTenna technology. In order to test Locata's TimeTenna technology a LocataNet was set up in an all-steel warehouse environment. This paper will present for the first time the results of trials comparing Locata's positioning solutions with a robotic total station set up as a truth system. The results demonstrate that Locata's TimeTenna enables cm-level positioning in severe multipath environments where conventional high-accuracy radiopositioning has previously been impossible.

# New Approaches in Laser Tracker Based

# High-Accuracy Indoor Navigation

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## 1 Summary

Laser trackers are capable of high-accuracy indoor navigation by tracking reflectors in 3D object space. Currently these navigation tasks, e.g. building applications, can be executed with high-dynamic absolute interferometer (AIFM) based laser trackers or also most recently with absolute distance meter (ADM) only trackers with automated target recognition (ATR) technology.

However, if a true 6 degree of freedom (6DoF) approach is required, e.g. for position and orientation determination simultaneously, a high-dynamic absolute tracker can be equipped with a special vision system. These aforementioned technologies delivering dynamic high-accuracy 6D data can be used for navigating tactile devices for probing or sensors for object scanning. Furthermore, these laser trackers based indoor navigation systems are then capable of positioning, guiding and controlling of robots and machines.

Within this presentation a selection of the new technological concepts of laser tracker based indoor navigation will be presented and their direct benefits and new potentials in various applications will be discussed.

## 2 Introduction

For large-scale and high-accuracy measuring tasks in automotive and aerospace industries laser trackers have become the standard metrology solution. With the recent progress in laser tracker technology, positioning, guiding and controlling applicatiosn can be executed with high efficiency.

## 3 Indoor navigation by high-dynamic absolute trackers

The core sensor for this kind of navigation is the laser tracker, or since the introduction of absolute interferometer (AIFM) technology the so-called absolute tracker. An high-dynamic absolute tracker consisting of two rotation axes equipped with angle encoders and drives, an AIFM, and a position sensitive device (PSD), is capable in closed-loop control of tracking a moving retro-reflector and determining the 3D coordinates of this retro-reflector in real-time.

Furthermore, Leica AT901 absolute trackers are equipped with built-in vision systems, enabling the reflector to be located and locked-on to. This functionality called “PowerLock” increases the efficiency of this optical positioning technology.

## 4 New approach: ATR based tracking

Whereas standard laser trackers base on PSD technology, the Leica AT401 is based on vision systems, i.e. the ATR. The benefit of having an extended field of view of the vision system is that the retro-reflector is tracked within the imaging sequence. This technology allows for tracking behind obstacles such as pillars or bars, increasing the ease of use in indoor navigation in an industrial environment. Figure 1 shows the Leica AT410 and in figure 2 a typical jig building application is depicted.

Figure 1: Leica AT401

Figure 2: Leica AT401 building jig application

## 5 T-MAC and Automation: 6DoF Tracking

By combining an AT901 absolute tracker with a high-speed camera system (T-CAM) for additional orientation measurements true 6DoF tracking becomes possible. This is used for navigating tactile devices for probing or sensors for object scanning. Furthermore, these laser trackers based indoor navigation systems are then capable of positioning, guiding and controlling of robots and machines when used with a T-MAC probe type as seen in figure 4.

Figure 3: Leica AT901 equipped with T-CAM

Figure 4: T-MAC on robot

## 6 Conclusions and Outlook

Nowadays, absolute trackers are fully integrated systems, i.e. even the basic 3D absolute tracker is equipped with a multitude of sensors and vision systems which allow for new applications and approaches towards laser tracker based indoor navigation.

Most recent technologies make now inline-inspections and real-time positioning possible. Combining laser tracker technology with different 6DoF based probes and scanners will be the next step in meeting the demands for laser tracker based indoor navigation.

# Positioning of robots by determining 6DOF

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## 7 Introduction

Within the "Sonderforschungsbereich Transregio 10" a process chain for flexible production and machining of extruded aluminum profiles is developed and put into practice. The project is a co-operation of the Karlsruhe Institute of Technology (KIT), the University Munich and the University Dortmund. The process chain includes robots for fully automated handling of the profiles. To guarantee the correct form of the extruded profile the robots have to be precisely aligned with it. Therefore their tool centre points (TCPs) have to be known exactly. A method is presented, which delivers the TCPs using 6DOF equipment.

## 8 Measurement tools

For the accurate surveying of the robots the Geodetic Institute of KIT used two of Leica's laser trackers – the LTD 500 and the Absolute Tracker AT 901 in combination with T-Cam and T-Probe. This device determines position as well as orientation (6-DOF) of an object, which is equipped with the T-probe. The T-Probe incorporates a CCR and IR-diodes. The position is measured conventionally by the laser tracker. Furthermore, a camera which is mounted on top of the AT 901 (T-Cam) takes images of T-Probe's IR diodes. Photogrammetric methods in the calculation routine analyze the spatial distribution of the IR diodes and determine the three orientation angles of the T-Probe. Although different styli can be attached to the probe to determine surface points we use the probe (instead of the regular T-Mac) for determining the orientation of the robot's tool adapter, to which it is attached.

## 9 Procedures and results

All measurements were carried out in a coordinate system based on the extruding press. The goal was to align the robot's tools exactly with the centre of the extruded aluminum. To reach that goal it was necessary to determine the tool-centre-point (TCP) of each tool. Unfortunately it was not possible to physically measure the actual TCP with tactile or reflector-less measuring methods. With the help of Leica's 6DOF measurement tool T-Probe the task was fulfilled nevertheless. The T-Probe was attached to the tool and a calibration routine determined the probe's tip in the coordinate system of the probe itself. During that routine the robot moved around its TCP. The result of this procedure was a virtual stylus definition with the tip of the T-Probe being the actual TCP. Hence every measurement with this virtual stylus delivers the actual position of the TCP. The accuracy of the tip's definition is influenced by the measurement accuracy of the T-Probe and the accuracy of the robot's movements during the calibration routine. The accuracy of the final tip definition was approximately 0.2 mm. By accurately determining the TCP it was possible to align the robot and the tool, respectively, with the centre of the extruded aluminum. Furthermore this procedure allowed to verifying the robot's accuracy.

For determining the robots synchronization measurements with both trackers at the same time were carried out. Each tracker observed one robot. Therefore a trigger signal from the robot's controller was sent to the trackers. By that, the trackers measured the robots coordinates with the same frequency and at the same time as the controller recorded the robots movements, i.e. the data is fully synchronized. To ensure the laser beam would not break during the measurements cat-eye reflectors were used. They provide a much wider aperture angle than the standard CCRs. First results of synchronized measuring with two trackers will be presented.

## 10 Conclusions and Outlook

If laser trackers are able to react on a trigger pulse, they a predestinated for spatiotemporal surveys of (cooperating) robots. Furthermore, the tip-calibration procedure of the T-Probe of Leica laser trackers can be efficiently used for virtual TCP-calibration. With these tools, calibration information for the robot's control can be derived.

# The Use of Kalman Filtering in Combination With an Electronic Tacheometer

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## 1 Summary

Modern electronic tacheometers offer the possibility to capture kinematic processes in real time. In case the kinematic process is observed with only one measurement system, we have no possibility to perform redundant observations that would enable the accuracy estimation of observations and computed values. The Kalman filter represents a method of advanced geodetic analysis and as such adjusts the redundant data in an optimum way. In combination with a Global Positioning System the use of Kalman filtering is wide spread and well known. Incorporating a time component directly into a processing of terrestrial kinematic observations demands good knowledge about the electronic tacheometer capabilities and also a procedure of processing kinematic terrestrial observations. For this purpose the developed model of Kalman filter for processing kinematic terrestrial observations was tested on the reference trajectory in the Geodetic Laboratory of the Technical University Munich.

## 2 Measurement System

The main idea of the work was to:

- perform kinematic processes,
- observe the process with an electronic tacheometer,
- develop an evaluation model for assessing the kinematic instrumental capability and estimating the kinematic position of the moving reflector,
- control the developed model within an independent reference frame.

The kinematic process was simulated on the known reference trajectory of 15 m length, providing an installation accuracy of 1 mm in horizontal and in vertical position respectively. The geometry of the reference trajectory was defined with the theodolite measurement system *ECDS3*. The kinematic measurements were carried out with an electronic tacheometer – *TCRA1201 Leica Geosytems*. On the trolley, the *GRZ4 Leica Geosystems* 360°-reflector was used. Sets of kinematic observations were carried out for different trolley velocities. The communication with the instrument was established with a (*Visual Basic*) *Leica Geosytems GeoCOM* interface.

## 3 Wiener Process Acceleration Model

The measurements were processed with a linear Kalman filter (KF) model, incorporating the law on propagation of variances and covariances. Because of high frequency of measurements, we assume in our work, that the movement of the prism can be described as a movement with approximately constant acceleration $a$ during each sampling period.

Consequently, the discrete third-order kinematic or discrete Wiener process acceleration model, DWPAM, which is three-dimensional per coordinate, was developed. The advantage of such model is that the process noise intensity can be well related to physical characteristics of the motion (acceleration). The same model was used for all three dimensions.

## 4 Evaluation of the model

The verification of DWPA model with the law of propagation of variances and covariances was basically controlled with:
- indicators of inner confidence,
- statistical methods and parameters and
- known reference trajectory.

The model of KF gives us on its own accord some indicators that enable the evaluation of outputs. Because these values are computed through the KF process they can only be used as indicators of inner confidence (observability, controllability, properties of the posterior system state covariance matrix and Kalman gain matrix). The next step is to implement statistical methods and parameters, which show the reliability of the model and computed values (σ-bound, consistency in the domain of the measurements, consistency in the system state domain). In our work, an additional, completely independent evaluation was performed with the known reference trajectory.

By observing the model through several numerical repetitions the best value of process noise parameters could be successfully defined. The results are related to those experiments, where no gross errors were present and where the movement of the trolley was approximately uniform, with no sudden changes in velocity.

## 5 Conclusions and Outlook

In our work the $1\,cm$-bound was taken as a limit for defining too big deviations. This value was defined after several experimental tests for different *Leica Geosystems GeoCOM* functions and according to the reflector inclination. The adequacy of developed DWPAM and statements of the work can be summarized in the following paragraphs:

- According to different tests on the trajectory, the expected accuracy of the reflector position depends mostly on the velocity of the trolley and the *Leica Geoystems* measurement function or program used.
- All evaluation tests showed the same outliers in the observations.
- The advantage of such a reference frame, i.e. reference trajectory, is the evaluation of the model and capabilities of the instrument at the same time.
- In each project the accuracy of measurements and output variables have to be defined. Consequently, the advantages and shortcomings of static and kinematic measurements have also been researched.
- The results of the numerical tests confirmed the appropriateness of the model for evaluation of geodetic kinematic measurements, where no redundant observations are available.
- The preceding simulations, when possible preceding measurements, are suggested for each project. According to preceding works the measurement accuracy can be estimated, and the best prior input values of KF can be defined.

## User Requirements

Auditorium D2

Wednesday, September 15, 10:30 – 11:45

# User Requirements for Localization and Tracking Technology

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## 1 Summary

Current advances in localization and tracking technology [1] have the potential to develop into much-needed tools for the saving of lives in emergency response and rescue missions, and for the safe-keeping of lives in rescue missions as well as military operations. However, different users face different environments and consequently have different user requirements [2]. *This paper aims to survey the different requirements for localization and tracking technology by mission type, so that researchers, industry and user groups can more easily determine their specific technology needs.* Although primarily aimed to describe requirements for military personnel, law enforcement officers, and firefighters, needs and constraints for several types of civilian operations are covered as well. Despite differences in requirements, it makes sense to develop technologies that will serve not only one but all of these groups.

## 2 Essential User Requirements

While law enforcement officers, firefighters, and military personnel have different requirements for localization and tracking systems, all three groups share certain key requirements. These are:

1. Stringent location accuracy, in the horizontal plane of no greater error than one meter in any environment so that the commander can determine the specific room in a building that the person occupies.
2. Stringent location accuracy in the vertical plane of no greater error than two meters so as to be able to determine the specific story in a building that the person occupies.
3. Constant accessibility for those who need the positioning data.
4. Robustness so that the system will operate reliably even under harsh conditions, including extreme temperatures and humidity, for instance by relying on a peer-to-peer communications system that can continue in operation even if the base station is lost (the Swedish RAKEL public safety network provides a common, encrypted communications platform for, among others, law enforcement, emergency response, and military units).
5. Encrypted communications and data transfer.
6. Integrity monitoring, with automatic estimation of localization errors (uncertainty) and detection of and warning in case of deliberate ECM.
7. Positioning data to be compatible to and integrated with other information, in particular personal health status (physiological monitoring) but also real-time map-building capability in the form of simultaneous localization and mapping (SLAM) of any unknown building as the team moves through it; SLAM should be automatic, without the need for user interaction (i.e. without the need for the team members to aim cameras and sensors in various directions).
8. The system should not depend on bulky antennas; antenna and cables should be incorporated into the individual's uniform or equipment.
9. Weight of personal localization and tracking gear (including processing unit and visualization interface) to be less than 1 kg, and not bulky.
10. The system must be energy-efficient, with battery power to last for at least 24 hours but preferably up to a week, depending on type of mission.

11. Presentation of positioning data to be intuitive and easy to understand, in particular for the personnel actually carrying out the operation.
12. A modular system would be most useful, since even the same user may face different challenges on different missions and occasionally have no real need for positioning data (research results show that different users differ on this need; law enforcement officers tends to prefer a modular system, while military users and firefighters instead expect always to carry the system as part of personal gear and activate it whenever needed).
13. Pre-installation of the localization system should not be needed.
14. In any armed operation, the system should present heading of own troops and in particular the heading of individual weapons. Data for distance and direction to targets and threats should also be presented.

## 3 Mission-specific User Requirements

In addition to the essential user requirements already described, there will be additional needs and constraints in localization and tracking capability. System requirements will differ depending on user and type of operation. For mission critical and life saving operations, some users will need Safety-of-Life critical systems in which accuracy and accessibility are more important than cost. These include military Special Forces personnel, police special weapons and tactics (SWAT) teams, and firefighters.

Other users, including regular military, law enforcement officers, and (in at least some countries, including those of the European Union) private security guards will find accuracy, accessibility, and cost of roughly equal importance when deciding upon a localization and tracking system.

The range of operations in which localization and tracking capability would provide an edge is wide. The most common types are listed in the full paper. These will be described in some detail.

## 4 Concluding Remarks

As has become clear from this survey of localization and tracking technology requirements, there is no doubt that military personnel, law enforcement officers, and firefighters despite their different mission types face very similar needs. It makes sense to develop technologies that will serve not only one but all of these groups. To facilitate this, we suggest the establishment of a joint facility for development of requirements together with representatives from these various branches and evaluation of existing and emerging localization and tracking systems. Such a facility would benefit from a pre-installed high-accuracy system against which new stand-alone technologies can be compared and evaluated.

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# Mass market considerations for indoor positioning and navigation

Lauri Wirola, Tommi Laine and Jari Syrjärinne *of Nokia Inc., Finland*

An aspect that is often neglected in research in the field of location services is that in order to have a solution that can be deployed in the mass market, the actual positioning algorithm is only a small piece of the puzzle. This paper looks at the indoor positioning and navigation problem from the architectural and system level point of view and highlights sectors, which may not directly relate to positioning, but need to be solved before indoor positioning can be taken to the mass market.

The success of GNSS-based positioning in mass market applications including navigation is firstly due to the self-consistent and controlled nature of the underlying positioning technology and secondly due to the availability of cost-effective map material. For example, in case of GPS there is a single organization controlling and taking responsibility for the system performance. Moreover, the GPS system itself provides all the information (orbits, clocks) required for positioning. Secondly, the availability of global cost-effective map material means that position information can be utilized in a meaningful manner to enrich peoples' everyday life. The question is how a similar performance could be achieved indoors.

Several solutions have been proposed for indoor positioning, ranging from RF fingerprint methods to distributing specific positioning tags, such as RFID tags, in the areas of interest. In addition, at least inertial sensors, magnetic fields, vision-based and WLAN-/UWB-ranging solutions have been proposed for indoor positioning and navigation.

While beacons specifically deployed for positioning purposes can be utilized in small scale deployments, they cannot be a backbone for global mass market indoor positioning solution due to scalability and cost issues. It is also not plausible to assume that a new type of a radio dedicated solely for positioning would be deployed across the variety of mobile device categories due to cost and size reasons. Therefore, it turns out that the mass market indoor positioning solutions must be based on utilizing the existing infrastructure (such as WLAN), commonly available measurements (such as signal strengths) and existing capabilities in the mobile devices (such as commercial-grade accelerometers, magnetometers and cameras).

When relying on the existing infrastructure it in fact turns out that the common aspect for all of these requirements is that there is no single authority maintaining the potential positioning infrastructure, such as WLAN nodes. Thus, the global players need to collect and maintain databases that store a variety of information relevant for positioning, e.g. fingerprints and indoor maps, in order to provide the service. For outdoors cases there already are a variety of commercial solutions – multiple industry players collect and maintain WLAN node databases that are based on crowd-sourcing WLAN measurement information tagged with GPS positions.

The same should now be done indoors. However, obviously the GPS-based data collection fails indoors and thus research efforts are greatly needed in the area of indoor data collection and how to make it as automated as possible. The challenges are manifold. The lack of an independent source of position information is the most serious one and a learning solution requiring significant human interaction does not scale and is error-prone. Moreover, the range of devices collecting data as well as the range of devices that need to be positioned is huge. As simple matter as signal strength values might not be directly comparable between devices due to various hardware and software issues. With a wide range of devices, it is also not feasible to have a positioning algorithm that would need to be tuned for each device. Thus achieving device-independency is one clear need in the future research.

The data collection using the user base is not a trivial task. The amount of data flowing into the server system is huge and thus the majority of the incoming data needs to be discarded – only relevant information should pass for further processing due to performance and storage reasons. Also the amount of false observations is high. Such false measurements may originate from hardware and software failures and malfunctions as well as from deliberate spoofing. Thus, especial emphasis needs to be put on the outlier detection in the learning algorithms. The same also applies to the positioning algorithms in order to guarantee the integrity of the position solution, which aspect is especially critical in emergency call positioning. Thus, the stringent quality control, potentially based on information from a variety of sensors, is a priority aspect for the indoor positioning research.

Not only the data collection is challenging, but also the positioning process itself involves some fundamental choices even before the position is estimated. These choices directly relate to the user experience in terms of either speed of positioning or accuracy. To exemplify, one such choice includes the location of the position determination. In device-assisted positioning the device reports the set of appropriate measurements to the server. From the integrity and accuracy point-of-view this may be a preferred choice, because the server should always have the most up-to-date information. However, the speed suffers due to the network and database latencies and the requirement to have connectivity is problematic due to possible data transfer costs and when bandwidth-constrained networks are used.

The speed aspect can, of course, be addressed by having the positioning assistance database in the device. It should be noted that this is in any case required for indoor navigation in order to provide continuous position fixes at high rate. When the database is in the device, the response time is minimal and no connectivity is required. However, a potentially large database must have been transferred to the device beforehand. The question then for the algorithms developed for the devices is how to select the data that is maintained in the device and when the data is to be updated from the master database.

Lastly, yet another interesting perspective to the current discussion is the relationship between the indoor maps and indoor positioning. So far the de-facto approach has been the architectural separation of maps and positioning. The research, however, shows that accuracy can be improved by taking the floor plan information into account in the position estimation. This shows that the architectural choices made for the GNSS-based mass market solutions may not hold in the indoor case. However, the maps used for representing the user position may have quite different requirements from the ones used for positioning. Thus, it would be essential to understand, what needs to be embedded in the indoor maps in order to make them suitable to assist indoor positioning as well as how to collect such data. Another issue of course is how indoor maps itself could be collected with the help of the large user base, because indoor positioning and navigation capability without indoor maps is useless.

In summary the discussion shows that taking indoor positioning and navigation to the mass market is a wider challenge than simply a set of beacons and algorithms. Challenges arise from the uncontrolled positioning infrastructure in large scale, the wide range of devices used in the data collection and positioning as well as from the database maintenance and lack of indoor maps. The paper identifies several key areas, where research and development effort is required before indoor positioning and navigation is mature for the mass market adoption.

# Requirements for positioning and navigation in underground constructions

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## 1 Summary

Today's underground construction challenges with ever more complex project demands and massive capital investment on the one hand and steadily growing pressure on price and completion deadlines on the other hand. Therefore, successful tunnel builders increasingly rely on intelligent surveying solutions as an integral part of their tunnelling equipment.

Currently positioning is still a big challenge in an underground project. Amberg Technologies offers a surveying solution that sets new benchmarks in measurement and automation for conventional tunnelling. The actual surveying solution uses total station and laser scanning technologies. In this abstract the requirements for a positioning and navigation system for underground construction are explained.

## 2 Typical surveying tasks in underground projects

The network measurements in underground projects are often done with conventional total stations. For bigger projects additional gyroscope measurements are carried out in combination with total station surveying. The heading process (construction surveying) is usually guided with total station systems and/or alignment lasers. The system which is used for the heading process must be user friendly so that foremen and surveyors can use the system.

Typical surveying tasks in an underground project are:

| **Surveying task** | **Accuracy [mm]** | **Job done by** | **Data latency** |
|---|---|---|---|
| Heading guidance | 10 – 50 | Foreman | real-time |
| Deformation analysis | 1 – 5 | Surveyor | real-time/post process |
| Machine guidance | 10 – 50 | Foreman | real-time |
| Profile control | 5 – 50 | Foreman/Surveyor | real-time |

## 3 Environment

Underground projects have some special characteristics compared to civil engineering construction sites. Especially the environment with darkness, dust, humidity and the lack of space requires special work flows to optimise the construction process.

Requirements and challenges for such a system are:

- No intervisibility necessary between the sensors → lack of space, many obstacles
- Required accuracy between 1 mm – 50 mm → depending on the task

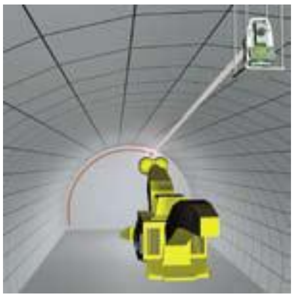
- Power supply → permanent availability
- Real-time data evaluation → just in time control
- Robust hardware → damages caused by ongoing construction (e.g. drill & blast)

## 4 Examples of surveying routines with TMS Solution

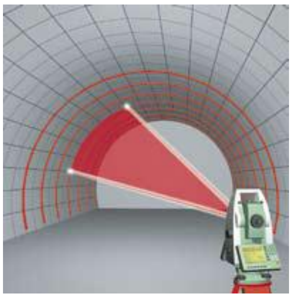
The operating concept of the tunnel measuring system (TMS) enables the foremen to perform routine surveying tasks themselves. Once the tunnel surveyor has set up the system, the crew can operate independently, using the total station as a motorised tunnel laser. That enables a highly flexible and productive work flow with less time on-site for the surveyor.

As easy as using a mobile phone, the tunnelling foreman can do the routine surveying tasks using the TMS SetOut Plus automatic functions in Production mode. Guided by the project-specific menu display, the tunnelling foreman selects a task rapidly and directly by pressing the function keys on the total station remote control.

Automatic set out of drilling points and orientation of the drilling carriage



Automatic, continuous display of the excavation profile



Immediate excavation checks and automatic visualisation of profile anomalies

Spot-on positioning of the arch formwork and setting out joint strips

## 5 Conclusions

Efficiency from the first round of advance to finished lining is the goal of any tunnel construction project. A key factor for project success is accurate excavation profile. Another key factor is to have a stable system with low maintenance work in a tough environment (changes in temperature, dust, humidity and vibrations).

One of the biggest benefits of total stations is that they can measure reflectorless. Additionally, the total stations used (e.g. Leica TPS1200) are sufficiently robust for this special environment. The total station is often mounted on a console which is located closely to the tunnel face (e.g. 10 m away). A big advantage is also the radio communication between the total station and the remote control. Therefore no additional cables are needed. Furthermore the receiver (prism) for a total station system doesn't need any power supply.

However, the flexibility and the achieved accuracy of some indoor positioning systems are impressive. To become viable alternatives to total stations in underground surveying in the future, they will have to meet the special requirements of the underground construction environment.

## GNSS Indoor, Pseudolites

Auditorium D2

Wednesday, September 15, 13:15 – 15:30

# A new Navigation System for Indoor Positioning (InLite)

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## 1 Summary

A new Indoor navigation system has been developed by Astrium which allows positioning of users inside large multi-level buildings with an accuracy of 2 metres without any aiding tools like inertial measurement units or other infrastructure inside the building. The possibility to navigate users in case of emergency inside a building is of high interest for fire brigade, ambulance, police or military operations. The InLite system consists of a set of 6 to 8 transmit stations positioned around the building, the user terminals inside the building and a monitoring and control unit for steering the transmit stations and for information broadcasting to the users. The transmit stations broadcast multi-carrier navigation signals with 40 MHz bandwidth from 420 to 460 MHz. The user inside the building receives the signals and calculates his position. The InLite signal design allows minimizing multipath effects so that the positioning accuracy even in massive multi-storey houses made of concrete, steel and metal-shielded windows reaches 2 meters. The InLite system has been successfully tested and presented to public at places in Germany and the UK. System architecture and measurement examples are presented and an outlook for future activities is given. This project is co-financed by the German Aerospace Center.

## 2 InLite System Architecture

Figure 1 shows the system architecture. The transmit stations (TC) are placed around the building. Each transmit station consists of an embedded PC, a navigation signal generator, a synchronisation unit in order to synchronize itself with the next neighbour transmitters, a GPS receiver for calculating the position of the transmit station, and a WLAN data link unit for exchanging data between the user, the monitoring and control station (MCS) and the TC´s. The ring synchronisation concept is started from one TC and leads to an overall synchronisation accuracy of 1 nsec for the navigation signals. This value is needed to achieve an overall indoor accuracy of 2 metres. Each transmit station is powered by a Lithium-polymer battery with 6 to 8 hours duration until the battery needs to be recharged. The navigation antenna of each TC can be expanded up to 4 meters above ground. Fig. 2 shows the set-up of a TC. Each user receiver (Fig. 3) consists of an embedded PC, a ranging signal receiver, a WLAN data link and a barometer. One of the TCs is equipped with a reference barometer and its data are distributed via WLAN network to each user receiver. This configuration allows a three-dimensional positioning. The MCS is the control unit in the system, which controls the TC´s. The MCS consists of a laptop. It provides a graphical user interface for the operator, broadcasts necessary information to the users (TC coordinates, reference barometer data, etc.), and also receives user information (position, etc.) for further analyses and monitoring.

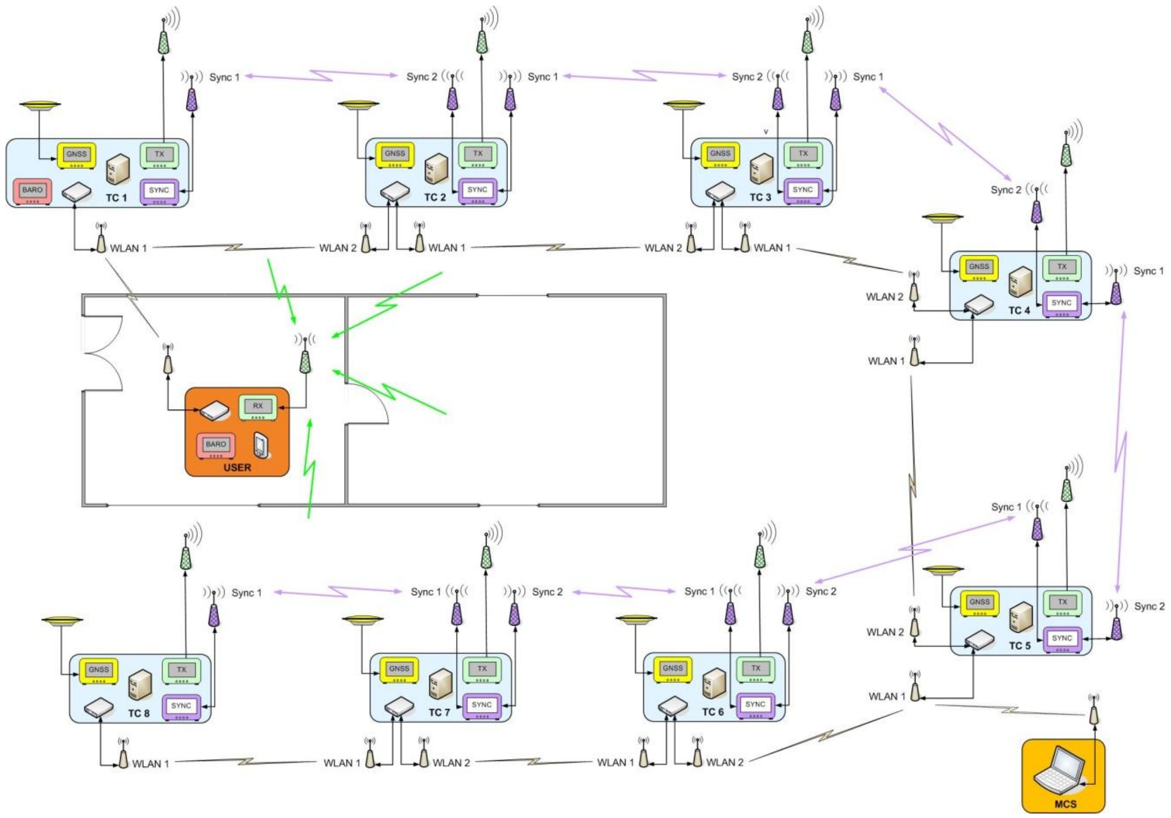



Fig. 1: InLite Architecture with eight Transmit Stations

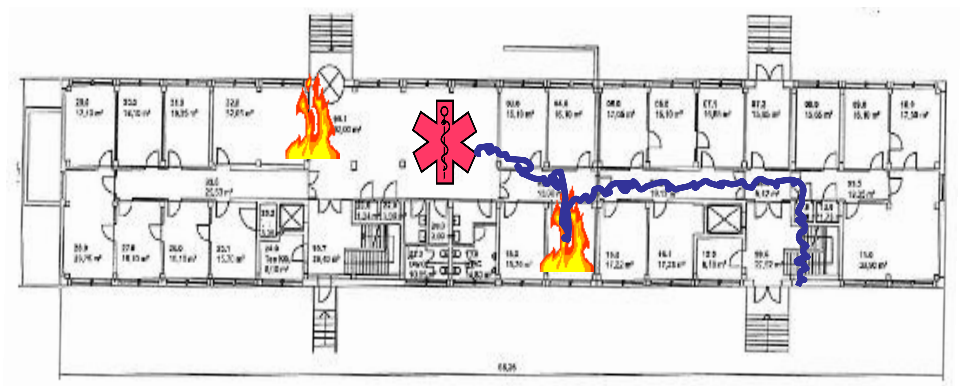

Fig. 2: Transmit Station Fig. 3 Test Receiver

## 3 Measurements

Measurements have been performed in different buildings. Figure 4 shows the results for a multi-storey building in Ottobrunn.

The five level building is made of reinforced concrete with outer walls of 60 cm thickness and metal coated windows. The results for a fire fighter scenario in the 40x10 m building are displayed. Required positioning accuracy is achieved for each floor. Results will be discussed at the conference.

Fig. 4: InLite Test Scenario



# Indoor Multipath Mitigation

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Today multipath errors constitute a limiting factor for the accuracy obtainable by satellite based positioning. Multipath depends on the environment. It cannot easily be predicted. Knowledge about the location can be helpful. In outdoor environment several secondary paths are arriving at the antenna. Multipath is not too difficult to mitigate outdoors.

Indoors the situation is different, and the signals are weaker. Moreover, we cannot always expect the direct signal to be present. So we cannot consistently remove all secondary signals in indoor positioning.

The research in the field is not yet mature. The research of indoor multipath error became a major scientific field about five years ago when the first high sensitivity receivers appeared. Most of the current algorithms for mitigation of multipath are not suitable in situations where we have more than three secondary paths and/or no line of sight (LOS) signal.

The present paper surveys what can be done to mitigate multipath indoors and describes some of the available techniques. We look for techniques which allow us to not just find the LOS signal, but also to extract all or at least the majority of secondary paths for further analysis.

The present study shows that out of approximately 40 known techniques, there are some useful ones which may be capable of dealing with indoor situations. Particularly we are interested in multipath mitigation techniques based on deconvolution. The main advantage of using this technique is that it is capable of distinguishing closely spaced secondary paths, under the assumption that enough samples of the signal are available. The more samples we have (or the higher sampling rate we use) the more clearly we can distinguish between two adjacent signals. This is an important property because the indoor secondary signal paths are close to each other in the time domain.

The scope of this paper is to show how the LOS signal can be better estimated and how to separate multiple paths indoors, even if they are closely spaced. We demonstrate this by using a controlled environment setup, e.g. using simulated signals. The usual deconvolution algorithm is modified such that it better identifies the individual multipath signals and yields an improved estimate of their time delay.

We tested the algorithm in various scenarios by differentiating each one using different SNR levels, changing the number of multipath signals, and changing the distances between separate signal replicas. The numerical examples demonstrate a much better performance of the modified algorithm compared to the traditional one. The results exceeded our initial expectations, because we found that we can separate secondary paths even at a very low SNR level when acquisition has difficulties in finding the signal at all. Knowing the number of secondary path signal replicas that are present in the channel and the distance between them will help to analyze how severe the multipath is, and adjust the situation accordingly.

Data sets created under controlled conditions are used for demonstration. The result of these tests show a better performance of the modified algorithm compared to the traditional one. Additionally, we compare some state-of-the-art techniques, but not other deconvolution based techniques.

Our analysis of various multipath mitigation algorithms with focus on heavy multipath environments will give a very useful overview for other research that is carried out in the field. We have found a few new useful techniques with a high potential to be used for indoor situations given that we have enough computational power. We also introduce our own enhanced method to mitigate multipath using deconvolution which shows promising results for indoor usage, at least in a simulated environment.

The numerical results demonstrate an improved performance. However, there are still situations we do not fully understand, so more investigations are needed. We are also interested in testing our new algorithm in real environments.

# Indoor Positioning Using GPS transmitters: Experimental results

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## 1 Summary

The paper presents the results of an experimental campaign of the GNSS transmitter based approach for indoor positioning. Details on the chosen setup are given and the main features of the system are fully described. Comments on the positioning obtained accuracies, together with the description of the real environment are provided and an in-depth analysis of the performance of the system is proposed.

For the next years the continuity of the positioning service indoors appears as a real challenge. GNSS, sensor networks or WLAN approaches are proposed in order to provide this continuity. The GNSS based approaches aim at making a better exploitation of the satellite signal on the receiver side. Unfortunately, techniques like HS-GPS or A-GPS do not seem to provide a definitive solution. Local infrastructure based solutions can aid to establish a final system with good accuracy and a large coverage: the approach described in the paper uses GPS transmitters that make GPS signals available indoors.

## 2 Experimental setup

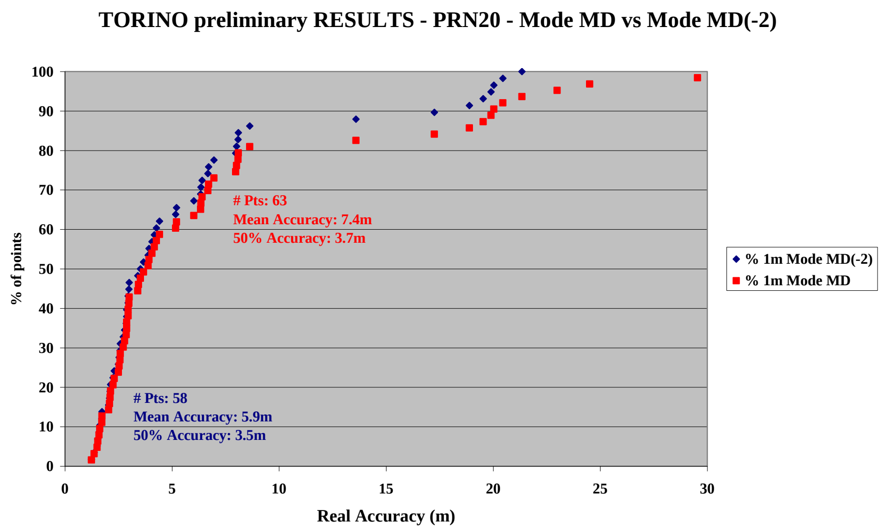
The system was deployed in Torino in the Telecom Italia premises. The GNSS repeater based approach, already described in previous papers, was used. The main features of the system are the following ones: a GSS6560 Spirent Generator is used to feed a set of four antennas located indoors, the so-called “repeaters”. This transmission is performed through coaxial cables, with no other treatment than amplification. Once the signals are received by the repeaters, they are retransmitted indoors by the repeater antennas. Since the simultaneous transmission would clearly create artificial multipath, a sequential approach is implemented, with only one repeater transmitting at a given time. A full cycle is obtained when all the four repeaters have broadcast the signal once. At the exact instant of the transition from one repeater to the next, a variation of the distance between the transmitting repeater and the indoor receiver occurs. After a complete cycle, one has four such differences available and may carry out the indoor 2D/3D location computations.

## 3 Modelling of the environment

A complete description of the indoor environment is made in order to define the best locations of the indoor antennas. It is then used to carry out propagation simulations that help us for the future analysis of the results, mainly in terms of importance of multipath for any given indoor receiver location. These simulations are carried out using the Ergospace tool and the paper gives a full description of the parameters used. Also described are the main constraints that must be followed in the current version of the system, such as the identical length of the cables which connect the Spirent to the repeater antennas, or the needed choice of the satellite codes generated by the Spirent in order to avoid outdoor interference.

## 4 Positioning results and perspectives

The main results presented include, among some other key points, the real accuracy obtained and the influence of multipath. Analysis of the pseudo-ranges evolution as well as the 2D positioning is provided using different calculation methods (namely the mean square and the sliding mode). Comments are also given concerning the best choice of satellites for optimising the positioning. Typical results are shown in the figure below.




Certainly the most interesting part of the paper deals with the very nice matching between the experimental results and the theoretical estimations. As a matter of fact, we used a NavX receiver from IFEN with 10 MHz of bandwidth. The receiving bandwidth is of upper most importance because the proposed indoor positioning method must be accompanied with adequate signal processing in order to remove the effects of multipath (we all know that this phenomenon is the most disturbing one indoors). Our approach is based on the use of the SMICL (Short Multipath Insensitive Code Loop) which reduces the error on pseudo-ranges down to a few meters, whatever the multipath. The SMICL needs a larger bandwidth than the usual 2 MHz, and the positioning results with the 10 MHz NavX are shown to be in very good agreement with the predictions.

Our future effort will be oriented towards a new experimental campaign with an even larger receiving bandwidth in order to definitively confirm the theoretical estimations. Indeed, an increased bandwidth of 15 to 20 MHz should provide the best positioning results.

# An Indoor positioning system using GPS signals

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**Abstract**

The civil Global Positioning System (GPS) has become very popular in recent years and it is in widespread use in many areas of application such as traffic management, navigation, medical emergency services as well as location based services in wireless handsets. Owing to the latest technological advances, GPS receivers are able to locate themselves with a standard deviation of 5 meters outdoors. Although GPS positioning is very successful in outdoor areas, it is hard to decode GPS signals indoors due to the additional signal loss of 10-30 dB that is caused by buildings and walls. There has been a wide research on indoor positioning systems utilizing different kind of technologies such as ultra wide band, RF, infrared and ultrasonic as well as hybrid solutions. These solutions can determine the position in indoor areas accurately. However, most of these solutions require to have their own infrastructure set-up which can contribute to large initial deployment costs. On the other hand, there are some cost effective indoor solutions that are based on existing infrastructures such as WLAN, GSM, and Bluetooth. As most of these systems are deployed for radio communication rather than positioning, the coverage of these solutions for positioning is limited to the infrastructure coverage. Due to a limited bandwidth and multipath propagation, the location calculated from the exploitation of the signals may not be sufficiently accurate in most cases.

In order to solve the indoor coverage problem, we propose a novel indoor positioning system based on GPS infrastructure. We propose an indoor positioning system that consists of GPS repeaters and a GPS receiver with an improved positioning algorithm. In order to analyze the proposed indoor positioning system, a novel directional GPS antenna with very low noise GPS repeaters and amplifiers has been designed, manufactured and measured. The positioning algorithms are implemented in a real time platform. The whole system is assembled and the positioning is achieved for the purpose of evaluation of the system performance. The results of the experiments show that the proposed system can be used for indoor positioning, and hence the continuation of the GPS service can be expanded indoors with additional repeaters to the buildings and a software update to the standard GPS receivers where the indoor coverage is needed. We have carried out an experiment in a hallway as shown in Figure 1, where there are no GPS signals due to heavy obstruction cause by the building walls. For various locations in the hallway, calculations are performed from the GPS data sent by the repeaters, and the positions with high accuracy (1 - 5 meters) are obtained as summarized in Table 1.

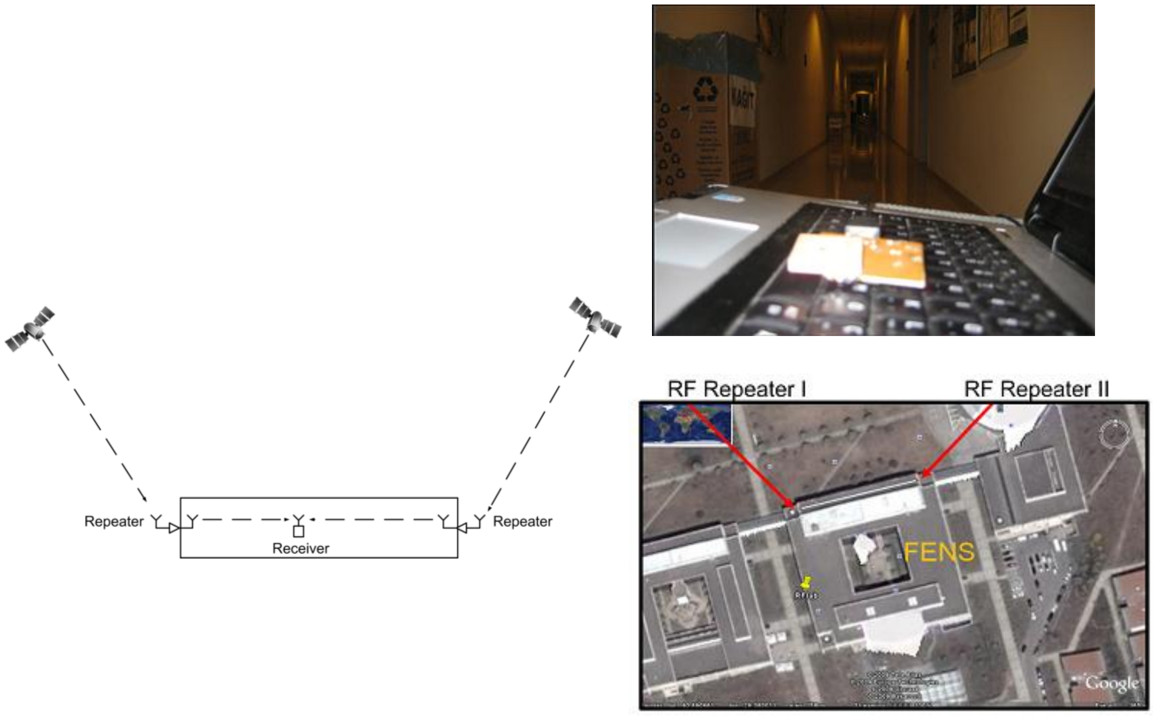


Figure 1: 1D positioning with 2 repeaters deployed at Sabancı University in the FENS building in a 60 meter long hallway

Table 1: Position errors obtained in the Sabancı University FENS hallway

| Distance from Repeater 1(m) | Number of samples | Calculated distance(m) (100 samples mean) | Error(m) |
|---|---|---|---|
| 12 | 100 | 11 | 1 |
| 12 | 100 | 9 | 3 |
| 18 | 100 | 13 | 5 |
| 18 | 100 | 15 | 3 |
| 27 | 100 | 31 | 4 |
| 33 | 100 | 34 | 1 |
| 50 | 100 | 53 | 3 |

# Pseudolite Indoor Localization Using Multiple Receivers

## - Performance Analysis of Increasing Receivers and Transmitters –

Yoshihiro Sakamoto(1), Haruhiko Niwa(2), Takuji Ebinuma(3), Kenjiro Fujii(4),
and Shigeki Sugano(1)

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*(3) University of Tokyo, Japan*
*(4) Hitachi Industrial Equipment Systems Co., Ltd., Japan*

## 1 Summary

The pseudolite has the potential to become one of the best solutions for indoor positioning due to its compatibility with GPS and its positioning accuracy. However, since cycle slips occur frequently indoors and their occurrence being difficult to predict, it is not easy to retain a sufficient number of consistent observation equations for the determination of position. There are two possible methods to avoid this problem: a) increasing the number of transmitters, which is known as an effective way for outdoor GPS, and b) increasing the number of receivers. In this paper, we evaluate the performance of these two methods for indoor positioning in terms of positioning success rates and the achievable accuracy. Our experiment shows that increasing the number of receivers is more effective than increasing the number of transmitters.

## 2 Introduction

Recently, GPS is the de facto standard for outdoor positioning because of its accuracy and availability. The advantage of using pseudolites is their compatibility with GPS; they can be built based on GPS devices, which have already been pervasive, with a minor change of their firmware. The goal of our research is to develop a pseudolite system that will achieve stable indoor positioning at centimeter-level accuracy. To accomplish this, one of the most appropriate techniques is real time kinematic (RTK) positioning. However, the RTK is subject to cycle slips, that are failures of the carrier phase tracking of the incoming signals. In our previous research, we proposed a method, that uses multiplex receivers as a solution for the cycle slip problem. This idea is similar to the increase of visible satellites for GPS in terms of the increase of the number of observation equations. This is not a direct solution for the cycle slip problem but the result is a higher redundancy that will improve the Positioning Success Rate (PSR). (PSR is the ratio between the time in which positioning is successfully done and the total measurement duration.) In this paper, we analyze the performance by increasing the number of receivers and transmitters for indoor positioning.

## 3 Pseudolite

Figure 1 shows the appearance of a pseudolite transmitter and receiver. The carrier frequency used in our system is 1575.42 MHz, which is the same as the GPS L1 band, and the PRN code numbers are 33 to 44. In order to keep the level under the Japanese license requirement, we set the output power from the transmitter's antenna to less than -70 dBm,. We used the SUPERSTAR II™ receiver from NovAtel Inc. as its hardware and OpenSourceGPS developed by Clifford Kelley et al. as its software. We multiplexed ten receivers - eight were used for the rover and two for the base station.

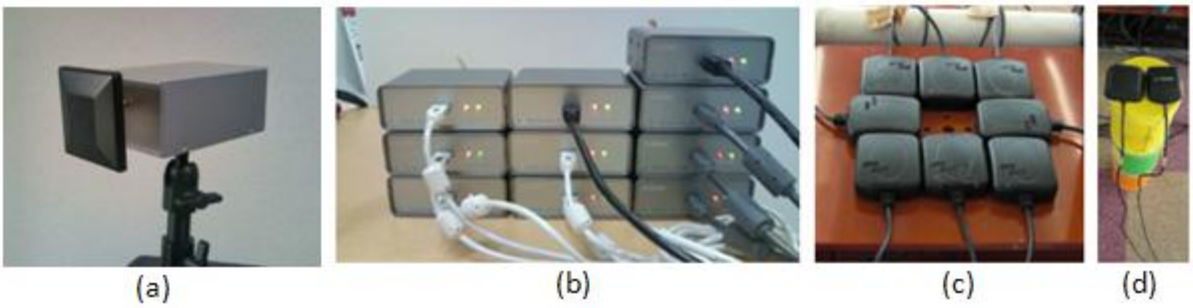

Figure 1: (a) transmitter; (b) appearance of multiple receivers; (c) and (d) are the antennas of the rover and the base station.

## 4 Experimental results

We deployed the transmitters on regular n-sided polygons with a radius of 2.5 m for each transmitter. We mounted the receivers on a robot and moved the robot 1 m back and forth for five round trips at a velocity of 20 mm/s. The data we got were PSR values (derived from cycle slip) and the positioning standard deviation. We made seven measurements using all receivers simultaneously as we changed the number of transmitters from 4 to 10. In each measurement, we captured data for 525 seconds at a rate of 2 Hz, which is equal to 1050 epochs. Figure 2 shows the results of the experiment. The picture on the left shows that the PSR gets close to 100% with an increase of the number of receivers. In the case of six or more receivers and six or less transmitters, the PSR is over 99 %. This also indicates that increasing the number of transmitters deteriorates the PSR. The picture on the right shows that as the number of transmitters increases, small position jumps occur frequently with the result that the positioning error gets larger.

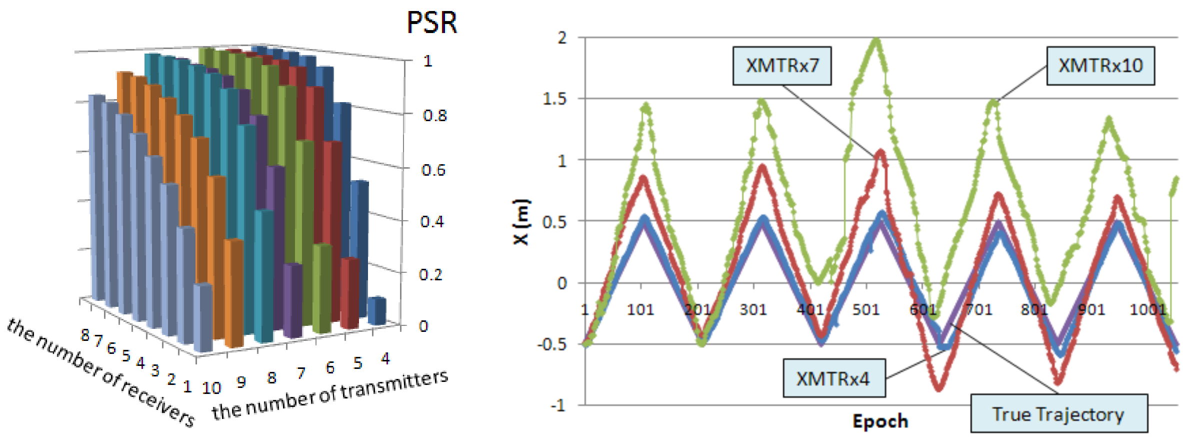

Figure 2: (left) relation between PSR and the number of receivers and transmitters; (right) estimated position on X-axis.

## 5 Conclusion

The experimental result suggests that increasing the number of receivers is more suitable than increasing the number of transmitters for indoor carrier phase positioning. The best explanation would be that the increase of transmitters increases the noise level in a room and deteriorates the signal reception. This finding could be a guideline for future research and applications, e.g., keep the number of transmitters to four, and change the number of receivers depending on the signal propagation conditions.

## High Sensitive GNSS

Auditorium D2

Wednesday, September 15, 16:00 – 18:00

Thursday, September 16, 08:15 – 09:45

# DINGPOS: High Sensitivity GNSS platform for deep indoor scenarios

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## 1 Summary

Deep indoor scenarios are one of the most challenging areas of application for satellite navigation (GNSS) in personal navigation devices. Especially severe signal attenuation, as well as heavy multipath is constraining the use of GNSS for deep indoor applications. The project DINGPOS is focusing on the development of a platform for pedestrian users which can acquire and track GNSS signals also in most adverse indoor signal conditions. The main idea of the concept is the extension of coherent signal integration time of the GNSS receiver to the domain of several seconds, which increases the correlation gain significantly. To facilitate this goal, a very long and very precise signal replica is needed. Therefore the system must reproduce the user motion, the navigation message data bits and the satellite constellation precisely. Hence the system uses a sensor suite of several state of the art indoor positioning sensors and innovative fusion algorithms.

## 2 Basic concept

Indoor GNSS scenarios are characterized by strong satellite signal attenuation resulting in very low signal to noise ratios (SNR) which makes acquisition and tracking of those signals very difficult. Since the rays are not travelling the same path for all satellites the attenuation of the individual signal varies strongly. This also bears the risk of false locks due to signal cross-correlation. Signal multipath is omnipresent in indoor scenarios and has a strong negative influence on the tracking performance of the signal tracking loops.

Increasing the coherent signal integration time seems to be a perfect way of dealing with the problems described above. Generally the SNR of weak signals is improved proportional to the square root of the integration time which compensates for the attenuation caused by walls. In addition to that, a coherent integration time of several seconds would mitigate three important indoor positioning problems: multipath, cross-correlation false locks, and the squaring loss. Common commercial of the shelf COTS receivers usually limit the coherent integration time to one code length, corresponding to 1ms of coherent integration time. High sensitivity receivers usually extend this up to the length of one navigation bit or 20ms.

Therefore a theoretical gain of up to 15dB and more could be expected by applying a very long coherent integration.

Nevertheless several aspects also prevent the use of very long integration times. Since data bit transitions can occur every 20ms, assistance data must be provided to the system and a reference station with open sky conditions must be available. In addition the internal clock often is not stable enough to provide sufficient accuracy for the replica construction due to oscillator jitter, if long coherent replicas are formed. Therefore a stable oscillator (OCXO) is necessary. The most challenging part is the reproduction of the user antenna motion with high accuracy to compensate the nonlinear dynamics on the pseudo-range and the signal Doppler frequency. The standard solution implies an inertial navigation system to reproduce the user motion during the integration interval. It turned out that current COTS micro electro-mechanical system (MEMS) type inertial sensors do not provide the stability to fulfill this task sufficiently, especially if they are aided by non-precise indoor position updates. Therefore an innovative algorithm had to be developed to reproduce the user motion by coupling a pedestrian navigation system with a modified inertial navigation system, called "micro-trajectory generator".

## 3 System Components

The DINGPOS platform contains several components and sensor subsystems to accomplish the tasks described above. The main integrating element of the entire system is a software GNSS receiver. The receiver integrates all additional sensors and subsystems and provides interfaces to a RF-front end, a MEMS type inertial measurement unit, a barometric sensor, a WiFi connection, a ZigBee connector and a precise OCXO type oscillator. Dead reckoning is performed by a pedestrian navigation system (PNS). The PNS uses the inertial measurement unit as main sensor, but also the built-in magnetometers and a barometric sensor. In the µ-trajectory generator the user motion is reconstructed to create the signal replica. Additional position updates are provided by the INPOS ZigBee based positioning system provided by Telespazio, as well as a custom WiFi based positioning system. The sensor readings are merged in an integrating Kalman filter to obtain a consolidated position solution.

## 4 Focus of the paper

The paper will give an overview on the developed DINGPOS sensor platform and its elements. This will include the sensors used in DINGPOS, as well as the subsystems and the algorithms merging the individual results. Several aspects of the algorithms will be highlighted. The performance of the unit has been tested in simulation and practical test campaigns. Since the project will be finished by the time of the conference, a final view on the concept and the performance of the unit can be provided.

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# Deeply Integrated GPS for Indoor Navigation

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It is widely recognized that the world has become reliant on Global Navigation Satellite Systems (GNSS) and specifically GPS for positioning and timing. It is also widely recognized that GPS availability and continuity cannot be assured when the signal is obstructed, for example, in urban canyons or indoors. Inertial navigation is seen as a critical system component when GPS is not available since it provides excellent short-term performance, but requires periodic external updates from various sources. Alternative GNSS technologies that can be applied for providing these periodic updates include electro-optic vision, human motion models, pseudolites, signals of opportunity and others. The obvious question remains, "what if the state-of-the-art GPS receiver technology is advanced such that precise GPS measurements can be extracted where they are unavailable today?"

The deeply integrated GPS receiver technology has been developed to enhance the robustness of GPS signal processing by implementing GPS/inertial sensor fusion at the signal processing level. As a result, this technology is capable of maintaining a complete tracking status (i.e., code phase, Doppler frequency and carrier phase) even for extremely week signals such as GPS signals that are attenuated by 30 dB from their open sky conditions. This paper will discuss the results of a feasibility study that was performed to provide precise (sub-centimeter-level) carrier phase GPS measurement indoors. The study was conducted using real data collected from actual GPS hardware in indoor scenarios.

The paper will overview deeply integrated receiver approach and then present results of the indoor GPS signal evaluation. Evaluation results will be presented for static and dynamic scenarios and will include characterization of the satellite availability, quality of GPS signal measurements (code phase and carrier phase) and identification of direct and multipath signals.

Three key components of the deeply integrated GPS receiver include:

1) Long coherent integration (on the order of one second) without any type of external aiding;
2) Open loop estimation of GPS signal parameters to enable rapid and robust tracking; and,
3) Identification of direct and multipath signal for mobile platforms with the subsequent capability to constructively utilize multipath signal reflections for navigation.

The deep integration eliminates conventional tracking loops and starts fusion of GPS and inertial data at the earliest processing stage possible by combining radio-frequency (RF) GPS samples with sampled inertial measurements. Inertial data provide the dynamic reference trajectory for the GPS signal integration inside GPS receiver correlators. Particularly, parameters of the internally generated replica GPS signal are adjusted for dynamic changes using the inertial aiding. Coherent signal integration over a one second interval is applied to recover very weak GPS signals (at a 15 dB-Hz level). The coherent integration time of one second exceeds the duration of data bits (20 milliseconds) in the GPS navigation message. A bit wipe-off is thus required to avoid energy losses during signal accumulation. A computationally efficient algorithm was therefore developed to search through possible bit combinations and choose the combination that maximizes the signal energy. The maximum energy bit combination is then applied to wipe-off navigation data bits. No external bit aiding is thus required.

Indoor applications are generally characterized by severe multipath conditions. On one hand, it is critical to distinguish between direct signal and multipath for robust localization. On the other hand, multipath reflections can be used as an additional source of navigation information, especially, for those cases where the number of direct path satellites is limited: i.e., instead of simply mitigating multipath reflections as it is done by conventional GPS receivers; these reflections can be used constructively for navigation purposes. In order to utilize multipath reflections in the GPS receiver architecture, multipath signal processing must be separated from processing of direct GPS signals. In indoor environments, accurate separation of direct and multipath signals using the code phase is generally not feasible due to close proximity of reflecting objects. On the other hand, instantaneous frequencies of multipath signals received by a mobile user can differ significantly from the instantaneous frequency of the direct path signal. These differences are primarily due to two factors: a non-zero receiver velocity, and significantly different line-of-sight (LOS) vectors from the satellite vehicle (SV) to the receiver and from the reflecting object to the receiver. As a result, frequency separation of direct and multipath signals can be efficiently utilized for independent processing of these signal components and subsequent use of multipath reflections in the navigation processor.

Deeply integrated technology was tested in three types of indoor environments: benign (e.g., a hallway outside an office with a window), moderate (e.g., a hallway away from windows), and difficult (e.g., deep inside a ground floor and away from windows). The experiments were conducted in two phases: one without motion (i.e., a static platform) and one with a moving platform. In the moving cases, in addition to direct signal evaluation, signal reflections from the floor and walls were identified and characterized.

Test results obtained indicate that GPS signal parameters can be reliably estimated in benign and moderate indoor environments. For the difficult environment, no satellites were detected using the current implantation; however, it is anticipated that signals might be found if the signal-to-noise ratio is improved via multi-platform and/or multi-satellite signal accumulation. Test results further indicate that the indoor satellite availability is generally quite sparse: i.e. a satellite can be available over a few-second interval after which it may disappear and then reappear again. As a result, GPS cannot be used as a sole mean of indoor navigation. However, the availability of even spares GPS measurements (carrier phase in particular) is extremely beneficial for the calibration of inertial error states and for improving robustness of other navigation aids (for example, for the initialization of depth of monocular video images). Therefore, deeply integrated GPS receiver is viewed as a key component of the multi-sensor fusion solution for indoor navigation.

# Doppler Rate Measurements in Standard and High Sensitivity (HS) GPS Receivers: Theoretical Analysis and Comparison

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Due to the capability of the Global Positioning System (GPS) to provide accurate, stable long-term navigation information, the use of a GPS receiver as an acceleration sensor has gained an increasing research interest. The receiver acceleration is typically computed from the Doppler rate measurements provided by the receiver carrier tracking loops. This leads to acceleration measurements with accuracies of a few $mm/s^2$ [1].

In addition to this, Doppler rate measurements can be used to improve tracking loop performance as suggested in [2]. In this case, Doppler rate information is used to aid the Numerically Controlled Oscillator (NCO) in order to produce a linearly varying local carrier frequency. This reduces the losses in the accumulated signal power. These losses are introduced by the mismatch between locally generated and incoming signals due to user dynamics. This is especially valuable in the case of High-Sensitivity (HS) GPS receivers where loops employing long integration time and low update rates are used [2].

There exist three different ways to estimate Doppler rate in GPS carrier tracking loops. The first option is to use the raw Doppler rate measurements obtained directly at the FLL filter output. The other two involve the use of a differentiator in order to derive Doppler rate measurements from other GPS observables such as carrier phase or, alternatively, raw Doppler measurements both provided by the Phase Lock Loop (PLL) [1], [3]. Thus, since Doppler rate measurements are obtained by processing the output of the carrier tracking loop, parameters such as the loop type and order, integration time and loop bandwidth strongly impact their quality.

The receiver acceleration can be obtained using either a Least Squares (LS) or Kalman Filter (KF) approach that extract the user acceleration from Doppler rate measurements. Thus, the final quality of the acceleration observations depends on the variance of the Doppler rate measurements and on the approach used for the acceleration computation. It is therefore desirable to be able to predict the quality of Doppler rate measurements, not only for quality control and for estimating the uncertainty of this information, but also for properly weighting the measurements in the LS and KF solution.

In this paper, a cohesive analysis describing the noise propagation process from the input of the tracking loops to the final Doppler rate and acceleration observations is provided. A theoretical model, allowing the evaluation of the Doppler rate accuracy is introduced and variance and bias of Doppler rate measurements are related to the carrier-to-noise density ratio ($C/N_0$), the user dynamics and the carrier tracking loop parameters. This type of approach is new and represents one of the main contributions of the paper. More specifically, a tracking loop can be approximated as a linear device extracting Doppler rate measurements from the input samples. The linear transfer function from the input noise to the final Doppler rate estimate is derived and the concept of Doppler rate bandwidth introduced. Doppler rate bandwidth parameter quantifies the portion of noise transferred from the input signal to the frequency rate estimates. The provided model is a generalization of the analysis provided in [4] where only Doppler frequency and velocity measurements were considered.

In order to get a complete model, all three types of Doppler rate measurements are considered. Moreover, the developed theoretical model is general and can be applied to different types of receiver architectures. To demonstrate this, this paper considers traditional sequential carrier tracking loops as well as a HSGPS receiver architecture adopting block processing techniques.

In addition to this, most of the studies in the area of Doppler rate/acceleration determination using GPS have been essentially limited to hardware receivers [1]. Hardware receivers do not provide any insight on how Doppler rate measurements are formed, preventing an accurate analysis at the tracking loop level. In this way, only the relationships between carrier phase or raw Doppler and acceleration have been investigated. Therefore, a Software Defined Radio (SDR) GPS receiver is used here as a fundamental tool for the analysis of the process of Doppler rate estimation. Given the benefits provided by a SDR GPS receiver, it was possible to achieve a deeper insight on the Doppler rate estimation process.

The SDR GPS receiver was used to support the validity of the developed theoretical framework that has been tested using live GPS data collected in various GPS operating environments. Both standard sequential and HS block processing architectures have been considered. Empirical results have been compared against the ones obtained using the developed theoretical model and in all cases the theoretical values were within 1σ of the mean of the empirical data.

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# On the state-of-the-art of GNSS signal acquisition – a comparison of time and frequency domain methods

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## 1 Summary

This paper summarizes high sensitivity GNSS signal acquisition algorithms used for ASIC and software receiver implementations. The pros and cons and those techniques are compared and discussed. Two algorithms (one ASIC algorithm in time domain and one software receiver algorithm in frequency domain) are implemented in a highly efficient way and are tested with a GNSS signal simulator and in real world situations. Both use the same L1/L5 RF frontend and operate on identical 2-bit samples. The sensitivity comparison is completed by including the newest commercial GPS chip evaluation boards in the test runs.

## 2 Motivation and Time Domain Correlation

High sensitivity GNSS signal acquisition is an approximately 10 years old technique and has revolutionized the GPS receiver market by extended the GPS service availability and allowing to integrate GPS chips into mobile phone handsets using cheap and low performing antennas. The techniques can be coarsely subdivided into time domain and frequency domain techniques. Many papers have been published but there are less concerning a comparison between both methods.

Reasonable acquisition in time domain requires a large number of correlators to detect signals in a limited time. This approach is implemented in hardware as a massive parallel correlation machine, built into the IFEN INTrack ASIC design shown in Figure 1. The INTrack-System has three main components – a navigation processing running on a COTS processor, the INTrack-ASIC that runs the acquisition and tracking, and the RF front end that performs analogue filtering, amplification, down conversion and digitalization. The INTrack-ASIC in parallel performs the acquisition on separate channels and has a double buffered correlation, and an elaborated mixed signal tracking in several channels.

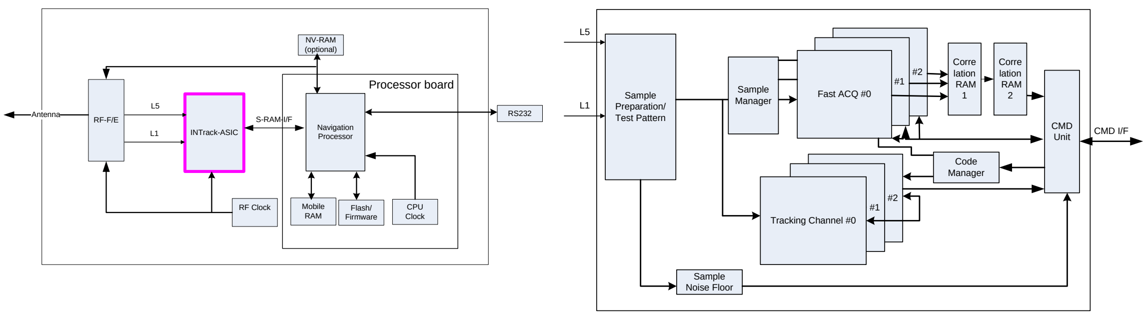


Figure 1. INTrack block diagram with a time domain acquisition scheme

The architecture allows to run either a larger set of Doppler bins in parallel for the same code, or to run a cold start scan over different codes. The coherent integration time may be set from 1 to 200msec and up to 2sec for non-coherent integration. The design also has the flexibility to deliver partial correlation products to a software post processing that may use a combined coherent/non-coherent approach. Tests have shown that the implementation is capable to detect signals down to 15 dBHz (with 20 ms coherent x 50 non-coherent) in a reasonable time using the built-in coherent/non-coherent integration.

## 3 Frequency Domain Correlation

Spread spectrum code acquisition with Fourier techniques have been first described in 1990 by Cheng et al. and search one Doppler bin for all code phase values in parallel by employing the convolutional theorem. For quasi periodic PRN code signals like the C/A code (it repeats itself 20 times within one data bit), the coherent integration time can be extended from 1 ms to 20 ms with Doppler-preprocessing causing only small additional computational costs as pointed out by Akopian et al. some years ago. For tiered code signals, a Doppler-preprocessing method focusing on peaks of the secondary code spectrum uses a similar methodology but needs generally higher computational load. If precise time assistance data is available, the inverse FFT of the convolutional theorem can be expressed with a much smaller length, thereby reducing the computational load. For the IFEN SX Navigation Software Receiver an efficient implementation of the Doppler-preprocessing method has been selected and is depicted in the left part Figure 2; a 17 dBHz correlation peak is shown for a real GPS C/A code signal. We used 200 x 16 ms, cancellation of strong GPS+GATE E1 signals and narrow band interference mitigation.

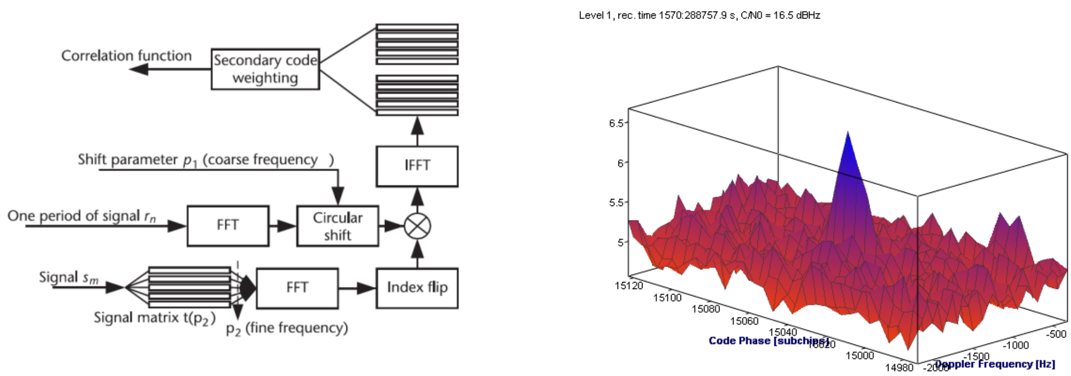


Figure 2. SX-NSR frequency domain acquisition scheme and correlation result for a real GPS C/A code (PRN 22) signal

Acquisition algorithms can not only be compared in terms of sensitivity. Most importantly, the number of mathematical operations or the number of gates defines the implementation costs. For periodic signals, frequency domain techniques show in an asymptotic $N$*log($N$) increase of the required number of operations (N ~ coherent integration time) whereas time domain correlation has an $N^3$ increase. However, the matched filter structure is well implementable on an ASIC. In the INTrack time domain correlation, code rate and Doppler shift can be freely adjusted, whereas frequency domain techniques use post-correlation compensation techniques to account for the code Doppler. Furthermore, frequency domain correlation allows only a finite Doppler bin size related to the coherent integration time. Doppler mismatch losses may reach values up to 3.9 dB. On the other hand, narrow band interference is easily mitigated in the frequency domain.

# Galileo / GPS Indoor Navigation & Positioning for SAR and Tracking Applications

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## 1 Summary

"INDOOR" is a German research project for providing a combined outdoor/indoor navigation capability for location based services of security-sensitive applications (SAR) as well as for important professional logistic or tracking applications, e.g. asset/child tracking. The project consortium is built of nine partners from industry, research institutes and universities with IFEN GmbH being the coordinator of the project. The work is funded by the German Aerospace Center DLR to support future applications for outdoor/indoor scenarios with a focus on the combination of GPS and Galileo, accompanied by assisted information. The activities undertaken in the project follow a three phase approach, consisting of phase 1 Core Technologies – Concept & Evaluation, phase 2 Core Components – Development & Verification and finally phase 3 Application / Demonstration, planned to take place by the end of year 2011.

## 2 Abstract

"INDOOR" is a joint research project consisting of nine German partners led by IFEN GmbH for providing a GNSS based outdoor/indoor navigation solution for location based services of security-sensitive applications (SAR) as well as for important professional logistic or tracking applications, e.g. asset/child tracking. The project INDOOR (http://www.indoor-navigation.de) is funded by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) with financial resources of the German Ministry of Economics and Technology (BMWi) under grant no. 50 NA 0504.

The motivation for the project was the fact that Galileo/GPS satellite infrastructure mainly addresses the navigation markets with direct line of sight (outdoor area) to the satellites. Many professional applications need positioning and navigation also inside buildings, halls etc. (indoor area), without direct line of sight to the satellites. Thus, a combined outdoor/indoor navigation capability is the key technology for location based services of security-sensitive applications (police, search and rescue, fire brigades etc.) as well as for professional location-based services, e.g. asset/child tracking. However, positioning and navigation inside buildings (indoor) or in „indoor-like" outdoor environments with bad visibility, signal damping, severe multipath etc. are very challenging for Galileo/GPS receivers. Therefore one main driver in the frame of the project is to develop a Galileo/GPS satellite navigation based solution, the INDOOR INTrack ASIC, which is small enough for mobile applications and having the power to get position results even under heavily deteriorated signal conditions, accompanied by external information like assisted data, inertial MEMS sensors etc.

The project is divided into three main phases, which are outlined in the paper.

Phase 1 Core Technologies – Concept & Evaluation: Here GNSS high-sensitivity technologies, assisted-GNSS & hybridisation in communication networks, modelling and calibration of INDOOR channel as well as combined information & hybrid sensors are investigated.

Phase 2 Core Components – Development & Verification: This phase analyses appropriate development platforms, antenna & HF-frontend, digital baseband processing, navigation algorithms, external sensors etc. Also the required verification tools: an IF-signal simulator, a HF-INDOOR signal generator using raytracing with 3D building models to generate realistic indoor multipath conditions and a SUPL 2.0 based assisted-Galileo server are investigated. Verification of the tools takes place in the GATE testbed in Berchtesgaden.

Finally, in the frame of the third phase, a selection of the developed prototype hardware and software is utilized to support two defined INDOOR demonstrations, a SAR Demonstration with the fire brigade of the Munich Airport and a child tracking demonstration with Disney Germany.

The paper gives an overview on the different activities of the project and presents first results of the 3D multipath simulator processing data of test buildings at the Munich Airport demonstration site. Furthermore, design and functionalities of two mobile positioning terminals, a PDA based user terminal with the INDOOR INTrack ASIC core development and a small-size low power GNSS based child tracking module will be presented in the paper. Finally, information on the planned demonstration scenarios will be given, i.e. the SAR demonstration with fire brigades of the Munich Airport using the PDA based user terminals and the child tracking demonstration at an event/location organised by Disney Germany, using the GNSS based child tracking modules.

# GNSS Positioning in Adverse Conditions

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## 1 Summary

High Sensitivity GNSS has made satellite navigation possible even in those environments which do not favour satellite signals. In environments such as forests, urban canyons, and even some building interiors, GNSS signals are not entirely obstructed, but rather attenuated. GNSS positioning is based either on the receiver's internal solution or on the processing of raw observation data. In adverse conditions, basic code-based solutions can cause major errors in the estimated position, primarily due to multipath effects. Positioning performance can be improved however, using appropriate processing of code and Doppler observations. Besides the common procedures for estimating the receiver's position, robust estimation methods have been used to minimise the effects of gross observation errors. Differential GNSS, elevation and SNR-dependent weighting do not perform well in adverse conditions where signal reception is poor.

## 2 High Sensitivity GNSS

High Sensitivity GNSS (HS GNSS) receivers are able to track very weak GNSS signals by employing a large number of correlators and by integrating the received signal over longer intervals than is common for regular GNSS receivers.

Most HS GNSS instruments output their processed data via NMEA messages; only a few of them are able to output raw observation data. All current HS GNSS receivers are only able to track GPS satellite signals on the L1 frequency. The processed observations are usually code pseudo-range, carrier phase and Doppler observables. A value for the signal-to-noise ratio (SNR) is usually available.

Determining the receiver clock offset and 3 coordinate unknowns is the goal of processing the raw observation data. The most common method of estimating an unknown position is the least square adjustment. The position and the clock offset of each satellite are derived from the navigation message. The basic positioning mode is autonomous, using only the code pseudo-ranges. Even under normal conditions, the error budget of a pseudo-range can exceed 10 metres. Differential GNSS (DGNSS) can mitigate some of the ionospheric delays and effects on the observations. However, DGNSS presumes similar conditions in the proximity of the base and the rover receiver. In other words, DGNSS does not significantly improve the rover's position when the rover is in an unfavourable environment for signal reception.

## 3 HS GNSS Raw Data Processing and Test Results

The custom developed processing procedures were tested on u-blox 4 and 5 series of HS GPS evaluation kits. The u-blox 4 series is only able to perform carrier-phase observations from strong signals. Therefore, the processing of raw data was limited to code and Doppler observations only.

Positioning based on code pseudo-ranges can cause large position errors in adverse conditions. Doppler observations point to changes in the range between the receiver and the satellite, hence reference ranges are required. Doppler measurements have similar characteristics to carrier-phase observations with some additional advantages, namely that cycle slips, which occur frequently in carrier-phase observations in adverse conditions, are of no consequence. Doppler positioning yields better results than code-only solutions, although it is not without its weaknesses. The most evident defect of the Doppler-only solution is a change of path-scale.

The developed solution is based on a combination of code and Doppler observations. The receiver clock offset is determined by Doppler observations only, thus protecting the offset determination from the sudden jumps which significantly affect code observations. The position is determined afterwards using the code pseudo-ranges and Doppler observables. Both types of observables are assigned the same weight. A robust estimation using the L1-norm weight function is applied, thus minimising the effects of gross observation error.

The tests were performed under different conditions, from good to partially adverse conditions, heavy multipath environments and even indoors. DGNSS does not work well in adverse environments. A weighting function which depends on the elevation and the SNR can work well in some instances, however, in other instances it can also cause large errors in the solution.

## 4 Conclusions and Outlook

By using HS receivers, GNSS navigation is possible in environments with a high degree of attenuation and multipath. Basic code-based positioning can cause large errors in the position and is therefore not particularly suitable to conditions that do not favour signal reception. Multipath is the main contributor to the error budget for code-only observations.

Improvements in the final solution can be achieved using a proper method of raw data processing by combining code pseudo-ranges and Doppler observations. The effects of gross errors on the estimated position can be significantly reduced by using robust estimation methods. The most critical aspect is the initial position which has to be determined by code pseudo-ranges only.

Further research includes the acquisition of a better initial position. This could be achieved by using DGNSS if the survey were to begin under normal conditions. DGNSS could also be used in any part of a survey in a certain mode. GNSS could be combined with other positioning technologies to achieve seamless navigation and improved results. The most promising technology for such a combination would be to use ultra-wideband positioning systems.

# Composite GNSS Signal Acquisition in Presence of Data Sign Transition

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Personal navigation and location based services using GNSS have gained worldwide popularity and extensive exploitation in recent years. This has been fueled by an increase in the number of consumer electronic devices in the marketplace, such as mobile phones, PDAs and popular in-car navigation systems that come equipped with GNSS receivers. As these devices become increasingly popular, their uses and applications will inevitably extend towards more challenging and harsh environments such as shopping malls, urban canyons and office buildings, where signal attenuations are introduced because of the existence of blocking obstacles (e.g. walls, floors, etc.). Consequently, high-sensitivity (HS)-GNSS receivers become essential to cope with such a severe impairment while still providing precise positioning information even though the radio environment is far from ideal at urban and indoor locations where extremely low power signals dominate. Location information of navigation devices in indoor environments has become a key issue for many emerging applications.

In the context of GNSS receiver design, the most critical part is related to signal acquisition for initial synchronization particularly in harsh environments. The signal acquisition provides coarse code epoch and Doppler shift estimates that will have to be refined later by subsequent signal tracking modules. For the particular case of HS-GNSS receivers, stringent requirements are imposed on the GNSS receiver sensitivity with the aim of reliable and robust signal acquisition at very low $C/N_0$ values.

The new ranging signals broadcast by modern Global Navigation Satellite Systems, such as the European Galileo, the modernized GPS and the Chinese Compass, exhibit several modulation novelties to meet the growing demand of location, navigation and positioning services. Among the several modulation novelties and new signals design, the presence of two channels, the data and pilot components, the adoption of tired codes obtained by cascading secondary and primary codes are just two examples of these innovations. These new modulations will allow for the development of more sophisticated and innovative techniques specifically to acquire the new composite GNSS signals.

Galileo will provide a navigation message at a higher bit rate with a consequent possibility of a bit sign transition in every spreading code period. Therefore, the bit sign transition could possibly occur in any primary code period. In this case, if FFT’s are used to perform the circular correlation, the bit sign transition occurring within an integration time may cause a splitting of the CAF main peak into two smaller lobes along the Doppler shift axis.

In this paper, the bit sign transition problem is analyzed in detail and the CAF peak splitting effect dependent on the bit sign transition position in the signal segment is also deeply investigated. It has been proved that the presence of bit sign transition does not destroy the information on the presence of the satellite in view, but it introduces an erroneous Doppler frequency shift estimation. The main effect of the CAF peak splitting along the Doppler frequency shift axis is an erroneous frequency estimation, while as far as the code phase delay is concerned, this CAF peak splitting produces a correlation amplitude reduction, without changing its correct peak position. In this paper the two steps signal acquisition scheme will be exploited in order to deal with such a CAF peak splitting effect. The main idea of the two steps acquisition scheme is to take advantage of these two disjoint effects affecting the CAF peak along the code phase delay and Doppler shift axes, respectively. The algorithm first try to recover the code phase delay in the first acquisition step so as to roughly remove the bit sign transition in the received signal and then to recover the correct estimate of the Doppler shift in the second acquisition step. In order to speed up both acquisition steps the fast acquisition approach based on FFT's has been adopted.

Due to the availability of data and pilot components separately broadcast in the new composite GNSS signals, the drawback of using only single channel independently is that half of the transmitted power is lost. When acquiring composite GNSS signals, such as the Galileo E1 OS modulation, if ignoring the pilot channel and processing only the data channel signal, only half of the useful signal is exploited and the GNSS receiver could not acquire signals that would be easily processed if all the useful signal power were used. This loss can be particularly troublesome at the acquisition stage especially in weak signal environment. In order to overcome the power loss problem and also to mitigate the CAF peak impairments, novel non-coherent, coherent and differentially coherent channels combining techniques employing the two steps acquisition scheme have been firstly proposed for jointly combining both data and pilot components to recover all the transmitted power from both channels.

In this paper, the aforementioned channels combining techniques for the joint acquisition of data and pilot components of the new composite GNSS signals have been deeply characterized from a statistical point of view. In particular, the false alarm and detection probabilities are given for each channels combining strategy. In order to support the theoretical analysis, Monte Carlo simulation campaigns have been performed on the simulated Galileo E1 OS signals to evaluate the performances of the proposed techniques. These simulation results have revealed that the proposed two steps based channels combining techniques provide much improved performance with respect to the conventional single channel acquisition and the single channel two steps acquisition approaches, which prove the advantages and effectiveness of the developed techniques. These proposed techniques solve the CAF peak splitting problem in presence of bit sign transitions and also enhance the acquisition sensitivity specifically adapting to weak signal environment.

In summary in this paper the novel channels combining techniques based on two steps acquisition scheme have been proposed for effectively recovering all the transmitted power in both available data and pilot channels and dealing with the bit sign transitions problem to fit the new GNSS signal modulation requirements. The proposed innovative acquisition techniques improve the performance and provide more reliable signal detection even in weak signal environment, which can be applied to the new composite GNSS signals where the secondary codes could change the relative polarity every primary code period. It is important to emphasize that a greater computational load is generally required to perform the acquisition process for each channels combining strategy when two steps acquisition scheme is adopted.

# Evaluation of a Peer-to-Peer Kalman Filter in Weak-Signal Areas using a Software GNSS-Signal-Simulator

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## 1 Extended Abstract

Since December 2005 95% of a network operator's in-service phones in North America must be Enhanced-911 (E911) compliant as induced by the E911 mandate from the U.S. Federal Communications Commission (FCC). E911 requires a position fix as soon as an emergency call is placed by a mobile phone. At the beginning mainly radiolocation techniques like Angle of Arrival (AoA) or Time Difference of Arrival (TDoA) were favored but this mandate soon became a major boost for integrating GNSS chips into all kinds of mobile devices. 30 % of all mobile phones that have been and will be sold between 2009 and 2011 are equipped with a GNSS chip [1]. This also changed the way satellite navigation is used today. Compared to May 2000 when the selective availability (SA) had been turned off and car navigation via satellite signals started to be interesting for civil users, many people today use their GNSS-enabled mobile phone or PDA also for pedestrian navigation. But this means that satellite navigation has to provide a position also in areas where it has traditionally not been intended to work like urban canyons or even indoors.

This development paved the way for Assisted-GNSS (A-GNSS). A server attached to a reference station provides assistance data (ephemeris, Doppler frequency etc.) to clients within an ambit of 100 km [2]. Although the number of mobile devices that are not able to apply assistance data is decreasing, the majority of mobile phones are still not equipped with a suitable unit. The usage of A-GNSS is also a matter of increased traffic load and costs for the necessary data transmission, which is paid by the user. In cases when decoding of the navigation data is not possible due to the low $C/N_0$ the assistance data facilitates the computation of position. Nevertheless the device at least must be able to track the satellite signals. In deep indoors not even this might be possible.

To avoid these drawbacks an approach was introduced for devices equipped with a compass or magnetometer, a pedometer and GNSS chip in [3] and [4] which favors local, temporal ad-hoc networks between mobile devices instead of requesting assistance data from a distant server. As soon as the mobile device is not able to acquire or track satellite signals it begins navigating by means of dead reckoning. The position estimated by dead reckoning can be improved by a Kalman Filter mutually applied on two or more users' devices. As the inertial computed position deteriorates with time each reacquisition of GNSS improves the users' position to standard GNSS error range again and can, thanks to the mutual Kalman Filtering, increase the precision of the users in the neighborhood. The simulations in [3] and [4] revealed some promising results but do not address a realistic view on the signal strength within buildings. The intention of this paper is to evaluate the peer-to-peer Kalman Filter as

introduced in [3] and [4] using a Software-GNSS-signal-simulator to emulate an indoor area in a more realistic way.

The signal simulator has been developed at the Institute of Geodesy and Navigation and deploys well-known models for outdoor signal decay, the Lutz-Jahn model [5] and indoor signal fading, the adjusted Saleh-Valenzuela [6] model. It provides a complete model of satellite-to-indoor channel and generates a “signal map” for different positions in a prototype building. Based on this map the performance of the peer-to-peer Kalman Filter is examined. A prototype building is emulated characterized by various parameters (e.g. levels, material etc.). In this building the movement of a number of users, here called peers, is simulated. The main focus of this paper is to verify the requirements of the simulation as described in [3] and [4] and to check whether this approach also proves of value when tested in a more realistic environment. Different scenarios are emulated and the practicability of the peer-to-peer Kalman Filter regarding position accuracy is examined. The modeling and simulation of the signals indoors offer a better view on the possibilities of pedestrian navigation in buildings.

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# Pulse shaping investigation for the applicability of future GNSS signals in indoor environments

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**Abstract**

One of the greatest challenges in Global Navigation Satellite Systems (GNSSs) is to provide users with sufficiently accurate position information in indoor environments where multipath propagation effects constitute a dominant source of error. So far, the majority of the satellite-based positioning methods are designed and optimized for outdoor scenarios and whenever indoor positioning is required, the use of assisted information by a mobile network is typically considered. While the use of satellite signals for indoor positioning has been regarded particularly challenging (i.e., due to the highly attenuated signal power), the introduction of new GNSS signals with improved characteristics acts as our ignition to study further their applicability indoors.

Depending on the receiver device and the positioning requirements, the carrier phase or the code delay of the signal can be used for estimating the distance between a satellite and the receiver. More precisely, carrier-phase based positioning is advantageous for applications with high demands on positioning accuracy since it can provide range measurements of sub-centimetre level. For devices in which cost is the main driver (e.g., mass-market Global Positioning System (GPS) receivers), the less complex alternative of code-based positioning is utilized. Carrier-phase information can be also incorporated in code-based range measurements (e.g., for smoothing) for improved performance, while keeping the implementation complexity at moderate level.

Regardless of the type in use (i.e., carrier-, code- based or their combination), the aim of enhancing further the positioning performance is a common denominator. A proactive approach is the one focusing on the optimization of the signal characteristics upon generation. For example, for GNSS signals such characteristics can be the modulation type (e.g., Binary Offset Carrier (BOC), Multiplexed BOC (MBOC) or other BOC variants), the Pseudo Random Noise (PRN) code and the pulse shape. While the first two have been extensively investigated in the literature, studies on the choice of the optimum pulse shape for the new Galileo and modernized GPS signals are modest. More precisely, the adoption of BOC modulation in the future GNSS signals introduces new challenges in the tracking stage which have not been considered in the traditional Code Division Multiple Access (CDMA) systems. Compared to the Binary Phase Shift Keying (BPSK) modulation used in GPS, with only one triangular shaped peak in the envelope of the AutoCorrelation Function (ACF) (if unlimited bandwidth is assumed), BOC modulation results in more complex shape of the ACF due to the presence of multiple peaks (e.g., the possibility to track a wrong peak is higher).

In this paper, we study the impact of different pulse shapes in the estimation of the signal's code delay and the carrier phase. The Cramer Rao Lower Bound (CRLB) has been chosen for the performance comparison. More precisely, we employ two types of bounds, both of which have been derived by the authors in a different research paper (submitted in International Journal of Satellite Communications and Networking). The first one, called single CRLB (sCRLB), represents the CRLB for a single parameter vector (i.e., code delay or carrier phase) that contains the values of each channel path and assuming that the other parameter is ignored (e.g., it is perfectly estimated). The second type, called joint CRLB (jCRLB) is used in the case where the code delay and the carrier phase are jointly estimated. The reason for employing both single and joint CRLB is to explore the impact of the various pulse shapes in each of the three cases (i.e., code-only, phase-only and code-phase combination) since all can be encountered when modelling a GNSS receiver. The novelty of this paper consists in applying the above-mentioned model created by the authors to various pulse shapes (rectangular, Root Raised Cosine (RRC), sinc and triangular) in order to find out the requirements for the best GNSS pulse shape in terms of delay tracking accuracy.

In order to test the performance with various pulses, we apply a semi-analytical approach, where the theoretical derivations are combined with Monte Carlo type of simulations. We focus on the future Galileo Open Service (OS) signals which, according to the latest standards are using Composite BOC (CBOC) modulation (i.e., a variant of MBOC modulation). Regarding the channel setup, we will focus on the static multipath channel because we would like to investigate the maximum achievable performance, and because modelling the phases in fading channels introduces additional errors. The channel model follows a decaying Power Delay Profile (PDP), where the number of channel paths varies between 1 and 4 and the carrier phase offset of each path is uniformly distributed between $-\pi$ and $\pi$. The time separation between successive paths is chosen in such a way, that it covers three cases of path separation: closely-spaced (i.e., more likely to be encountered in indoor scenarios), moderately-spaced and distant-spaced. At the receiver side, both infinite and finite bandwidth cases are considered; the former for reference purpose and the latter for realistic representation.

We expect the simulation results to shed light upon the impact of various pulse shapes in the estimation of the signal's synchronization parameters. Also, the results will indicate what the best choice of pulse shape is for indoor environments and whether we need to employ different shapes when dealing with code-based or carrier phase-based estimation. Such a way of optimizing the performance of the receiver's synchronization module is one of the several methods we study in our endeavour into mitigating the effects of multipath propagation, which is our main longer-term research direction.

# Indoor positioning using low cost GPS receivers: tests and statistical analyses

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## 1 Summary

In recent years, GPS chipset technologies have been changed completely in order to allow for positioning under extreme conditions, such as in indoor environments. The necessity of always having a positioning capability is rising, but what accuracy level can be reached? Some specific tests have been carried out to estimate the limits for indoor positioning. It has also been evaluated whether this technique can be used for GIS applications. A low cost receiver tailored to indoor positioning, has been used in several tests in a test field, in both kinematic and static mode. The results show that the obtained performance in indoor positioning is encouraging, but still needs to be improved using additional sensors (i.e. INS, RF).

## 2 Introduction

Indoor positioning is a novel challenge in the field of navigation. It can be realized by combining different signals such as radio frequency localization (i.e Beacon, Wi-FI) or integrated methods such as image-aided inertial navigation (INS and images) or when possible, the use of the newer GPS chipset that has been dedicated to indoor/hybrid positioning. In our research, the latter approach has been adopted, focusing in particular on the accuracy level that can be obtained.

In order to obtain a statistical analysis, a low cost GPS receiver devoted to indoor positioning has been used in several tests. The solution obtained with this receiver, in both real time and in post-processing, has been compared with a reference solution which was defined using traditional topographic instrumentation.

## 3 Tests

In the first step, a test field composed of trajectories and control points was established and the reference coordinates were determined by topographic methods (a total station). This way a mm-level of accuracy of the trajectory and the control points could be achieved, see Figure 1(a).

A cart with a pole, a laptop and a battery array was instrumented, see Figure 1(b). A patch antenna was placed over the top of the pole. A u-blox 5T GPS receiver was used during the tests because this sensor allows both, indoor positioning and the dynamic model to be set.

Static and kinematic sessions were held in order to assess the difference performances,. During the static session, each control point was occupied for 10 minutes. A post-processed solution and a “epoch-by-epoch” solution were been determined for each session a PVT solution,. Each trajectory was covered many times, in order to be able to conduct a statistical analysis.

Figure 1 (a): Topographic relief

Figure 1 (b): Instrumented cart

## 4 Results

The raw data of each static session has been processed using two different commercial software packages: Leica Geomatic Office (LGO) and Waypoint GRAFNAV. Leica realizes a standard solution that is only a filtered solution. Using GRAFNAF, it is possible to estimate a combined solution (forward + reverse), which is fundamental when kinematic single frequency data are processed, in particular if the phase ambiguity needs to be solved. These solutions usually offer good performances, but in our case the bad pseudorange and the low quality of the carrier phase have had a negative influence on the results.

In the static tests, each solution offered a lower quality than the pseudorange solution even though L1 was acquired. The difference between the estimated solutions and the reference points was about 4.5 – 8 m.

The kinematic solutions that were carried out take into account all the trajectories, but the accuracy was quite low. The metric differences were been assessed, comparing this solution with the reference. An example of trajectory is shown in Figure 2, which compares the reference measurements with the kinematic GNSS ones

Figure 2: Indoor kinematic test

## 5 Conclusions

The latest GPS receivers devoted to indoor positioning allow 3D coordinates to be determined, even in hard conditions. An accuracy equal to 4.5-8 meters is not enough for topographic applications, but if additional sensors (i.e RF, INS) are considered, these performances could be improved.

## Applications of Location Awareness

Auditorium D2

Thursday, September 16, 10:15 – 11:45

# Evaluating the Behaviour of Museum Visitors using RFID

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## 1 Summary

Museums are interested to learn about their visitors: what do they do, where do they go, how long do they stay, where do they spend their time? RFID is used for a cell-based localization of visitors in museums: visitors carry RFID tags, reception ranges of the RFID antennas define the localization cells. A set of software applications allows to map the floorplan of the museum, record beginning and end of a museum visit, collect data, and visualize the data according to the needs of the museum. Visualizations include statistical evaluations (visits per cell/room, time per cell/room) as well as reconstructions of individual paths through the museum. The talk will demonstrate the visualizations using data from field trials.

## 2 Extended Abstract

Museums are interested to know the behaviour of their visitors: which rooms do they visit, which paths do they take, how long do they stay in different parts of the museum, what do groups of visitors (families, school classes) do, e.g. do they stay together? And they need statistical data: how many visitors visit a room, how long do they stay in a room, filtered according to age, gender, or other sociografical data. With traditional, non-technical means, such data cannot be collected.

RFID technology allows to collect data needed to answer these questions. Since RFID antennas are relatively inexpensive and can be installed easily and almost invisibly, they are well suited for museums. Their reception range defines the localization cells. With high attenuation of the antennas, the cells can be reduced to diameters of about 5 m, i.e. a cell will typically cover a whole room of medium size or part of a bigger room.

The visitors are asked to carry RFID tags during their visit to the museum. A software application (cashier support and data collection) supports the handout of the tags by the cashier, registering the start of the visit, and allows to enter sociografical data, e.g. age, gender, or whether the visitor is carrying an audio guide. When leaving the museum, they hand back the tag and the end of the visit is recorded. During their visit they continuously enter reception cells, stay within for some time, and leave again. This cell based location data is collected, namely time spent within a cell.

All visualizations are based on the layout of the museum and the position of the cells. A second application (museum editor) allows to capture this. Together with cell position and size, technical data concerning the antennas can be entered (IP-address, attenuation), which is used to configure the hardware installation.

The third application (visualizer) supports various evaluations and visualizations of the collected data according to the needs of the users, i.e. the museum curators or administration. Three groups of evaluations are supported:

1. Global statistics:

   Total number of visitors (with RFID tag) per day over a selectable time period, divided by age group or gender. If tags are handed out in a systematic way, this gives an overview over the visitor population.

2. Floor statistics (see Fig. 1):

   Per cell or per room: number of visitors, duration of stay per visitor (average, max, min), total time spent, in each case over a selectable time period, and filterable by sociografic data, in addition distributions according to sociagrafical data are available. These statistics answer the questions of the museums stated above. They allow to detect places of big interest or with a lack thereof, places of long stays or visited in passing, childrens' vs. adults' interests, etc.

3. Individual and group behaviour (see Fig. 2):

   Paths of individual visitors or groups of visitors can be reconstructed and visualized. So beyond statistical information the behaviour of individuals can be studied: which path through the museum was chosen, which rooms were visited and how long, which were not visited or only passed, etc. How does a group, e.g. a school class behave: do they follow their assignments or not? What do families do: do they stay together or do children and adults follow their own paths of interest?

Algorithms had to be developed to clean the data from effects of attenuation by the human carriers of the tags. Paths were reconstructed using an A*-algorithm. The main innovations are the visualizations of the data according to the needs of the museum personnel.

During a first field trial prototypes of the applications were tested and data was collected. Experience, data and feedback from this trial served as the basis for the development of the productive versions of the applications which were used in a second field trial in spring 2010.

The talk will demonstrate the visualizations using the data from the field trials and show examples of insights which can be gained.

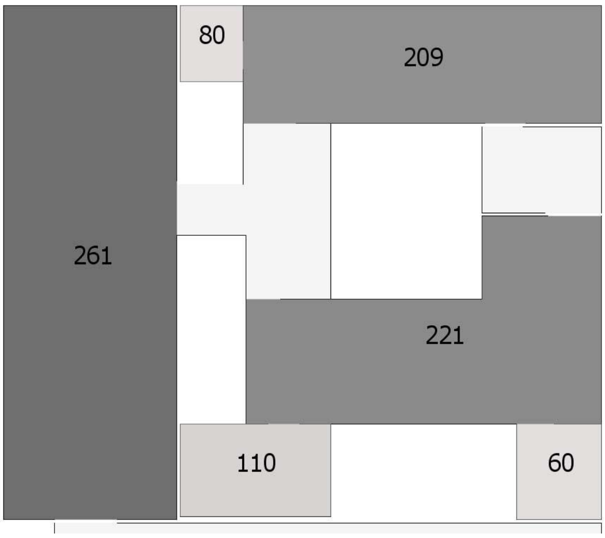


Fig. 1 Floor statistics

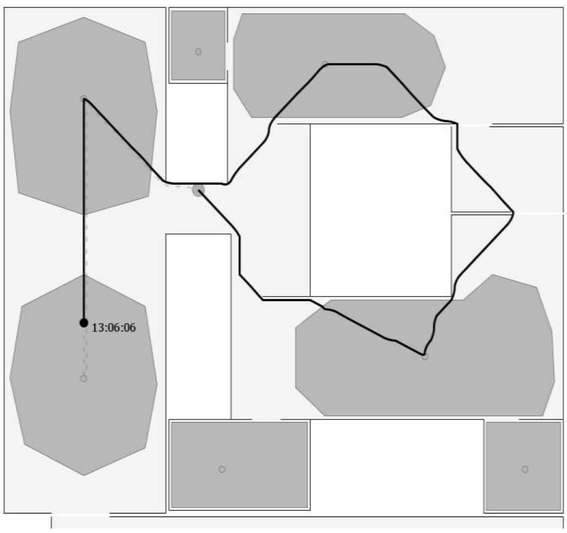


Fig. 2 Path reconstruction

# CCD Camera and IGPS Tracking of Geophysical Sensors for Visualization of Buried Explosive Devices

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## 1 Summary

To find small buried explosive materials such as Anti-Personnel (AP) landmines, high-resolution images of the ground surface and shallow subsurface are needed. A key requirement to produce sharp visualizations is centimetre-precise sensor positioning with real-time imaging results. We are pursuing two complementary approaches to accomplish this task: 1) Sensor tracking with a CCD camera, 2) and large work volume Indoor GPS. In outdoor field tests both methods have successfully imaged small landmine targets.

## 2 Motivation: The need for portable and real-time sensor tracking to find AP mines

Conventional landmine detection depends on highly trained and focussed human operators manually sweeping $1m^2$ plots with a metal detector and listening for characteristic audio signals indicating the presence of AP landmines. We are in the process of developing a high-resolution landmine scanning system which produces horizontal slices of the shallow subsurface for visualization of buried explosives and inert clutter. As many AP mines contain minimum amounts of metal, metal detectors need to be combined with a complimentary subsurface imaging sensor. Ground Penetrating Radar (GPR) is widely accepted for subsurface sensing in the fields of geology, archaeology and utility detection. The demining application requires real-time imaging results with centimetre resolution in a highly portable package. The key requirement for sharp images of the subsurface is the precise tracking of the geophysical sensor(s) during data collection. We are currently testing two different approaches for this task: 1) A real-time sensor tracking system based on a CCD camera and image processing and 2) Indoor GPS (IGPS) normally used in large equipment assembly. Goal of this collaborative research between the University of Tohoku and University of Miami is to produce precise and high resolution scans of ground surface and shallow subsurface so demining personnel can visually identify the presence of AP mines.

## 3 ALIS camera based sensor tracking

At Tohoku University we have developed and field tested the Advanced Landmine Imaging System (ALIS) since 2002 [1]. ALIS has detected more than 40 AP landmines in mine fields in Cambodia since summer 2009. ALIS uses a CCD camera attached to the handle of a combined metal detector and GPR system for sensor location tracking. The CCD camera captures 5 images per second of the ground surface. The relative movement is calculated, and the sensor position can be tracked. Figure 1 shows an example of the metal detector signal map resulting from multiple random sweeps with the ALIS system. To our knowledge this is the only system which can visualize in real time metal detector and GPR data maps acquired by hand scanning. The CCD camera method provides cm precise local x,y position data for individual mine sweeping devices at a low equipment cost. GPR and position data are acquired sequentially in time, and used for data processing. Scan area is typically 50cm x 50cm and data acquisition takes a few minutes.

## 4 High-resolution 3DGPR imaging with IGPS positioning

Tohoku University and University of Miami are collaboratively working on the application of 3DGPR for detection of buried explosive devices. Currently we are investigating the use of IGPS, a large work volume metrology method, as a complementary tracking device for the CCD camera. IGPS can provide absolute and better than centimetre precise x,y,z coordinates to multiple mine sensors at the same time. At the University of Miami we have developed a novel 3DGPR system for efficient and high-resolution 3D shallow subsurface scanning of larger areas (25 $m^2$ to thousands of square meters) with irregular topography [2]. We have conducted first field measurements, and found that the 3DGPR system can visualize small buried low-metal landmines with high resolution (Figure2). In this system, position data by IGPS and GPR are stored independently, and data will be merged when the data will be processed.

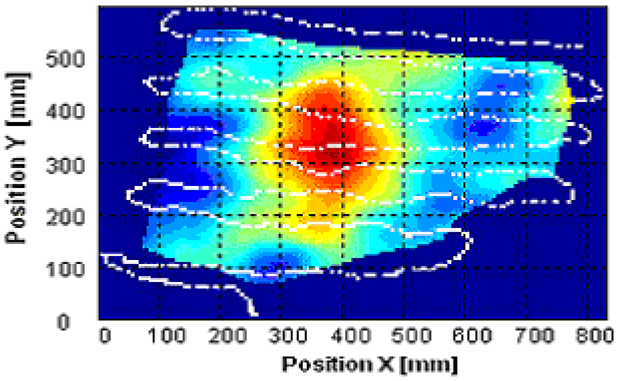


Figure 1: GPR map of an AP landmine generated by random sweeps (depicted as white lines) of the ALIS system tracked by CCD camera.

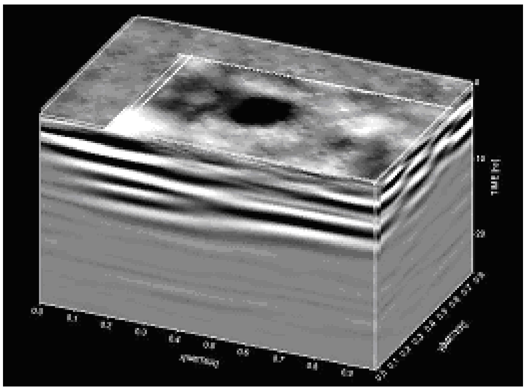

Figure 2: 3DGPR Image of an 80 mm diameter low metal PMN-2 mine. Data acquired on a 25 x 25 mm grid with a 500 MHz GPR antenna positioned with IGPS. The top surface of the displayed 3D cube measures 1000 x 800 mm.

## 5 Conclusion and Outlook

The initial field tests show that the combination of CCD camera local sensor tracking with large work volume IGPS has the potential to deliver the centimetre resolution ground surface and subsurface images necessary to find small low-metal content AP landmines. With such a combined tracking solution, scan data acquired simultaneously by multiple demining teams working at a mine polluted site can be geo-referenced in real time and used for integrated target analysis.

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# Ultrawideband-based location awareness towards smart industrial applications

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## 1 Summary

The localisation technologies have been witnessing a tremendous improvement over the last few years especially in terms of robustness and real time tracking. Moreover, location aware applications have become more required for industrial and research applications.
The technology, presented in this paper, uses the standardized ultrawideband (UWB) radio positioning technology between 6.5-8 GHz to determine, based on angle and time difference of arrival information measured from fixed sensors, real time 3D locations of hundreds of tags attached to people, objects and assets to within 15 centimetres of accuracy.
This paper presents the principles of the Ubisense ultrawideband localisation technology, describes the requirements for a successful integration into smart spaces and illustrates the smart location aware solutions with concrete examples from the actual application spectrum.

## 2 Real Time Ultrawideband Localisation Principle

The Ubisense location platform uses ultrawideband (UWB) radio positioning technology to determine the 3D locations of people and objects to within 15 cm. Small tags are attached to the objects to be located, or are carried by people. These tags emit UWB radio signals which are monitored by a network of base stations (sensors) mounted at known points in the environment. The Ubisense location platform combines measurements from two or more sensors to find each tag's position. In conjunction to that, Ubisense has also developed a scalable middleware platform which can manage and distribute large volumes of real-time location information to very many clients, and which simplifies creation of location-aware applications. More details about the methodology of localisation will be given in the full paper.

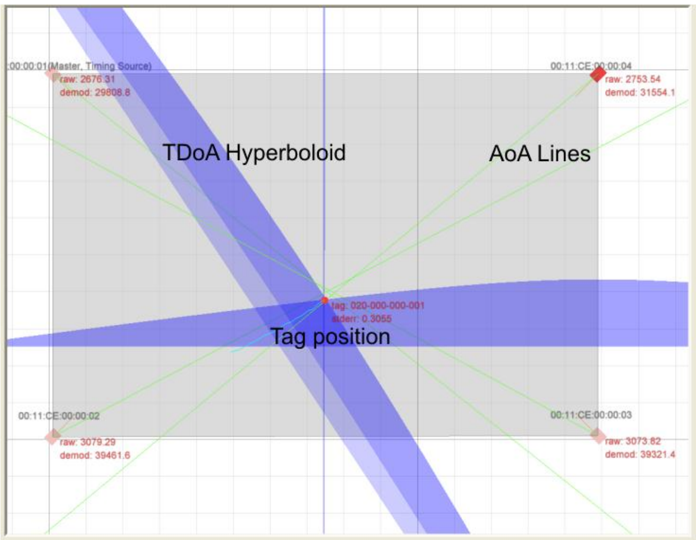


Figure 1: Localisation based on the Angle and Time Difference of Arrival (AoA and TDoA)

## 3 Smart location awareness applications

There are many RF tagging systems on the market which provide some kind of location capability. But different systems differ hugely in capability and cost. Ultimately it is the applications and the benefits they provide in the short term and longer term that count. The measure of a location tagging system is the applications that it enables.

Ubisense has developed a platform for building Smart Space applications. It addresses the key requirements for building accurate 3D positioning, scalable real-time performance, and development and deployment tools. This section deepens the key requirements and describes how the location platform components meet them.

The advanced sensing and middleware technology has been adapted towards smart solutions, including especially car manufacturing (smart factory), security, logistics and military training. The end applications for the location-aware technology in these markets are varied and range from tool assistance systems (at the car assembly line) to monitoring and results analyzing systems for military trainings with simulation devices. Some of the most important factors to be addressed when considering the deployment of location-aware systems include:

1. Value: This represents the most important factor. In order to be successful, a technology must address a real need. Most of the effort is needed in identifying real-world situations, where location-awareness can bring a considerable return on Investment (ROI). Examples include the smart factory (tool assistance system at the car assembly line), which will be described in the full paper version.

2. Robustness: Besides the ROI, a successful location aware solution must solve the customer problems robustly anywhere and anytime. Robustness must be considered at all stages of the design and implementation of location sensing hardware and processing software.

3. Infrastructure: There is obviously a cost involved with installing infrastructure in an environment, but this cost can be reduced by appropriate design and quantified before the system installation. A properly-designed infrastructure will have minimal maintenance requirements once installed. Some practical examples from industrial and research applications will be given in the full paper.

4. Technology for scalable solutions: With several practical applications of location awareness, the same UWB-based location technology can satisfy the requirements of a number of different markets involving in-building tracking.

5. Standardization: In the long term, an integrated standard for location and low-rate communication could create huge value.

## 4 Conclusions and Outlook

Location-awareness can solve real problems for which there is no existing effective solution.

UWB offers a compromise between good accuracy inside buildings, reasonably low levels of infrastructure, good performance outdoors, small tag size and fairly low power consumption. However, each of the existing radio frequency localisation systems, such as vision, GPS, thermography, inertial navigation…, has its own strengths and it may be appropriate for some sites to use a hybrid solution with the fusion of different sensing technologies.

# Indoor Positioning Aware Radiation Measurement (IPARM)

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## 1 Summary

The IPARM research project was started in order to develop methods for collecting and synchronizing indoor positioning data with radiation measurement data collected by using the portable measurement unit VASIKKA, developed by the Finnish Radiation and Nuclear Safety Authority STUK.

## 2 VASIKKA

VASIKKA, a portable measuring unit for radiation measurement, is Java software running on a small notebook with radiation measuring detectors for collecting radiation measurements. It can be easily carried in a backpack and accessed through a Bluetooth enabled mobile device such as a mobile phone. Apart from collecting general radiation measurement data, VASIKKA can also identify the nuclide in question. This is important in making real-time evaluations about whether the collected information is within the naturally occurring limits of such radiation.

## 3 LINSSI

The data collected through VASIKKA is sent to LINSSI. LINSSI – LINux System for Spectral Information is SQL (Structured Query Language) database designed by STUK and its Partners (Ihantola, 2009).

## 4 Ekahau Positioning Engine (EPE)

In order to take use of IPARM, the person carrying a VASIKKA has to activate and carry a suitable Ekahau Wi-Fi positioning tag with them while performing the radiation survey. The EPE server collects and analyses the data it receives from the Wi-Fi tag in order to offer an approximation of the location of the surveyor.

## 5 Indoor Positioning Aware Radiation Measurement (IPARM)

In its current form, VASIKKA has not been integrated with any indoor positioning technology. Because such functionality is highly desirable from usability point-of-view, a joint research and development project called IPARM (Indoor Positioning Aware Radiation Measurement) was initiated between STUK and Laurea University of Applied Sciences in 2008.

IPARM is a Java application that, in its current revision, connects to an available Ekahau Positioning Engine (EPE) server in order to fetch relevant positioning data. This data is then processed by IPARM into a suitable format and written in to the corresponding field in the LINSSI database. Meanwhile, VASIKKA enters its radiation measurement findings in to the same database tables. The data is synchronized via time-stamp information available in both feeds (Garlacz, 2009).

## 6 Mobile Measurements

The collected data can be subjected to further analysis in a STUK-created specialized mapping program called Mobile Measurements. Within the program, visualizations created from the relevant LINSSI database entries can be observed. These are displayed in a simple-to-understand movie-like time-line and present positioning information in relation to any abnormal radiation measurement data collected during the survey. Any surveyed abnormalities can be clicked upon and analyzed thoroughly. The analysis can be done on-site or off-site.

## 7 Conclusions and outlooks

During the ongoing IPARM project, we have created a Java application that collects indoor positioning data from an Ekahau EPE server and processes and inputs the collected data into the LINSSI database, created and used for collecting radiation measurement data. This data is then used for creating informative visualizations that make rapid assessment and analysis of the radiation measurement data intuitive.

IPARM, coupled with the portable radiation measurement unit VASIKKA, promise to enable national authorities like STUK (the Finnish Radiation and Nuclear Safety Authority) to carry out safety related radiation measurement surveys in a more efficient fashion, reduce the chance of human error in the collection and marking down of relevant positioning data and make analysis of the collected data more simple and intuitive.

In the future, we plan to append the IPARM system to include support to other available indoor positioning technologies. In addition to using WI-FI based positioning, we have been testing a system based on step length and orientation information (Ilander et al. 2010). Supporting multiple platforms in collecting relevant positioning data can be foreseen to offer major benefits to the applicability of IPARM on the field. We are also investigating the possibility of supporting the applicability of displaying indoor positioning data in real-time visualizations similar to those described in chapter 6.

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# Tracking Patients

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## 1 Summary

Tracking patients while they are waiting for care at an Emergency Department is important because they may wait a few hours to be seen and their status may deteriorate during that time. Further, caregivers in an Emergency Department can be too busy to monitor these patients. Situations have occurred where a patient was found dead in a restroom, long after the staff had assumed that the patient left the hospital. The SMART system was developed to monitor these patients. We evaluated several tracking systems for inclusion in SMART for patient and caregiver tracking.

## 2 Introduction

Currently several systems use RF for indoor localization. [OIL, Ekahau, Radianse] There are some strong advantages to using these systems which depend on WiFi signal strength for localization: there are no infrastructure deployment costs as WiFi Access Points have become reasonably ubiquitous. With user-based surveys, the cost of professional surveying is eliminated as well. There are, however, some challenges: the RF signal strengths received from local wireless access points are not consistent. Figure 1 shows the RF signals collected over a 24 hour period by a stationary laptop.

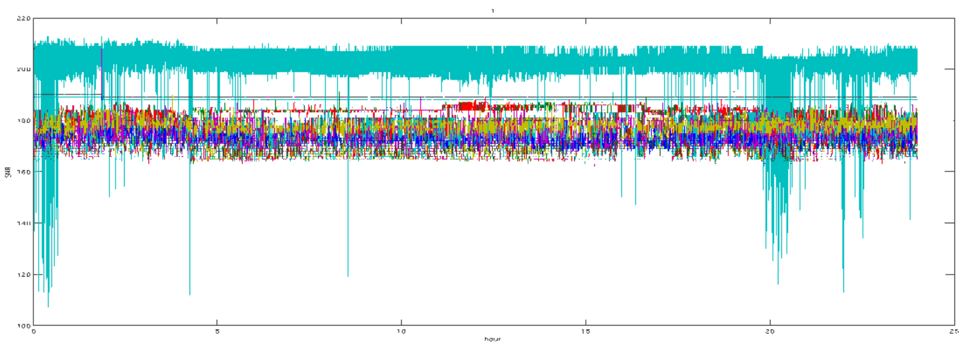

Figure 1: WiFi signal strengths observed over a 24+ hr period

When developing the SMART patient monitoring system [SMART], we initially used the Cricket location system [Cricket], which had been developed in a neighboring research group. Cricket is uses RF plus ultrasound. The infrastructure consists of beacons that periodically emit an RF message along with an ultrasound pulse. The RF message indicates the name of the beacon. Each beacon's name typically refers to the room in which it is deployed. The listener, worn by the patient, receives RF messages and ultrasound pulses from a variety of beacons. Using the familiar thunder and lightning approach, i.e., the difference in the time of arrival of the RF message and the ultrasound pulse, the listener can compute how far away it is from each beacon and choose its location near the closest beacon. The approach scales well: there can be many listeners with no effect on the system.

Unfortunately, one problem with the Cricket approach is that it can be difficult to match up ultrasound pulses with their corresponding RF messages, so, from time to time patients appear to "fly" across the room. We speculated that some filtering might cause the estimates to be more stable. Due to time pressures to begin an extensive study with real patients and other pragmatic issues related to packaging for the beacons, we chose to evaluate some commercially available options.

The system we eventually chose was Sonitor [Sonitor]. This system is based on patients wearing tags that emit ultrasound messages while the patients are moving and for a short time after they stop moving. Each tag's message contains its unique ID and its battery status. Ultrasound detectors are placed on the walls and relay tag sightings to a central computer. These messages include the amplitude of the message received by the detector as well as the tag's ID. The central computer assigns the patient's location to be near the detector that received the message with the highest amplitude for the patient's tag.

The SMART system was deployed for eighteen months at the Brigham and Women's Hospital in Boston, Massachusetts, USA. It was used to monitor and track 145 patients who presented with shortness of breath or chest pains.

## 3 Open Questions

While the deployment of the Smart system with the Sonitor Indoor Positioning subsystem was successful, there are several open questions: Can the processing of RF signal strengths be improved to get better accuracy? Can RF signals be augmented with other signals to improve accuracy? Are there strategies for using ultrasound for tracking people in crowded situations?

## 4 Acknowledgements

I would like to thank David Lambeth and Seth Teller's Organic Indoor Localization group at MIT's Computer Science and artificial Intelligence Laboratory and Nokia for Figure 1 and for many interesting discussions about indoor localization issues. This work was supported in part by the National Library of Medicine, N01LM33509.

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# Realizing an Emergency Call System on a Real-time Location Application Platform for Healthcare

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## 1. Summary

In modern hospitals, opposing forces between cutting costs and demands on service quality, growing workloads versus staff reductions, stimulate the need for systems that automatically support procedures in the background.

Intelligent real-time positioning solutions can partially fill the gap. The ProAct® application platform addresses the common needs of Real-time location applications in healthcare. It enables the rapid development of rule-driven, location-based solutions for different problem domains. It is designed for multiple healthcare application areas including patient and staff security, asset management, clinical process analysis and context-sensitive information provision and guidance.

This contribution will introduce the real-time location application platform ProAct and how it is used to realize an emergency call system in a psychiatric department.

## 2. Extended Abstract

Cost containment is an issue of increasing priority in healthcare. Healthcare facilities try to reduce personnel expenses as the most important cost factor. On the other side expectations and requirements are continuously growing driven by stakeholders, legislation and quality standards. To meet all these demands either more personnel is needed or intelligent systems must be found which can decisively support clinical workflows. Such systems should be able to assist personnel in daily procedures by continuously assessing situations in terms of: *what happened? – where and when did it happen*? *– who did it? – what has to be done?*

We call this kind of applications *Intelligent Real-time Location (iRtL) Solutions.* Common needs of iRtL applications in healthcare have been identified and generalized into concepts and services of the ProAct® application platform:

- *Monitoring and visualizing the real-time location and state of tracked persons or assets.* Applications differ in types of tracked entities (e.g. patient, nurse, IV pump), in state domains, in sets of alert types and vary in visual presentations by symbols and terminology.
- *Data secrecy*. Applications have varying standards of data secrecy and data lifetime limits, particularly if the tracked entities are persons. The platform must support fine-grained data secrecy rules in order to adapt to application-specific privacy policies.
- *Classifying state and generating events*. An iRtL application must be able to distinguish important state from ordinary state. The criteria that render state important are typically application-specific depending on properties of the current location, the organizational unit, the tracked entities, and on temporal, spatial or more complex relationships between tracked entities. The ProAct platform permits to define high-level, semantically rich events when designing an application. A generated event can trigger pre-defined actions like raising alerts, collecting real-time data or controlling electronic devices (cameras etc.).

- *Multi-channel, multi-level notification of alerts*. Application design includes the definition of different types of system- and application-level alerts. Notifications can be delivered to receivers by an extendible collection of protocols or channels, like pager, popup window, e-mail or third-party systems. A setup defines who is to be notified and when depending on alert origin and type. Multi-level notification rules of first-level and escalation-level message receivers can be specified.

- *Clinical process data collection and analysis* require the collection and processing of operational data. Application events can trigger the counting of certain events, the measuring of time durations and relate that data to locations, entity types, organizational units or procedures. The platform provides basic tools to view and analyse the collected data at different aggregation levels. Moreover the data should be accessible by third-party analytical processing tools.

- *Integration into hospital information systems.* Healthcare applications require the exchange of patient or asset data with ERP and clinical information systems. Depending on the application requirements and the existing system landscape it might be necessary to link data from different systems. E.g. patient master data and medical case data has to be merged to achieve specific application objectives.

- *Self-monitoring and malfunction detection* is important especially in patient and staff security applications that rely on the high availability of the system. Therefore, it is essential that the system detects any faulty state of involved components and notifies reduced reliability to everybody concerned.

- *Independence of positioning technology.* Positioning data can be obtained from a variety of real-time location providers, using different sensing technologies, both hardware and software. Pros and cons of each technology need to be balanced depending on specific application requirements, characteristics of the installation site (regarding other medical equipment, building layout etc.) or pre-existing investments of the customer (e.g. Wi-Fi environment ready). ProAct applications are largely independent from specific positioning technologies. The most appropriate alternative can be selected in each case.

The staff of psychiatric hospitals is often exposed to the risk of being attacked by patients. The need for an emergency call system is evident. The core function is the notification of pre-defined receivers like attendants, physicians, security staff etc., that *help is needed* and *where it is needed*. The help request could easily be communicated by simple radio equipment, but the information *where* it is needed isn't that easy to collect. An important constraint of the system is the minimum positioning accuracy.

Many non-technical aspects have to be considered: Individuals are concerned when their behaviour is potentially under surveillance and might decline such a system. Another issue is the indistinct anxiety of radiation from sensing technologies. To make the system widely accepted it is essential to take employee's concerns seriously.

This paper will introduce to the *Intelligent Real-time Location Application Platform* ProAct by the example of an emergency call system at the Psychiatric Department of the University Hospital of Innsbruck. It will present requirements, considerations and concerns we had to balance to realize an appropriate solution in the special environment of clinical practice.

## Optical Systems

Auditorium D2

Thursday, September 16, 13:15 – 15:00 & 15:30 – 16:45

# Towards Real-Time Camera Egomotion Estimation and Three-Dimensional Scene Acquisition from Monocular Image Streams

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## 1 Summary

The estimation of a camera's egomotion is a highly desirable goal in many different application fields such as Augmented Reality (AR), visual navigation, robotics or entertainment. Especially for real-time modelling the former estimation of the camera trajectory is an elementary step towards the generation of three dimensional scene models. Based on ideas recently introduced in the field of Simultaneous Localisation and Mapping (SLAM) and classical Structure from Motion algorithms (SfM), which were derived from basic principles of photogrammetry, this paper presents a framework for simultaneous recovery of scene structure and camera motion by combining visual and inertial cues (Inertial Aided SfM). For this purpose two different system designs are proposed: a loosely-coupled system, which follows a classical approach for solving the five-point relative orientation problem for estimating the camera trajectory, and a monolithic design, which adapts ideas from non-linear state estimation as Extended Kalman Filtering (EKF) for structure and motion recovery.

## 2 Motivation for Inertial Aided Structure from Motion

The self-acting estimation of cameras ego-motion has been a fundamental problem of computer vision for decades. Especially for Augmented Reality (AR) applications the vision-based recovery of camera trajectories has become an important problem and many different solutions were proposed in recent years. Those vision-based techniques for 3D scene or object modeling are already introduced, but their usage in real-world applications is still limited due to several problems with robustness and computational costs. Since all SfM-algorithms are based on finding corresponding distinctive features in subsequent frames of a video sequence the accuracy of those methods are mainly influenced by the robustness of the used feature extraction and matching procedures. Thus the concept of aided-SfM (aSfM) was established in recent years to overcome the typical drawbacks of SfM. This paper will introduce a general concept for the development of a Visual-Inertial Scene Acquisition (VISA) device which realizes robust recovery of cameras egomotion and scene structure in real time. This is achieved by implementing a prototype of a loosely-coupled system. In this constellation a visual- and an inertial-route are running almost independently from each other. In contrast to that it is contemplated to combine the measurements of both devices in a monolithic inertial-visual system. In this concept non-linear state estimation methods are implemented in a single filtering-stage for estimating structure and motion.

## 3 Loosely-Coupled System Design

The first milestone in the development of an inertial aSfM device is the implementation of a loosely-coupled system. Here both tracks (visual and inertial) are run almost separately in such a way that there are two ego-motion estimates from the inertial route (InR) and from the visual route (VisR). As shown in Figure 1 it is possible to establish several interfaces between both routes to improve the results of the overall system in terms of accuracy, robustness, long-time stability and computational efficiency. One example for such an interface is a pre-warping-scheme which is based on estimated homographies for increasing the robustness and reliability of matching corresponding points by extracted texture-patches. Also the drift-error, which is a logical consequence of double-integrating signals in the InR, can be compensated by incorporating the trajectory-model from the visual information.

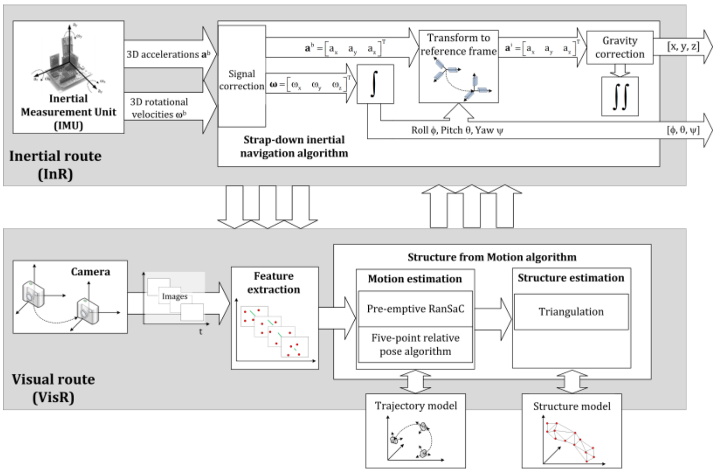


Figure 1: Loosely-Coupled System Design with visual and inertial route

## 4 Monolithic System Design

Based on the findings from the loosely-coupled system a single monolithic system for SfM is proposed which fuses not only results from SfM and strapdown navigation but also the measurements of the IMU and the vision-sensor directly in a single system. Those systems are always based on non-linear state-estimators for fusing the measurements from two or more sensors with the goal of predicting (hidden) states of the system. The following figure is visualizing a setup for the monolithic system design which incorporates EKF for estimation of the camera's egomotion and scene structure.

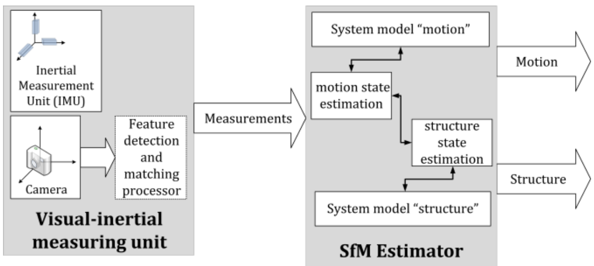


Figure 2: Monolithic system design

## 5 Conclusions and Outlook

Towards the development of a handheld scene acquisition device the usage of aSfM-algorithm which incorporates inertial measurements is able to overcome typical limitations and drawbacks of systems which rely only on visual-information. Future work will consist of the implementation of the proposed framework on embedded hardware and the corresponding considerations regarding parallelization and multi-rate sensor fusion.

# Learning Efficient Vision-based Navigation

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## 1 Summary

Cameras are popular sensors for robot navigation tasks as they are inexpensive, lightweight, and provide rich data. However, fast movements of a mobile robot typically increase motion noise and reduce the performance of vision-based navigation due to motion blur. In this work, we present a reinforcement learning approach to choose appropriate actions for vision-based navigation. The learned policy chooses actions so as to minimize the time to reach the navigation goal and implicitly mitigates the impact of motion blur on observations. Our system integrates odometry and visual features in an unscented Kalman filter for localization. Extensive simulated and real-world experiments with wheeled and legged robots demonstrate that our learned policy significantly outperforms policies using hand-optimized navigation strategies.

## 2 Introduction

Completing navigation tasks reliably and efficiently is one of the most essential objectives for a mobile robot. For this, the robot needs to know its pose (location and orientation) with respect to the environment. Cameras are popular sensors used for localization as they are relatively inexpensive, lightweight, and provide rich data. However, in particular in low-light indoor environments, the movements of the robot typically affect its camera images with motion blur. The faster the robot moves, the more its perception will be degraded by motion blur (see Fig. 1), which potentially leads to a wrong pose estimate. On the other hand, by moving slowly, the robot can avoid motion blur but will not reach its goal efficiently. Thus, the robot needs to learn how to trade off a fast velocity against an accurate localization. In this work, we present our approach for efficient vision-based navigation for wheeled [Hornung et al. 2009, 2010] and humanoid robots [Oßwald et al. 2010] that implicitly takes the influence of motion blur into account by learning a policy to reach the goal reliably and efficiently.

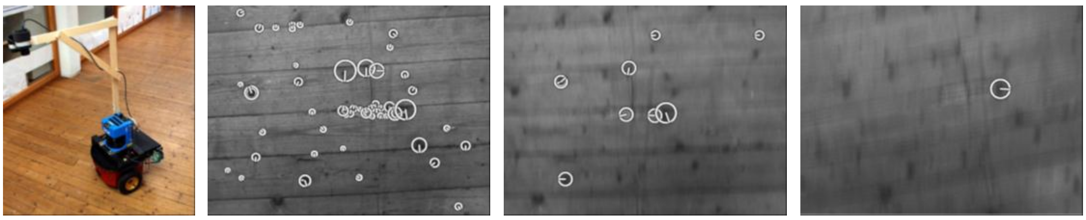

Figure 1: Wheeled robotic platform and camera image with detected features at 0.05 m/s, 0.4 m/s, and 1.0 m/s (from left to right)

## 3 Vision-based Localization

The robot’s pose is estimated in an unscented Kalman filter. Hereby, odometry information from the robot’s wheel encoders or its walking algorithm serves as control input. As observations, we extract Speeded-Up Robust Features [Bay et al. 2006] from the images of the cameras which observe the floor in front of the robot. The descriptors of these features are then matched to a map of landmarks which was constructed beforehand.

## 4 Learning Navigation Policies

The goal of our approach is to reach a target location as fast as possible. We formulate this task as a reinforcement learning problem, and use the Sarsa(λ) algorithm to solve it. In our augmented Markov Decision Process, we represent the state with the features distance and angle to the next waypoint, as well as the entropy of the estimated pose as measure of the uncertainty of the localization. The rewards are based on the time to reach the goal, which drives the robot to reach it as fast as possible. In case of a wheeled robot, the actions consist of selecting the velocity for the underlying navigation controller. For the humanoid robot, the actions directly correspond to walking commands guiding the robot to the goal. In the learning framework, we simulate motion blur by modifying the probability of observing a given landmark depending on the movement velocity of the camera with respect to the world.

For evaluating the performance of the wheeled robot, we compare our learned policies with driving at constant velocity and with a heuristic approach which applies the maximum velocity as long as the robot is confidently localized, otherwise stopping it to relocalize. On the humanoid robot, we compare the learned policy to a manually optimized navigation strategy. In all simulated and real-world scenarios, the robot was able to reach the goal significantly faster using our learned policies. The wheeled robot learned which velocity to choose to efficiently complete the navigation task without getting lost, while the humanoid robot learned the correct navigation actions in order to reach the goal fast and reliably.

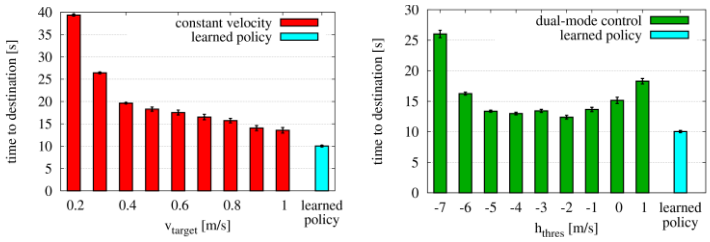


Figure 2: Performance of the learned policy for the wheeled robot compared to constant velocity and dual-mode heuristic. For all parameters, the learned policy is significantly faster.

## 5 Conclusions

We presented an approach which enables a mobile robot to learn efficient policies for vision-based navigation despite inaccurate execution of motion commands and noisy observations. In our learning framework, the robot learns to trade off an accurate localization against a fast velocity. We demonstrated that the learned policy significantly outperforms strategies which apply a constant velocity and more advanced heuristics with respect to the time to reach the destination.

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# DAEDALUS: A versatile usable digital clip-on measuring system for total stations

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## 1 Summary

DAEDALUS designates an automated on-line measuring system which was designed and developed at the Geodesy and Geodynamics Lab (GGL) at ETH Zurich primarily for automated on-line astro-geodetic measurements. It consists of a small CCD camera which can easily be clipped on a total station instead of the ordinary eye-piece, a pluggable front lens, a low-cost GNSS receiver, and dedicated software for steering, imaging and on-line processing. The system enables new possibilities for fully automated high-precision digital angle measurements, unaffected by human interference, both in outdoor as well as in indoor applications. Furthermore the software is capable to perform image template matching thus allowing optical target recognition by using various image processing algorithms. Although DAEDALUS was initially designed for astro-geodetic use, the results obtained revealed new and unexpected possibilities in other disciplines such as automated terrestrial and engineering surveying, deformation, vibration, and frequency analysis and photographic documentation. For applications where event timing allocation is needed, high-precision time-tagged measurements are possible by means of a GNSS receiver, equipped with an external antenna for indoor applications. Beside some aspects of astro-geodetic measurements the paper describes selected applications using TCA 1800 total stations from Leica Geosystems to demonstrate new and still unexploited possibilities of this new technique.

## 2 System description

a. Hardware: The system has been designed under the constraint that no mechanical hardware changes to the total station are allowed and to use it as a clip-on tool in connection with different total stations. A small CCD camera is replacing the eye-piece which is normally needed for human observations. This configuration allows replacing the observers' eye by a digital image sensor thus avoiding any personal influence on the measurements. An additional piggyback mechanics with a small stepping motor, a reduction bevel gear unit, and a tooth belt around the focussing ring allows autofocus imaging. Furthermore this technique helps to accelerate the observation process and to enhance the system integrity.

2.2 CCD camera: The CCD camera chosen is of type Guppy F-080B from Allied Vision Technologies GmbH (AVT) with 1032 x 778 pixels and a chip size of 4.8 x 3.6 mm. The data of the chip is transferred by a Firewire IEEE 1394a-interface with a transfer rate of up to 400 Mbits/s. The camera is equipped with a trigger level controlled shutter and provides up to 30 full frames per second. In connection with a low-cost GPS receiver from μ-blox offering event handling, the system performance allows time tagging of the exposures (epochs) with an accuracy of about 200 microseconds with respect to GPS/UTC.

Due to mechanical reasons the delivered CCD camera does not allow to measure at telescope elevations above 45 degrees. Therefore the housing of the camera is removed and the four electronic prints are separated by a specially designed flexible print. This technique enables enables to displace three of the four electronic prints such that measurements even in zenith direction are possible. Figure 1 and 2 show the camera and the focal mechanism.

Figure 1: Modified CCD camera instead of the eye-piece. The bended small box below comprises three small electronic prints belonging to the camera. The CCD replaces the human eye and is fixed to the telescope with an identical mechanical interface as the ordinary eye-piece (ocular).

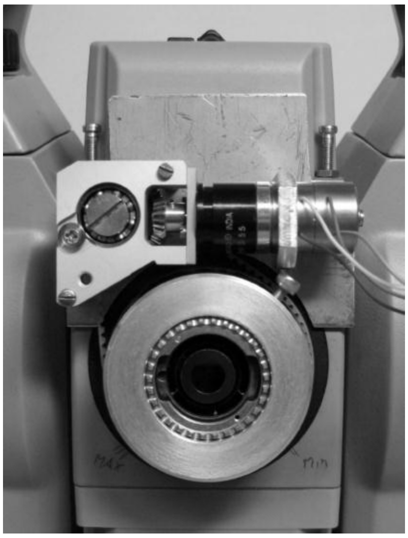

Figure 2: Focussing mechanics as developed by the Technical University of Dresden (Germany) consisting of stepping motor, reduction gear unit, and tooth belt around the focussing ring of the telescope. The software module enables autofocus capabilities. The camera in this picture is removed for clearance.

## 3 Applications

3.1 Indoor/outdoor Engineering surveying: Total stations and DAEDALUS enable fully automated high-precision static and dynamic intersections (micro triangulation) for machine control such as, e.g., hydroelectric turbines, accelerator components, inaccessible machines, dam and structure deformations, and airplane quality control in assembly hangars).

3.2 Deformation measurements in the context of strain and stress analysis of construction elements in static and dynamic load experiments.

3.3 Vibration measurements / frequency analysis in real-time: Due to the high frame rate of the CCD camera, DAEDALUS is well-suited to measure vibrations effects with up to 30 frames per second.

3.4 Simultaneous reciprocal vertical angle measurements for investigations in the field of indoor/outdoor refraction, scintillation, and turbulence experiments. For this purpose special power diode arrays serve as optical targets.

3.5 Geodetic astronomy: DAEDALUS allows fully automated measurements of stars. The software provides on-line processing for any chosen observation technique such as, e.g., the method of equal heights (deflection of the vertical) or azimuth determination.

## 4 Conclusions

The clip-on system DAEDALUS opens new aspects for fully automated high-precision observations in indoor and outdoor engineering, dynamic surveying, machine and structure control, atmospheric refraction analysis, and geodetic astronomy.

# Visual Tracking for Augmented Reality

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## 1 Summary

Localization of mobile devices is an essential task in Augmented Reality and has therefore been an active research topic for many years. Typically, indoor tracking approaches, such as methods based on infrared or ultra-wide-band, require preparations of the environment and special hardware sensors. Conversely, image feature tracking approaches can provide orientation estimates without special tracking hardware installations. With the advent of mobile devices equipped with sensors such as digital cameras, image based localization gains importance in Augmented Reality. Typically, fiducial marker tracking was considered as a standard image based localization method. We propose the use of natural image feature based tracking methods, which are a generalization of the same principals but do not require the presence of fiducial tracking targets.

## 2 Vision based Localization for Augmented Reality

Augmented Reality (AR) is a powerful user interface for mobile computing. AR superimposes registered 3D graphics on the user's view of the real world, allowing the user to perceive overlaid information that is spatially registered to the environment (see Figure 1). In this context, tracking provides indoor localization to correctly register digital information, e.g. navigational hints, to the user. Computer Vision-based localization techniques offer great advantages over other localization methods based on infrared, WLAN/Wi-Fi or ultra-wide-band. Image-based measurements allow very high precision in the pose estimation and self-contained operation without complex and expensive infrastructure. In computer vision, the problem of location recognition has been addressed in the past by a variety of approaches. The most successful methods rely on wide baseline matching techniques based on sparse features such as scale invariant interest points and local image descriptors. The basic idea behind these methods is to compute the position of a query image with respect to a database of registered reference images, planar surfaces or 3D models. Assuming a static scene, geometric verification can be used to determine the actual pose of the camera with respect to the exemplary database. Different viewpoints or illumination changes are largely handled by robust feature descriptors, such as SIFT [5], that provide invariant descriptions of local image patches. Vocabulary tree based image retrieval and inverted file scoring [2] allows for fast search of large SIFT descriptor databases.

## 3 Localization for Mobile Devices

In recent years mobile computing devices and state of the art mobile phones in particular, have seen immense progress in miniaturization and performance. These devices are well-established and offer a convincing hardware package containing all components necessary for vision based localization and information visualization. The first approaches for mobile phone localization were client-server based where tracking is outsourced to a PC connected via wireless link. But, these approaches suffer from restricted bandwidth, the imposed infrastructure dependency limiting the scalability in the number of client devices and high response times. As a consequence server-based approaches are not suitable for AR.

However, recent approaches have shown that natural feature tracking with 6 Degrees Of Freedom (DOF) can be realized in real-time using mobile phones [1]. Point based visibility of data base features are used in this work for reduced computational- and memory requirements. Moreover, Takacs et al. [3] present an outdoor localization system directly performing keypoint detection and matching. Features are clustered in a 2D grid and pre-fetched by proximity. Each grid element contains a set of clustered meta-features representing the most repeatable features. Geometrically consistent meta-features are created. However, no 3D model is used and thus true geometric consistency is not enforced and no full 6DOF pose is computed.

Figure 16: User is equipped with a mobile device that accurately renders 3D structures and information directly on top of the orthographic photo [4].

## 4 Tracking Data Acquisition and Outlook

For 6DOF pose estimation, a full 3D localization of feature points is necessary. If a simple known planar texture is used as tracking target, these positions are given by design. For larger work spaces, this 3D database acquisition step becomes challenging. We propose to use triangulated natural image features, obtained with a structure from motion (SfM) reconstruction system. These 3D points are registered into a global coordinate system and partitioned into a representation suitable for efficient localization on mobile phones (see Figure 2). The need for efficient and reliable image based tracking increases as the development of mobile devices featuring video cameras as potential positioning sensor continues.

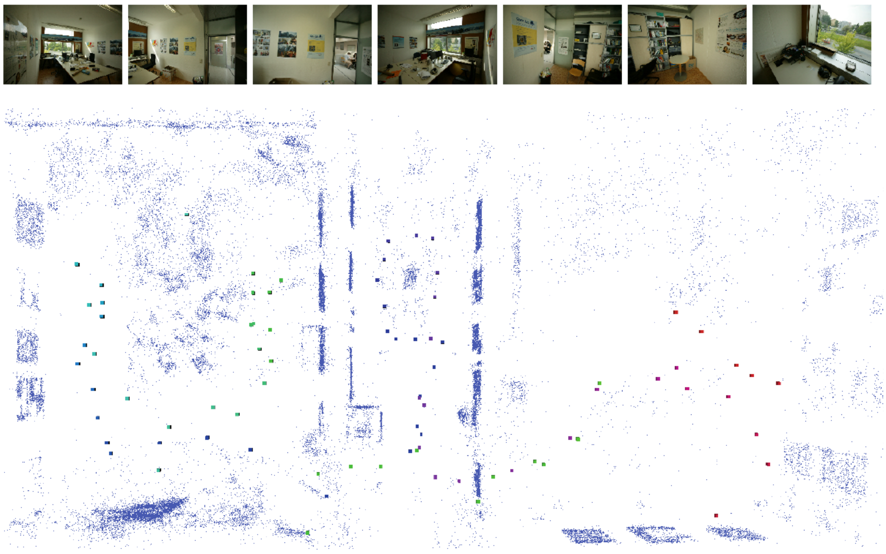

Figure 17: Sample source images used to create the 3D reconstruction (top). 3D point cloud database resulting from the reconstruction. The point cloud shows two rooms from above. Small blue dots represent triangulated feature points and larger dots represent the computed 3D locations of the mobile phone. Colours indicate the timeline and show the user’s motion. (bottom).

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# Range Imaging Sensors and their Opportunity for Real-time Indoor Positioning

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## 1 Summary

We present a novel indoor positioning method based on the acquisition and interpretation of range images from a time-of-flight based range imaging sensor. The local 3D Cartesian coordinates of the scene are computed automatically. The actual coordinate accuracy is driven by the distance measurement accuracy which is in the order of centimetres for range imaging sensors such as MESA's SR4000 or PMDTech's CamCube. The detected 3D point cloud or alternatively the automatically extracted edges and corners will be matched with a CityGML, which is a fine GIS model that can include walls, doors and built-in furniture of indoor environments with a global geodetic datum. From the 3D point cloud the position of the range imaging sensor itself can easily be determined by resection. In contrast to common indoor positioning approaches, the procedure presented here does not require local physical reference infrastructure, such as WLAN hot spots or reference markers.

## 2 Positioning using Range Imaging and CityGML

This first step has the goal to identify the room in the CityGML data base, where the camera is located. The detection and identification of objects is the key part of this step, which can be achieved from the amplitude image of the range imager that is similar to a grayscale optical image of the scene. The detected object properties are the main criteria for the comparison with the data base. This way, the unknown camera position can be reduced to a small number of possible rooms. By detecting distinct properties the room can be identified uniquely and additional semantic and geographic information can be extracted from the 3D geo-data base.

The second step of camera localization is the precise positioning part. This step compares and transforms the local coordinates of the objects that have been recognized by the camera into the reference coordinate system of the database. The reference points for the transformation are the corners of the room, vertices of doors, windows and other fixed installation or furniture. The accuracy of the objects in CityGML should be at centimeter level and should lead to position determination of the camera with cm-accuracy using a least squares adjustment with a redundant number of reference points to determine the 3D camera position. One requirement for the camera is that its interior orientation has been determined previously. The exterior camera orientation and position are determined by a technique that combines trilateration (based on the distance measurements) and spatial resection (based on the image coordinates that are translated into horizontal and vertical angles). If there has been an ambiguous solution in the identification at room level in step 1, the precise positioning step has the potential to disambiguate and deliver only one unique solution for the correct room. Further research needs to be investigated with the goal to exploit the semantic information that the CityGML data base holds.

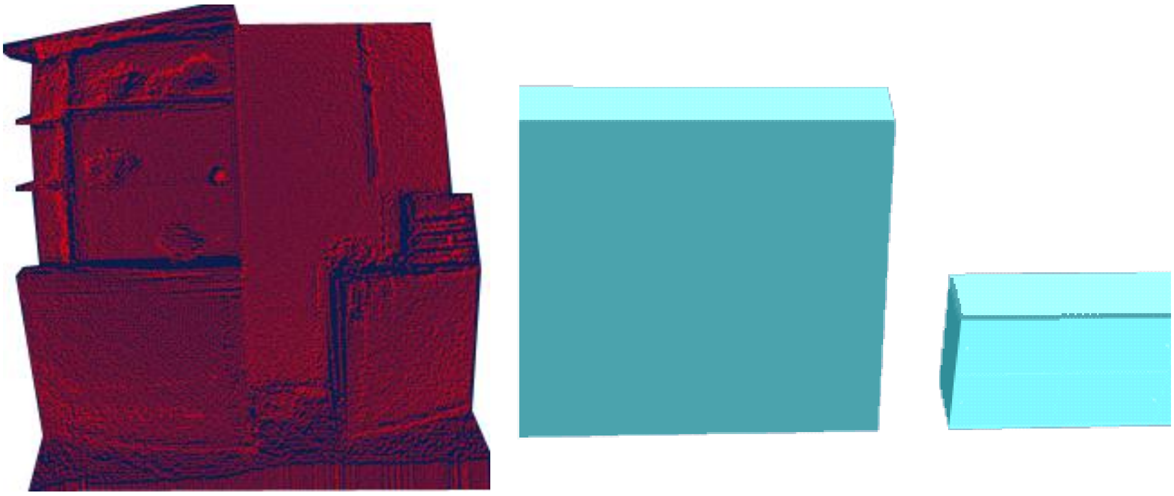

Fig. 1 Object comparison between a range image (left) and form primitives from data base (right)

## 3 Opportunities and limits of the proposed method

CityGML seems to be an appropriate basis for the positioning method. Kinematic acquisition of 3D-coordinates in real-time allow for efficient recognition of rooms and the position of objects in those rooms in relation to a given model. The identification of objects can be trained with the help of neuronal networks. Modern Range Imaging sensors are able to measure distances unambiguously between 5 – 10 m at an accuracy level of centimeters. The ambiguity problem arises from the frequency of the modulated signal of the Range Imaging sensor and can only be solved with additional prior information.

Another problem pose the so-called mixed pixels, that are obtained when the signal from the Range Imaging camera hits an edge of an object. In the point cloud, these pixels appear as single unconnected points that seem to float in the air and that do not belong to any object.

## 4 Outlook

First steps towards a realization of the proposed indoor positioning method have been carried out with a Range Imaging camera. In parallel, parts of an office building at the ETH Zurich have been modeled in CityGML. The next steps are the implementation of the coarse and the fine positioning method. These methods need to be tested in order to figure out an ideal concept for an indoor positioning method based on range imaging and semantically rich geospatial data (CityGML) instead of relying on physically deployed infrastructure. Furthermore the level of accuracy and the application scenario for that method have to be investigated.

# CLIPS – A Novel Optical Indoor Positioning System

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## 1 Summary

This paper presents the current research activities in indoor positioning at the Institute of Geodesy and Photogrammetry at ETH Zurich with focus on our novel optical indoor positioning system CLIPS (Camera and Laser based Indoor Positioning System) [1][2]. There is an enormous variety of indoor positioning systems exploiting the processing of i.e. Ultra Wide Band (UWB) or WLAN signals, the application of Inertial Measurement Units (IMU) or optical methods. No indoor positioning system is currently able to satisfy all user requirements for inexpensiveness, mobility and high accuracy without a sophisticated system setup. The goal of CLIPS is to fulfil these requirements within one system by determining the relative orientation of a digital camera with respect to an inverse camera which consists of a laser emitting light source for projection of a flexible reference field and replacement of a second camera.

## 2 Principle of CLIPS

The central idea of the new indoor positioning system is to determine the relative orientation of a digital camera with respect to a laser emitting light source that we call “laser-hedgehog”. This device projects well-distributed laser spots as flexible reference points on the ceiling, walls and furnishings in any indoor environment. The projecting light source consists of sixteen focused laser-beams that originate from a static, well-defined central point.

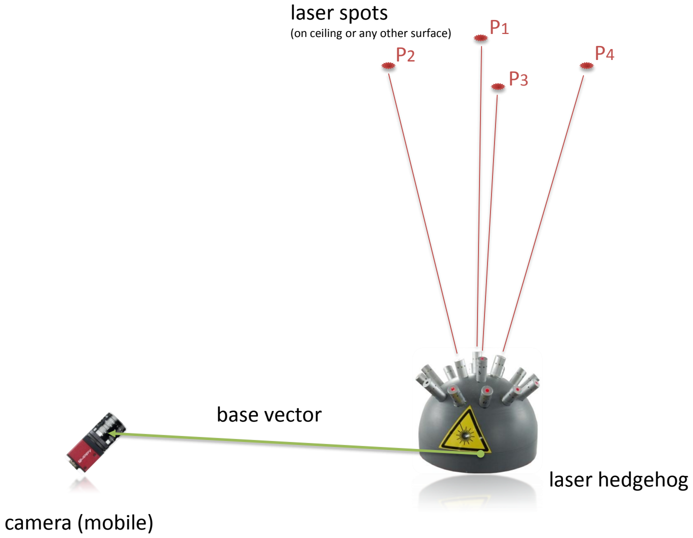


Fig. 1: Principle of CLIPS

The 3D directions of the laser-beams are also precisely known through a one-time high precision calibration. Therefore we are able to simulate the image of a virtual camera by projecting the laser-beams on a virtual (i.e. mathematical) plane. The main functions of the laser-hedgehog can be summarised as, (a) the projection of flexible reference points on any surface and (b) the simulation of a second camera.

The advantages of that approach are twofold. Because of (a), the system is not depending on an existing field of reference points. Therefore, CLIPS has a high degree of mobility allowing for quick and immediate application in any indoor environment. Secondly, the system costs as well as the computational costs can be reduced since one camera is replaced by the laser-hedgehog. Through camera simulation (b) the steps of point detection and identification for the virtual picture can be omitted.

## 3 Determination of the relative Orientation

By observing the projected reference field with the digital camera the relative orientation can be determined subsequent to point identification by introducing the coplanarity constraints of epipolar geometry. For this task the 5-point-algorithm by Stewenius & Nister has been chosen [3]. The two input images consist of the "virtual image" of the laser-hedgehog and the real camera image. Since the solution of the 5-point-algorithm can consist of up to 10 different possible camera positions (i.e. essential matrices), the correct essential matrix is identified by embedding the algorithm into a RANSAC framework. The result (i.e. position and orientation of the camera) is decomposed into a translational vector **b** and a rotational matrix **R** describing the spatial attitude of the camera and finally refined by using more than the minimal number of 5 points and applying a least-squares minimisation for the improvement of the relative orientation parameters.

## 4 Introduction of the System Scale

One challenge is the introduction of the system-scale which cannot be determined by relative orientation. Out of several options, the simplest option was chosen by directly measuring the distance (base vector c.f. Fig. 1) between the laser hedgehog and the camera using a tachymeter. The distance measurements are carried out only for the first four camera positions. Then, the four 3D vectors between the hedgehog and the camera positions are computed and the spatial coordinates of the laser points are determined by intersection. Once the 3D positions of the laser spots are known, the relative orientation parameters for further camera positions are determined by spatial resection.

## 5 Conclusions and Outlook

The advantage of the 5-point algorithm for the relative orientation is that the geometry of the laser spots is not restricted. The algorithm is stable even for geometrically critical surfaces such as planes. Therefore, the novel system is designed for being independently operable in any indoor environment. First experiments have shown that the relative orientation of the camera could be correctly determined in all cases and that our new system has the potential to achieve mm-level accuracy or better. However, the overall system performance has been limited so far due to an imprecise determination of the system-scale. In the future, more practical solutions for determining the system scale will be considered, e.g. the use of two laser-hedgehogs.

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# Optical Indoor Positioning using a camera phone

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## 1 Summary

This abstract describes a system for the determination of the user's position inside a building by using a camera phone. For calculating the position only one image of an object that is known in a local building reference system is required. The spatial resection is used as the algorithm for the position estimation. Digital cameras are nowadays included in almost every mobile phone. Therefore, the aim is to develop a system that allows indoor positioning using a camera phone. In the following, the technical realization of the system is described and first results of positioning with a camera phone using spatial resection are presented.

## 2 Technical realization

The basic idea is to determine the position of a person inside a building by using a calibrated camera phone. First, an object (e.g. a door) signed with a code is photographed. The code includes unique site-specific information of the door. Then, the photo is sent to a server via wireless communication technologies. On the server the image coordinates ($u_i$, $v_i$) of the door's corners as well as the code information are extracted by image processing algorithms. The object coordinates ($X_i$, $Y_i$, $Z_i$) can be identified from the code information and the corresponding corners that are stored in a database. With these corresponding points, the 3D-position of the camera phone ($P_0$) can be calculated. Then $P_0$ is displayed in a CAD model of the building that is also stored on the server. The clipping of the CAD model with the position information of the camera phone is sent back to the mobile phone. Preconditions for the mobile phone are: a digital camera with a fixable focus, WiFi – functionality and programmability.

## 3 Positioning with spatial resection

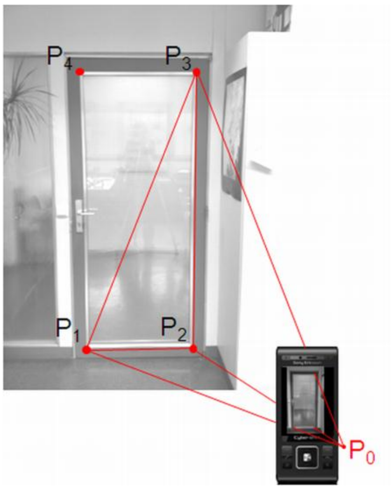


Figure 1: configuration of a photo adaption by the camera phone

An essential part of the realization of this system is the calculation of the position by taking only one picture. Using spatial resection the 3D position of the camera phone can be determined in the reference system. The position and orientation of the camera is arbitrary. Standard algorithms based on a linearized model rely on approximate values and therefore cannot be used in this case. Modern nonlinear approaches for computing the spatial resection like Rohrberg's approach offer the opportunity to determine the orientation without approximate values. Only the inner orientation of the camera has to be known. Using three control points $P_i$ with known coordinates in the reference system as well as in the image coordinate system, up to four possible candidates for the real position for $P_0$ can be calculated. In order to identify the correct solution $P_0$, further combinations of the points have to be used for the computation, e.g. ($P_2$, $P_3$, $P_4$, $P_0$).

## 4 First results of camera phone positioning

To test the described concept the camera was positioned on certain view points. The coordinates of these viewpoints have been determined previously by a geodetic measurement system and are assumed to be check points. Taking a photo of a visible door that is also known in the reference system of the viewpoints, the camera position was calculated.

Table 1: excerpt of comparison of camera phone positions with check points

| **Number of check point** | **$d_X$ [m]** | **$d_Y$ [m]** | **$d_Z$ [m]** | **$d_P$ [m]** |
|---|---|---|---|---|
| 30 | 0,05 | 0,11 | -0,14 | 0,18 |
| 37 | 0,02 | -0,08 | 0,02 | 0,08 |
| 38 | 0,01 | 0,06 | 0,03 | 0,07 |
| 39 | -0,62 | -0,03 | 0,04 | 0,62 |
| 103 | 0,33 | -0,06 | 0,02 | 0,34 |

Table 1 shows an excerpt of comparison of coordinates, calculated by camera positioning with the check coordinates of the viewpoints. In most of the cases deviations are within a few cm except in point 39 and 103. On one hand this is due to a bad configuration of the tetrahedron spanned by the door and the camera phone, see Figure 1, on the other hand gross errors caused by a false selection of a solution can cause the bad solution. Currently they are not detected and therefore decrease the quality of the solution.

## 5 Conclusions and Outlook

The results of the first experiments show that the system seems to be suitable for indoor positioning. The results justify the realization of such a system because it offers more precise solutions than e.g. positioning based on WLAN. Therefore, future work will be the development of robust techniques for finding the correct solution and furthermore the implementation of methods for an automatic detection of the object's image coordinates. More over the idea has to be adapted for cell phones with respect to the limited resources of mobile devices.

## Context Detection & Awareness

Auditorium D2

Friday, September 17, 08:15 – 09:45 & 10:15 – 12:00

# An Energy-Aware Indoor Positioning System for AAL Environments

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## 1 Introduction

In the last years, there is a growing demand for new technologies and social systems to improve the quality of life for all people in all stages of their lives. These research activities are covered under the topic AAL, Ambient Assisted Living (http://aal-europe.eu/, http://partner.vde.com/bmbf-aal). A special aspect within the AAL context is the interlinking of domestic infrastructure like heating, air conditioning or lighting to support every day household activities. With the increasing number of single person households and more households with elderly people, another aspect is the need to monitor the activities and health status of these people. Both aspects require a positioning service which allows indoor user tracking within a home environment.

The coupling of a positioning solution with AAL applications can be loose, i.e. position calculation and application are separate architectural subsystems, or tighter by integrating position evaluation and application-level processing in networked, multi-functional devices. Our system realises the latter concept in a handheld device that is both the positioning target and an integral, networked part of an AAL application architecture, exchanging data with other nodes and presenting contextual information beyond mere positioning data.

In a home setting, installation and operating of positioning appliances becomes a matter of reliability and accuracy, but also of ease of use, integration and energy consumption. System designs initially neglecting energy efficiency issues involve the risk of massive redesign when a low-energy objective is added later in a project. We therefore propose to consider energy efficiency at an early stage of system design for positioning systems.

We present an approach based on a ultrasound and RF system for three dimensional indoor positioning and tracking. Main design goals of the system are easy installation within existing households and very low energy consumption. The positioning algorithm, not focused in this paper, needs to provide indoor positioning with sub-meter accuracy in the horizontal plane.

## 2 System Description

Our system uses a TDoA (Time Difference of Arrival) distance measurement approach using radio packets and ultrasonic pulses, similar to [1]. The system is composed of custom-engineered wall-mounted nodes with ultrasound transceivers and RF transmitters and mobile positioning target nodes based on a generic development handheld device enhanced with ultrasound transceivers and RF receivers. To generate TDoA information, each wall node sends a radio packet followed by a given delay, followed by a burst of ultrasonic chirps. A mobile device within reception range detects the radio packet and measures the time delay until the ultrasonic pulses are received. Thus, distances to all wall nodes within reception range can eventually be calculated by the mobile device, and it can determine its location relative to the well-known locations of the wall nodes using a multilateration algorithm.

While the basic system takes a popular approach to indoor positioning, it is enhanced by connecting the mobile nodes to the ambient system context by ZigBee low-rate wireless personal networking technology (Figure 1). Only a small fraction of the embedded processor performance is used for positioning, and an embedded touch screen display allows position-based presentation and interaction with the AAL context like the status of nearby appliances.

## 3 Energy Efficiency

One promising target for energy optimization of positioning systems are transmission and reception activities because they involve transformation of notable amounts and thus a certain loss of energy, both for modulated RF and acoustic waves. A minimum amount of energy per transmission is necessary for a given transmission range, so we set the objective to keep the number of message transfers for a measurement cycle at a minimum (Figure 1).

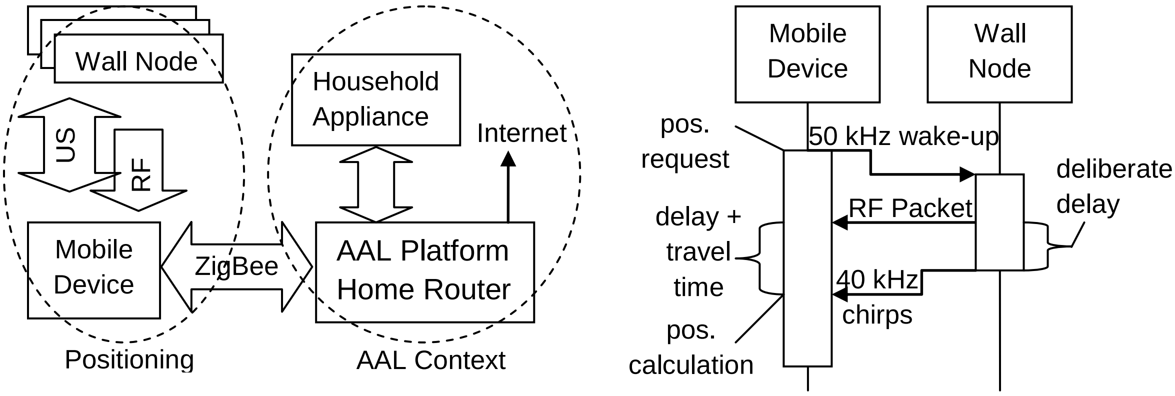


Figure 18: Positioning and AAL Context (left) and Message Flow (right)

Since the only task of wall nodes is the transmission of messages providing positioning input, our approach to further reduce the energy consumption of wall nodes is to let them enter a low-power sleeping state between positioning cycles and wake them up by a distinct ultrasonic pulse from the mobile devices. Still, the monitoring of wake-up signals during the sleeping state can be an energy-wasting factor, so we designed an autonomous, low-power electronic circuit that generates from 50 kHz ultrasound pulses a logic signal that is used to reactivate the powered-down processor. The frequency of the wake-up pulses is offset from the measurement pulses such that interference can be avoided by an electronic filter stage.

## 4 Future Prospects

Indoor user tracking is a special aspect within the context of AAL. It is obvious to use the position information and the remaining resources of the mobile device for different AAL services. Another aspect for future development is to use the reduced power consumption to build self-sustaining wall nodes, powered by a solar cell charging a supercapacitor or battery.

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# Using Context Information to Improve Indoor Localization

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## 1 Extended Abstract

Localization is an essential service in many context-aware applications and in ambient assisted living (AAL). A promising localization approach is based on Wireless Sensor Networks [1]. These solutions estimate the location of the mobile sensors (also called *mobiles*) with respect to a set of fixed sensors (or *anchors*) whose position is known. In this work, we consider a range-based localization [2], that exploits measurements of Received Signal Strength Indicator (RSSI). The use of the RSSI does not require any special hardware and it is available in most of the standard wireless devices, and it has received considerable interest in the recent literature [3]. In RSSI based localization, each beacon packet exchanged between an anchor and a mobile provides an RSSI measure that, by means of a propagation model, is used to estimate the distance between the two devices. In this work we consider the one-slope propagation model [4], which assumes a logarithmic dependence between the path loss (dB) and the distance between the transmitter and the receiver. The propagation model needs a time consuming calibration procedure that involves several RSSI measurements in the environment where the localization system is deployed. Context aware applications (in particular AAL applications) collect a number of information (called context information) about the users. We observed that some of this information can be used to refine the localization of a user. For example, when the user turns on the light in a room, this fact can be use to infer that the user is in that room (or, even better, in front of the light switch). We exploit such an information showing that the use of the restriction significantly improves existing RSSI based localization algorithms, such as those based on multilateration and Least Mean Square (LMS) [4], [5].

In our work we consider two localization algorithms, the Intersection Points (IP), which is based on multilateration, and the LMS. Given a set of *n* anchors $a_1 \; . . . \; a_n$ , let $r_1 , . . . r_n$ be the respective RSSI measurements between each anchor and the mobile. The IP algorithm first selects the three anchors with a greater RSSI. Without loss of generality, let $a_1$ , $a_2$ , and $a_3$ be such anchors. Then, for each anchor $a_i$ $(i \in [1, 3])$ the IP algorithm estimates its distance from the mobile by applying the propagation model to $r_i$ . Anchor $a_i$ is the centre of circle with radius equal to $d_i$ . The IP algorithm computes the intersection points among the three circles centred in $a_1$ , $a_2$ , and $a_3$ (note that the intersection points can be up to 6). Then, it estimates the position of the mobile as the centre of mass between these intersection points. An example of how the IP algorithm works is shown in Figure 1.

The LMS algorithm exploits an RSSI map of the environment that is computed during the deployment of the localization system. This map is a list of pairs *<coordinate, RSSI tuple>* that express, for a given point of coordinate *(x,y)* in the environment, a tuple of RSSI measurements among the anchors $a_1$ , $a_2$ , and $a_n$, and that point. Typically, this list is computed for a regular grid of points in the environment whose granularity depends on the required precision of the localization (however, beyond a given granularity, the effects on the localization precision become negligible). At runtime, the LMS algorithm takes the tuple of measured RSSI $R_M = < r_1 , r_2 , . . . r_n >$ and it finds in the list the RSSI_tuple $R'_{(x,y)} = < r'_1$ ,

$r'_2$ , . . . $r'_n$ > that minimizes the mean square error between the two tuples. Then, it outputs the coordinate pair *(x,y)* corresponding to $R'_{(x,y)}$. Given a localization strategy, we call it *restricted* if the filter of RSSI based on the context information is used, otherwise we call it *inclusive*. In the IP-restricted algorithm, the restriction occurs after the intersection points are computed, thus the IP-restricted computes the centre of mass between the intersection points that fit within the room ($I_1$ and $I_2$ in Figure 1). In the LMS-restricted algorithm, only the pairs <*coordinate, RSSI_tuple*> computed in the room are used. The comparison among this four localization algorithms was performed by experimentation. The environment used for the experiments is an area (in our laboratory) of approximately 7m by 11m. In the experiments we used a wireless sensor network composed of 7 MicaZ [6] equipped with the Chipcom CC2420 radio subsystem implementing the IEEE 802.15.4 standard. Figure 2 shows the Cumulative Distribution Function (CDF) of the localization error $\varepsilon$ by using both the restricted and the inclusive strategies, together with the LSM and IP algorithms. The CDF of $\varepsilon$ is defined as the probability that the localization error takes a value less than or equal to *x* meters. This Figure highlights that, in this setting, the IP algorithm outperforms the LMS; in fact, in 70% of the cases the localization error is lower than 1.6m, 2.4m, 2.6m, 2.9m, for the R-IP, I-IP, R-LMS and I-LMS, respectively. Most important, it is clearly seen that the restricted strategy significantly improves both LMS and IP. In particular, when the LMS is used, if the requirement of a localization system is to achieve an error below 2 meters, the restricted strategy improves the performance of about 20% with respect to the inclusive one. Instead, when the IP algorithm is used, the restricted strategy improves on about 25% with respect to the inclusive one if the requirement is to reach a localization error below 3 meters, but there is no significantly difference between these strategies if we need an accuracy below 1.5 meters. The full paper will provide all the technical details missing in this abstract.

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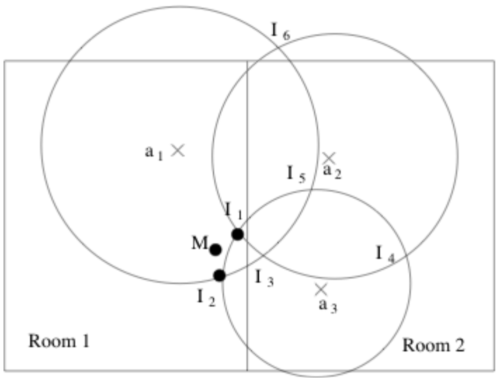


Fig. 1. IP-restricted localization algorithm.

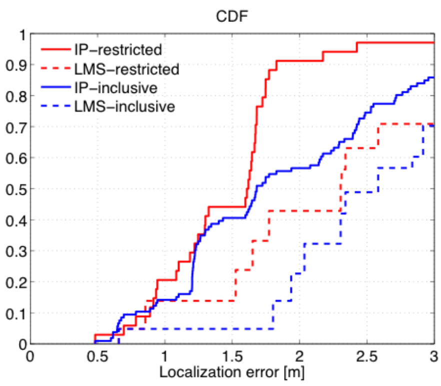


Fig. 2. CDF of the $\varepsilon$ by using context information.

# Situation-Aware Indoor Tracking with High-Density, Large-Scale Wireless Sensor Networks

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## 1 Introduction

Given the continuous technological advances in computing and communication, it seems that we are rapidly heading towards the realization of paradigms commonly described as ubiquitous computing [1], pervasive computing, ambient intelligence, Internet of things or, more recently, "everyware" [2]. These paradigms envision living environments pervaded by a high number of visible and invisible devices affecting and improving all aspects of our lives. All these paradigms are substantially based on the need of knowing the physical location of users.

Outdoor location-aware applications are already widespread and popular today whereas indoor localization is still an open research problem. In the last few years, several indoor positioning systems have been proposed [3]; we are more and more capable of computing precise positions of moving targets, but unfortunately we are rarely capable of exactly understanding what they are doing.

In this paper we propose an innovative approach to the problem of indoor position estimation that aims at extending tracking to a new level of “awareness” bringing to bear new ambient data and opening the possibility of “reasoning” not only on simple positioning but also on the situation at hand.

The remainder of the paper is organized as follows. Section 2 describes the approach giving an architectural overview and detailing the components used for its implementation. Section 3 describes the evaluation environment and finally Section 4 draws the conclusions.

## 2 Situation-Aware Indoor Tracking

We propose an approach to indoor tracking that exploits situation-aware techniques in order to improve accuracy and precision. The approach is mainly based on: (i) a low-cost and energy-aware localization infrastructure; (ii) multi-sensor, statistically based, localization algorithms; (iii) logic-based situation assessment techniques.

In order to validate the described approach, we implemented a positioning system called Situation-Aware Indoor Tracking (SAIT). The architecture and the main components of the SAIT system are shown in Figure 1.

The localization infrastructure of SAIT is based on Wireless Sensor Networks (WSN). The network is organized hierarchically, includes mobile and fixed nodes and implements energy-aware data-collection algorithms. The WSN nodes have been designed and built expressly for this system (mostly because nothing suitable was commercially available).

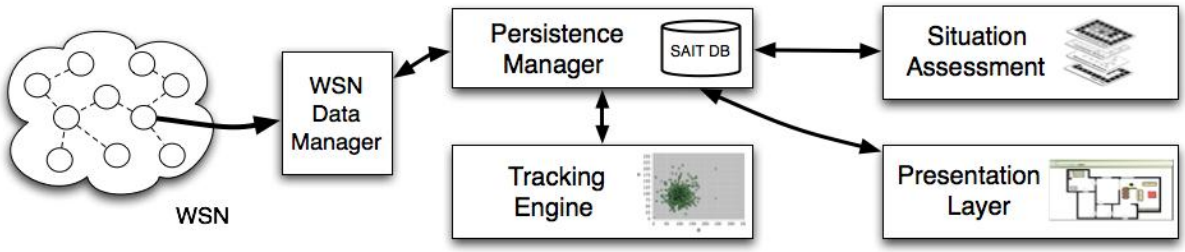


Figure 1: The Architecture of the SAIT System.

The fixed nodes, besides providing RSSI data, include motion and range-finder sensors (used for improving the accuracy of tracking) and environmental sensors (used for gathering contextual data, such as brightness, temperature, humidity and so on). Moreover, every mobile node includes a complete six-degrees-of-freedom (6DoF) inertial measurement unit (IMU) that is used to track the user movements.

The SAIT Tracking Engine component aggregates the collected motion and position data and computes the target position using a multi-sensor localization algorithm based on particle filters (PF).

Situation awareness can be achieved introducing a logic-based context model of the environment and using logic programming techniques to reason about contextual data. For example, given a set of target positions computed by the SAIT tracking engine with a certain likelihood *P* at a given time *T*, the logic program can use the available contextual data to validate these positions and moreover it can reason about several preference criteria to identify the best solutions and the improve the result of tracking.

## 3 Evaluation

We evaluate the SAIT system in comparison with several commercial systems, mainly based on UWB, Wi-Fi and WSN technologies (the full list of systems and the description of evaluation test will be given in the full paper). The comparison highlights a promising behaviour, showing that exploiting the movement data (e.g. the users' heading and speed) for updating the PF motion models used in the tracking engine can improve the accuracy of tracking up to 42% in comparison with a Wi-Fi system.

## 4 Conclusions and Outlook

This paper described approaches to the indoor position estimation based on situation-aware techniques. The sheer number of deployable sensor and computer devices has a chance at making much more difference for indoor location-aware applications. We believe one of the main improvements will be the possibility of making the environment aware of what is happening (either because of human intervention, or because of physical phenomena). In other words, we have a chance at making the environment aware of the situation (on whatever scale it might be meaningful, from a single elderly person in distress to an earthquake endangering millions of people).

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# Automatic Context Detection of a Mobile User

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## 1 Summary

Mobile devices have obtained a significant role in our life providing a large variety of useful functionalities and features. It is desirable to have an automated adaptation of the behavior of a mobile device depending on a change of user context to fulfill expectations towards practical usefulness. To enable mobile devices to adapt their behavior automatically there is a need to determine the mobile user's context.

In this paper we introduce an integrated approach for the automatic detection of a user's context. Therefore, we summarize and discuss existing approaches and technologies and describe a service architecture that takes into account information from the interaction of the mobile device with communication networks and positioning systems, from integrated sensors, and planned behavior of the user from e.g. his calendar or activity list. Additionally the architecture considers the social network of the user to derive further information about his context and finally it takes into account the user's customs through a behavior model.

## 2 Introduction

The omnipresence of mobile devices requires the ability to adapt the device's capabilities. Simple implementations of this feature are already in place in most common mobile devices. So the user can limit the usage of the device's interaction features for example muting the ring tone, deactivating the network interface radio, etc. To simplify the configuration the settings are often grouped into configuration profiles, so the user only has to select a defined profile and gets a suitable setup for a situation. In real environments the context continuously changes and therefore it is desirable to support automatic detection of the user's current context. This would increase the usage comfort due to improved adaptability of the device. As an additional feature the current context of the user in combination with his current position can be used to improve the location based services by providing this information to the service.

In this paper we discuss existing and new approaches to determine a mobile user's context. We analyze their prospects, possible drawbacks and the technical requirements. The paper introduces some new ideas to determine a mobile user's context and describes our vision for future development.

## 3 Integrated Context Detection Architecture

Existing approaches only consider a certain aspect or technology to discover a user's context. Thus, we propose that a combination of several approaches is desirable to offer an overall adaptation to a mobile user's context. We also propose that detection of a mobile

user's context should be provided by the mobile device as a service, so that all applications can have access to the context information and can adapt their behavior accordingly.
The integration approach of the Context Detection Service is based on a three layer architecture. The data or signal source layer consists of the available sensors, radio network interfaces, the built in clock, and or even the connection interface to the user's community. The source layer provides information in form of data or signals which comprise the information layer. In order to be of use for the Context Detection Service this information needs to be processed into knowledge which forms the third layer of the architecture. The transformation of information to knowledge is done by additional Information Processing Services which map the information events from the source layer to knowledge tags with the help of suitable patterns defined in the Pattern Repository.
The most significant criteria to determine one's mobile context seem to be his geographical location, the current time, and his planned activities. On one hand all these criteria have a direct impact on ones context and on the other hand the corresponding technologies, like calendars, location based directories, and time dependend schedulers are already part of prevalent mobile applications.

## 4 Conclusions and Outlook

In our paper we discuss different approaches to automatic context detection and proposed an integrated service architecture which can combine information from different approaches. We think this is necessary to gain a precise view on the user's context which is the main preposition to developing context-aware mobile applications. As a basic requirement for an integrated service the context information from the data or signal source layer is transformed into knowledge which can be interpreted by the context detection service and then be provided to mobile applications running on the device or as basis for the device configuration.
The selection criteria for the most suitable context detection approaches should be on the one hand pervasiveness of the underlying technology, e.g. UMTS and WLAN networks of the radio signal approach, and on the other hand the obtainable accuracy for the derived user context. Today's mobile environments are characterized by highly available, pervasive mobile communication networks, mobile calendar based job itineraries, and mobile devices with high computational power. Under these preconditions it is recommendable to combine these with radio based approaches in UMTS/GSM networks for the detection of the user's current geographical region. A rough context of the mobile user can be deduced there from in combination with the event and activity list from his calendar. This rough context can then be refined with the help of the radio based approach in WLAN infrastructures that the user will enter, cross, or leave.
To determine the context of a mobile user in an automated way it is necessary to process knowledge from several sources and services. Thus, there is need for common ontologies for the description of the context concept, knowledge description tags characterizing a defined context, and even the events provided by the signal layer. The next implementation steps for the proposed context detection architecture are the definition of a suitable context ontology and the interaction design of the discussed components of a Context Detection Service.

# Indoor-Navigation with Landmarks

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## 1 Summary

The complexity of large buildings, like airports, and the omnipresence of mobile devices ask for the ability to navigate people through these buildings with help of their mobile device.
Mobile indoor positioning systems do not provide the accuracy required by common navigation systems, since they determine the geographical position based on trilateration of radio signals, e.g. from WiFi or GSM (Global System for Mobile Communication). Also, GPS (Global Positioning System) is not usable in indoor scenarios because buildings absorb the signals.
So there is a need for navigation systems, which do not require precise or even any signal based positioning system. Most people tend to express navigation information as a sequence of waypoints and navigation commands enriched by using landmarks. Therefore, we introduce an approach for indoor navigation, which implements the use of landmarks in an automatic navigation system. The system provides the ability to determine a user's position and guides her to a selected target.

## 2 Introduction

As determining geographical positions inside buildings is either imprecise or requires special and expensive hardware, a navigation system for indoor scenarios has to work without or at most with imprecise position information. In this paper we describe an approach, which uses human's common sense of route description to provide the ability for indoor navigation with today's mobile devices.
In Section 3 we introduce some basic concepts used in the discussion of the approach in Section 4. Section 5 concludes our work and gives a short outlook on further research.

## 3 Concepts

Navigation is defined as the control of movement to reach a destination from a known starting position. In case of a mobile device it means the device offers the user information that helps her choosing the right way to reach her destination.
The natural human method to describe a route is to use easily recognizable objects to mark positions and describe headings. These recognizable objects are called landmarks. So such landmarks may supplement navigation commands.

## 4 Approach

As base of our approach we use a model for possible movements of the user. This movement model is a directed graph consisting of nodes that represent positions and edges

that represent possible movement directions inside a building. A position in this case is not an exact geographical position but a certain area of a building. E.g. a position could be a corridor, an intersection, or a corner of a hall. A navigation route is equal to a path in this graph.
To communicate these paths to the user and to determine a current position the graph is annotated with landmarks. Textual descriptions, symbols, or photos can describe these landmarks. Furthermore, all edges are annotated with their length and a description of their planar position with respect to each consecutive edge. The length of an edge is given in meters and the relative planar position of an edge to another consecutive edge with the help of following discrete relative angle descriptions: ahead, diagonally left ahead, diagonally right ahead, left, diagonally right, back, diagonally left back, and diagonally left right.
With the help of the length annotations of the edges it is possible to reduce the number of landmarks required to navigate the user along a route, if landmarks are too close together, e.g. two shops that are next each other, then only one landmark is needed.
In this way it is possible to produce navigation advices based on two basic commands “traverseTo:” and “traverseBy:”. The annotation of relative angles for consecutive edges provides the possibility to produce navigation advices based on the additional command “turnTo:” and the corresponding discrete direction description of the next landmark, e.g. “turnTo: left”.

## 5 Conclusion and Outlook

The movement model discussed in this paper provides the possibility to navigate a user in indoor scenarios to her destination with the help of landmarks. The three basic movement commands combined with landmarks and discrete angle descriptions are sufficient to enable a user to transfer a path planned out in the movement model to the real surroundings.
Further investigations will be made to generate natural language instructions from the movement model and to use imprecise positions provided by the users’ mobile device to adjust the navigation command generation.

# Indoor Navigation Approach Based on Approximate Positions

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## 1 Summary

Until now navigation aids have primarily focused on outdoor scenarios, whether driving on highways or, more recently, walking through cities. These systems use the Global Positioning System (GPS) for position information. Indoor navigation however cannot rely on GPS data, as the signals do not penetrate building structure. Thus other techniques were developed to provide position information indoors, but most of them lack the precision of GPS. In this article the approach of an indoor navigation system based on imprecise position information is presented. To compensate the deficit of precision the position information is combined with a movement model. This movement model is automatically generated from the maps which are already required for navigation.

## 2 Introduction

Tools for navigational assistance have become an essential element in today's traveling society. Interactive software, available for mobile phones, is capable of guiding users who are driving cars, riding bicycles or walking. Until now such tools have focused on outdoor environments and are hence based on the precise data of the Global Positioning System (GPS) to determine the current position of the user. But indoor navigation bears several challenges.

First, GPS positioning information cannot be used for indoor scenarios since GPS radio signals do not propagate into buildings. Second, within buildings navigation does not rely on streets or footpaths but on traversable areas and certain connections between such, e.g. corridors, rooms, staircases and elevators. Thus such areas and also the altitude of the user, i.e. the floor he is currently standing on, and possible connections to other floors have to be considered. Third, the description of a path needs to be intuitively understandable for humans instead of giving precise distance instructions as they are used in cars or other devices with odometers.

The first issue, a positioning technique for indoor scenarios, was addressed among others with the Device Whispering technique (Krempels and Krebs, 2008). The third issue on intuitive navigational instructions is considered for outdoor environments in (Dale et al., 2003). Based on this state of the art we present a prototype indoor navigation system for a mobile device, which generates navigational instructions from sectorized building maps with the help of Voronoi diagrams and imprecise localizations from Device Whispering.

## 3 Prototype Navigation System

Any navigation system must convey the route to the user, typically using a combination of graphical map (with highlighted path) and textual instructions. Information about the local

geometry is of course required to compute paths. In indoor scenarios it is especially important to ensure that generated routes do not pass through walls or go outside of the building.
A convenient way to provide route information to users are natural language instructions (NLI), which offer rich and flexible means of describing paths. Such descriptions can also be followed without positioning information, for example cars are equipped with odometers, thus instructions of the form “turn after 300 meters” are easier to follow than for a pedestrian. Further, NLI can describe paths inside a “sector”, which represents an area inside which positioning is possibly impossible due to the approximate nature of the Device Whispering approach. NLI, when created by people, are heavily based on landmarks. Landmarks are distinctive features of the local geography, e.g. churches, malls, fountains and traffic lights outdoors, and specific shops, fountains and staircases indoors. One important distinction that has to be made for indoor scenarios are different floors in a building, which add a third dimension to the geography of a location. Landmarks can also represent connections between floors, e.g. stairs and elevators, which cannot be displayed at all in a purely two dimensional map.
In our decentralized approach every location is responsible for providing the map information locally, for instance by using the local Wifi infrastructure which can be assumed to be available since it is used by the Device Whispering technique for localization. Thus, it is not required to establish a network link to the user’s mobile provider to equip the mobile devices with up-to-date geographical data. This is generated by a preprocessor, which also provides a GUI to create and maintain the data structure of the building maps. Therein, locations are represented by polygons, inside which the Wifi access points and landmarks are positioned.
The client software is supposed to run on mobile devices, which do not have the computational power and memory available to notebooks or desktop computers. Therefore, a preprocessor was developed to perform the computationally intensive tasks beforehand. The client is left with the tasks of computing routes in the provided building maps, communicating these routes to the user both graphically and verbally to navigate her through the building.

## 4 Conclusions and Outlook

Tests of the prototype system uncovered that common network interfaces do not modulate transmission power as required for Device Whispering, when the interface is instructed to do so: all access points which are detected already respond to the lowest power request. Pending further inquiry, we are currently assuming that transmission power modulation is not implemented, possibly to reduce the chip’s area. Therefore, an adaptation of the Device Whispering technique is the objective of ongoing research to address this issue.
The implemented text generation system produces NLI which are quite satisfactory, especially concerning its minimalistic approach. In both cases, output and generation complexity, the system compares favorably with CORAL: the generated text is not quite as eloquent, but is generated with much less effort. This indicates that our approach of skeletons annotated with landmarks provides adequate information for the NLI generator. The very simple approach to text generation leaves open many possibilities for extension, e.g. adding more rules to improve both the natural language as well as for selecting landmarks to use in the text.

# Navigation Based on Symbolic Space Models

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## 1 Summary

Existing navigation systems are very appropriate for car navigation, but lack support for convenient pedestrian navigation and cannot be used indoors due to GPS limitations. In addition, the creation and the maintenance of the required models are costly and time consuming, and usually based on proprietary data structures. In this paper we describe a navigation system based on a human inspired symbolic space model. We argue that symbolic space models are much easier to create and to maintain, and that they can support routing applications based on self-locating through the recognition of nearby features. Our symbolic space model is supported by a federation of servers where the spatial descriptions are stored, and which provide interfaces for feeding and querying the model. Local models residing in different servers may be connected between them, thus contributing to the system scalability.

## 2 Introduction

In recent years, there has been an effort to extend the convenience of outdoor navigation systems into the indoor environment. However, resorting to similar space models and routing algorithms has proved to be difficult and unpractical due to GPS limitations and the lack of geometric models for buildings. Stahl and Haupert [1] propose a solution based on hybrid space models and indoor positioning systems. However, as in other approaches, this solution requires some level of technical expertise, access to CAD drawings and a considerable amount of time to build the appropriate geometric models.

There are, however, other systems where very simple models are used to assist navigation. One good example, where a simple topological model is used without any technological positioning system, is the underground transportation map. It is a graph in which vertices represent the stations and edges represent connections between them. In this system, positioning is based on the station names that are advertised at their entrances and inside the stations in places visible from inside the trains. Each user identifies his/her location according to the station name and defines a route by visual inspection of the lines connecting the stations. In this paper we describe a navigation system that exploits human mental models of spaces and self-location through the recognition of nearby features.

## 3 A Symbolic Space Model for Indoor Navigation

Human mental spaces are defined as mental constructions consisting of elements and spatial relations among them [2]. They are created as a result of our interaction with the environment, as well as of our imagination as we see or hear about places, or of the combination of both. Similarly, our space model consists of *objects* and *relations* between objects [3]. Each *object* represents a place (a building, a room, or an elevator), and is characterized by a name, a type, a URI, and a set of attributes. *Relations* connect objects within a specific semantic context, such as *Is_Near*, *Is_In*, *Is_Next_To*, or *Is_Accessible_From*. Each relation can also be characterized by an arbitrary set of attributes.

Our symbolic space model is supported by a federation of servers – Contextualizers – that store the objects and relations between them, and provide interfaces for feeding and querying the model. Since relations between objects are defined within a semantic context, reasoning algorithms are used by the Contextualizers when queries are performed. The model is continuously updated with data collected from sensor networks [3].

The advantages of this symbolic space model for indoor navigation are manifold. First, it is much easier to understand by because it is based on the human mental models. Second, each person can build his/her own model by creating objects and relations between them, without the need for any geometric reference. Third, each local model can be stored on a local Contextualizer, and objects in one server can be related with objects in other servers through their URIs, thus contributing to the system scalability. Fourth, it supports routing applications that rely on a self-locating approach based on the recognition of visual landmarks (such as wall colours or door codes) described in the model as objects' attributes.

The whole navigation system includes the federation of Contextualizers, a Space Editor, a Visual Browser for model naviagtion, and a routing application with a web interface. This last application uses the query interface of the Contextualizer to access the model and retrieve information about the origin and the destination objects. It then uses the semantics of the *Is_Accessible_From* relations, including its eventual symmetry, to compute the shortest path between two locations. The response to a routing request is an ordered list of places, and its characteristics, that must be visited sequentially to go from origin to destination.

## 4 Conclusions and future work

We briefly described an indoor routing platform supported by symbolic space models that can be created collaboratively by a group of users based on their mental space models. In the future we plan to exploit other relations, such as *Is_Next_To*, to improve the route description provided to the users.

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# Indoor Location Services and Context-Sensitive Applications in Wireless Networks

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## Introduction

Development of context-sensitive applications has become a dynamically evolving area of information technology. Position as a context can on its own provide valuable information, but in conjunction with other knowledge bases, it makes services that grow to be integral parts of our daily lives possible. While outdoors the ability to determine geographic coordinates has given birth to a whole navigation industry, indoors this revolution is yet to be achieved. We, engineers, have to come up with solutions that integrate with our usual behaviour imperceptibly, but are able to provide such extra functions and ease of use that may change the way we look at our environment. Using indoor location, devices knowing the position of persons and objects surrounding them may very well realize such a vision.

Research projects and commercial products have been available for multiple years now that utilize the signals of Wi-Fi networks to calculate people's positions inside a building. However most of the currently used systems are based on the radio fingerprint principle that makes the thorough survey of the area necessary before deployment and after every change in the network infrastructure. Realizing this burden, our goal was to develop an algorithm that lifts this constraint while retaining the accuracy and performance of the previous systems.

On its own, knowing the location of a mobile device or a person only enables us to build simple applications. By adding semantics to the floor plan, declaring static and dynamic attributes on persons, devices, groups and locations, and taking into account informations such as the time of day or even the weather, richer and more powerful services can be provided. We plan to incorporate these functions into a framework, making information accessible via a well-defined programming interface, thus allowing upper layer applications to use context-sensitive and location-sensitive data.

This project started out as a university research at the Mobile Innovation Centre of the Budapest University of Technology. In cooperation with an industrial partner, it is the subject of a tender sponsored by the Economic Development Operational Programme of the Hungarian National Development Agency, partially financed by the European Regional Development Fund. The goal of the project is to develop a mobile based indoor location and navigation system usable in office environments, offering a complete solution including the client, the server infrastructure, the operator interfaces and the location algorithm itself, with basic context-sensitive navigation services built on the top.

## Indoor Location Algorithm

The motivation for developing a new location algorithm is threefold. Albeit being highly accurate and fast, methods utilizing radio fingerprints are strenuous to deploy and require full re-surveying every time an access point is replaced or moved. For this reason they are not well-suited for an ever-changing office environment: a simple wave propagation model based algorithm would be preferable, where system parameters and access point locations can be changed independently. Secondly, the new algorithm has to be extremely resource-efficient in order to scale up to serving a multitude of people simultaneously in real time. It should run distributed on central servers, so that regular equipment and clients with very low processing power could be used. Thirdly, its accuracy should not be much worse than the currently existing radio fingerprint technologies, with the option of finer calculation in specified locations. This is done by integrating the radio fingerprint based principle and the propagation model, selectively relying on one or the other, having surveyed only the critical areas of the floor plan.

The selectively surveyed data set is overlaid on the map, and the missing areas are determined, where a mathematical model is used to calculate the expected signal strength values. Thus a distribution pattern is generated, much like a radio fingerprint map, so location-time operation is reduced to the usual nearest neighbour search in a vector space, using the average of squared differences of signal strength vectors as the distance factor. This way where accurate survey data exists, it will be used to determine the location, but we can still use another approach where it is not available. To increase accuracy, we statistically filter input, taking the median value of the last few measurements. Output is also filtered, its credibility is tested, and its oscillation is smoothed out. Different device models may be used simultaneously, since measured signal strength levels can be translated to a common scale.

The recalculation of the expected signal strengths is only necessary when the environment is changed. Calculated values are stored in a database as a materialized view, merged with the surveyed data set. In order to achieve fast computation of the propagation model based algorithm, we chose an equation based on the Motley–Keenan Model, augmented with factors from the New Empirical Model of Cheung, Sau and Murch. On its own it still would not be sufficiently accurate, so we added some heuristics to the algorithm taking into account the floor plan, distribution of walls, previous walking directions and typical indoor movement patterns, as well as data from G-sensors and digital compasses built into modern handheld devices. Each of these information sources and the propagation model define a probability distribution over the map, these layers are then weighted and summarized to get the final coordinates. To avoid the need to run a lengthy simulated annealing in continuous space at every iteration, we decided to represent the map as a set of discrete points at the intersections of a grid over the map. This way calculations can be simplified, each probability layer can define the points to be evaluated on, and the introduced error is not greater than half of the grid diagonal, practically the space occupied by a person.

**Context-Sensitive Framework**

Beside the location of the devices used, special areas of interest can be marked on the map, and the floor plan is also represented. Attributes are declared on individual persons, devices, groups of people, device classes and areas. These informations combined in a geometry model can be used to infer special knowledge: is someone in the same room as another person, can they see each other, where is the nearest exit, how long does it take for the nearest repairman to get to a specific place, how often do tracked people stop in front of a store etc. Data may be entered directly or inferred from other pieces of information by a rule-based reasoner, and one can use smart database views or custom queries to access properties associated with individuals either by assignment or in an indirect manner.

We use the geographic functions of Oracle Locator (subset of Oracle Spatial) to interface the attributes stored in the database with the coordinates and areas on the map. We implemented the algorithms in the PL/SQL programming language, and created database views to merge all the context informations belonging directly or indirectly to the entities. The framework can be queried by the upper layer applications via SOAP requests, thus enabling local and remote software running on either the server, an operator workstation or a client device to use the information stored in the database.

# Geolocation Server – Coordinates become context aware

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## 1 Summary

This extended abstract describes a geolocation server for indoor environments. Most of the available tracking or localisation technologies use a coordinate based approach. They describe the current location through a set of coordinates. Although the position is described sufficiently with this set of coordinates, the circumjacent context is not. This work describes an approach to overcome this lack of contextual awareness for an industrial indoor localization. It introduces a service layer which enriches given coordinates based on existing blueprints with context information. The identified entities of the circumjacent context of the coordinates are communicated via a machine readable interface. The interface provides the logical entities' geometry and a set of attributes which can be used to obtain further information like electrical or mechanical connections.

## 2 Introduction

Tracking technologies can be classified into symbol based or geometric approaches [4]: use a predefined reference system and describe the current location through a set of coordinates.
Problem: Detailed knowledge of the used reference system and the context where the localisation system is active is needed to obtain further information from these coordinates. A user of the localisation system is not supposed to have this detailed knowledge. A location which is only described by a set of coordinates is context-free. Information about the circumjacent context (e.g. object references) of the coordinates is necessary for a LBS.
Motivation: It is possible to create a meaningful localisation for the user and other services by adding context information to the coordinates. A spatial assistance system which offers information about surrounding objects can help the user to perform his task more efficiently or even enable him even if he is unfamiliar with his environment.
Use Case: This work took place with the Siemens AG which has a Smart Automation Center (SmA) in Nürberg Moorenbrunn. The SmA is a research facility where a LBS is introduced for service technicians in industrial environments. This LBS serves as a part of a spatial assistance system. For example service technicians are in front of a switch cabinet to perform a maintenance task. The hand held device can only provide Cartesian coordinates obtained by the installed tracking systems. But the knowledge of the raw coordinates is not giving any context information like blueprints, mechanical / electrical connections, maintenance instructions or notes regarding the current position. The spatial assistance system needs to have this translation (*geolocation process*) from coordinates to the context of switch cabinet.

## 3 Related work

Most of the work within the research field of indoor localisation and tracking focuses on concrete technologies for locating ones position. WiFi Fingerprinting [3], Bluetooth [2], RFID [1] or GSM [6] focus on enabling an indoor localisation without creating additional infrastructure. Typically the geometrical based systems show one's position on available floor plans on a room level [5]. The "where" is communicated but the surroundings of the "where" are neglected. For the use case the coordinates are supposed to have additional information e.g. object references of nearby components.

## 4 Concept

A method to assign context information to a specific coordinate has to be developed to realise a LBS serving context information. This is similar to a standard reverse geocoding process where coordinates are translated into an address. In this case tracked coordinates need to be annotated with object references of their surrounding context. This process is from now on referred to as a geolocation process. The nature of a geolocation process is geometrical since most of the available indoor localisation systems offer coordinates in a predefined reference system. It is possible to obtain information about the surroundings of the coordinates by blending existing blueprints and floor plans with the tracked coordinates in a common reference system. Annotations in the blueprints point toward additional resources which can hold functional descriptions or topological information. Within the use case, this could be electrical / mechanical connections, maintenance instructions or notes form colleagues.

## 5 Realization

A prototypical implementation of a service like this was deployed by using a WFS and Filter Encoding (FE). Existing CAD files of the SmA were converted into 2.5D shapefiles and annotated with URIs pointing toward additional information stored in ontologies. The usage of FE allows one to query for a set of coordinates with or without buffers. The retrieved context of the coordinate is transmitted, encoded in the GML and serves the URI along with the geometry of nearby objects. The URIs can be used to gain additional information of any kind. This approach allows one to use this LBS - the Geolocation Server - as a machine readable middleware layer for other applications assisting users at their task.

## 6 Conclusions and Outlook

This abstract describes the means and development for a more meaningful localisation for indoor localisation and tracking technologies using current standards. The first realization of a service like this allows up to 2.5D models of the environment. The usage of well known standards allows its introduction into any service chain, allowing one to enhance traditional tracking with context based information. With the introduction of GML 3.0 supporting 3D data, it is most likely that the standards of the WFS and FE will soon be capable of handling 3D data as well. This would allow the storage of 3D CAD data directly in a spatial database with annotations. Thus a full 3D contextual tracking would be possible.

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## Passive RFID

Auditorium D8

Wednesday, September 15, 10:30 – 11:45

# Accurate Indoor Position Estimation by the Swift-Communication Range Recognition (S-CRR) Method in Passive RFID systems

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**Summary**
RFID (Radio Frequency IDentification) systems have become meaningful as a new identification source that is applicable in ubiquitous environments. One of the important technologies that use RFID systems is the indoor position estimation of RFID readers. Using conventional methods, the system needs at least two RFID tags for the accurate indoor position estimation, and the accuracy itself of position estimation is not so high. In this paper, we propose a new method for accurate position estimation of passive RFID systems. The proposed method is capable of accurate position estimation in near real time regardless for large numbers of RFID tags.

## 1 Introduction

One of the important applications that can make use of the RFID technology is indoor position estimation. It is used in such a way that the system estimates the location of an RFID reader or an RFID tag. The performance requirements of most applications using RFID for position estimation are demanding, e.g. for navigation of a moving robot. Today, there exist already conventional methods for indoor positioning of RFID readers [1]-[2]. However, using the conventional methods, the system needs at least two RFID tags for the accurate position estimation, and the accuracy of the position estimation is not so high. In this paper, we propose a new method for a more accurate position estimation of passive RFID readers. The proposed method is capable of the accurate position estimation in near real time regardless for large numbers of RFID tags and it is based on S-CRR that is one of the position estimation methods for passive RFID systems.

## 2 The position estimation of the RFID tag by S-CRR

The position estimation of an RFID tag is one of technologies that has wide applications for localization of objects [3]. Today, we have already proposed too effective position estimation methods of RFID tags, Communication Range Recognition (CRR) and Swift-CRR (S-CRR) [4]-[5]. Note that our proposed methods are based on direction antenna. Here, we treat the S-CRR method.

The S-CRR method is an extended improvement of CRR according to the requirement time for the position estimation of RFID tags. In the S-CRR, the system detects two communication boundary angles of RFID reader antenna where the RFID reader is able to communicate with an RFID tag in one observation point. Thus, the RFID tag's position is estimated as the intersection of two circumferential lines of the communication area model of the RFID reader at the boundary angles. Since the system can estimate the position of the RFID tag at only one observation point, S-CRR enables the position estimation of the RFID tag in near real time. Even if a lot of RFID tags exist, all RFID tags can be recognized by a unique ID. Consequently, the S-CRR method is much more efficient than CRR.

## 3 The Proposed Method & Experiments

In the method, we assume that RFID tags are attached at a wall in equidistant intervals. Each RFID tag contains information of its own position and direction. Moreover, we assume that an RFID reader is mounted on a mobile robot. The mobile robot is rotating the RFID reader antenna in a horizontal plane during it's moving along corridors of buildings. Doing so, the mobile robot is radiating the signal from the RFID reader antenna to the RFID tags at regular intervals. When the RFID reader detects one of the RFID tags, the mobile robot stops and the current position is set as an observation point. Then, the system estimates the position of the RFID tag at this observation point using S-CRR, assuming that the position of the RFID reader is the origin of the coordinate axis, as shown in Fig.1. The RFID tag returns the information of its real position to the RFID reader. From this information, the system compares the estimated and real position of the RFID tag and obtains the difference. Then, the system calculates the estimated position of the RFID reader by sifting the difference. If there are two or more RFID tags, the system estimates multiple positions of the RFID reader. In this case, the estimated position of the RFID reader is defined as the central position of gravity of those estimated position coordinates. This method achieves an improved position estimation in near real time regardless for large numbers of RFID tags.

We compared the performance between the conventional CRR and S-CRR. Fig. 2 shows the experimental environment of S-CRR. The robot arm moves from point A to point B. The distance between the RFID tags and the straight line is L [cm]. Figs. 3 and 4 show the estimated position error of S-CRR and CRR. In both figures, the estimated position error of CRR is relatively large up to a moving distance of 55 cm. On the other hand, the estimated position error of S-CRR is always less than 20 cm. That is, even if the moving distance of the robot arm is small, the position of RFID tag can be estimated accurately by S-CRR.

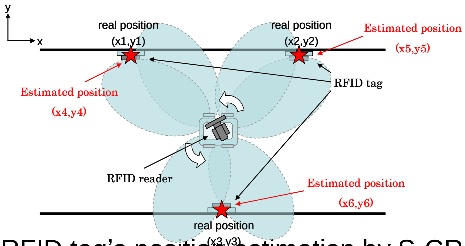
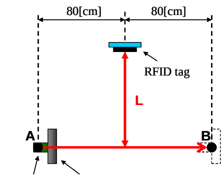
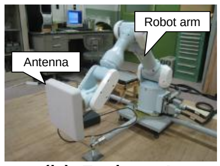



Fig.1: RFID tag's position estimation by S-CRR




(a) Moving route of robot arm (b) Robot Arm

Fig.2: Experimental environment

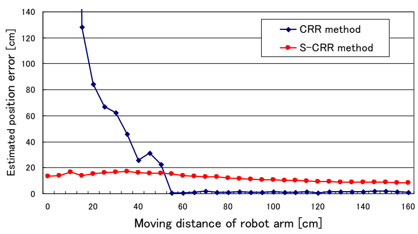



Fig.3: Estimated position error (L=80 cm)

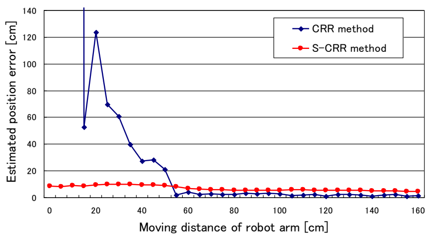



Fig.4: Estimated position error (L=100 cm)

## 4 Conclusion

In this paper, we have proposed a new method for a more accurate position estimation of passive RFID readers using S-CRR. We have shown the effectiveness of the S-CRR by experiments. We consider that our proposed method is much more efficient than the conventional methods.

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# Concrete Embedded RFID for Way-Point Positioning

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## 1 Short Summary

RFID markers are proving to be a cheap and reliable enabler for indoor positioning in applications such as warehousing, facility management and guidance for the blind. Motivated by this we have developed a low-cost concrete embedded RFID marker technology for robust and long-lasting way-point identification. Embedding passive tags in concrete significantly reduces their read range and hence, usefulness as markers. By appropriate modification of the antenna and packaging of passive tags we have extended hand-held readability to over one meter, a distance previously unachievable for concrete embedded RFID. This paper details the background research and subsequent development of our modified tags, including results from our measurement campaign. Some applications of our technology are also discussed.

## 2 Extended Abstract

There are many solutions to the indoor positioning problem, ranging from the exotic to the expensive. In the radio domain, ranging methods include pulse timing of ultra wideband signals, field strength measurements in Wi-Fi networks, and near-field electromagnetic ranging, requiring active tags. Non-radio methods include infra-red and other optical systems such as bar-codes requiring line of sight; ultrasonic methods using microphone arrays and direction finding; and mechanical dead reckoning systems for simultaneous location and mapping (SLAM). Of all of these methods, way-point methods using proximity detection of passive markers are generally the least expensive to install and to maintain.

Way-point positioning and navigation is based on a known grid of identification markers which are each associated in a database with their location. A good example are the pallet bays in a warehouse which might be simply labelled A1, A2, B1, B2, etc. This is the simplest way-point positioning system, and a forklift driver must know where bay B2 is and what goods are stored there. A more sophisticated way-point system was developed by Georgia Institute of Technology whereby two distinct radio frequencies are injected into the power-line grid of a building. Because of the irregular topology of the power-line grid, the electromagnetic radiation pattern from the injected tones is different in each room, and can thus be recorded and stored in a database. This way-point system is based on field strength measurements and a lookup table.

In between these extremes of complexity, passive RFID tags are a prime candidate for way-point positioning, being both extremely cheap and easy easy to deploy. They don't have the line-of-sight requirement of bar-codes, making them suitable for all sorts of environment. The readers which are used as the positioning device can easily access the position database using Wi-Fi for an indoor deployment. A commercial example of such a solution is the RFID-woven carpet tile produced by Vorwerk in Germany. These tiles enforce proper cleaning of carpeted facilities by requiring the cleaning equipment to register passing over all carpet tiles at specified cleaning intervals.

In recognition of the ubiquity of RFID for way-point based indoor positioning we have taken the concept of Vorwerk to a new level of ruggedness, by embedding RFID tags in concrete paving stones. There is an academic and industrial track record of concrete embedded RFID over the last few years, which we review in detail in our paper. We conclude in our review that use of commercial, off-the-shelf passive tags results in unsatisfactory read ranges and coverage for positioning applications. This has motivated our work on tag modification for embedding in concrete.

The first part of our work revolves around the selection and testing of existing hardware (both readers and tags) for the given application. It is found that the best hand-held read ranges are reduced by anywhere from 60% – 90% by the embedding process (depending on the tag type). In order to improve upon these disappointing results, we embark upon some trial and error tests of various tag-antenna design modifications, underpinned with basic theoretical results from electro-magnetics and taking account of altered dielectric of the concrete substrate. Modified tags were successfully embedded in the stones, and thanks to these improvements we now have low-cost smart-stones, RFID readable to distances of above 1m, which was our goal.

There are a number of exciting applications for this technology, two of which we highlight here. The first is in the positioning and navigation of automatic guided vehicles (AGVs) for logistics applications. These are typically guided by optical navigation, using for example painted lines on the floor. However, firms such as Scirocco in Sweden, and Auto-Tug in the UK, have demonstrated AGV positioning using floor mounted RFID markers. In an industrial environment, ruggedised tags are essential, and our concrete embedded tags should serve this application well.

A second application is navigation systems for the blind. The Swiss railway network SBB is currently provided with CARENA paving stones, which have a tactile feature distinguishable by the visually impaired using a cane. This allows their blind customers to navigate safely along platforms and throughout stations. Embedding RFID in paving stones at train stations and other public spaces, will allow RFID enabled hand-held devices act as navigation systems for blind people through an audio interface. The beauty of this system will be the discrete nature of the solution, with no visible markers and perhaps even elimination of the need for a cane.

What we do not cover in this paper are the areas of our ongoing research such as the optimal distribution of our paving stones for way-point positioning, the design of the database containing our geographical information system (GIS) and the best design for an application interface to this system. Our focus is more on the development of enabling technology for robust way-point positioning rather than the use of that technology.

As an interesting addendum some comment on the future of concrete embeddable electronics is also presented, such as the use of passive sensors for temperature, vibration and strain measurement in structural health management. However, these thoughts are secondary to our main result on the feasibility of concrete embedded RFID for way-point positioning.

# A New Approach for an RFID Indoor Positioning System Without Fixed Coordinates for Visually Impaired and Blind People

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## 1 Summary

In the project "Ways4all" passive RFID-tags are used to identify indoor routes, barriers and means of public transport. The basis for this project is the tactile guidance system where RFID-tags are placed at strategic spots (entrance, platforms). Those RFID-tags send their code through an RFID-reader to the user's mobile phone. The phone sends the code to an RFID-database server where all the tags together with some additional information are saved as location points. For the routing a new navigation software, the so called "Gerwei-Method", has been developed. Before leaving, the user has to enter his/her destination by which the server with the "Gerwei-Method" calculates the optimal route. The mobile phone receives real-time routing information (including interruptions, delays and platform changes) from the database server. On the phone the routing information will be sent in an acoustic way to the blind person. This way, the blind person gets his/her indoor route instructions from the system.

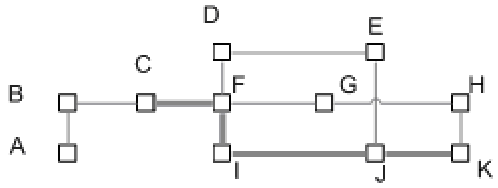
## 2 The Project "Ways4All" and Related Work

Currently RFID technologies for routing blind people are used in different projects in public transport and navigation. Example projects are 1) Sesamonet, Italy which uses passive RFID-tags and a white cane with a built-in RFID-reader for a special route along the promenade at Lake Maggiore. 2) RouteOnline, the Netherlands which uses active RFID Tags and a hand held reader to find a route at different stations. 3) BIGS, Korea which uses a smart floor (each tile of the floor has a passive RFID tag) and the portable terminal unit. 4) Bus-ID, Germany, uses RFID tags for sending public transport information towards a reader and a database. 5) RFID Information Grid which uses the RFID tags for indoor routing in the Campus. The RFID tags are programmed with spatial coordinates and information to describe the surroundings. No centralized database or wireless infrastructure for communication is used. Taking these examples into consideration it can be concluded that different institutes are researching the use of RFID tags to make daily life for visually impaired and blind people more enjoyable. The project "Ways4all" is using low frequent passive RFID-tags to indentify indoor routes, barriers and means of public transport.

## 3 RFID Navigation for Blind People

Most navigation systems require a method to define one's absolute position within a closed system. For example from the Global Position System – GPS – you get the longitude and latitude. This helps you to get to a target destination, which is also defined with absolute coordinates. In buildings, satellite based systems are not available and the internal construction can change very easily.

For an RFID based indoor navigation the following requirements are: a) passive RFID tags b) no absolute position data stored on the tags, c) simple and cost-friendly distribution of the RFID tags, d) recording, data-enrichment and storing of the tags in a central database and e) a mobile application for tag-reading and navigating designed for blind people. The distribution of the tags is done in a very simple way, as a part of the construction activity. The construction worker gets a set of tags and a manual where these tags should be placed – at strategic spots on the tactile guidance system inside the building (entrance, platforms, intersections). Only the tag-ID is stored on the tags and they can be built-in randomly. The next phase is recording the position of the tags. During this process all tags and the relations between the tags – neighbour tag, distance and all sorts of barriers – are stored in a central database. To use the particular positioning algorithm this data enrichment is necessary. The "Gerwei-Method" needs no absolute position (coordinates) of the tags but uses the tag relations to find a way through the network. The method connects many tags to a network graph, which allows the user to find the best way to his/her target. The user gets his/her direction information from the system – go left, straight ahead or right – or gets a description from the surroundings, depending on how he/she sets up his/her user profile.




| | | | | | |
|---|---|---|---|---|---|
| C | ↑ | C | ↑ | C | ↑ |
| F | → | F | ↑ | F | ← |
| I | ← | G | ↑ | D | → |
| J | ↑ | H | → | E | → |
| K | ↑ | K | ↑ | J | ← |
| | | | | K | ↑ |

Figure 1: Gerwei Method with the routing form C to K

Besides the "Gerwei-Method" an easy to use recording-software including an online database to access the tags with a mobile device is developed. The online Database is designed to store tag-sets of various locations in our case the tag sets of various railway stations. Furthermore a mobile application was designed to be used in the indoor navigation. This project focuses especially on visually impaired and blind people because the biggest challenge is to give visual information to this user group. In a survey with visually impaired and blind people we got the feedback that using a mobile phone for indoor navigation is fine. So, the task was to design a mobile application that can be used on a very large set of common mobile phones. For this reason the Java Mobile Edition was chosen as development platform.

With a common mobile telephone it is possible to download a part of the RFID database. To reduce the data download, only a subset of the database is cached on the phone, for example all tags for one railway station. With the help of the "Gerwei-Method" and the "Dijkstra" routing algorithm the shortest path inside of the station is calculated. A mobile RFID reader, which is connected via Bluetooth with the mobile phone, reads the RFID tags on the tactile guidance lines and guides the person on the calculated path. The user interface is especially designed for blind people with a simple list based user dialog, which is suitable for various screen reader software.

## 4 Conclusions and Outlook

During the project some problems were encountered. It is not useful to equip each tile with a RFID tag that provides too much information and causes an uneconomical increase in the costs. The RFID tags should be deployed only at strategic spots. Furthermore, there is no RFID standard, so not every RFID reader can be used. For non-blind people the system can be expanded with inertial navigation and optical marks, for example the QR-code (quick response code). Due to the limitations of the mobile application for further development the use of a smart-phone platform like Android is recommended.

# A new paradigm of passive-RFID based localization systems

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## 1 Summary

A new localization paradigm based on passive RFID systems with low radiated power is investigated and simple localization algorithms are presented. A theoretical model has been developed and tested by means of numerical and experimental analyses. Our model allows a mobile device with an RFID reader to localize itself with respect to a grid of fixed tags used as reference anchors. Simple localization algorithms based on a proximity technique allow a real-time localization. The localization accuracy can be tuned by varying a set of parameters. Experimental results show both the feasibility and the reliability of the proposed method.

## 2 System description and experimental results

Various emerging applications of wireless technology like location based services, emergency services, tourism and people management, healthcare monitoring, logistics and many more require systems and devices with location sensing capability. While the technology is well-established for localization in outdoor environments, it is still evolving for indoor environments. Different technologies with a multiplicity of localization techniques have been proposed, in particular the Ultra High Frequency (UHF) Radio Frequency Identification (RFID) technology seems to be promising for some applications whose services are based on identification and positioning of items and people. Localization systems based on UHF passive-tags and radio connectivity information (i.e. which tag is detect and which is not) have the advantage of low cost and simplicity in implementation. They can be deployed using off-the-shelf technology without additional equipments, hardware modifications and sensitive calibrations that are required by other localization RFID based systems [1], [2]. Passive-tag based systems however have some drawbacks. Because of the poor sensitivity of the IC transponder, the interrogating device is required to radiate a high level of power (~1W) to allow tags to reply from long distances. This requirement may be unsuitable for small readers integrated inside handheld devices having multi-function capability (e.g. integrating an RFID reader with a cell phone) because their energy source may be quickly discharged. These systems usually require a high density deployment of tags which may be impractical and expensive, moreover complex localization algorithms (as those based on optimization methods) are used for positioning. Finally, passive-tags are very sensitive to indoor multipath which makes them unreliable for position estimation.

For these reasons a new localization method that allows the use of passive tags, low radiated power, with simple localization algorithms, coarse grid of tags and multipath-resistant is investigated. It allows 2D localization of moving users (machines and people). A simple proximity technique (i.e. the measurement of the nearness to a known set of reference points) allows a mobile device to localize itself in real-time. A tag is detected when it enters the so called read region which is a space volume nearby the reader location where the power collected by the tag exceeds the IC sensitivity and the tag is activated [3]. Each detected tag, labelled by the unique identification code of its IC, transmits its coordinates to a handheld interrogating device which handles these data to determine the user's position. The proposed localization paradigm exploits both the extension and the shape of the read region to carry out localization. The shaping is achieved with a suitable design of reader's and tag's antennas while the extension is controlled by varying the emitted power. The parameters affecting the read region (i.e. the power emitted by the reader, the tag sensitivity, the radiation pattern of both reader's and tag's antenna, the orientation of antennas and also the nearby scenario) are encoded into geometrical parameters describing the space volume of the read region. This permits to transform the localization problem into a geometrical problem which does not require any kind of measurements except the acquisition of the answers of the tags. Hence, any possible localization error is attributable to the discrepancy between the geometrical model of the read region and the actual read region. For this reason, an evaluation of the practical feasibility of the shaped read region has been developed by means of a theoretical and an experimental analysis, and the reliability of the localization paradigm has been evaluated experimentally.

The performance of the proposed system has been experimentally evaluated in terms of localization and tracking of people. The experiment has been carried out in a laboratory room that is a highly scattering environment with shelves, desks, chairs, and many instruments. The experimental setup (at 870 MHz) consists of a reader (CAEN-A948) with a commercial patch antenna for circular polarized signals. A square mesh grid of ad-hoc designed tags is deployed on the ceiling (3 m in height). The distance between the tags is 1.2 m. The reader's antenna is kept about 1 m above the floor by the hands of a person that walks along a prearranged path. During the walk a computer stores the tags' readings, determines the user's position and controls the reader's parameters. The input power of the reader is 50mW. Experimental results show that the deviation between the estimated path and the actual path is lower than 0.5 m.

Our results show both the feasibility and the reliability of the localization method that has many degrees of freedom (i.e. frequency, input power, design of reader's and tag's antennas, IC sensitivity). Our method can be improved in its accuracy and can be tailored for specific environments. The advantages of the proposed method are manifold. It is suitable for sensor fusion (e.g. inertial sensors). The low input power permits to integrate the reader inside multi-utility handheld devices which can exploit the localization information for specific services using other wireless communication facilities. Passive tags are not sensitive to power outages. , In case of a electricity failure (e.g. a fire of other emergencies) all the other networks (e.g. for communications and lights) are cut off but the passive-tag based localization system remains functional and may help users to find the way out and supports fire fighters to act more safely. Passive tags are easy and cheap to install while the maintenance is marginal.

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# RFID Tag Localization Using Pattern Matching

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## 1 Summary

In this paper, we investigate the use of passive RFID technology for object localization. Due to the limitation of a RFID (Radio Frequency IDentification) reader when using a RFID with traditional methods, a reader can only determine whether the tag is inside or outside its data transmission range, but cannot necessarily localize the exact position of the specified RFID tag within the communication range of the RFID reader. However, in order to find the trajectory and location of a specified tag, we log the trend graphics (Fig. 2) of some tag reading success ratio in advance, then we provide a pattern matching algorithm in order to track the reading success ratio of the specified tag. At last, the exact position can be determined from the trajectory of the specified tag. In our experimental results, a Fujitsu RFID Reader was used, and the localization was achieved with an accuracy of roughly 10 cm.

## 2 Introduction

Traditionally, a RFID reader can only determine whether the tag is inside or outside the transmission range of the RFID reader. Traditional methods cannot localize the exact position of a RFID tag when the tag is inside the communication area of the RFID reader. The UHF RFID technologies are used in a wide application area, such as for supply chains. This technology can support to read multi-tags by a RFID reader. So we need to determine the exact position of a RFID tag that is in the  communication range of a RFID reader. However, this paper provides a method to track the variation of the success ratio of the specified RFID tag when it enters the transmission range of a RFID reader in order to find the exact position of the tag. This method can provide good performance on automatic localization of the specified tag. Furthermore, the provided algorithm can detect the orientation of a tag that passes through the transmission range of a RFID reader. Certainly, we also can locate the RFID reader itself more precise by moving the reader as reported by [1, 2].

The following steps have been implemented in our algorithm:

1. Training and establishing of a database with the reading success ratio and trajectories.
2. Monitoring of the reading success ratio for a specified tag.
3. Assembly of a sequence of the reading success ratio of the specified tag.
4. Matching of the sequence with the reading success ratio and the trajectory curves which are retrieved from the database.
5. Compute the most likely position of the specified tag using a pattern matching algorithm.
6. Output the position of the specified tag

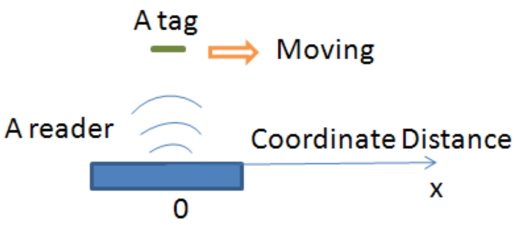


Figure 1: The test environment.

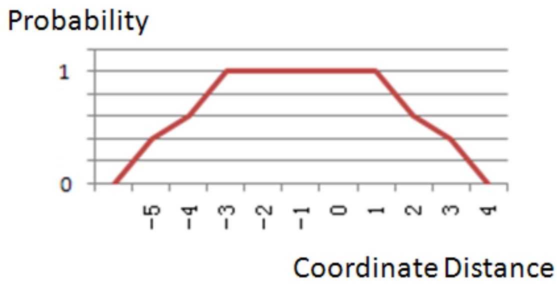


Figure 2: A sample of the reading success ratio in a test.

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## Active & General RFID

Auditorium D8

Wednesday, September 15, 13:15 – 15:30

# Simple Navigation with RFID-enabled cell phones

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## 1 Summary

This paper presents a navigation application based on RFID-capable (i.e. NFC-based) cell phones. The cell phone is used to read-out, at various locations fixed, HF-RFID tags, to receive, first, the position of the RFID tag, and second, the map environment surrounding the RFID tag. Therefore, the distributed RFID tags contain their fix positions and an extract of the basic map, which shows the tag's nearby environment. This combination of RFID tags and cell phone generates a particular navigation application improving the performance of an indoor navigation system. By using a cell phone the user is provided with a graphical user interface leading the user transponder-by-transponder to its final destination. The advantages of the system include a non a priori knowledge and a small positioning error due to the limited range of the NFC technology.

## 2 Introduction

The sale of navigation systems is still growing and growing, because the trend, for knowing exactly where objects or persons (mainly the person itself) are located, is still unbroken. That is one of the reasons why global navigation satellite systems (GNSS) have become very popular. The usage of GNSS systems is mainly distributed and somewhat limited to outdoor navigation. Multipath effects, high fading and blocking of satellite navigation signals, usually limit the usage of satellite navigation systems in indoor areas. In the past, indeed, great efforts were made to handle these drawbacks for the indoor area. Techniques for indoor navigation systems are, for instance, based on WLAN, UWB, Infrared, Bluetooth, GSM, etc. For instance, SpotON and LANDMARC are RFID-based navigation systems. Generally, both of these systems are based on measuring the RSS to get the current position. The SpotON approach estimates the distance between transponder, exploits the density of the transponder, and uses multiple RSS measurements to improve the localizing resolution. Whereas the LANDMARC system uses so called *reference tags* to generate more reference points within the system. The RSS information is evaluated between every tag-to-reader link. However, both systems, SpotON and LANDMARC, use active RFID tags leading to higher costs per tag (manufacturing and service).

Therefore, we suggest a navigation system working as described briefly in the following, referring to Fig 1: The user starts the Java-based mobile application *RFID* on the cell phone. After that, the application asks the user to choose between loading a previously available map or generating a new map. Assuming there is no previously defined map available, the user generates a new map and is prompted to enter the coordinates of the *final destination* in latitude and longitude. In general, these coordinates could also be local defined, instead of being global coordinates. Subsequently, the application asks for the first RFID tag. According to Fig. 1 this would be RFID tag #1. Reading out the data of the tag will give the user the current position (in latitude and longitude coordinates) and an overview of the surrounding

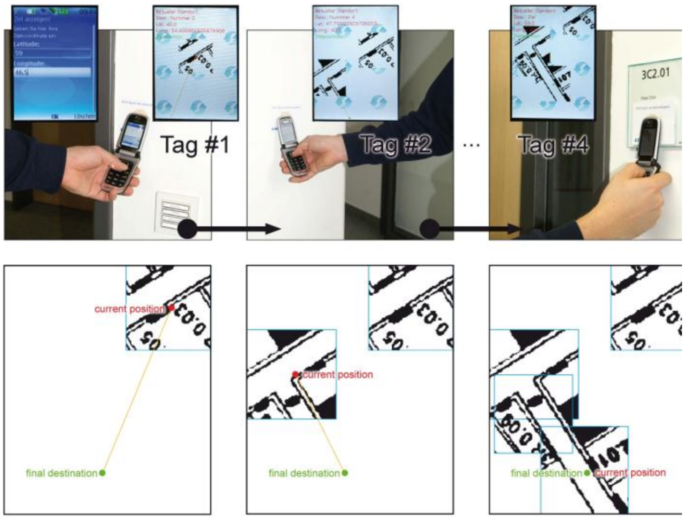


Figure 1: Process of navigation

environment of the RFID tag. In that case the cell phone would show the map with the rectangular area of map #1 (seen at the lower left edge of Fig. 1). In addition to the current position the tag also provides (if desired) local information about the object or spot it is attached to, e.g. a room number. The cell phone draws a red dot, which shows the current position (respectively the position of the RFID tag) of the user. Furthermore, a green dot shows the final destination and a orange line links the red and the green dot. However, the user walks along the floor and reads out tag #2. Therefore, the current position changes (red dot) and the map is expanded (by map #2) through the additional data, stored on tag #2. The cell phone shows the extended map and the new current position and if available an additional description. Following this procedure the user reads out tag #3 and #4, until the final destination is reached (red and green dot are very together).

## 3 RFID-based navigation system

The RFID-based navigation system (Fig. 1 shows the operating principle) splits into two main parts. The first part of the system consists of an RFID-capable cell phone, whereas the second part consists of various distributed RFID tags. These tags are fixed to objects in particular locations, e.g. office plates, walls, etc. The data stored on the tags include, among other data, the position of the fixed tag. Position data covers latitude, longitude and elevation. Additionally, a description of the location is also stored on the tag (e.g. the room number). Reading such a tag would offer the user only the position and a description of it, whereas the environment (e.g. the surrounding area and/or map) is still not considered. Beyond that, our proposed RFID-based navigation system extents the location data, by additionally storing data on the RFID tag, including graphical data like an extract of the map or the surrounding area of the tag. Featuring such additional graphical information enables users of these RFID-based navigation systems to orient themselves in the near environment of the RFID tag or current position, provided that the graphical data on the tag represents the near environment. Getting back to the first part of the system, consisting of the RFID-capable cell phone. The user of the system requires the cell phone to read out the RFID tags and also to show the position of the tag and the graphical information of the tag along the way (here tag #1 to #4) to the final destination. An NFC (i.e. Near Field Communication)-based cell phone is used for this navigation application as it might be possible that more and more new cell phones will inherit the capability to read HF-RFID tags or even communicate via NFC.

## 4 Conclusions and Outlook

The proposed navigation application based on, currently RFID-HF technology, shall be ported, in future releases, to the RFID-UHF region under usage of passive UHF RFID tags. Therefore, future work includes the development of a cell phone-based UHF-RFID reader.

# An Investigation of 3D GIS-Aided RFID Indoor Positioning Algorithms

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**Summary:** The probabilistic location fingerprinting algorithm is investigated for its potential people mobility tracking applications indoor using Radio Frequency IDentification (RFID). The environmental impacts on the radio frequency (RF) signal propagation in the training phase and the positioning errors due to the received signal strength (RSS) variations are two key limiting factors for precise indoor positioning. A 3D Geographical Information System (GIS) ray tracing algorithm for location fingerprinting training phase and probabilistic maps for personal positioning phase are developed and evaluated. Results suggest that the new algorithms developed can reduce the workloads and increase the positioning accuracy by utilising the spatial information provided by a 3D GIS.

## 1 Introduction

It is a challenge to provide accurate positioning service with low-cost devices in a large area indoor (e.g. across an entire floor of a building). Highly accurate techniques suitable for indoor positioning either are expensive, such as Ultra-Wide Band (UWB), or have a very limited area of coverage, like ultrasonic positioning techniques. RFID is a low-cost positioning technique and its signals can propagate for a relatively long distance (about 30m) indoor. However, its main disadvantage is that the RSS are highly dependent on environments surrounded. This contribution proposes new algorithms to overcome the detrimental effects from the environments and increase the positioning accuracy by utilising the spatial information in a 3D-GIS for RFID positioning.

## 2 RFID Location Fingerprinting Algorithms

The location fingerprinting algorithm is applied for RFID positioning. The algorithm is composed of two phases, the training phase and the positioning phase. In the training phase, a database of RSS distributions is created first and in the positioning phase, the position solution is obtained by matching the measured RSS with the values in the database established in phase one. In the probabilistic approach, the best position is determined according to the Bayes' rule. The information obtained from a 3D GIS is used in both the training and the positioning phases to improve the performance of the positioning algorithms.

## 3 3D GIS Based Training Phase

In the training phase, a fine-grid (normally 1×1m) RSS distribution needs to be generated to represent the variations of the RSS values indoor precisely. This means that tremendous work is required for the establishment of the database in a relatively large area (e.g. a level of a large building). Traditionally, interpolation methods are used to refine the grid values based on a relatively small amount of RSS samples to simplify the process. However, this method is prone to large errors in the matching process due to the fact that the smooth trends of the RSS variations are distorted by the surrounding objects. In order to overcome this detrimental effect, a 3D ray tracing algorithm for the determination of RSS distribution is developed based on a GIS database (see Figure 1).

A number of evaluations were conducted at a junction of the corridors in an RMIT University building, where the RF signal propagation was obstructed and significant reflections from the surrounding environments were experienced. Both ray tracing algorithm and Kriging interpolation algorithm are used for the generation of RSS distributions in the experimental areas and their results are compared. The ray tracing algorithm provides more accurate estimations in the boundary of the corridor where the RSS trend is not continuous but less accurate in the middle of the corridor Than using Kriging interpolation. This may be due to the limitations in the number of RF signal reflections of the ray tracing algorithm used.

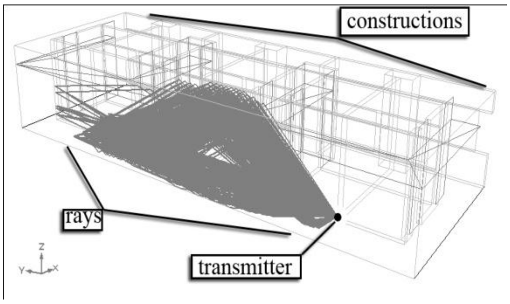


Figure 1: A sketch plot of 3D ray tracing for location fingerprinting training phase

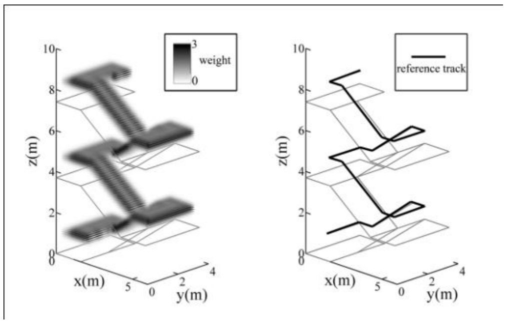


Figure 2: Sketch comparison plots of the 3D GIS based probabilistic map (right) and the conventional map (left) for map matching

## 4 Probabilistic Maps for Pedestrian Map Matching

In the positioning phase, the information from the 3D GIS is used to generate likely pathways in the building in order to constrain the estimated trajectories of a pedestrian. This is recognised as map matching algorithm. The map matching algorithm is widely used in vehicle navigation applications. This conventional algorithm mainly generates the projection of the estimated position on a selected path or calculate the most possible positions along the path based on the assumptions that the vehicle is always restricted in the lane it travels on. This algorithm can improve the positioning accuracy by reducing the number of dimensions. However, the assumptions of moving along a certain path may not be true for personal positioning. Pedestrians may have more freedoms in their kinematics than a vehicle. People are not restricted in a certain lane or a certain direction on their pathways as strong as for a vehicle. The reduction of the dimensions in the estimation process using a conventional map matching algorithm may increase the errors for personal positioning. To alleviate this problem, a 3D probabilistic distribution along the pathways is generated (termed a probabilistic map, see Figure 2) instead of using the pathways from a 3D GIS directly. This map is used to update the prior probability information of the pedestrian's position in the location fingerprinting algorithm. The number of dimensions of the solution is not reduced using this algorithm and eventually the positioning accuracy for pedestrians will be increased.

Due to the difficulties of obtaining high-accurate kinematic reference positions indoor, simulations were conducted to evaluate the performance of using probabilistic maps for investigating pedestrian map matching algorithms. We demonstrate that the new algorithm developed is superior to the conventional map matching algorithms. As a result, instant movements from the left to the right side of the stairway can be correctly represented.

## 5 Conclusions

New 3D GIS based ray tracing algorithms for RFID location fingerprinting training phase and probabilistic maps for personal positioning phase are developed and evaluated. The ray tracing algorithm developed provides more accurate RSS distributions than the interpolation method when the RSS variation trend is distorted due to the surrounding environments. In the positioning phase, the 3D probabilistic map, which is specific to pedestrians' kinematics, can improve the positioning accuracy. It is concluded that the workload can be reduced and the positioning accuracy can be increased by using the newly developed algorithms which utilise the spatial information from a 3D GIS.

# Improving RFID-Based Indoor Positioning Accuracy Using Gaussian Processes

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## 1 Bayesian methods for indoor location

Most local positioning systems (LPS) for indoor environments based on radiofrequency signals lack the capability to measure the range from emitter to receiver, but instead estimate the location of the mobile user from the received signal strength indicator (RSSI). As the RSSI depends not only on the range, but is also affected by multipath propagation, interference, and blocking caused by obstacles, in an essentially unpredictable way, efficient location estimation can be achieved by Bayesian techniques [Fox03].

In Bayesian localization, the position of the user is considered a random variable, whose probability density function (pdf) *p(x)*, is updated sequentially from time *t-1* to time *t*:

$$p(x_t \mid RSSI_t, u_t) = p(RSSI_t \mid x_t) \int_x p(x_{t-1}) \, p(x_t \mid x_{t-1}, u_t) \, dx \ , \qquad (1)$$

where $p(x_t \mid x_{t-1}, u_t)$ is a motion model with the available information $u_t$ about the user's displacement (obtained with an odometer or an inertial sensor), and $p(RSSI_t \mid x_t)$ is an observation model which relates the measured signal strength $RSSI_t$ to the position $x_t$. This observation model should fit the experimental distribution of the RSSI as accurately as possible. For simplicity, it is assumed that the model follows a Gaussian distribution:

$$p(RSSI \mid x) = N(\mu_{RSSI}(x), \sigma^2_{RSSI}(x)) \, . \qquad (2)$$

Simple observation models consider that the signal strength varies only with the range *r* between the emitter and the receiver [Koutsou 2007], but this assumption of isotropy sets a limit to the attainable precision. Gaussian processes (GPs) provide non-parametric, probabilistic function regression between position *x* and signal strength RSSI, and have been applied successfully to RF-based indoor and outdoor localization [Ferris 2006], showing accuracy comparable to fingerprinting techniques.

## 2 Preliminary experimental results

We have developed a Radiofrequency Identification (RFID) based LPS [Koutsou 2007], in which the user carries a reader and determines his position from the RSSI of signals received from a set of active tags placed at known positions. In the calibration stage, RSSI measurements for all tags were sampled at 100 random positions; figure 1 shows the results obtained for one particular tag placed at the corner of our lobby hall, where clearly the signal strength dependence with position is far from isotropic.

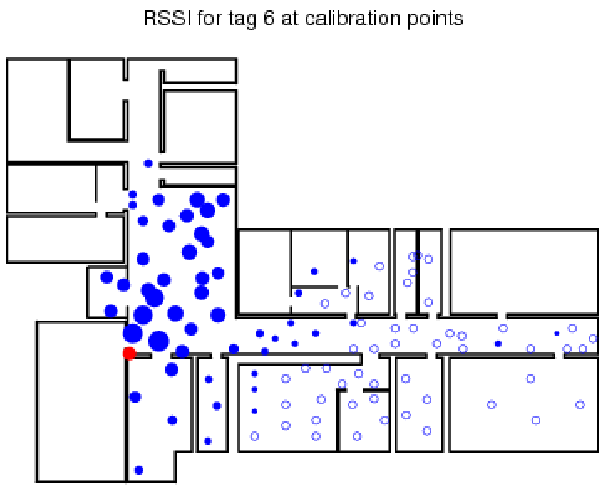


Figure 1: Signal strength samples for one RFID tag (red point) at several calibration points. RSSI measurements are indicated by full circles, whose size corresponds to the obtained RSSI value. Open circles denote points where the tag was not detected.

Figure 2 shows a GP sensor model (of the form given by eq. 2) learned from the empirical tag data, reflecting the anisotropic nature of RF signal propagation. The variance of the estimated RSSI is higher in places where calibration measurements are not available, indicating larger uncertainty at those points. We are currently evaluating how this GP-based observation model improves the accuracy obtained with earlier versions of our RFID- LPS. Future work includes fusion between Bayesian location methods and inertial sensors (INS) to estimate the user's motion (see [Jiménez 2010], presented in this conference).

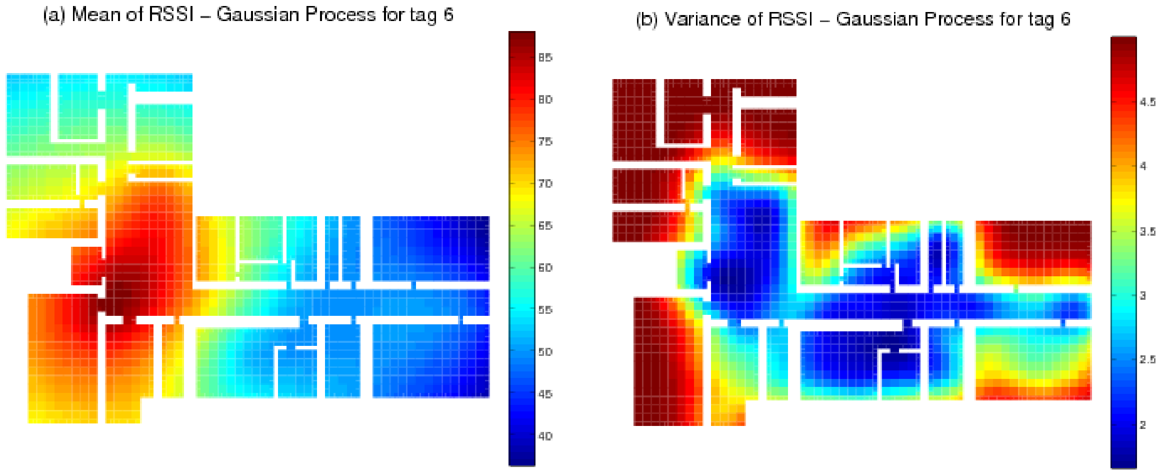


Figure 2: Gaussian process model prediction for the RSSI distribution on the complete building, based on the data from figure 1: (a) mean $\mu_{RSSI}(x)$; (b) variance $\sigma^2_{RSSI}(x)$.

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# Experiences with Time-of-Flight Positioning

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The increasing availability of active RFID systems with its wide communication range of about 200 m (e.g. ZOMOFI [1], nanoEdge [2]) allows a cost-efficient monitoring of large areas with a low number of RFID readers. While short-range RFID technologies allow a relatively precise localization within the vicinity of tag and reader, this is no longer possible with long-range systems just by detecting the presence of a tag, as the area of coverage can be larger than the required positioning accuracy. For such systems, advanced localization methods are required to achieve a spatial resolution of 2-3 m, as it is required for most applications in asset tracking. An even higher resolution is required for use cases related to quality management in the automotive industry.

As of today, the evaluation of Received Signal-Strength Indicator (RSSI) is used for localization in almost all conventional wireless communication systems (e.g. Ekahau [3]), including active RFIDs. However, with its fundamental limits on accuracy [4], they do not meet the requirements of most industrial applications. In the work of Elnahrawy et al. [4], the upper bound of RSSI-based systems is given as 3,05 m (median error) and a 97 percentile of 9,14 m with a high sampling effort. The bound for a more reasonable sampling effort is given as 4,57 m (median error) and a 97 percentile of 12,19 m.

Based on the need for higher accuracy and stability on the one hand and the desire to utilize simple, if possible commercial off-the-shelf hardware (COTS) on the other hand, we have designed a system that uses the time-of-flight information instead of the RSSI.

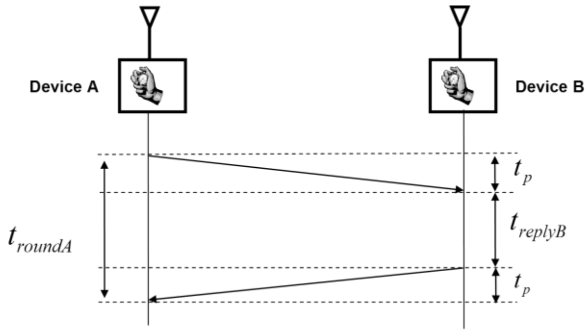


Figure 1: Measurement method

Our measurement method has been inspired by the ideas of Günther and Hoene, 2004 [5] and consists first of all of a distance measurement using a simple ping-pong packet exchange to measure a Round-Trip-Time (RTT). Such packet exchange can be found in many commercially available communications protocols; for example a typical data-acknowledge frame exchange in IEEE 802.11 WLAN. This also allows us to work with mobile devices which we don’t directly control. Utilization of the round trip time measurement as source for location estimation, as shown on Figure 1, removes the need of synchronization between the readers involved or between the readers and tags.Once the distances have been obtained from at least three measuring stations, simple algorithms like multilateration [6] or more advanced strategies like neural networks can be used to calculate the 2D/3D position. We have also developed additional location algorithms that show a better performance than the state-of-the-art.

For a test implementation, we have used the ZOMOFI active RFID hardware platform, a product from Albis Technologies. ZOMOFI provides active RFID readers with a communication range up of 80 meters and small, battery-powered tags. The devices contain 8MHz/16MHz quartz oscillators driving the microcontrollers and radio chips. The radio signals have a 1 MHz bandwidth and use the 2.4 GHz ISM band. A simple block diagram of the platform can be seen on Figure 2 below.

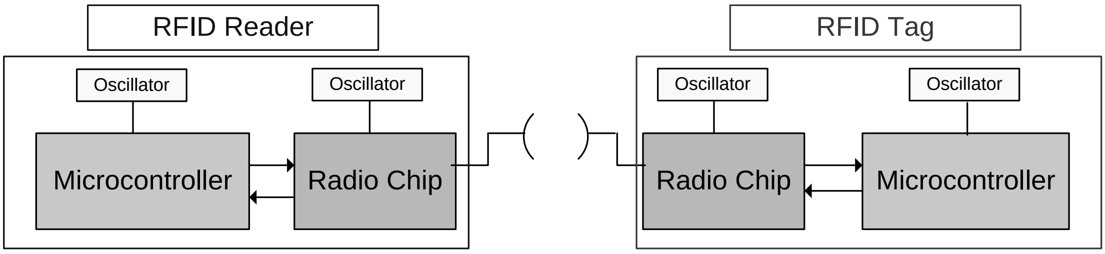


Figure 2: Basic block diagram of the hardware platform

For our first indoor measurement campaigns, we have chosen a business complex. The chosen environment is quite harsh to radio signals as all walls, doors and ceiling are metallic. We set-up four RFID readers separated 18 meters from each other; none of the readers had a direct line-of-sight with each other. Randomly chosen positions were distributed among 7 offices. The Non Line-Of-Sight (NLOS) measurement campaigns show an accuracy of 2.8 m (median error) with a standard deviation of 0.7 m. The results achieved are significantly better than the upper bound of RSSI systems on unmodified hardware platforms.

A very strong resilience has been experienced, with a precision of 1.1 m when repeating a measurement at the same position under a changing environment. For example, we opened and closed the metallic doors between and around the readers and the tags as well as shuffled metallic containers around. The same precision was maintained when rotating the RFID tag on its vertical and horizontal axis.


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# TraceMe – A Tool for Safety and Security in Clinical Governance using RFID and Integration of Location Services in a Hospital Environment

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## 1 Summary

TraceMe is an indoor location and tracking solution for people and assets, being a valuable tool that can be used in clinical governance to map, monitor and measure the status and location of high-value assets. It also provides critical data needed to improve workflows and processes associated with these assets. Besides its use as a simple location-based system it can also be used in access control applications for restricted areas, triggering alarms whenever anomalous situations occur, e.g. when a specific equipment is taken outside its area, or when a tag is violated. It is now being installed and tested in a hospital in Portugal, where it is being integrated with other systems such as BabyMatch™ and AIDA (Agency for Integration, Archive and Diffusion of Medical Information). For hospital administrators, TraceMe rapid-impact implementation and fully managed service model not only supports healthcare business processes, but also reduces costs and increases revenue.

## 2 Introduction

One of the main objectives of this system is to locate Radio Frequency Identification (RFID) devices with low or no human involvement, with sufficient precision to allow the location between areas in an indoor environment. Its main features include the ability to visualise user/assets location in real time, appropriate identification of people and objects, and thus their tracking between monitored zones, including the generation of alarms and allowing routes to be recorded and visualized.

The proposed solution comprises of many RFID equipments. These are chosen accordingly to each specific hospital scenario. For example, Dynasys™ for staff, patients, visitors and equipment, BabyMatch™ for child security control and AIDA to Integration, Archive and Diffusion of Medical Information. TraceMe, however, being an open platform and device independent, is able to integrate other hardware and software systems. This feature allows low cost, quick integration of existing systems already installed in hospitals, such as CCTV (Closed-Circuit Television), ERP (Enterprise Resource Planning), and clinical software. TraceMe is currently installed on CHTS (Centro Hospitalar do Tâmega e Sousa, E.P.E.), in Portugal. This project is the result of a technological partnership between ISA (Intelligent Sensing Anywhere) and CHTS, in which Hospital Padre Américo is the main supporter. This project also had the participation of University of Minho in the interaction with AIDA.

## 3 System specification

The physical architecture of the system is based on the active RFID concept. In order to determine the location of a given tag, a network of readers covering the building where in which the location has to be determined, is deployed. This network is connected to the TraceMe Server. Appropriate adjustment of the system precision is done by changing the position and the number of equipments inside the building.

Each person or object to be tracked has an associated tag that can operate in two modes. In the first mode, each tag sends a periodic signal, at 868MHz. This beaconing behaviour of the tags, can be programmed. In the second mode, tags respond (at 868MHz) to a stimulus sent by readers at 125kHz. When the tag responds to the 125kHz signal, it indicates to which reader it is responding (information used for location purposes). Whenever a reader receives information from the tags, it transmits it to the TraceMe server. Based on this data, the server updates a references database where information about the room, antenna and tag are cross-checked. While the detection at 125kHz indicates the place where the tag is, the detection at 868MHz indicates that the tag is in a larger area (e.g. inside the building).

## 4 Integration with BabyMatch™

BabyMatch™ is an RFID solution that allows the location and tracking of newborn babies, using bracelets with anti-opening protection. Communication between bracelets and RFID readers is done at 433MHz and readers activate the bracelets at 125kHz. Bracelets are equipped with rechargeable batteries and do not need to be programmed for its activation. They are activated whenever they are placed on a baby. Providing that BabyMatch™ is a proprietary closed system, and thus incompatible with other used technologies, it was necessary to integrate it with TraceMe. To this extent, a specific interface was developed so that it could receive, send and configure events of devices managed by MabyMatch™.

## 5 Integration with AIDA

AIDA is a platform on which the process of problem resolution uses agents or multi agent systems, to potentiate the archive and the diffusion of complementary diagnosis resources inside healthcare units. It also allows the integration of legacy systems or possible future systems, either inside or between health units, using a global approach, avoiding point-to-point connection of different applications. TraceMe stores a set of information obtained in AIDA and it generates information that can be used by the hospital and its management systems. The integration of AIDA has the main objective of avoiding data duplication.

## 6 Conclusions

TraceMe installed in the CHTS allows the safety and security of people and goods, reducing the risk of child abduction and loss of patients with dementia. It enables better care of inpatients and improves comfort of users, visitors and staff. TraceMe aims to process efficiency through workflow optimization, by collecting workflow data and cross-reference with indoor location together with the capacity to process large amounts of data, TaceMe is a Business Intelligence tool capable of extracting information and turning that information into actionable knowledge. This boosts Cost Management, Productivity and Medical Outcomes.

## Mapping, SLAM

Auditorium D8

Wednesday, September 15, 16:00 – 18:00

# Simultaneous Mobile Robot and Radio Node Localization in Wireless Sensor Networks

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## 1 Summary

Accurate and cost effective localization is a basic issue in the field of mobile robotics. This work shows how it can be solved by using wireless radio nodes as landmarks. Mechanical scanning is employed at the mobile robot to measure the angle of arrival of radio signals. A measurement integrity check is realized by means of normalized cross correlation. This enables the recognition of multi path propagation and radio interferers, thereby ensuring high robustness. A simultaneous localization and mapping approach is implemented to localize the robot and to build a map of static radio nodes simultaneously. This allows localizing the robot in unknown environments in an ad hoc and unobtrusive fashion.

## 2 Method to measure the angle of arrival

The foundation of this work is a new method to measure the angle of arrival in wireless networks based on the received signal strength indicator (RSSI). It requires the antenna on the robot to be rotated about a vertical axis while recording the RSSI. This results in a radiation pattern in the azimuth plane. Its cross correlation with the known reference radiation pattern of the antenna allows to determine the relative angle. A detailed description of the method and a thorough error analysis are given in [1] and [2]. A schematic of the setup is shown in figure 1. To ensure a distinct radiation pattern, a monopole antenna is slightly modified by the attachment of a reflector plate.

This increases the uniqueness of the angle given by the cross correlation. The advantages of this method are its robustness to antenna anisotropy of the static nodes and the possibility for measurement integrity by the consideration of the maximum correlation coefficient, which is a measure for the similarity between the recorded and the reference radiation patterns. Thereby the localization is robust in multipath environments. Further the presented method does not require any modification of the sensor network and thus allows the use of commodity radio hardware. It also does not assume any propagation models and therefore does not require any parameters to be known in advance enabling localization in completely unknown environments.

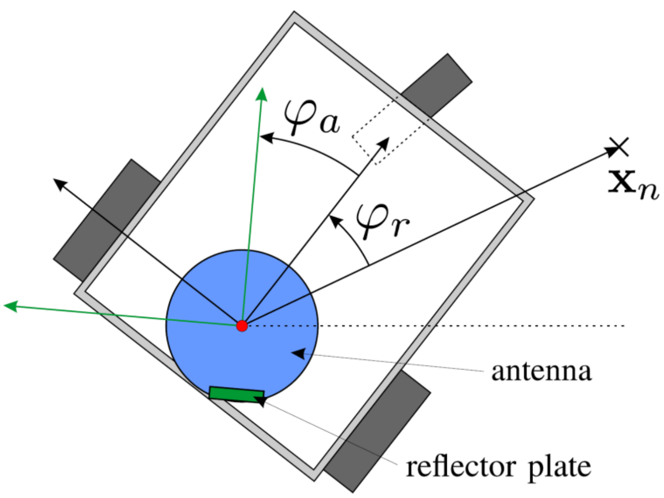


Figure 19: Setup for the determination of the relative angle: $\varphi_a$ is the rotation angle of the antenna, $\varphi_r$ is the relative angle to the static node with position $x_n$.

## 3 SLAM

Based on this measurement method we apply the SLAM approach to simultaneously localize the robot and the radio nodes. Therefore Bayesian filtering is employed that incorporates the odometry of the robot using a motion model. To localize the robot and the nodes an Extended Kalman Filter (EKF) is used. Since only the angle of arrival is available and the measurement model is not linear, a particle filter is used to initialize the location of the static nodes. Once the uncertainty of the particle filter falls below a certain threshold a new node is inserted into the EKF where its location is further tracked and where it simultaneously serves as an anchor node to localize the robot.

We have carried out experiments in outdoor and indoor environments. An optical tracking system is used to determine the ground truth position of the robot indoors and a real time kinematic GPS outdoors. A sample run is shown in Figure 20. A comparison with our localization method shows a mean error for the position of the robot below 10cm in both environments. Based on the outdoor experiments we show the contribution of the RSSI based localization by implementing batch processing global optimization to determine the location of the nodes and the robot without odometry, similar to bundle adjustment. The experimental results show, that odometry and a motion model are accurate on a short distance and are thus useful to detect outliers. Complementary to this our method for RSSI based localization gives an accurate absolute reference.

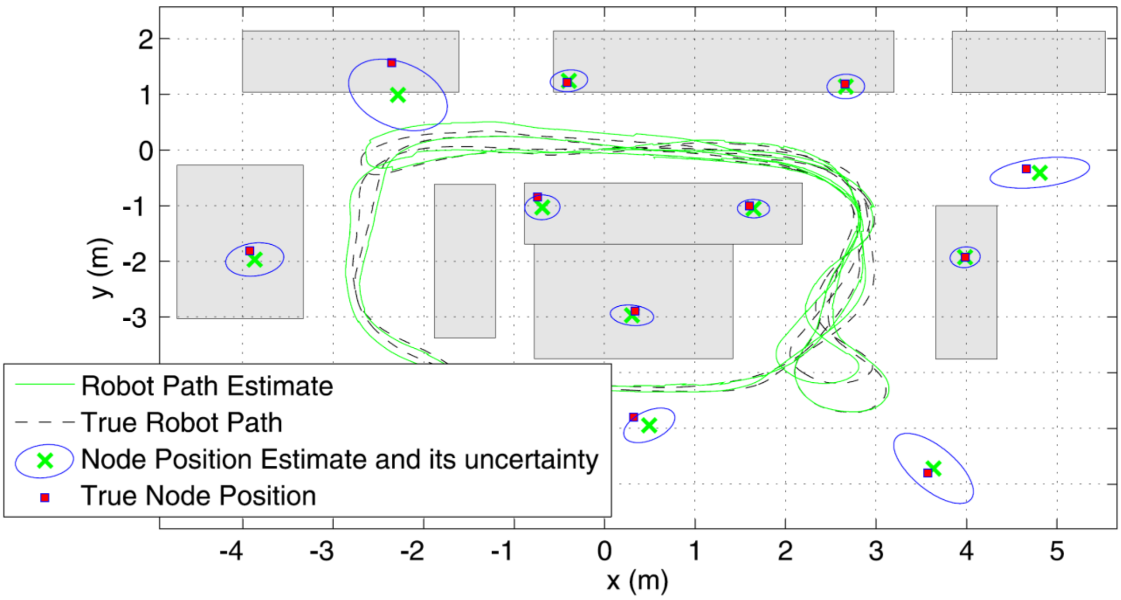


Figure 20: Results of an exemplary run in an office environment: The robot travels between tables and cupboards (indicated by the grey rectangles). Line-of-sight is not given in most cases. The estimated path of the robot is shown by the green line. The estimated node position is shown by the green crosses. Its uncertainty is indicated by the blue ellipses.

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# Modeling and Simulating Assistive Environments in 3-D with the YAMAMOTO Toolkit

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## 1 Summary

We present the map modelling toolkit YAMAMOTO, which allows to efficiently model and design assistive building environments in 3-D. We focus on the tool's ability to represent and simulate sensors and actuators, i.e. navigational beacons used for indoor positioning and navigation purposes. An interactive avatar can be used to simulate and evaluate location-based applications in the virtual model. Vice versa, the model can be used to visualize the state of the real world, including the location of the user and the content of public displays.

## 2 Modeling the Building Structure in 3-D with the YAMAMOTO Toolkit

In this paper, we present the YAMAMOTO (**Y**et **A**nother **MA**p **MO**deling **TO**olkit) toolkit for the modelling, designing, and simulation of assistive environments. Application domains comprise pedestrian navigation, home automation, and ambient assisted living. The typical workflow to create a building model with YAMAMOTO is to use a floor plan as backdrop image and to trace the outlines of rooms and corridors in 2.5-D as spatial regions that are represented by vertices and edges. Optionally, polygon data can be imported from CAD systems. The spatial regions should partition the space, so that each coordinate can be mapped to exactly one region, i.e. to query the room in which the user is currently located. Multiple levels can be represented as horizontal planes that are arranged along the z-axis in 3-D space. Although the spatial regions are represented as "flat" objects, they can be visualized from an egocentric (avatar) perspective in full 3-D using parametric objects; based on semantic annotation of regions and edges with information about type and passableness, parametric objects automatically generate the geometry for walls and doors, as shown in Figure 1.

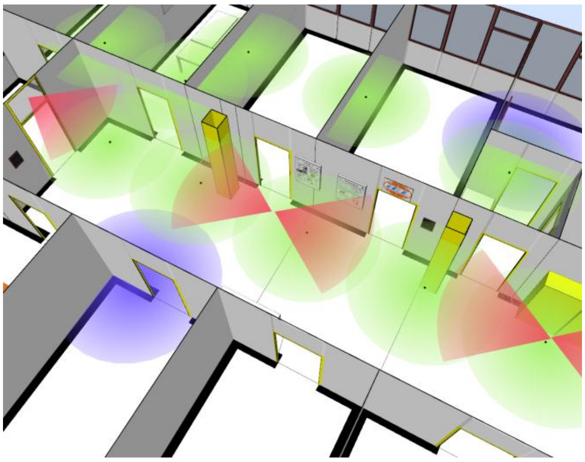

Figure 1: To estimate the position of the user, our lab has been instrumented with active RFID tags (green), directional infrared beacons (red), and Bluetooth access points (blue) to recognize users by their mobile phones.

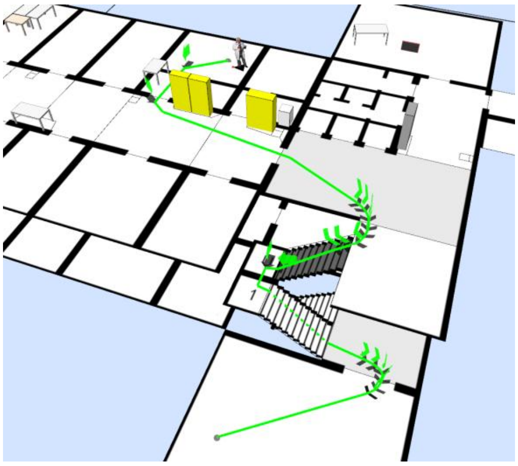

Figure 2: The shortest path between the current avatar's position and the exit has been calculated and is displayed as green line. Arrows indicate turning points.

In order to represent the rooms' furnishing, further 3-D objects can be used to model shelves, cabinets, and tables, which are specified by their type and dimension. All regions and objects can be labelled with symbolic identifiers to refer to an external database or ontology.

## 3 Modelling Instrumented Environments with Sensors and Actuators

Indoor positioning requires an arrangement of sensors and actuators to measure distances (signal strength or time of flight) or angles in order to estimate the location of the user by trilateration or triangulation. Therefore the location of the devices must be known to the positioning system. Figure 1 shows the instrumentation of our lab with RFID and IR beacons, which are received by a mobile terminal that computes its position based on the known position of the beacons (Schwartz et al., 2010). The YAMAMOTO toolkit further allows to geo-reference the model according to known points or aerial photographs (by manual alignment), so that local (model) coordinates can be converted to geographic (Longitude/Latitude) coordinates for a seamless transition between indoor and outdoor (GPS) positioning systems. Modelling buildings in 3-D allows to visually identify obstacles between sender and receiver units, and to represent geometrically challenging situations, such as staircases. Modelling the interior of buildings on a high level of detail further helps the designer to plan the coverage and precision of the positioning infrastructure according to the users' activities.

## 4 Navigational Aid for Pedestrians

Seamless route-finding is supported in indoor and outdoor environments without the need for explicit modelling of path networks. The YAMAMOTO toolkit includes the PATHFINDER component that has been implemented to find shortest paths in multi-level building models. The semantic annotation of edges (doors or walls) allows the algorithm to perform an *A** search directly on the spatial regions. Figure 2 shows an example route from the first- to ground floor.

## 5 Simulation and Evaluation of Assistive Environments in VR

The toolkit provides an interface to get and set the state of all modelled objects through external programs, hence it is possible to visualize the measured position of the user by the avatar in the virtual model. Vice versa, the avatar can be controlled by the user to simulate a precise indoor positioning system in VR to evaluate location-based applications. The virtual display objects implement a video streaming client (*VNC*) so that any content from an external application can be shown in real-time in the 3-D world. Our kiosk-based pedestrian navigation system VISTO recognizes users via mobile Bluetooth devices. For the simulation, we implemented virtual proximity sensors; as the avatar enters their range, they send the user's ID to the application and user-adapted output is streamed from real to virtual displays.

## 6 Conclusions and Outlook

YAMAMOTO has been designed as an easy to learn and efficient modelling toolkit for buildings. Semantic annotation allows for the automated generation of 3-D geometry and route finding. The tool also supports the simulation of assistive environments, i.e. for indoor positioning applications and navigation. For the future, a physical simulation of radio signals, considering obstacles and materials, would be of interest for the planning of positioning systems.

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# Automated Localization of a Laser Scanner in Indoor Environments Using Planar Objects

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## 1 Summary

A method is presented for automated localization of a laser scanner in an indoor environment. Planar features extracted from the range data undergo a linear plane matching model to estimate the relative scanner positions in consecutive scans. The performance of the method is demonstrated using a dataset of six panoramic scans of an interior, and the accuracy evaluation of the computed positions indicates localization errors of a few centimetres.

## 2 Introduction

A new trend in terrestrial laser scanning is the development of an autonomous system that is able to scan an indoor environment from a number of predefined positions, register the scans, and provide an accurate and complete point cloud of the scene. Such a system would require the automation of two main processes: scanner localization and the registration of the scans. In theory, automated registration precedes the localization problem, because a correct registration of consecutive scans provides the relative position and orientation of the scanner in every pair of scans. In practice, however, existing registration methods are slow and iterative, and require an approximate estimate of the transformation between the two scans. Alternatively, if the motion of the scanner from one scan position to another can be estimated from the data, it can serve as an initial approximation to perform an iterative fine registration of the scans, which will in turn lead to an improved accuracy for the localization of the scanner. In this paper, we describe a new method for the localization of the laser scanner using planar objects. The method is based on inferring a transformation from a set of corresponding plane-pairs within a linear least-squares plane matching model. The benefit of the linear estimation model is that it requires no initial approximations, and leads to a more efficient search for correspondences. The correspondence problem is approached with an initiate-and-extend search strategy, which begins with initial correspondence hypotheses and extends the correspondences when more plane pairs fit into the estimated transformation.

## 3 Overview of the method

The underlying principle in the plane matching model is that given a minimum of three plane correspondences in two scans (subject to the condition that the planes intersect in a point), a similarity transformation between the scans can be estimated such that the norm distance and difference in the direction of normals between the planes is minimized. Formally, the plane matching equation is expressed as: $\pi_j^1 = \mathbf{H}^{-T}\pi_j^2$ where $\pi_j^1$ and $\pi_j^2$ are planes in the two scans, and H is a transformation between the scans. Given a number of corresponding plane-pairs, the plane matching equation is rearranged to form a system of linear equations wherein H is estimated in a least-squares fashion.

To establish correspondence between the planes, we perform an initiate-and-extend search strategy, which works in two steps. In the first step, initial combinations of three or four plane pairs are created using a small subset of the planes in each scan. At this stage, loose constraints are imposed to reduce the number of initial combinations while maintaining the correct correspondences. A transformation is estimated for each initial combination. In the second step, each initial combination is extended with new planes in the two scans that fit into the estimated transformation. Extending the initial combinations provides a straightforward method for finding the correct transformation by picking the largest extended match set (the winning match set).

## 4 Experimental results

The performance of the plane matching method was evaluated using two indoor datasets. Figure 1 shows the reflectance image pertaining to one scan in the first dataset. This dataset consisted of six panoramic scans of an anterior of about 8 x 25 x 3 meters dimension. The position of the scanner at each scan was measured by a total-station to serve as reference in evaluating the localization results. Planar segments were extracted from each scan using a segmentation algorithm, and plane parameters were obtained by performing a least-squares fitting procedure. The plane matching process was performed with planes in all six scans in a pair-wise fashion, and the position of the scanner at each scan was computed. Figure 2 shows the computed scanner positions together with the reference measurements. The closing error shown in the magnified box represents the accumulated error of localization in six scans. The closing error was found to be 2.7 cm, while the RMS error of the computed positions amounted in 6.0 cm.

Figure 1: Reflectance image of one scan.

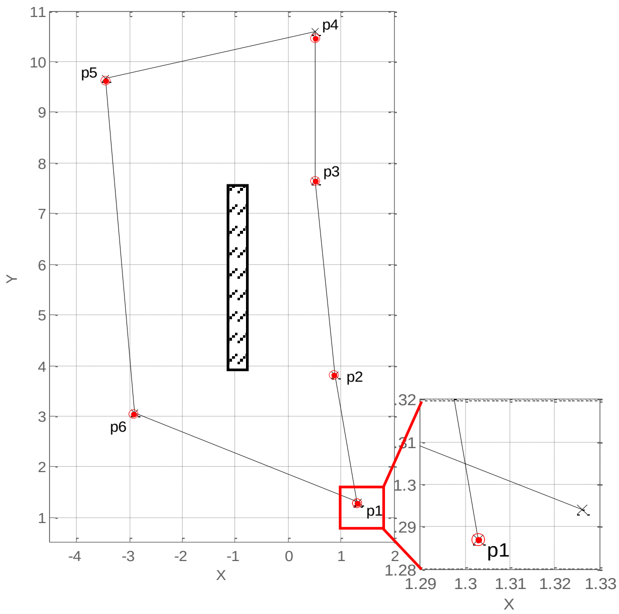


Figure 2: Computed trajectory of the scanner.

## 5 Concluding remarks

We introduced a plane matching method for the localization of a laser scanner in an indoor environment. The method is shown to perform robustly and reach localization accuracies in the order of centimetres. A main requirement of the method to yield a unique localization solution is the availability of a minimum of three planes (in each scan) that intersect in a point. A possible degenerate configuration of the planes is one with only walls in the scans, which cannot constrain the motion of the scanner in vertical direction. Such a constraint can be provided by including the planes of the floor or the ceiling in the plane matching estimation model.

# UWB SLAM with Rao-Blackwellized Monte Carlo Data Association

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## 1 Introduction

The scenario envisioned in this work is an emergency, where a building is filled with dust and smoke. A robot should build a map of a building and locate itself on it (simultaneous localization and mapping, SLAM). In this scenario, conventional means of navigation, i.e. optical systems, do not work. A bat-type UWB radar array, i.e. two RX antennas and one TX antenna in the middle, is suitable for this task. The main challenge is data association, the task of assigning measurements to corresponding landmarks. A solution is presented in this article using a Rao-Blackwellized particle filter.

## 2 Related Works

The great advantage of the bat-type UWB radar is the fact that it works without a priori knowledge of the surroundings and without any kind of infrastructure. This sets it apart from other means of indoor navigation, for example based on WLAN or RFID. Although those systems do not have to cope with data association, they are often not suitable for an emergency scenario as they need infrastructure. UWB is also a good choice for this task as it can provide additional information like life signs of humans, material characteristics, or even information about objects inside or behind walls. This work builds upon previously published results that also deal with the bat-type sensor array.

## 3 Overview

The bat-type configuration consists of an antenna array with one transmitter in the middle and two receivers to the left and right. An M-sequence UWB radar is used to measure impulse responses of the surroundings. By evaluating the peaks in the time-of-flight measurements at different positions, it is possible to deduce the location of features like walls, corners or point scatterers. Those features are used as landmarks for navigation and build a feature-based map of the building. They are tracked using a state-space model and an Extended Kalman Filter (EKF) to estimate their positions. The state vector **x** comprises of the robot pose and the landmark positions in two dimensions:

$$\mathbf{x}=[x_{robot}, y_{robot}, \varphi_{robot}, x_{landmark\ 1}, y_{landmark\ 1}, \ldots, x_{landmark\ n}, y_{landmark\ n}]^T$$

## 4 Data Association

For the Kalman Filter to work properly it must be known which measured time-of-flight belongs to which landmark. A basic method to accomplish data association is the Nearest Neighbor (NN) method. Here, we use the predicted measurements of the EKF. For all measurements $z_i$ we calculate the measurement probability

$$p(z_i|\mathbf{x}_k^-, c_i=j)$$

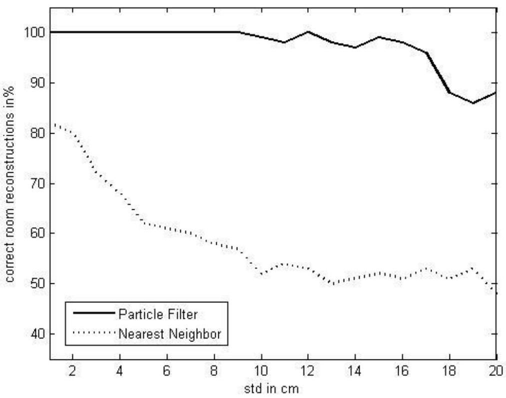
for all landmarks j, where $c_i$ is the correlation variable that stores which landmark is the assumed source of the measurement. The landmark with the highest probability is then associated with the measurement. This method works reasonably well for conditions with low noise, good position estimates and no false measurements. However, these preconditions do not always hold. For enhanced data association, we have to look not at a single, but at multiple hypotheses. One mean to do so is to use the Monte-Carlo-method also known as particle filter. In our case, we use the particle filter only for data association. Estimates of the state are calculated using Kalman Filters. The resulting filter is known as Rao-Blackwellized Particle Filter (RBPF). Each particle $p^{(l)}$ comprises the state estimation $\mathbf{x}^{(l)}$ and the error covariance matrix $\mathbf{P}^{(l)}$, both used in the EKF. The correlation vector $\mathbf{c}^{(l)}$ contains the actual data association, and the weight $w^{(l)}$ quantifies how good the hypothesis matches the reality of the measurements:

$$p^{(l)}=[\mathbf{x}^{(l)}, \mathbf{P}^{(l)}, \mathbf{c}^{(l)}, w^{(l)}]^T$$

In each step, for every particle the following quantities are computed: The new state estimate and the estimated measurements are calculated based on the old one using the basic EKF equations. Then, for all measurements $z_i$ an importance distribution $\pi_j^{(l)}=p(z_i|\mathbf{x_k^-}, c_i=j)p(c_i=j)$ is calculated and normalized. From this probability distribution the data association is drawn by Monte Carlo methods. With this data association, the state is updated and the new weight $w_k= w_{k-1}\ p(\mathbf{z}|\mathbf{x_k}, \mathbf{c})$ is calculated. This is done for every particle. Resampling occurs if the number of effective particles falls below a threshold.

## 5 Results

First results are shown in Figure 1 (left). Shown is the percentage of correctly reconstructed rooms for a simulated test scenario plotted against position uncertainty. The RBPF (solid line) with 100 particles is significantly better then the NN (dotted line). In Figure 1 (right), every $10^{th}$ measurement is replaced by a false measurement, which still leads to acceptable results.



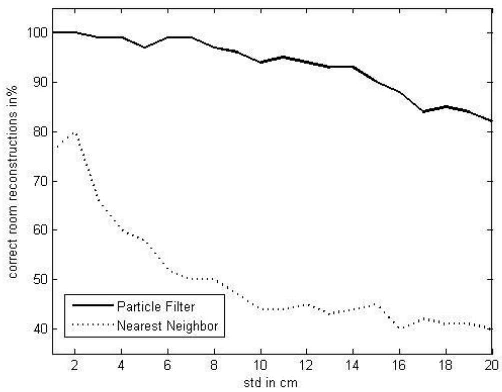




Figure 1: Percentage of correctly reconstructed rooms for RBPF and NN. Left: no false measurements. Right: 10% false measurements

## 6 Conclusions

The RBPF proved to be an appropriate tool for accomplishing the task of data association. Although it requires more computational power than the simpler Nearest Neighbor (NN) algorithm, it is still fast enough to allow for real-time applications. It is better than the NN in terms of reconstruction quality, and has a better ability to cope with false measurements.

# Developing an Integrated Software Environment for Mobile Robot Navigation and Control

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## 1 Summary

A flexible modular robotic software environment based on the popular MRPT toolkit is reported in this paper that is able to easily integrate path planning, navigation and control algorithms from several sources. The different modules (responsible for SLAM, trajectory tracking, sensor and actuator handling, visualization etc.) communicate with each other via a carefully developed network based protocol set that ensures transparency and robust operation. The system can also be used as a simulation environment and it is capable for the comparative benchmarking of different navigation algorithms. The laser scanner based map building and navigation of an autonomous wheelchair is shown as an application example to illustrate the features of the developed software environment.

## 2 Motivation and aims

Currently, there have been numerous navigation and control algorithms and techniques in the field of indoor mobile robotics. Available robotic software toolkits present several implemented algorithms, but *system-level integration still remains a challenging task*. This inspired us to create a high-level, modular robotic software environment based on a selected toolkit to handle our special application requirements and significantly extend previous functionality. Beyond the standard requirements for a robotic software environment such as *robustness* and *portability*, our high-level, integrated system was designed to meet the following main requirements: a) *strongly modular construction*, b) *multi-host, distributed architecture*, c) *probabilistic computational framework*, d) *such an environment where the incorporation of new algorithms and features is easy.*

## 3 Basic tools

Our system is based on Mobile Robotic Programming Toolkit (MRPT) [1]. MRPT was selected because this framework uses a coherent probabilistic approach that is very useful in solving indoor navigation tasks. Furthermore, it contains a large amount of algorithms and software tools like SLAM techniques [2], Kalman Filter, Particle Filter, hardware drivers, data structures for several kinds of maps, visualization, and many auxiliary utilities. Using the algorithms implemented in MRPT, a set of separate modules were created using codes also from external sources or from our own implementations.

## 4 Design principles and properties of the modular system

Each module is responsible for a specific task like *SLAM*, *path planning*, *trajectory following control*, *handling of sensors and actuators*, and *visualization*. Apart from the above tasks, additional modules were implemented that allow us to use the system as a *simulation environment,* too. Such modules are responsible for recording the measured data and playing it back, and for monitoring the inner state variables of the system**.** The architecture

provides transparency between the real and simulated experiments. Running different algorithms simultaneously on the same data can also be done, thus *comparative benchmarking* is possible. Extending this system by adding new modules is quite easy. Using the module's connection interface provided by our framework, the algorithm running in the heart of the module obtains all data to process. There is no need for further modifications in the algorithm as only the incoming and generated data structures should be adjusted to the other module's data representation. Separating the system's functionalities into modules ensures *robustness and safety*: if a single module fails, it will not cause the whole system's failure generally, since other independent modules can work properly. The unified form of data representation used at the communication allows us to change specific modules without modifying any settings or parameters in other modules. This unification was solved by the MRPT built-in object serialization.
The modules communicate with each other via a well-defined interface and protocol set, while performing their tasks. The communication protocol defines message types containing specific data (e.g. robot position, planned path, motion command, etc.). The transport is solved by using the standard TCP/IP protocol, while the distribution of messages is handled by a central module using publish-subscribe based architecture. The network handling layer is completely transparent for each module, which means that the modules have (and need) no knowledge about the specific data sources.

## 5 Application example

Our long-term project is to develop an *autonomous wheelchair* for handicapped schoolchildren. The reported robotic software environment was developed partially for this indoor mobile robotic task. Our project's testbed was a PowerBot robot equipped with a SICK LMS100 laser range finder. With the help of our system, we were able to investigate several algorithms' attributes: regarding the SLAM, we compared scan matching based algorithms, i.e. the classical Iterative Closest Point (ICP) registration algorithm [3] to the ICP with Levenberg-Marquardt optimization [4]. In the field of path planning, we compared A* and D* Lite algorithms. The current capabilities of the software system enable the robot to perform autonomous navigation in indoor environment including SLAM, planning and execution. For the illustration of application possibilities, Figure 1 shows integrated visualization in operation where several modules' output can be seen, e.g. SLAM, path planning.

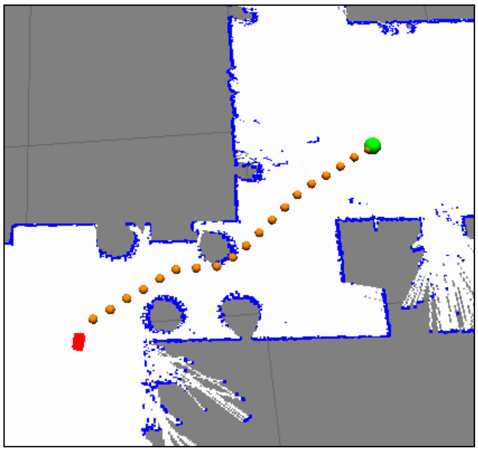

Figure 1. ICP-SLAM built metric map. In the left region the robot, in the right region the target is located, between them, a planned path can be seen.


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# Indoor Pedestrian Simultaneous Localization and Mapping

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## 1 Summary

This extended abstract presents a doctoral project in its initial phase. The objective is to implement a precise localization and mapping system that is able to track a pedestrian in known and unknown environments. To achieve this, the well-known SLAM (Simultaneous Localization and Mapping) method will be applied that is already used for mobile robots. The pedestrian will be equipped with a short-range laser scanner, an inertial measurement unit (IMU), and a wearable computer for processing purposes. To obtain localization, the sensor data will be fused and processed with an algorithm based on the Extended Kalman Filter and Rao-Blackwellized Particle Filters. Mapping will be achieved with grid mapping.

## 2 Introduction

Localization and tracking of persons, agents, objects, etc. has been the object of significant studies among research groups over the last years. The pursuit of knowing the position of an agent, and even tracking it, is of crucial importance in many applications. Localization can be divided into two different scenarios: outdoor and indoor. These scenarios are addressed in different ways, and are solved through diverse methods and implementations. Outdoor localization methods can be obtained with GPS, field strength measurements (WLAN, GSM, Bluetooth), etc. For a precise indoor localization GPS cannot be used due to attenuation and scattering of the signals [1]. Preferred methods for indoor localization are the utilization of pre-installed indoor communication infrastructures, laser, radar, sonar, camera, motion sensors, etc. Assuming that not all buildings have a pre-installed communication infrastructure, the field strength measurements methods also cannot be used. For a precise indoor independent localization, it is important to perform sensor fusion with the above-mentioned methods [2].

## 3 SLAM

Simultaneous Localization and Mapping (SLAM) is a well-known solution in the area of mobile robotics. Many other approaches have been proposed for solving this particular problem. The most popular algorithms to solve the problem are based on the Extended Kalman Filter and the Rao-Blackwellized Particle Filters [3]. The problem has been solved in general, but it probably needs some algorithmic improvement.

This method basically works as follows: The mobile robot is equipped with a laser scanner, mounted on top of it, to take horizontal measurements. With this laser it is possible to take measurements of different landmarks, obtaining distances and angles. Landmarks are basically features in an environment that can be used as reference and for the registration of multiple scans when combining different measurements from diverse positions. For example, in an indoor environment, landmarks could be lines, walls, corners, edges or more specific obstacles. The data obtained from the laser are fused with the mobile robots odometry; using the proposed algorithms it is possible to establish an approximation of the robot position at all times. At the same time a 2D map is constructed of the environment.

## 4 Indoor Pedestrian SLAM

The implementation of SLAM for pedestrians is based on [2] for this project. For pedestrians, the SLAM problem must be addressed in a different manner, due to the different movement conditions. Pedestrians have a much more complex odometry than mobile robots: they differ in the type of movements and degrees of freedom. The laser scanner position with mobile robots is stable compared to the surface. This cannot be guaranteed for human beings. Furthermore, the human body is specific to each person, as is motion. Thus, the challenge is to extract the odometry for each pedestrian and to obtain stable laser scanner data.

In this project, the pedestrian will be equipped with a short-range scanner and an Inertial Measurement Sensor (IMU). Positioning of the sensors is crucial to noise reduction and/or incorrect measurements. In mobile robots, the laser scanner is implemented on top of it and is able to scan a horizontal plane. The most stable positions on the human body to place the sensors are the shoulders and hips. To obtain horizontal laser scans, the raw data requires processing with the IMU data and projection onto the horizontal plane. Additionally, to reduce false laser scan readings, the scanner will be regulated with an electro-mechanic stabilizer so its measurements are always taken horizontally.

To extract odometry from the pedestrian, the data from the Inertial Measurement Unit will be processed to obtain step length and direction. Thus, by combining pedestrian odometry, laser scanner data, and using an Extended Kalman Filter or the Rao-Blackwellized Particle Filters, it is possible to achieve a precise localization.

The mapping can be accomplished by using a grid mapping method. This basically works by dividing the environment into small grids, and deciding whether that grid is occupied or not by scanning the environment. If a grid is occupied, then the system assumes that there is a solid object there; so it is drawn in the map.

Data processing will be accomplished with wearable computing devices, so there will be total independence of any main computer or network.

## 5 Conclusions

The proposed method is a different way to address localization of pedestrians. It is independent from the indoor environment; no a priori information is needed and it is comfortable to wear.

This tracking and mapping method is not meant to be used by any person, it is rather built for specific applications, where precise localization and mapping of a pedestrian is needed.

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# Creation of an Urban Spatial Model for In-City Positioning Using Laser-Scanning

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**1. Summary**

The investigations are based on the evaluation and the analyzes of high accuracy *LIDAR* images taken over Lithuanian cities, thereby taking into account the geodetic control measurements and foreign expert experience. The progressive aerial laser scanning approach with combination of digital photogrammetry technology, – a *GPS-IMU* system and a digital aerial photography have been used for the creation the urban spatial model. The application feasibility is investigated. A description of equipment, technological features and application possibilities is presented.

**2. Technological features**

Digital photogrammetry technology fused with laser scanning data is analyzed considering in-city location determination that can be used for indoor positioning, e.g., surveys of excavation, design of industrial equipments, reconstruction of architectural monuments, etc.

*1. LIDAR images***.** This includes Lithuanian urban areas scanned by *Geokosmos* (Moscow) using scanner *Optech ALTM* 3100 from the airplane *Antonov-2. Z-Max GPS* receivers for reference point measurements were used. Geopositioning has been achieved by the inertial navigation system *Trimble 750 GPS - Applanix POS/AV IMU*. The spatial coordinates of reflected laser scans were determined. The *ALTM 3100* operates in the infrared spectrum range, because low signals are reflected from the water surface.

*Other flight data*: speed: 205 km/h, distance between strips axes – 300 m; side overlap – 30%; laser point density: 3-4 points/$m^2$; average distance between points: 0.5 m. The accuracy requirement for scanner spatial positioning: standard deviations of less than 5 cm. Required accuracy for *LIDAR* measurements: for height points 15 cm, horizontal 30 cm. Laser scanning data have been filtered, edited and Digital Surface Models were created. According to the morphological features the DSM was classified into the categories buildings, vegetation, bridges.

*Digital aerial images.* The images have been taken separately from the *LIDAR* flights using digital aerial camera *UltraCamD* (*Vexcel Imaging*, Austria), with a focal length of $c_k$ = 101,4 mm, frame size of 7500 x 11500 pixels. The flying height was 600 m. The created digital orthophotos have a scale of 1:2000.

Spatial city models have been created by fusing *LIDAR* and orthogonal image data.

**3. The accuracy of LIDAR images**

The laser scanning accuracy depends on the scanner characteristics, the flight height, the scan angle, the laser beam frequency and distribution, positioning of the GPS-IMU system, the reflecting surface properties and some other factors. *The LIDAR* laser beam measures ranges to the solid surface with an

A significant systemic error was found.

*LIDAR* pulse point positioning has been investigated in the 24 reference (test) areas with asphalt covers. In the selected test areas there have been about 1000 control points identified and measured. Some *LIDAR* data accuracy analysis results are presented in Table 2.

Table 1: Results of *LIDAR* point heights accuracy investigation compared with geodetic control measurement

| Reflected surface | Number of control points | Accuracy assessments [m] | | | |
|---|---|---|---|---|---|
| | | Min. | Max. | Mean deviations | RMS |
| Test area – *Kaunas* | | | | | |
| Asphalt | 74 | -0.05 | 0.14 | 0.04 | 0.07 |
| Field | 113 | -0.08 | 0.17 | 0.10 | 0.11 |
| Field with brushes | 119 | -0.11 | 0.30 | 0.06 | 0.09 |

Table 2: Some results of laser pulse point position accuracy

| Test area/ number of reference areas | Accuracy assessments according to the reference areas [m] | | | |
|---|---|---|---|---|
| | Height accuracy | | Horizontal accuracy | |
| | Interval of deviations | RMS | Interval of deviations | RMS |
| Kaunas/ 3 | -0.07 - (+0.06) | 0.04; 0.04; 0.03 | 0.10 - 0.25 | 0.16; 0.18; 0.18 |
| Vilnius/ 5 | -0.10 - (+0.09) | 0.09; 0.07; 0.08; 0.08; 0.05 | 0.10 - 0.22 | 0.14; 0.17; 0.16; 0.17; 0.12 |

## 4. Conclusions

Laser scanning from the aircraft combined with orthophotogrammetric data is useful for accurate land surface mapping and fulfils the requirements for the creation of spatial city terrain models.

The *LIDAR* pulse points positioning accuracy shows that the average standard deviation for height points is 0.05 - 0.12 m. The horizontal accuracy is 0.25 m when the flying height is about 1000 m and 1.26 m when the flying height is about 2000 m. The systematic errors can be reduced by calibration of the GPS, IMU and the scanner. The water surface absorbs electromagnetic energy significantly, especially when the carrier wavelength is about 1.5 µm.

It can be stated that, under the current accuracy the laser scanning data can be integrated with the orthophotographic base and is suitable for the creation of spatial 3D models for the urban surface, relief, buildings and other ground-based objects under large-scale topography and GIS needs.

**UWB (Ultra Wide Band)**

Auditorium D8

Thursday, September 16

08:15 – 09:45, 10:15 – 11:45, 13:15 – 15:00 & 15:30 – 16:45

# Low Power ASIC transmitter for UWB-IR radio communication and positioning

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## 1 Summary

At the Electronics and Signal Processing Laboratory at EPFL (formerly UNINE), an experimental platform has been designed and built to demonstrate the feasibility of Ultra-wideband Impulse Radio (UWB-IR) technology applied to indoor positioning [1]. This office-scale demonstrator has proven to be a valuable research tool, with the flexibility to study, test and assess the performance of various system architectures and signal processing algorithms.

Based on this successful experience, a subsequent project was setup to extend the lab's research on certain topics that could not be addressed by the office-scale demonstrator. This new R&D project pursues two main objectives: a) designing and building a large-scale UWB-based Local Positioning System (LPS), including installation, calibration and operational testing in a real industrial environment; b) conceiving and developing Application Specific Integrated Circuits (ASICs) to target cost-competitive solutions. The details related to the first objective a) are out of the scope of this paper and can be found in [2].

In turn, this paper focuses on objective b) and presents the design of a Low Power UWB transmitter ASIC that complies with ECC spectrum regulations for UWB-IR low duty cycle, as well as with FCC spectrum regulations. This transmitter has been implemented in UMC 180 nanometers CMOS technology and works with a power supply of 1.8V.

## 2 UWB ASIC transmitter Design

The existing office-scale demonstrator is composed of 4 receivers mounted at given positions within a room and several mobile, small transmitters. The position of the latter can be estimated by using time of arrival measurements. For this demonstrator, the transmitters were built using discrete off-the-shelf components operating in a frequency band below 1 GHz. However, for the large-scale UWB-based LPS currently under development, the transmitters had to be redesigned to reduce production costs for higher volumes, to decrease their size, to lower the power consumption, and to be compliant to ECC spectrum regulations. To achieve these goals, an ASIC has already been developed and successfully tested.

The new transmitters are based on a triangular shaping pulse generator, a local oscillator at 4.1 GHz and a mixer. The frequency band between 3.4 GHz and 4.8GHz can be used accordingly to the ECC spectrum regulations, provided that the duty cycle is sufficiently low. In a positioning system, where a sequence of pulses only needs to be transmitted at the intended position update rate, this restriction can be easily respected.

By switching off the pulse generator between two transmission sequences, the power consumption can be lowered significantly. Additionally, a further reduction can be achieved by considering another duty-cycle inherent to impulse radio. For this application, a pulse repetition rate (PRR) of 10 MHz was chosen, corresponding to a 100 ns repetition interval, and the pulse duration is less than 5 ns. Therefore, we have included in the design some circuitry that switches off the supply of several blocks, in particular the output power amplifier, between two pulse transmissions. A wake-up strategy has also been included to ensure the repeatability of the pulse emission in term of latency, shape, amplitude and polarity.

## 3 Transmitter test platform

The test of the ASICs was performed in several steps. At first, since the outputs of the chip are differential, a PCB using an external triggering and a differential SMA output was made. To characterise the chip, we connected the board to two channels of an oscilloscope and combined them using the mathematical functions of the oscilloscope to visualize a single ended signal.

Since most wide band antennas on the market are single ended, a second PCB has been designed. It includes a ceramic balanced-unbalanced transformer and an on-board 10MHz triggering to remove the constraint of needing an external triggering signal.

Currently, the pulse generator has been integrated successfully in an ASIC. However it does not yet contain circuits for the modulation. As the LPS demonstrator is intended to work with several transmitters [2], each transmitter has to provide identification and hence requires some modulation or spreading scheme. A future version of the ASIC will include these required circuits. Adding binary phase shift keying (BPSK) on the ASIC will consist of adding a multiplexer only, because all the internal signalling is balanced. Other modulations schemes, such as On-Off-Keying (OOK) and Pulse Position Modulation (PPM) can already be implemented using a few external components by delaying or suppressing the triggering pulse.

## 4 Conclusions

This paper describes in detail the design and realization of a Low Power UWB-IR transmitter dedicated to position and communication to be used in a UWB-based large-scale deployable local positioning system. This ASIC version of transmitter have been successfully realized, it is compliant with current FCC/ECC spectrum mask. The total averaged power consumption is less than 85uW for a 16-pulse burst at a burst repetition rate of 1Hz. The chip area including pads is less than 1.5mm2, while the core itself is 0.56mm x 0.4mm. The chip was implemented in a standard UMC 0.18um CMOS technology.

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# UWB Sequential Monte Carlo Positioning using Virtual Anchors

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## 1 Introduction

In previous work [1], we have introduced an indoor positioning concept using ultra-wideband (UWB) radio signals together with available floor plan information. Our approach uses so-called virtual anchors (VAs), which are mirror images of the beacon node with respect to the room walls. It has been shown [2] that such VAs can enhance the positioning accuracy in a cooperative scenario. In our contribution we make use of available floor plan information which allows to compute the locations of the VAs. Hence we can obtain a set of anchor nodes from just one single physical transmitter. Using range estimates to the VAs, extracted from the UWB channel impulse response (CIR) [3], we have shown how to construct a likelihood function for our range estimates, conditioned on the unknown receiver position. With this function, the position can be estimated using standard techniques like maximum likelihood- (ML) or maximum a-posteriori probability- (MAP) estimation.

It has been shown that this positioning approach results in a very good performance (80% of the estimates within 50cm accuracy), if prior knowledge concerning the receiver position is assumed. In this contribution we present techniques to obtain this prior position information. Using a moving receiver and state-space estimation performed by a particle filter allows for the approximation of the position probability density function at each time step. This information is used to enhance the accuracy and the robustness of the positioning algorithm.

## 2 Problem formulation

Our positioning algorithm consists of two steps: In the first one, a vector **z** of range estimates to the VAs is extracted from the CIR. The second step uses this vector to calculate a measurement likelihood function for **z**, conditioned on the unknown receiver position. In [1] we have presented the mathematical form of this function and how it accounts for both uncertainties in the range extraction process and certain geometric ambiguities.

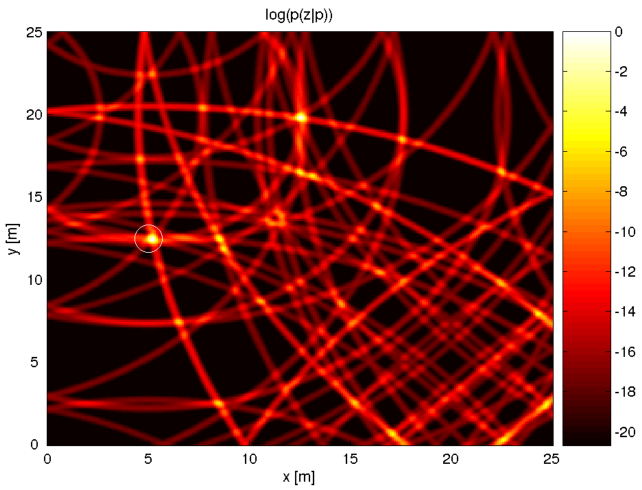

Figure 21: Measurement likelihood function (example)

This contribution aims at making our positioning concept more robust with respect to such uncertainties. Fig. 1 shows an example for the logarithmic measurement likelihood function, where the white circle indicates the true position. Ambiguities manifest themselves as multiple modes in the likelihood function. These cause outliers in the position estimation via a straight-forward ML method. However, if we propagate the information of a previous position estimate to the next time step, we can exploit the correlation in successive positions of a moving receiver to suppress these outliers. This can be done using Bayesian state estimation.

## 3 Position estimation techniques in this contribution

Bayesian state estimation is often implemented using particle filters. For the implementation of the particle filter, we need a proposal density function for the particles, which is obtained using a standard motion model for the receiver. For the recursive calculation of the particle weights, we can use our measurement likelihood function. Particle filters are also more suitable for our state estimation problem than e.g. standard Kalman filters because of two reasons: First, our measurement likelihood function is multimodal and non-Gaussian, and second, our measurement equations are nonlinear in the position parameters.

A particle filter can handle both of these circumstances and approximates the probability density function of the position each time step, however, the computational complexity can become large. An alternative is to approximate this density with a Gaussian centered at one mode of the likelihood function. Again the correlation of successive positions can be used to track the location of this mode.

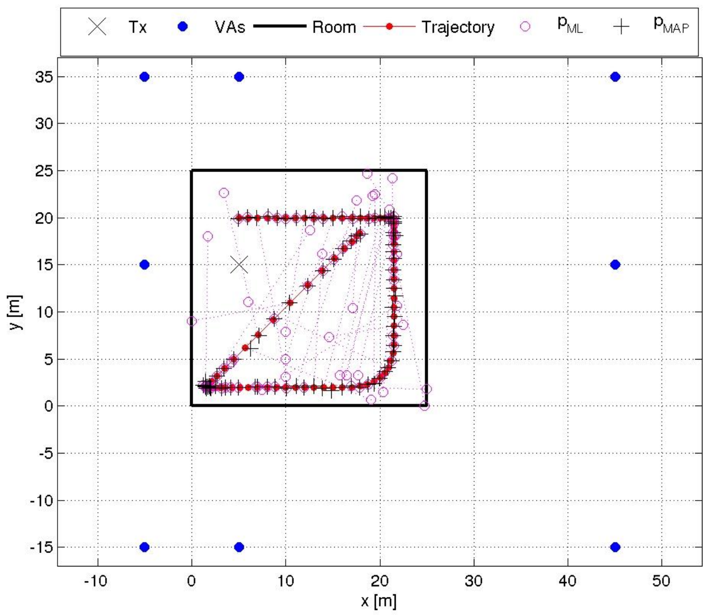


*Figure 22: Scenario with VAs, trajectory, ML an MAP estimates*

Fig. 2 shows a scenario in which our positioning concept is used. We see that available prior knowledge, here in the form of a rather broad Gaussian distribution around the true position for the MAP estimator, can highly improve the positioning accuracy. The outliers of the ML estimation are avoided effectively. Our final contribution will present the details of an implementation of the presented concepts using Bayesian state estimation.

## 4 Conclusions and Outlook

This contribution augments our virtual anchor based positioning concept with state space estimation considering a moving receiver node. We show the mathematical formulation of the estimation problem, which allows for the usage of the theory of Bayesian state estimation to exploit correlation of successive position estimates of a moving receiver. Approximations of the probability density function of the position are used to further enhance accuracy and robustness of the positioning algorithm.

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# An accurate UWB radar imaging method using indoor multipath echoes for targets in shadow regions

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## 1 Summary

UWB pulse radar is promising for surveillance systems in terms of its high-range resolution. To realize a low-cost and high-quality indoor security system, we propose a UWB radar imaging system using indoor multipath echoes for targets in shadow regions. A multipath wave can be used as an approximation of an imaginary echo from a mirror image antenna to the target, except for phase rotation and attenuation. Conventional studies [1, 2] only dealt with locating point-like targets, not estimating the shapes. We apply interferometry using these mirror image antennas to estimate target shapes. If only this method is applied, many false image points are estimated because it is difficult to uniquely determine the corresponding mirror image antenna to each echo. We propose an effective false-image reduction algorithm to obtain a clear image. Numerical simulations show that most of the false image points are removed and the target shape is accurately estimated.

## 2 System Model

We deal with a two-dimensional problem for simplicity. Fig. 1 shows a model of the system, where an antenna and a target are located in an L-shaped room made of PEC (Perfect Electric Conductor). An antenna is scanned along a straight line $y = y_0$ at fixed intervals of $\Delta x$ in the $x$ direction, where $y_0 = 1$ m and $\Delta x = 0.1$ m. Raised-cosine-shaped UWB pulses, with a centre frequency of 60 GHz and a bandwidth of 1.4 GHz, are transmitted and echoes are received by the same antenna. $s(X, Y)$ is the received signal at the antenna location $(x, y) = (X, y_0)$, where we define $Y$, with time $t$ and the speed of radio waves c, as $Y = ct$. A PEC circular target with a radius of 0.5 m is located at $(x, y) = (-3$ m, $4$ m$)$ in a shadow region that is defined as the area where direct waves cannot be received from the antenna. The $j$-th mirror image antenna location is $(x^{(j)}_i, y^{(j)}_i) = (x^{(j)}_0+i\Delta x^{(j)}, y^{(j)}_0)$ $(j = 1,..., N)$, where $N$ is the number of mirror image antennas and $\Delta x^{(j)}$ is the interval of the $j$-th mirror image antenna's location.

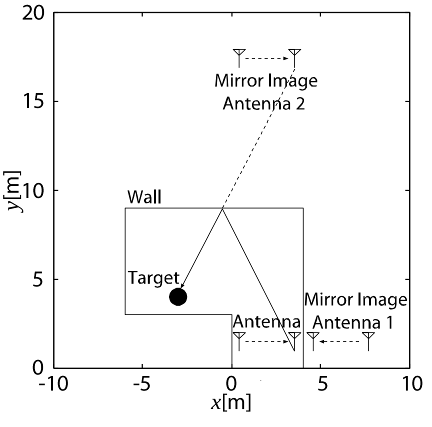


Figure 1: System model with an L-shaped room.

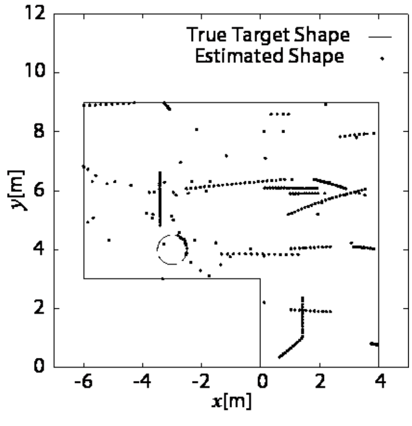


Figure 2: Estimation without false-image reduction.

## 3 Interferometry Imaging in Indoor Environment

First, we extract peak points $(X_i, Y_{i,k})$ from $s(X, Y)$, where $X_i$ is the $i$-th actual location of an antenna and $Y_{i,k}$ is the $k$-th peak of the signal received at $(X_i, y_0)$. Next, we pick up pairs of adjacent peak points satisfying the condition $|Y_{i,l} - Y_{i+1,m}| < cT_0$, where $T_0$ is the length of the transmitted pulse. Finally, we apply interferometry to these peak points, where the images are estimated as the intersection point of a couple of ellipses with long axis $Y_{i,l}$ and $Y_{i+1,m}$. The foci are $(x^{(p)}_i, y^{(p)}_i)$, $(x^{(q)}_i, y^{(q)}_i)$, and $(x^{(p)}_{i+1}, y^{(p)}_{i+1})$, $(x^{(q)}_{i+1}, y^{(q)}_{i+1})$. Note that it is unknown to find a correct combination of each peak point and the corresponding mirror image (or actual) antenna. We thus apply this estimation process to all possible combinations of pairs of peak points and antennas to obtain an estimation image. The image estimated by this method is shown in Fig. 2, where a broken line and black dots represent the actual target shape and the estimated image. This image has many false image points because it contains incorrect combinations of peak points and antennas.

## 4 Proposed False Image Reduction Method

To remove the false image in the previous section, we propose the following method. First, we calculate a rough image using the conventional time-reversal method [3] assuming point targets as in Fig. 3. In this figure, the target location is approximately observed, although a target shape cannot be seen because of its low resolution. We use this target location to estimate the combination of a peak point and an imaginary antenna. Here we pick out the consistent image points that satisfy the relationship between the antenna scanning direction and the estimated range values, and we assume that true image points exist within a radius of $\mu$ from the maximum pixel in Fig. 3, where $\mu$ is 0.6 m. The estimated target shape by the proposed method is shown in Fig. 4. In this figure, most of the false images are removed and the true target shape is accurately estimated.

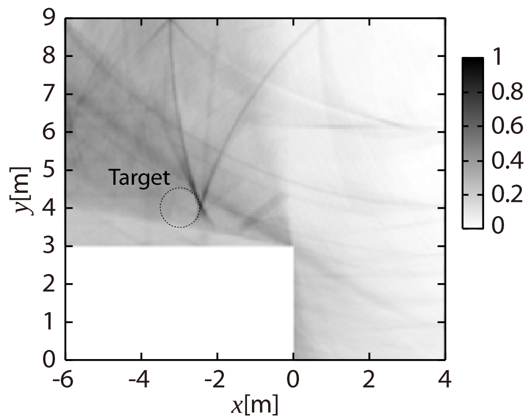


Figure 3: Normalized time-reversal Image.

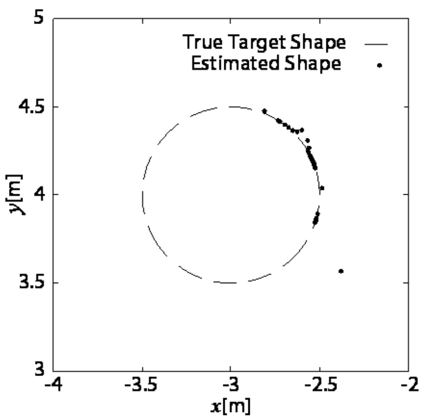


Figure 4: Estimation with false-image reduction.

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# An Impulse Radio UWB Transceiver with High-Precision TOA Measurement Unit

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## 1 Summary

This paper describes a monolithic integrated transceiver chipset intended for impulse radio (IR) Ultra-wide band (UWB) applications including indoor communication and indoor localization. The chipset operates in the higher UWB band centered at 7.68 GHz and it is optimized for a pulse bandwidth of about 1.5 GHz. The average pulses repetition rate of 60 MHz and an octagonal pulse position modulation (8-PPM) allow for raw data rates up to 180 MBit/sec. The available high bandwidth is used for precise indoor localization employing a dedicated time-of-arrival (TOA) measurement extension. This unit runs with a system clock of 3.84 GHz, which allows a measurement accuracy of 260 picoseconds. As demonstrated this UWB transceiver chipset is well suited for two-way ranging (TWR) potentially in harsh environments. Under perfect line-of-sight conditions a spatial resolution of about 3.9 centimeter could be achieved.

## 2 Introduction

Impulse radio (IR) UWB systems are expected to provide the best performance in Time-of-Arrival (TOA) measurement based localization systems like the Two-Way-Ranging (TWR) [1] or Differential Time-Difference-of-Arrival (DTDOA) [2]. Impulse radio transceivers require proper broadband signal design on the RF part as well as high-speed digital circuitry to achieve the expected sub-nanosecond time resolution for precise indoor localization. Energy detection receivers benefit from their simple implementation but suffer from the inability to derive any information about the received signal like pulse center frequency and pulse phase. This complicates the separation of the desired received signal from interfering signals caused by multi-user interference (MUI) and multi-path reflections in indoor environments. A dedicated TOA measurement extension to a typical non-coherent transceiver can overcome these restrictions by delivering a high-resolution time stamp of the leading edge for the received signal. The effort inside the transceiver for such a stopwatch can be kept small, if it runs synchronized to the clock of the baseband processor referring to the same crystal oscillator.

In the remainder of this paper we will present the extension to a non-coherent transceiver for precise TOA measurements. First, we start with a description of the overall UWB system, dedicated for wireless sensor network applications in industrial and logistics environments [3], [4]. In particular, the localization scheme will be described including their implications on transceiver and TOA unit design. This will be followed by a detailed overview of the IR-UWB transceiver architecture and the embedded TOA measurement extension. Finally, we discuss implementation issues and present recent measurement results. The remaining part of this extended abstract is limited to important figures, which will be significantly enriched with detailed descriptions in the upcoming full paper.

## 3 System Overview and Ranging Results

Fig. 1 shows the basic localization scheme of the presented system. Assuming an industrial environment, a stationary infrastructure of anchor nodes at known positions is the base of the localization system. The mobile nodes shall have communication and TOA measurement capabilities to allow independent and autonomous two-way ranging, initiated by the mobile nodes. This enables the mobile nodes to determine their own position. The advantage of two-way ranging as basic localization principle is the simplification of the infrastructure by avoiding expensive cable connections and the unlimited scalability of the system. The figures 2, 3, and 4 show the block diagrams of IR-UWB transmitter, receiver, and the dedicated TOA measurement unit [5], [6], [7], which finally allows for a hardware raw resolution of 260 picoseconds, corresponding to a spatial accuracy of 7.8 cm.

The two chips (transmitter and receiver) were fabricated using a 0.25µm SiGe:C BiCMOS technology of the IHP. Under optimal LOS conditions in a laboratory the demonstration platform could show the expected ranging accuracy, proofing the hardware concept. As visible in the GUI snapshot (figure 5), there were no drift of ranging results over time. Keeping the measurement setup static, a ranging accuracy of 3.9 cm could be achieved.

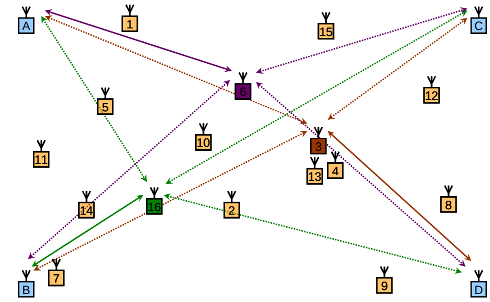


Fig. 1: Localization principle

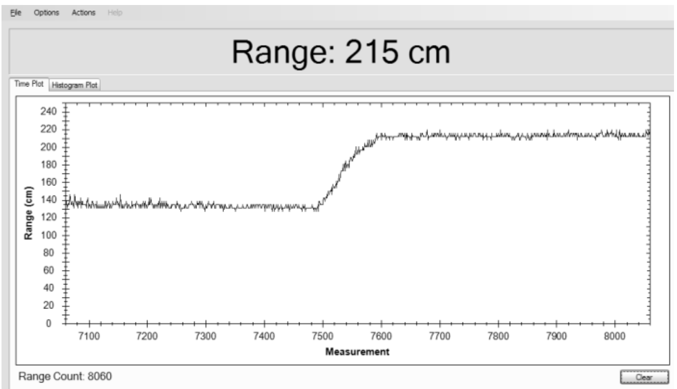


Fig. 5: Ranging results

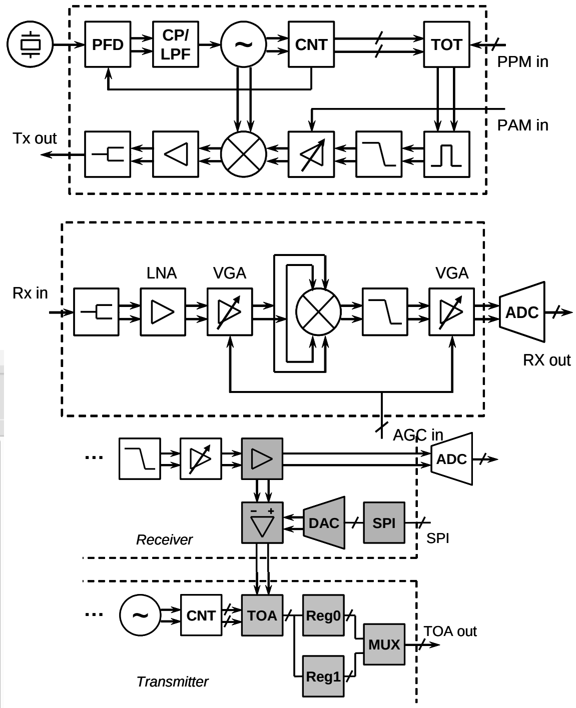


Fig. 2, 3, 4: Transceiver block diagrams


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# Experimental Validation of a TOA UWB Ranging Platform with the Energy Detection Receiver

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## 1 Summary

The ultra-wideband (UWB) technology is recognized as an ideal candidate to provide accurate localization in challenging indoor environments where other technologies, e.g. WiFi or ZigBee, cannot yield good accuracy due to their signal bandwidth limitation. The energy detection receiver is currently one of the most promising low complexity non-coherent architectures that neither requires high sampling rates nor information about the channel.

This paper presents results of experimental validation of the designed and implemented UWB ranging platform with the energy detection receiver. Insights into practical limits on the performance of the platform are provided. These include, among others, an analysis of the link budget and system parameters. The presented theoretical analysis is validated through laboratory measurements.

## 2 Extended Abstract

Ultra-wideband has several attractive properties that mainly stem from the wideband nature of its signals and include very fine time and spatial resolution, and multipath immunity. This technology enables precise ranging in challenging indoor environments with accuracies in the order of centimetres depending on the bandwidth and signal-to-noise ratio.

Despite a vast body of research results on UWB ranging and localization available, knowledge about practical implementations of the proposed ideas is limited [1]-[4]. Moreover, most of the implementations [2], [3], [4] are down-scaled versions of real systems with respect to the operating frequency or, due to the inherent correlation, require very high sampling rates which obviously are not realistic in practical applications. Furthermore, some of the platforms require off-line data processing [3], [4].

In this paper, a UWB technology-based ranging platform with real-time signal processing is experimentally validated. It is based on the time-of-arrival (TOA) method and energy detection receiver architecture. The ranging platform consists of a signal generator, UWB pulse generator, sampling oscilloscope, phase-locked loop (PLL) board, and UWB antennas. All signal processing done by the receiver is performed by a software application written in Visual Basic and operating real-time on the oscilloscope. Our measurement results indicate that with our signal processing method being currently in the process of a patent application, it is possible to achieve accuracy of 1-2 cm with the sampling rate of 500 MS/s and with max. 3 bits of the analog-to-digital (A/D) resolution. It is expected that in the final paper this method will be explained. Practical limits on the performance of the platform, including the maximal operational range, are first determined via theoretical analysis. Then, the presented results are validated through laboratory measurements performed in the time domain. Several receiver positions are considered.

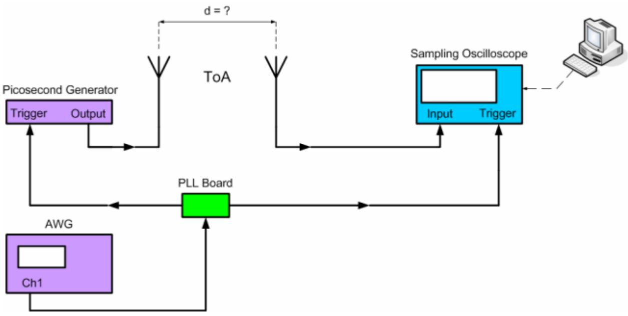
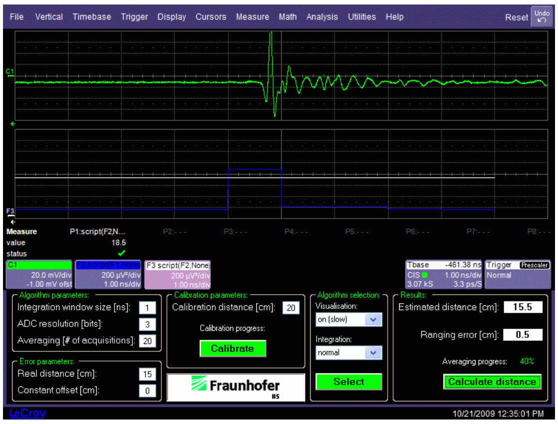



Fig. 1. The high level block diagram of the practical UWB ranging platform implementation.



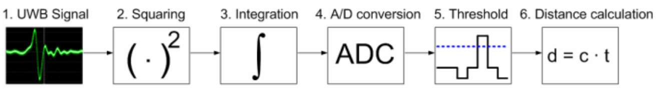




Fig. 2. Signal processing operations performed at the receiver.

Fig. 3. The developed GUI running on the oscilloscope. The received signal after two antennas is shown in green and the integrated signal in blue. The threshold is represented by the grey horizontal line.

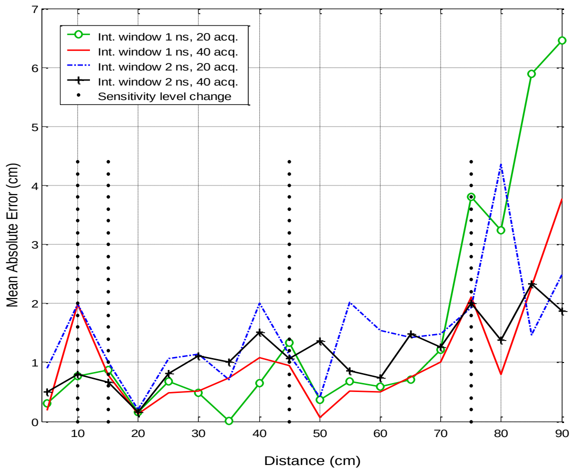



Fig. 4. Mean absolute error for the integration window
sizes of 1 and 2 ns with averaging over 20 and 40 acquisitions.

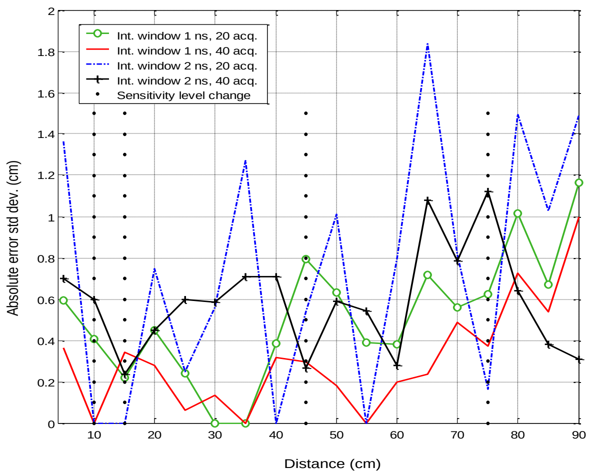



Fig. 5. Standard deviation of the absolute error for integration window sizes of 1 and 2 ns and with averaging over 20 and 40 acquisitions.

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[1] K. Hamaguchi, R. Kohno “Development of Experimental TDOA System Test-Bed for Indoor Applications,” IEEE Int. Conf. on Ultra-Wideband ICUWB 2008, pp. 201-204, 2008.

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# UWB Positioning Using Known Indoor Features – Environment Comparison

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## 1 Summary

In our previous papers, [1] and [2], we presented a novel system using reflections from known reflectors to allow 3D ToA UWB indoor positioning with two receivers. The system was verified using measurement campaign data from just one example environment - a lecture room. Since then we performed measurements in two more common indoor environments – a cluttered room (laboratory) and a corridor. In this abstract we will present our positioning system results for the three environments and compare them, drawing conclusions about strengths and weaknesses of the positioning system, in other words a short sample of our perspective paper. .

## 2 3D ToA UWB Positioning With Two Receivers

The used positioning system is described in [2]. We perform positioning of a mobile transmitter using a network of set-position synchronized receivers. Receivers are able to do time of arrival (ToA) ranging. They will detect not only the direct path component of the signal but also distinct multi-path components (MPCs). A two step algorithm is used:

1. *Result Circle(RC) calculation:* Using direct-path ranges to two receivers, calculate a circle the transmitter should be close to. Let us call it RC.
2. *Find point on RC with maximum likelihood :* Assuming that detected MPCs contain MPCs connected with reflections from known reflectors, assign likelihood to points on RC, find point with maximum likelihood.

## 3 Measurement Setup

Measurements were performed at Warsaw University of Technology (PW), Department of Electronics and Information Theory (EiTI), in cooperation with Dr. Jerzy Kolakowski, Radiomeasurement Laboratory. The transmitted signal was an impulse corresponding to the 3.4-4.8 GHz band. Three environments were a sparsely furnitured lecture room, 5.6 x 5.2 m, an extremely cluttered laboratory, 5.4 x 6.2 m, and a cases-lined corridor, 12.8 x 2 m.

## 4 Measurement Results

Average results achieved by our algorithm are presented in Figs 1 to 4. In the case of the lecture room, our system is currently achieving better results than standard Assumed Height for receivers in adjacent corners (Fig.1) and opposite corners. In the case of a much more cluttered lab, only with receivers in opposite corners (Fig.4) the results were better This is because in this case Assumed Height algorithm faces 2 possible transmitter positions and must choose one randomly. Proposed algorithm is better at this choice. In the case of the corridor results were better than default algorithm, for the same reason. In most cases the optimal number of used reflectors is around 3. That is because of the lack of good reflectors. Usually, apart from ceiling and floor, only one or two walls are close enough to flat reflectors.

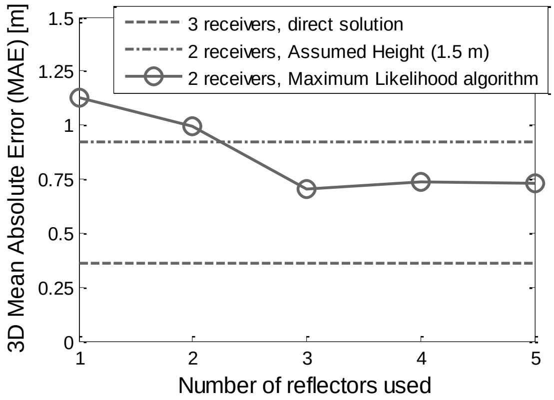


Figure 23: Lecture room, adjacent receivers

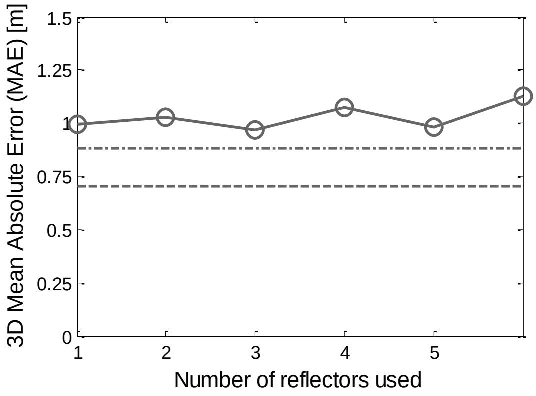


Figure 24: Lab, adjacent receivers

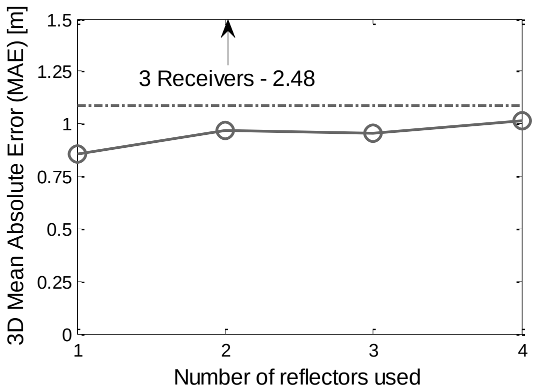


Figure 25: Corridor

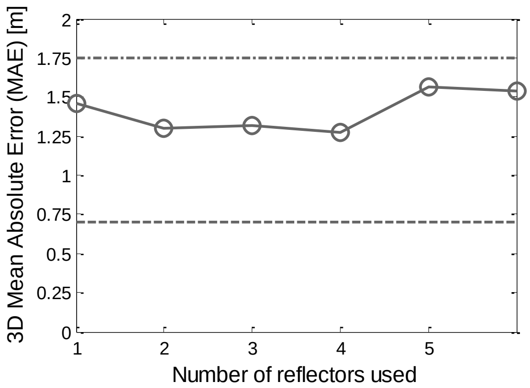


Figure 26: Lab, opposite receivers

## 5 Conclusions

Results of our algorithm for data gathered during measurements performed in three different environments will be presented. As could be predicted, the algorithm works best in the case of not too cluttered rooms, like lecture halls. However, even in the case of very cluttered rooms, like a laboratory, it can be successfully used to distinguish between two possible transmitter locations. Our algorithm can be used to increase accuracy of low-density positioning systems as well as a backup in higher receiver density systems.

## References

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# Improving Non-Line-of-Sight Performance of UWB Localization Systems Using Neural Networks

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## Introduction

UWB is able to provide high precision positioning using TDOA/TOA in Line-of-Sight (LOS) conditions. However, in Non-Line-of-Sight (NLOS) conditions, the precision can be completely lost i.e. even determining whether an object (tag) is inside or outside a room will become difficult. A Neural Network based solution is described in this paper to improve the performance of UWB positioning systems under these kind of NLOS conditions.

## System Overview

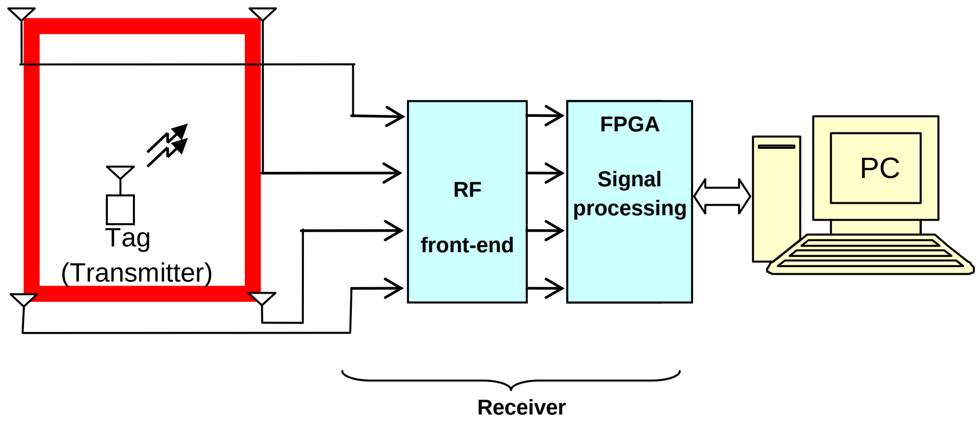


Fig. 1: UWB positioning system used to locate whether the tag is within or outside the room

The system block diagram of the localization system is shown in Fig. 1. UWB pulses transmitted by the mobile tag are received by the four UWB antennas mounted on the ceiling at the four corners of the designated cell (room). Upon receiving the four-channel signals from the RF front-end, the FPGA calculates the TDOA of the UWB pulses between the antennas. These time differences are subsequently routed to a personal computer through the serial port. Neural Network localization algorithm running on MATLAB eventually grabs these timings, performs computation on the data to determine whether the tag is located within the designated cell and displays the result on a GUI.

## Design and Analysis

The machine learning algorithm used for this NLOS environment was Neural Networks. Exploiting the generalization property of neural network was the key in achieving good performance. Since this is a NLOS system, the input data is going to be noisy. Having a well generalized network will filter out most of the noise and provide reliable results. The network used is the cascaded feed forward network with back propagation. Since our classification problem is not linearly separable, the function to learn is a bit more complex. Due to this reason we require a multi-layer neural network. Previous studies have proven that a 2 layer neural network is sufficient for most problems. The number of neurons required in the output layer is determined by the number of classes we wish to classify. For this application we just needed to know if the tag (person) is within the marked area (room) or out. This makes it a two class problem. A single neuron is used at the output and its output of 1 or 0 is decoded as inside or outside the room, respectively. Since the output is a binary, Sigmoid functions were chosen for the hidden and output layers.

Fig. 2 illustrates the block diagram of the network used in MATLAB to process the data. Choosing the a minimal number of neurons in the hidden layer is crucial in order to avoid over fitting. An initial value of 35 hidden neurons were chosen. Training data for both within and outside the marked area were captured by placing the tag at discrete predefined points. Once the network was trained using back propagation algorithm, Singular Value Decomposition was performed on the weight matrix to eliminate neurons that do not contribute significantly. Then the network was trained again. This was repeated until the minimal number of neurons required for this function was found. Most of the generalization was already achieved at this stage, but to further improve its generalization properties, regularization was implemented in the back propagation learning algorithm. Regularization prevents the weights from changing in large steps and, in a way, prevents over fitting. Finally, 23 neurons were used in the hidden layer to reduce the error to lower than $10^{-2}$ using the training data.

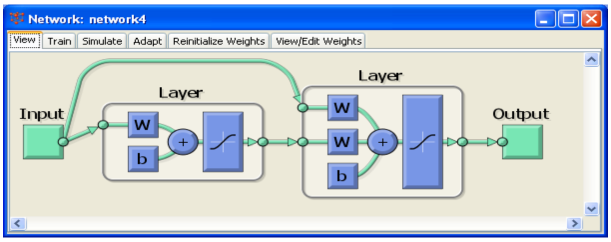


Fig. 2: Feedforward Neural Network used in the system

After finalizing the Neural Network, testing was done using actual field data. The test data consisted of measurements done both within and outside the marked area. Table 1 summarizes the results. When in LOS the system performs extremely well with 100% accuracy. Even under NLOS conditions, the system was able to classify correctly with better than 90% accuracy. All the errors were found to be within 1 feet from the boundaries, which is very good for an RF based system. If the boundary conditions can be relaxed to allow for errors within 30cm on both sides of the boundary, the system was able to provide 100% accuracy. In contrast an optical system would give 100% accuracy only under LOS condition. Under NLOS, the optical system would completely fail.

Table 1: Measured performance of system under LOS and NLOS conditions

| | **Total number of sample** | **No. of samples correctly classified** | **Performance of system** |
|---|---|---|---|
| **Line Of Sight** | 200 | 200 | 100% |
| **Non-Line of Sight** | 200 | 182 | 91% |

## Conclusions

In this project, a UWB system was used to precisely locate whether an object is within a boundary under NLOS conditions. The selected network type (cascaded feed forward network with back propagation) was initially trained with LOS field data and subsequently regularized to further improve its generalization properties. Test results show that the system is able to perform with 100% accuracy in LOS condition and 91% accuracy in NLOS condition. When the boundary condition for NLOS is relaxed to allow an error of 30cm, the accuracy was found to reach 100%. This showed that the Neural Network is a good tool to improve the performance of the UWB localization condition under NLOS conditions.

# Ultra-Wideband System-Level Simulator for Positioning and Tracking (U-SPOT)

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## 1 Introduction

Realistic simulation of Ultra-Wideband (UWB) positioning and tracking is a tough and challenging task. Lots of parameters have a significant impact on the final performance of the positioning system, such as parameters of transmitted waveform, radio regulations, channel, receiver, ranging-, positioning- and tracking-algorithm and finally the geometric setup. A realistic simulation framework is needed to develop and optimize positioning algorithms. This work proposes a novel framework for realistic UWB positioning simulations. All stages of influence have been modelled carefully. While ray-tracing simulators focus on a given user defined scenario, our approach uses statistically defined environments. Random processes are used to select channel impulse responses from a measurement database, according to an algorithm that introduces realistic large and small-scale variability with space. In particular, line-of-sight (LOS) and non-LOS (NLOS) channels are used at a defined ratio.

In this work the application of the simulation framework is demonstrated to compare the performance of a least-squares (LS) positioning algorithm and standard and extended Kalman filter (SKF and EKF) tracking algorithm in environments with a large ratio of NLOS range measurements. Furthermore, the IEEE802.15.4a standard is analyzed with respect to its positioning performance.

## 2 Positioning Simulator

In this work, the transmitted signal is generated according to the IEEE802.15.4a preamble, as the preamble is the most important signal part for a positioning system. Many parameters are defined in the standard, whose influence on the ranging capabilities has been studied in [1] [2]. Next, measured channel impulse responses are loaded into the simulator and are convolved with the preamble sequences. A channel selection algorithm is applied, which chooses the measured channel impulse responses corresponding to LOS and NLOS probabilities and from random measurement pools. The transition from one local measurement pool to another is performed according to a user defined transition probability. A measurement pool is a set of locally concatenated measurements, which include, small scale fading. The received signal strength is modelled according to the EC/FCC regulations [2] and the channel models from [3]. A coherent and a non-coherent receiver are implemented to evaluate the capabilities of high and low complexity positioning systems.

## 3 Performance Evaluation

This section shows the performance evaluation with the positioning simulator and compares an LS positioning algorithm to an SKF and an EKF tracking algorithm in a virtual office environment with 70% LOS links, using a coherent receiver. The Kalman filters employ a position, velocity and acceleration model (PVA).

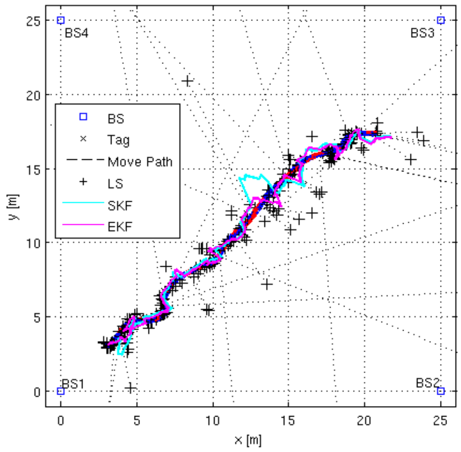


Figure 27 – Positioning Scenario

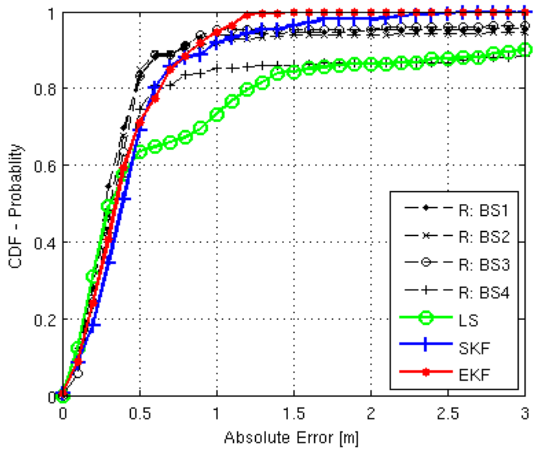


Figure 28 – Positioning / Tracking Analysis

Figure 1 shows the positioning scenario with a random trajectory ("Move Path") and the positioning results, where "Tag" means the real position of the mobile. The device shows an average speed of 1.45m/s, an update rate of 14 Hz and a Gaussian distributed random acceleration. The four base stations (BS) are placed on a square of 25x25m. It is observable that LS shows very large outliers due to NLOS links. As the LS output is the input for the SKF, an outlier rejection is needed for good performance. Thus the outlier rejection has been optimized using the simulator, concluding a rejection of the estimated position is performed if the estimation is outside the operating area or if it indicates too high instantaneous acceleration. Figure 2 shows the analysis of the cumulative distribution function (CDF) of the absolute error, where the ranging results (R) show better performance in comparison to the LS positioning results. The robustness of the positioning can be improved significantly using Kalman filters, whose absolute error achieves nearly 100 percent less than 1.5m. The EKF performs slightly better than the SKF.

## 4 Conclusions and Outlook

A novel UWB positioning simulator is presented, which uses statistically defined virtual environments to enable mixed line-of-sight and non-line-of-sight simulations. A novel channel selection algorithm is presented to enable realistic simulations with experimental data. The simulator has been used for the analysis of the IEEE 802.15.4a standard with respect to its positioning capabilities with a coherent receiver. A least squares positioning algorithm is compared with a standard and an extended Kalman filter. It shows that the tracking algorithms can be used to improve the performance in NLOS scenarios significantly, by rejecting and smoothing the outliers. The full paper will contain a detailed mathematical description of the simulation framework. Also a detailed comparison of the coherent receiver and the energy detector will be presented in NLOS-intensive scenarios. A detailed analysis of the least squares positioning and the Kalman filters will be shown.

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# Advancement in UWB Positioning Performance through Mobile Robot Systems


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## 1 Introduction

Recent substantial progress in the domain of indoor positioning systems and a growing number of indoor location-based applications are creating the need for systematic, efficient, and precise experimental methods able to assess the localization and perhaps also navigation performance of a given device.

Our contribution, rather than presenting novel technical methods, aims at showcasing how mobile robotic platforms can serve as a systematic and precise evaluation tool for indoor positioning systems, and in turn, how innovative indoor positioning techniques such as those based on ultra-wideband (UWB) can help mobile robotics improve localization and navigation performances in indoor settings. In this context, our contribution first presents the miniature Khepera III mobile robot (12 cm in diameter) integrated in a precise, real-time ground-truth evaluation system. It then focuses on the benefits of UWB positioning technology as complementary positioning information for such miniature robots.

## 2 General Context

In contrast to outdoor navigation, where crude positioning of sub-meter accuracy often satisfies user needs, indoor applications may require accuracies in the order of a centimeter. Furthermore, outdoor positioning and navigation has been well explored and standardized, whereas indoor navigation remains a recent research area which is still in the process of generating numerous new systems and algorithms.

A growing number of real-life applications that depend on automatic object location detection and navigation capabilities create the need for efficient and accurate testing methods. Also, as the miniaturization of application devices poses challenges to the integration of new technologies, additional test-beds must be considered. In our efforts to help improve indoor navigation capabilities, we pose the mobile robot as a fundamental tool enabling systematic testing under controlled conditions.

This research effort is part of a recently launched project which focuses on the implementation of a novel localization system using impulse-radio UWB (IR-UWB), based on results which have emerged from the latest phase of the MICS NCCR project [1]. In comparison with known positioning technologies, and especially in indoor environments, in absence of global navigation satellite systems (GNSS), the potential strengths of an IR-UWB localization system become apparent: high precision, high positioning rate, scalability, reduced sensitivity to line-of-sight (LOS) occlusions, low cost and low power. Also, by outsourcing the complexity of the positioning algorithms to an external system, an IR-UWB positioning infrastructure is adapted even to miniature robots, given that the localization information can be transmitted to the robots through standard narrowband communication channels. Thus, a successful implementation promises advantages over current positioning systems and excellent suitability for multi-robot (of potentially very small scale) systems.

## 3 The Khepera III Mobile Robot

With hundreds of Khepera III robots in academic use today, this platform has an important potential for single and multi-robot localization and navigation research. Based on extensive experimental analyses, we have developed a set of models for mobile robot navigation with the Khepera III platform. Within the framework of an extended Kalman filter, distance sensor readings are fusioned with odometry. Whilst at this point we do not integrate UWB signals, we rather create an experimental baseline by in particular addressing robot calibration and characterization. In addition to providing technical precisions on the Khepera IIII platform which reach beyond the robot's data-sheets, we have shown that by using our models and exclusively on-board sensors, the Khepera III is able to localize itself with an error that is below 1.5cm in average (which is in the order of our ground truth measurement error).

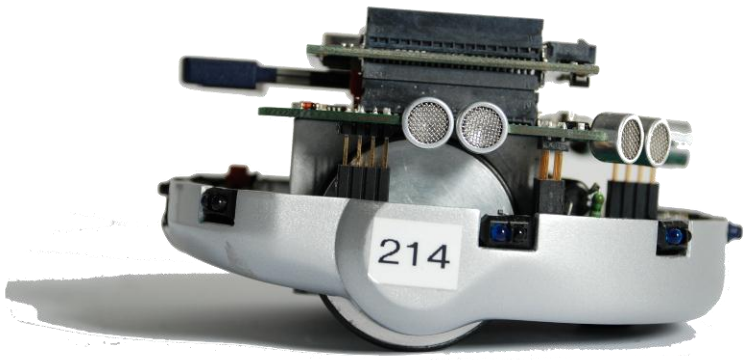


***Figure 29: Khepera III Mobile Robot***

## 4 Systematic Evaluation of UWB Positioning Performance

In order to integrate single- and multi-robot systems into systematic and precise evaluation frameworks, it is practical to reduce the individual robot size to its minimum possible, without stripping it from vital resources such as autonomy, computation, and sensing. The Khepera III platform has been developed in an effort to optimize all the above requirements, thus enabling us to conduct systematic performance evaluation under controlled conditions in a closed lab space, where one or multiple mobile robots are equipped with UWB emitter antennas and stationary base-stations compute ranging information.

## 5 Conclusions and Outlook

In conclusion, we hope to motivate and reinforce the interaction and interdisciplinarity of UWB expertise with single- and multi- robot localization research by demonstrating its utility and potential.

## 6 References

[1] National Center of Competence in Research; Mobile Information & Communication Systems (MICS NCCR). http://www.mics.org/.

# Experimental Demonstration of Self-Localized Ultra Wideband Indoor Mobile Robot Navigation System

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## 1 Summary

A self-localized Ultra-Wide-Band (UWB) system is introduced, that is suitable to navigate mobile robots (MR) in indoor environments. In impulse-based UWB systems, positional accuracy is inversely proportional to the signal bandwidth. The Federal Communication Commission (FCC) has regulated the spectral usage of UWB signals for various applications. In the current implementation, 2ns pulses having a -10dB bandwidth of approximately 1GHz have been used primarily due to hardware limitations (unavailability of high-speed ADC at the time of writing this abstract). We have recently received a faster ADC (1.5GS/s) that allow for sampling signals with lower pulse-width (increased BW) in order to get better positional accuracy. In the proposed scheme, a number of anchor nodes are located in fixed positions in the indoor environment, and transmit synchronized 2ns pulses with Differential Binary Phase Shift Keying (DBPSK) modulation. This self-localization GPS-like configuration was used because the final goal consists on run localization and position control algorithms locally on the MR and estimate the trajectory instead of one position at a time using a Bayesian method. An UWB receiver mounted on the MR uses Time Difference of Arrival (TDOA) between pairs of synchronized transmitting anchor nodes for localization. A prototype non-coherent UWB system using off-the-shelf components is implemented where signal acquisition and localization algorithms run on a Field Programmable Gate Array (FPGA). Measurement results indicate sub-15cm positional accuracy with Line Of Sight (LOS) and Non-Line of Sight (NLOS) conditions relative to fixed anchor nodes in a typical indoor environment.

## 2 Introduction

Industrial mobile robots, stock control and logistics in warehouses, mobility assistance for handicapped people or patient monitoring in hospitals are some scenarios that require accurate position estimation in indoor environments. Sensors based on ultrasound, lasers, and cameras are often used for these applications. Optical and ultrasound sensors have poor performance in low visibility conditions, and harsh or loud environments, respectively. Radio Frequency (RF) sensors have a wide range of usage as the electromagnetic waves propagate through most typical environments. Impulse-based ultra wideband transceivers offer accurate ranging accuracy with low cost. Although the advantages of UWB systems in ranging and localization have been known, application in indoor positioning in the presence of multi-path components required further study. In this paper, an indoor navigation system is introduced that is based on impulse-based UWB technology.

## 3 System Overview

In the proposed scheme, a number of synchronized anchor nodes are located in fixed positions in the indoor environment. These anchor nodes transmit synchronized UWB pulses.

The mobile robot is equipped with an UWB receiver. Time Difference of Arrival (TDOA) is a well known technique where the time difference between pairs of synchronized transmitting nodes is measured in the receiver for localization. The position is estimated in every control cycle in order to update the robot localization and control the navigation system. The time between successive estimations determines system tracking capabilities and maximum robot speed.

Differential Binary Phase Shift Keying (DBPSK) modulation is used since it allows using a non-coherent receiver while offering 3dB gain with respect to Pulse Position Modulation (PPM) systems. The anchor nodes transmit each information symbol over a time interval of $T_s$=*8x80ns* that consists of $N_f$=*8* frames. At the beginning of each frame, a short pulse of 2ns modulated by a 3.5GHz carrier is transmitted (Fig. 1). Frame length of $T_f$=*80ns* is selected considering delay spread in typical indoor environments. Gold code with a length of *7* is used to discriminate the anchor nodes. Time Division Multiple Access (TDMA) is used to avoid interference between transmitted signals from different anchor nodes. The receiver (Fig. 2), mounted on the mobile robot, consists of a Low-Noise Amplifier (LNA), I/Q direct down-conversion mixers, a fast Analog to Digital Converter (ADC), and a Field Programmable Gate Array (FPGA). Omni-directional electrically-small UWB antennas, implemented as planar structures, are used in RX/TX nodes. Maximum operational range of the system depends on maximum transmitted power, position refresh rate (since many pulses can be integrated), and receiver sensitivity. The power consumption of the receiver is dominated by the high-speed ADCs and the FGPA, and can improve with technology scaling. Figure 3 show a typical laboratory environment where the measurement was conducted. Using the algorithm proposed in a complementary publication and the aforementioned prototype, position accuracy of better than 15cm could be reached using only one symbol. It is noteworthy that this accuracy is improved as more symbols are acquired; this will be particularly useful in NLOS situations.

## 4 Conclusion and Outlook

The obtained results indicate that the proposed system can be used to accurately localize mobile robots in indoor environments with high accuracy. Future steps include integrating the receiver and transmitter on an integrated chip to reduce the size, cost, and power consumption. Moreover, frequency up-conversion is better done locally in each anchor node. In that scenario, only the digital baseband signal needs to be distributed to each anchor node.

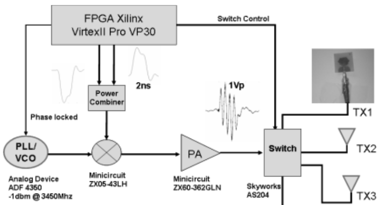


Fig 1. Transmitter architecture

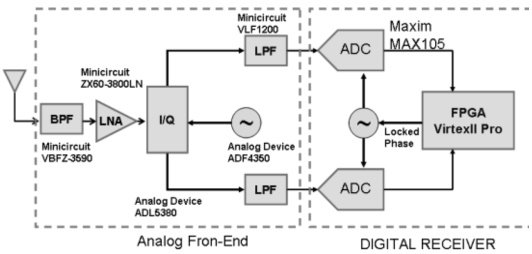


Fig 2. Receiver architecture

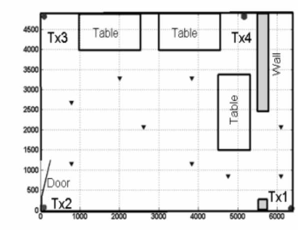


Fig3. Environment floor-map

# Evaluation of requirements for UWB localisation systems in home-entertainment applications

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## 1 Summary

This paper discusses basic requirements for a passive ultra-wideband (UWB) localization system that aims at home-entertainment applications such as a smart audio system, which can adapt the sound according to the user location, so that an optimum listening experience is provided to the user. The requirements were evaluated using data measured by a real-time UWB channel sounder. Over hundred thousands channel impulse responses were measured in different scenarios by means of two antenna types in different constellations with a varying number of listeners who were moving along various tracks. The performance of the passive localization is demonstrated by a selected measurement example.

## 2 Extended Abstract

Our envisaged application of the passive localisation system assumes that one person in a living room is to be localised just by electro-magnetic (EM) waves reflected from the body. Antennas of the UWB localiser are supposed to be integrated in loudspeakers of an audio system. The obtained position estimates should drive smart audio algorithms, which optimise and/or direct the sound interactively depending on the listener position. In order to evaluate basic requirements for such a localisation system, we performed a measurement campaign using the UWB channel sounder [1]. We used omni-directional (in two dimensions) bi-conical antennas and directive Vivaldi antennas. The antennas were arranged in 3 different measurement constellations:

- Soundbar – a linear array, about 1 m in length, with one transmitting (Tx) antenna in the middle and 4 receiving (Rx) antennas,
- 2-point ambient sound constellation – a larger linear array with one Tx in the middle and 2 Rx placed in the left corner of the room and 2 Rx in the right corner of the room,
- multiple-speaker constellation with the antenna arrangement similar to the 5.1 audio system – 1Tx at the position of the central speaker and 4 Rx at the position of loudspeaker satellites located in the corners of a room.

Thousands of channel impulse responses were recorded in real time. During the measurements, one person was walking through the room along predefined tracks, or sitting on a couch at different positions. The data were processed by the algorithm described in [2]. The most challenging part is the detection of a person. This is due to the fact that EM waves reflected from a person are weak in comparison to the direct wave or to reflections from dominant static objects such as walls. They are almost invisible in unprocessed data (see Fig. 1 left). Therefore, in the first step the raw measurements are processed by a background subtraction algorithm that eliminates strong time-invariant signals and reveals weak signals reflected from time-varying targets (see Fig. 1 right). We have defined a signal to clutter ratio (SCR) as a basic system parameter. This parameter compares the power of the signal reflected from a person with the power of a clutter signal. In our case, the clutter represents the strongest signal component present in the received impulse response. Usually, it is the direct wave that propagates from the Tx antenna to the Rx antenna. In case of a localizer capable of gating out the direct wave from the measurement, the strongest signal is a reflection from dominant static objects.

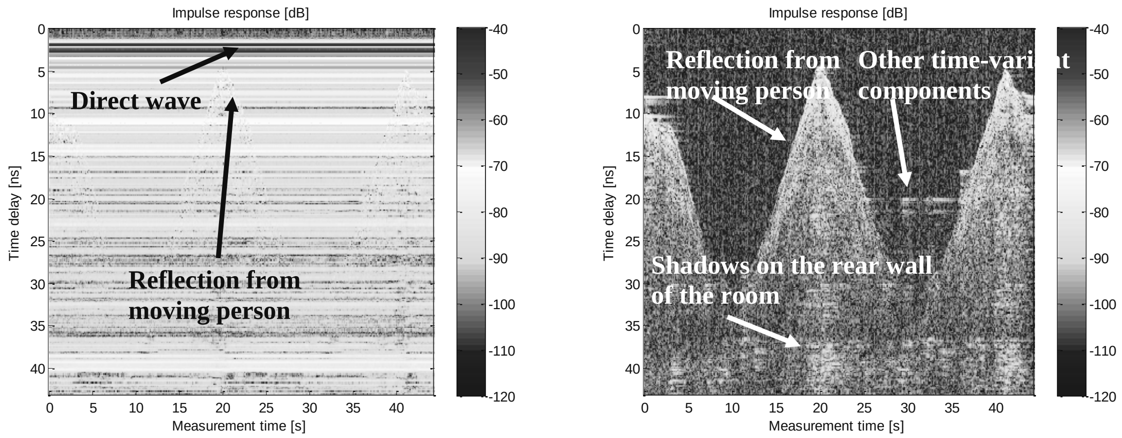


Fig. 2 Measured (left) and processed (right) impulse responses in the home-entertainment environment

Results of our analysis are summarized in Table 3. The most challenging scenario is the soundbar. Due to the closely spaced antennas the influence of the strong direct wave on the SCR parameter is evident. The closer the Rx antenna is to the Tx antenna, the higher is the dynamic range required for the passive localization system. Despite using directional antennas there are still about 40 dB at an antenna distance Tx-Rx of about 35 cm. In order to avoid this strict requirement it is possible to use a system capable to gate out the strong direct wave. This would reduce the dynamic range requirement to about 25 dB for directional Vivaldi antennas in all scenarios. Note that the estimated values are related to the size of the room, which was in our measurement about 6.4 m x 6.2 m. If a moving person should be localized in a bigger room the estimated dynamic range limits must be scaled up.

Table 3 Minimum SCR in different scenarios for localization of a moving person

| Scenario | Gating | No | | Yes | |
|---|---|---|---|---|---|
| | Ant. Dist. / Antenna | 35cm | 71cm | 35cm | 71cm |
| Soundbar | Bi-conical | -52.5dB | -45.5dB | -24.5dB | -23dB |
| | Vivaldi | -41.5dB | -35.5dB | -22dB | -21.5dB |
| 2 point ambisound | Bi-conical | -39dB | | -36dB | |
| | Vivaldi | -28dB | | -21.5dB | |
| Multiple speakers | Bi-conical | -37dB | | -34dB | |
| | Vivaldi | -29dB | | -26dB | |

## 3 Conclusions and Outlook

Our results show that the passive localisation system needs to be very stable with low jitter and high SNR assuring real-time dynamic range exceeding at least 25dB depending on the system configuration. The localisation performance is demonstrated using measured data.

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[2] R. Zetik, S. Crabbe, J. Krajnak, P. Peyerl, J. Sachs, R. Thomä, “Detection and localization of persons behind obstacles using M-sequence through-the-wall radar”, SPIE Defense and Security Symposium, Orlando, Florida, USA , 17-21 April 2006

# UWB-based Local Positioning System: from a small-scale Experimental Platform to a large-scale Deployable System

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## 1 Summary

At the Electronics and Signal Processing Laboratory at EPFL, an experimental platform has been designed and built to demonstrate the feasibility of Ultra-wideband (UWB) technology applied to indoor positioning. This small-scale demonstrator has proven to be a valuable research tool, with the flexibility to study, test and assess the performance of various system architectures and signal processing algorithms.

Based on this successful experience, a subsequent project was setup to extend the lab's research on certain topics that could not be addressed by the small-scale demonstrator. This new R&D project pursues two main objectives: a) designing and building a large-scale UWB-based Local Positioning System (LPS), including installation, calibration and operational testing in a real industrial environment; b) conceiving and developing Application Specific Integrated Circuits (ASICs) to target cost-competitive solutions.

This paper addresses the main design issues analysed during the definition phase of the large-scale UWB-based LPS requirements, considering that the new system should inherit whenever possible the design features already existing on the small-scale demonstrator.

## 2 UWB-based Indoor Location Experimental Platform

The existing demonstrator is composed of 4 receivers and a few transmitters, all of which were built using discrete components off-the-shelf. The connections between the receivers and the central PC are based on USB interfaces and the network for the receivers' clock synchronization is performed via coaxial cabling in a daisy chain topology, configuring one of the receivers to act as the master clock.

The transmitters emit baseband pulses centred at 500 MHz. A unique spreading code composed of 16 pulses which are Pulse Position Modulated (PPM) with an average Pulse Repetition Rate (PRR) of 100 KHz is transmitted carrying its identification. The generated signal covers a -10 dB bandwidth of approximately 750 MHz [1].

On the receiver side, the architecture follows that of a Software Defined Receiver (SDR), i.e. the signal is first amplified and then directly sampled by an 8-bit ADC at 2.88 GS/s. The digital signal is then transferred to a FPGA where all signal processing occurs in real-time. The outcome from these algorithms can be accessed by the central PC using the USB connection to the receiver. At the PC level, the system software was developed in Matlab customized to the demonstrator's scale (i.e. 4 receivers and a few transmitters) [1].

## 3 Large-scale Deployable Local Positioning System Requirements

As mentioned previously, one of the main objectives of the on-going R&D project is to install and test a large-scale UWB-based LPS in a real industrial environment. This implies that the system needs to fulfil fundamental requirements, such as:

- It must be fully compliant with worldwide established UWB regulations; and
- It must be flexible to the point of enabling its scalability to various installation scenarios (i.e. larger coverage area requiring the installation of additional receivers; more people/objects to be tracked requiring handling more transmitters, etc.).

This latter requirement implies addressing new challenges, including considering ways to reduce production and installation costs, simplify onsite calibration procedures without compromising network clock synchronization accuracy, handle efficiently increased volume of data communication between receivers and the central PC and increased probability of collision of transmitters' communications, review position computation methods and develop user-friendly visualisation and configuration Graphical User Interfaces (GUIs).

## 4 From small to large-scale LPS: Upgrading Design Considerations

To fulfil the two requirements presented before, both the hardware and software of the system have received important design modifications that will be described in detail in this paper.

At the hardware level, a new ASIC transmitter has been successfully developed and tested to be compliant with FCC/ECC regulations. It emits pulses with a -10 dB bandwidth of 750 MHz centred at 4.1 GHz at a maximum achievable PRR of 15 MHz [2]. On the receiver end, a high sensitivity analogue front-end was developed, tested and added before the high speed ADC, bringing the new signal centred at 4.1 GHz back to baseband and enabling the reuse of the already existing design of the experimental platform receiver. Also, the FPGA has been equipped with a software processor to simplify the development of more refined signal processing algorithms for demodulation of the transmitters' identification and to boost the receiver's sensitivity. Other important modifications to the receiver design have also been introduced, e.g. at the data communication and clock synchronization networks, power supply, etc.

Finally, a new software package is being developed for the central PC incorporating user-friendly GUIs for system configuration and visualization on a map of the transmitters' location.

## 5 Conclusions

This paper describes in detail the major design modifications that were undertaken to upgrade a small-scale UWB-based indoor position experimental platform into a large-scale deployable local positioning system, both at the hardware and software levels.

## 6 References


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# On benefits and challenges of person localisation using UWB sensors

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## 1 Summary

Precise localisation of persons in their living environment is part of many upcoming applications such as wireless entertainment systems or home-based medical supervision. Ultra-wideband (UWB) sensors are especially interesting due to specific advantages over narrowband solutions. This paper lists some advantages and demonstrates challenges of implementation with a measurement example. A proposal for robust ECC-conform localisation concludes the paper.

## 2 Benefits of UWB sensors for short-range localisation

UWB sensors use a large measurement bandwidth $B$ and therefore provide a high range resolution $\delta$ for separation of close objects. The common relationship[1] is given as $\delta \approx c/2B$, where $c$ is the wave propagation velocity. Sub-dm resolutions are readily possible, but there are also a number of less obvious advantages. UWB sensors can work in a very flexible passive (or non-cooperative) mode, where the person does not need to carry any devices. For convenience and acceptance reasons, this non-interactive scenario is preferred in many cases. Furthermore, clever device concepts[2] spread the stimulus energy in time as well as frequency domain. This translates into low power spectral densities and harmless maximum wave amplitudes promoting license-free operation. ECC regulation is a bit more restrictive than the American FCC counterpart, but the frequency band 6 - 8.5 GHz is available for indoor use. Another advantage is low interference with other wireless services. As will be described in the section below, the high resolution capability cannot always be used to increase localisation precision. However, UWB sensors are sensitive to even small changes in the scenario under test and can provide additional information apart from plain position. Especially for patient supervision, posture of the person might be of interest. It is even possible to assess basic vital data remotely[3]. In the microwave frequency range, some materials are penetrated and persons behind obstacles (such as furniture) can be detected, too. Finally, device concepts like [2] are integration friendly and provide low-cost solutions.

## 3 Major challenges of UWB localisation

To find the 2D position of one person moving in a room, at least one transmitter and two receivers are necessary for trilateration. A major issue of data processing is the separation of static reflections of the environment from the target by background removal techniques. In most indoor cases, clutter signals from walls or furniture are often much stronger than backscattering from a person. A common approach is to look for changes in measured data and assign them to be caused by the moving target. The receivers must provide sufficient dynamic range to enable detection of small changes despite the presence of strong clutter. Moreover, a static environment is assumed which is not always the case in frequently used rooms. Adaptive algorithms are necessary to keep track of slow changes. Even if background information is constantly updated, other effects influence detection and assignment of a target response. A moving person will always obscure part of its environment and consequently changes will appear in the data at the range of the target as well as the shadowed objects leading to ambiguous interpretation. The same is true for multi-path propagation or device clutter leading to multiple images of a single reflection. The high range resolution of UWB sensors helps to mitigate such problems. Often, a region of interest (ROI, i.e. feasible range interval) is defined and the strongest or nearest reflections are used. Furthermore, tracking algorithms can be used to solve assignment problems. Especially with the minimal two receiver configuration, some drawbacks still exist. Figure 1 shows an example dataset after background removal from one receiver acquired with a 2 GHz bandwidth sensor. The person moved within an empty 10x10 m² area. It becomes clear that its reflection has a complex footprint in range domain despite the high theoretical resolution (≈ 7 cm). Due to high sensitivity for small changes (compare benefits above), it will fluctuate when body geometry varies (i.e. shaking arms, etc.) even though the person does not move. One must find a robust way to define the actual range to a reflector and the final question is: "What exactly is the position of a target much larger than the possible range resolution?"

## 4 Proposal for robust indoor localisation using an UWB sensor network

Figure 2 shows the concept of an ECC-conform, low cost, UWB sensor network for observation of a person in ambient assisted living (AAL). Each node has a small M-sequence sensor[2] with integrated coaxial calibration measuring reflection with a single antenna. More than three nodes will be used to sequentially measure target distance. The resulting redundancy will be used to overcome ambiguities and increase robustness in complicated scattering environments. While the person is resting, respiration detection is also aimed.

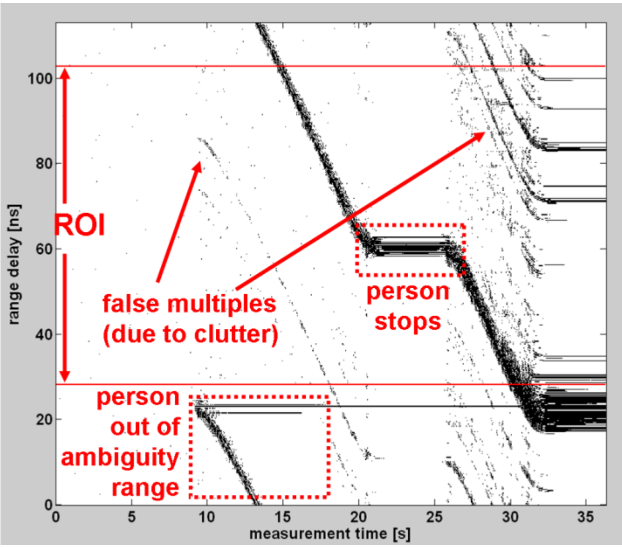


Fig.1: Response from person moving towards receiver

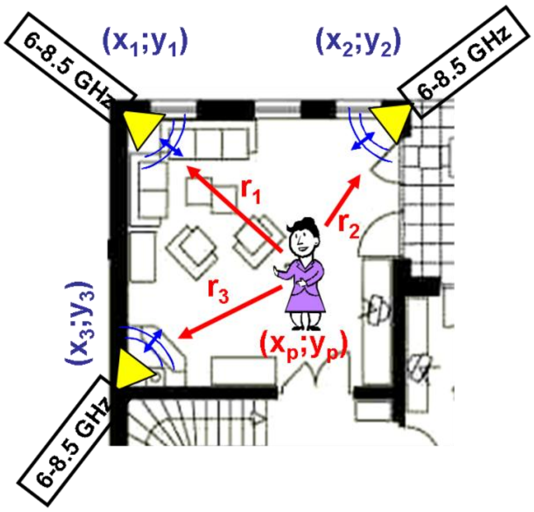


Fig.2: New UWB sensor network for AAL

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# Accuracy Considerations of UWB Localization Systems Dedicated for Large-Scale Applications

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## 1 Summary

This contribution considers the accuracy limits of ultra-wideband localization systems dedicated for large-scale applications. Industrial environments are known for being extremely difficult in terms of wireless communication, mainly because of high concentration of large metal objects, like containers or machines; leading to strong multipath propagation. In this work a detailed 3D model of the warehouse is used for wave propagation simulations. In the simulation, the transmitter is moving along the predefined path and the receiver infrastructure consists of eight base stations. The aim is to model the tracking system and asses its accuracy – firstly the accuracy upper bound is determined for the ideal case and secondly the precision estimation when including effects of hardware non-idealities is done. Effects like the the influence of pulse detection methods and geometrical configuration of base-stations are investigated. The position calculation of the mobile beacon is realized using Time Difference of Arrival approach. Eventually the accuracy of obtained results and the theoretical limit are considered based on dilution of precision evaluations.

## 2 Ray-Tracing simulation and channel parameters

The assembly hall of the Institut für Produktionstechnik at the Karlsruhe Institute of Technology was chosen to serve as a reference for the simulation of the UWB localization system. The exact model of the building (800 $m^2$ surface, 9 m height) as well as the inside facilities has been created and simulated with the Ray-Tracer (RT). RT is a deterministic wave-propagation simulation tool. The channel transfer function H(t,f) was evaluated in a frequency range between 2.5 and 11.2 GHz with discrete frequency increment of 3.125 MHz, hence the unambiguous range of the impulse response is 320 ns. The calculated mean excess delay for this environment is 50 ns for the probability of 99%. This determinates that the maximal pulse repetition rate shouldn't exceed 20 MHz to avoid inter-symbol-interference. More detailed frequency and time domain specification of this channel will be presented in the full paper.

## 3 Pulse form, noise and threshold detection

The pulse form used in this research is the $5^{th}$ derivative of the Gaussian pulse with standard deviation equal to 51 ps and FWHM of approx. 250 ps. This pulse fits the FCC emission mask well and is realized on chip. The amplitude of the pulse and PRF are optimized for compliance with the FCC peek power limits, in order to increase SNR at large distances. No additional interference, apart from thermal noise, is considered. The energy-detection-based receiver was modelled in Agilent ADS, based on measured data of its components. The detailed information on this topic, as well as on the threshold determination procedure, will be given in the full paper.

## 4 Non-line-of-sight detection, positioning method and measurement decorrelation

First problem, that has to be overcome in localization systems, is that the algorithm, that estimates the position, has to be supplied with valid data. Signals coming from NLOS situations have to be detected in order to exclude them, as they include a time bias. This detection is done by applying “velocity filter”, which evaluates the times of arrival of consecutive pulses on one receiver. If the PRF is known and the mobile transmitter has limited maximal velocity, the sudden changes in ToA can be detected and later discarded. It is required that at the beginning of the measurement the transmitter is in line-of-sight. After the invalid data have been removed, the time differences between base-stations are built and fed into the TDoA algorithm. First the starting point for the search is peaked with the modified Bancroft-Algorithm and second the iterative methods are applied. The optimal iterative algorithm was chosen based on evaluation of the speed-accuracy-ratio that would allow real-time operation of the system (details in full paper). When using time differences, it is necessary to decorrelate the measurements, because the differences are all calculated to one base station, so all difference measurements will be correlated with the noise of that base receiver. The dercorrelation based on Cholesky decomposition of the time measurement covariance matrix will be shown in the full paper.

## 5 Results

The predicted error, resulting from the threshold detection (defined as three times the 3σ of the range measurements) multiplied with PDOP (positional dilution of precision) value for the corresponding position was found to be 18 cm (complete explanation in full paper). The calculated rms error along the route was found to be 8 cm and should be considered as the upper bound for this scenario.

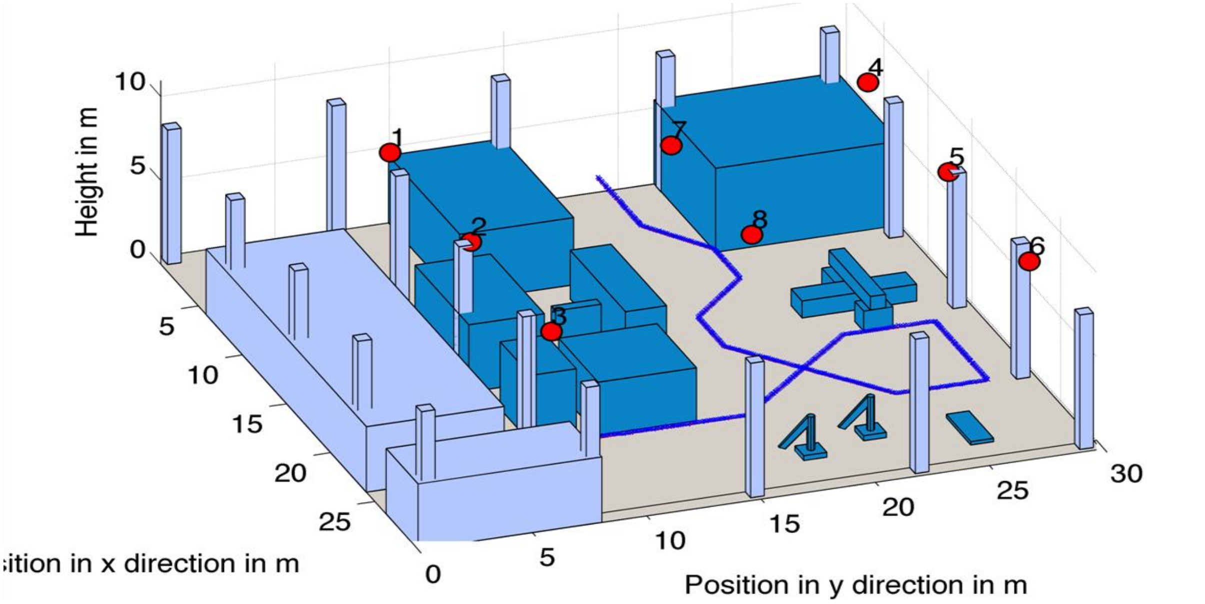


Figure 1: Simulated industrial scenario with marked receivers (red dots), the route of the transmitter (red line) and estimated positions (blue crosses) that overlap with the route.

Aside from the aforementioned aspects, the following issues will be handled in the full paper: influence on accuracy of additional system noise, receiver clock and synchronization between base-stations. Improvement of false measurement detection (NLOS) by implementation of receiver autonomous integrity monitoring (RAIM).

# A system level approach for node localization in IEEE 802.15.4a WSNs

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## 1 Summary

Node localization in distributed wide area WSNs is a challenging task which is becoming crucial for both scientific and industrial communities. For this purpose, the IEEE 802.15a standard has recently been proposed to achieve high accuracy within the ranging phase. This paper proposes three different algorithms based on the Time of Arrival (ToA) approach together with a technique that allows the estimation of the outcome's reliability.

## 2 Introduction

Wireless Sensor Network (WSN) applications cover a wide domain of many scenarios such as industrial processes, home automation, security control, medical monitoring and military applications. The possible use of mobile nodes allows a high degree of flexibility and adaptability, paving the way to new fields of applications. In this context, the features of localization and positioning assume crucial relevance. In 2007, IEEE released the 802.15.4a standard [1], which defines a novel air interface for low data rate Wireless Personal Area Networks (WPANs). The leading technology for the PHY layer is based on the Ultra Wide Band (UWB) transmission, due to low power, low implementation costs and relatively high data rates communication, but also allowing an improved ranging accuracy, thanks to higher time resolution.

Aiming at the determination of the upper limits of the localization accuracy, we have up-sampled the input signals of all the algorithms which are described in the following. This paper proposes three different algorithms which determine the distance between the nodes within a network:

1. *Clean template*: it achieves the ToA estimation through a classic correlation receiver in order to find the peak of the cross-correlation between a replica of the transmitted SFD and the corresponding received one.
2. *Dirty Templates*: the dirty templates basically provide a correlation template made up with a segment of the received signal, for example a non-modulated symbol [2].
3. *Two-Steps Dirty Template*: the previous algorithm requires a very high sampling rate and consequently the storage of a very large correlation template. Hence, a new version of the Dirty Template algorithm was developed. It consists of two steps: an initial correlation with a low sampling frequency version of the SFD dirty template in order to achieve a pulse level precision estimation, followed by a second correlation performed around the previous estimated time with a high sampled template of a single received pulse. Both correlation methods use dirty templates.

In order to perform ranging the beginning of the communication frame has to be known: for this purpose we use the correlation between the transmitted and the received frame.

## 3 Performance Evaluation

The simulations have been carried out for the Office LoS scenario according to the IEEE 802.15.4a standard. Initially, we assumed the distance between the transmitter and receiver equal to 5 meters, and determined the ranging error for the three proposed algorithms by varying the SNR in the communication channel. The performance of various receivers is shown in Fig. 1 Then, we reported the ranging error vs the distance between the transmitter and the receiver. For a dirty template receiver the results for SNR equal to 70 dB are shown in Fig. 2.Within a simple sensor node scenario, it is important to also study a method that allows discovering whether the ranging estimation can be deemed as reliable or not, in order to reduce the calculation time and the amount of information to be stored. In case of small errors in the ranging estimates, the ratio of peak cross-correlation and mean value of samples of cross-correlation has a value greater than 30 dB. For this purpose we have defined a parameter that represents the ratio as

$$R = 10\log\left( \max\{c_i\} \Big/ \sum_{i=1}^{N} \frac{c_i}{N} \right)$$

where $N$ is number of samples in the cross-correlation and $c_i$ are the samples. Conversely, if the error in the estimate is significant, the ratio $R$ also falls far below the value which has been previously indicated. These cases are graphically illustrated in Fig. 3.

## 4 Acknowledgements

This work has been supported by Italian Research Program (PRIN 2007) Satellite-Assisted Localization and Communication system for Emergency services (SALICE). Web Site: http://lenst.det.unifi.it/salice

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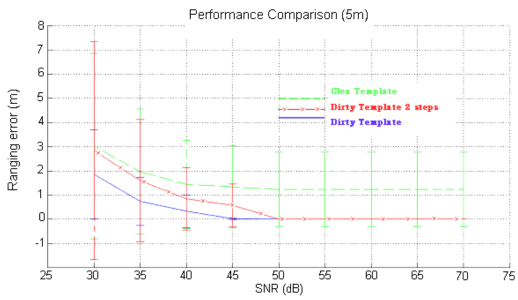


Figure 1: Ranging method comparison, distance between Tx and Rx equal to 5 m.

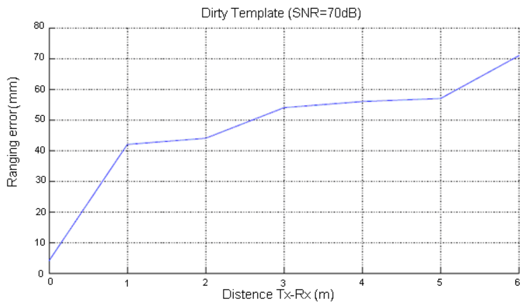


Figure 2: Performance at 70 dB SNR for various distances in a Dirty Template algorithm.

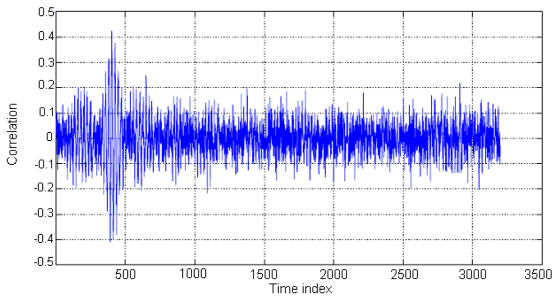


Figure 3: Cross-correlation when ratio is above 30dB.

# Performance assessment of a new calibration method used for clock synchronization on impulse radio based Ultra-Wideband receivers

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## 1 Summary

Some applications, such as Local Positioning Systems (LPS) based on time-of-arrival (TOA) measurements of a radio signal at several receivers located at known positions, require very accurate time synchronization of these receivers. One possible approach to estimate the timing offsets for all the receivers consists on placing a transmitter at a known position and estimating the TOAs of the signal at the receivers. This approach is used for example in a LPS demonstrator that has been developed in our laboratory [1]. However, this method requires an accurate knowledge of the transmitter's position. An inaccuracy in the transmitter's position during this system calibration phase results in a systematic error in the estimation of the receivers' time offsets and, hence, in all the following position estimations of the transmitters during normal system operation. It has been shown that the position accuracy of our LPS is currently limited by the accuracy of the receivers' time synchronization [2]. In this paper, we present a novel calibration method and assess its performance by deriving the Cramer Rao Lower Bound (CRLB). The tightness of the bound is verified by simulations and the achievable accuracy is compared to other existing calibration methods.

## 2 Introduction and theory

Ultra-Wideband (UWB) based positioning systems have received an increasing interest over the last decade. Impulse Radio UWB (IR-UWB) uses very short pulses with duration of less than few nanoseconds each [3]. Therefore, high resolution ranging can be achieved in the order of tens of centimeters, which renders this technology very attractive for indoor positioning.

One of the main issues regarding a TOA-based UWB LPS is the timing synchronization of the receivers, which has direct impact on the overall positioning performance of the system. A typical IR-UWB system requires clock synchronization circuits with the accuracy of tens of picoseconds [4]. To avoid a frequency drift, a convenient approach is to provide a master clock to each receiver. Due to the propagation delay of the clock signal over the cabling, each receiver clock is delayed by a specific unknown amount of time. A measurement of these propagation delays is feasible, for example during the installation of the system, but may require specialized measurement devices. It is more convenient to use the capabilities of the LPS itself to estimate these clock offsets. One method is to place the transmitter at a known position and measure the TOA of the signal at all the receivers. By solving the equations relating the TOA to the unknown transmission time and the known time of flights (TOFs), the clock offsets can be estimated. This approach is straightforward and does not require any extra software and hardware, but operationally it requires a great amount of preliminary human effort in preparing the grounds for placing the transmitter at known positions within the full coverage area of the system. In other words, it is a time consuming procedure, especially for large-scale deployable systems.

To tackle this issue of manual calibration of the UWB receivers we propose a novel method which requires minimal amount of human effort and can be easily implemented. Moreover, it is more suitable for the case of large-scale deployment of the receivers.

The paper is organized as follows. We first demonstrate analytically the feasibility of our approach. Then, we derive the CRLB for the estimation of the receivers' clock offsets for each method. The CRLBs are then used to assess the achievable performance of the different methods and highlight their trade-offs. The tightness of the bounds is also verified by simulations.

## 3 Conclusion

In this paper we present a new calibration method used for impulse based ultra wide band receivers and derive the associated CRLB. Tightness of the bounds are verified by simulations and compared with other existing methods for calibration.

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# Indoor Ultra Wideband Location Fingerprinting

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## 1 Introduction

The high temporal resolution of multipath components of Ultra Wideband (UWB) channel impulse responses (CIRs) offers various opportunities for high precision and robust localization. An alternative to common approaches based on time of arrival (ToA) or angle of arrival (AoA) estimation is to interpret a CIR received from a transmitter as a fingerprint of its position. This paradigm of position location is commonly known as location fingerprinting and is mainly applied in WiFi networks.

## 2 Location Fingerprinting

The considered location fingerprinting system assigns a received CIR (location fingerprint) to a region of the surveillance area where it is most likely transmitted from. The surveillance area is organized into a number of rectangular regions as shown in Figure 1. The position location algorithm is realized in a two phase procedure. In the first phase, the training phase fingerprint parameters are estimated from measured radio frequency signals, which are transmitted from nodes located somewhere in the various regions. In the second phase, a signal from a transmitter with unknown position is observed and the most likely region of this transmitter is determined based on the stored location fingerprint parameters.

We model the CIRs of a region as a Gaussian random vector where the elements of the random vector represent channel taps. The according location fingerprinting parameters the mean vector and the covariance matrix.

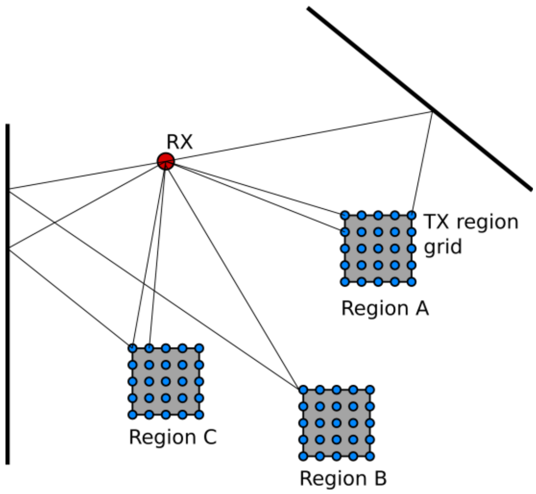


Figure 1

## 3 Office environment measurement campaign

In order to show that the location fingerprinting technique is suited for high precision indoor position location with non-LoS situations, a measurement campaign in an office environment was conducted. CIRs from grid points of six regions (see Figure 2) with grid size 28 cm x 28 cm and a grid spacing of 1 cm were measured. During the measurement campaign line of sight (LOS) and non line of sight scenarios (NLOS) were considered.

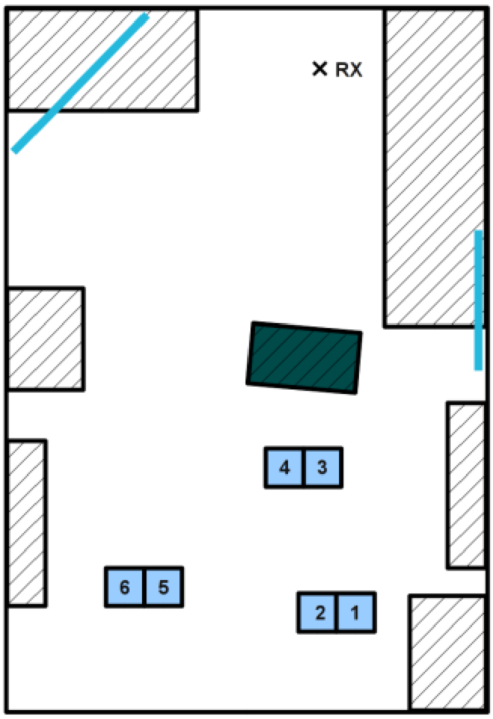


Figure 2

## 4 Performance evaluation and results

The performance of the location fingerprinting system is evaluated by calculating the probability of making decision errors and the average positioning error. For the evaluation we split all CIRs of a region grid into a set of training CIRs used to estimate the fingerprint parameters and into a set of test CIRs used to test the fingerprint parameters. The evaluation is done by varying region size, number of observations from a transmitting node, SNR level and the number of CIRs used for the training phase.

# Multilevel Complementary Sets of Sequences and their application in UWB

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## 1 Summary

In this paper it is proposed a new algorithm to generate multilevel complementary sets of sequences. It can be considered a generalization of previous algorithms [1], by using generic multilevel Hadamard matrices. In contrast to previous works [2], it is analyzed the conditions that must satisfy the Hadamard matrix to generate not only a pair of multilevel complementary sequences but also *M*-Multilevel Mutually Orthogonal Complementary Sets of Sequences (M-MO-CSS), where *M* is a power of two ($M=2^m$, $m \in N - \{0\}$).

Moreover, in this work it is generated new Multilevel Loosely Synchronized (LS) sequences from two pairs of multilevel MO-CSS, being a generalization of the binary LS sequences.

Finally, it is proposed the use of these multilevel sequences in a Local Positioning System based on Ultra-Wideband (UWB). An UWB link has been simulated, where the sequences are directly transmitted through the UWB channel model. At the receiver, the detection is carried out by means of the correlation between the received and transmitted sequences, and their performance is compared to chaotic sequences and binary LS sequences.

## 2 Definitions

Given a set of multilevel sequences of length *L*: $\{s_p\}$, $1 \le p \le N$; whose elements are real numbers, are considered as multilevel complementary sequences if they satisfy the constraint (1)

$$\sum_{p=1}^{N} \xi_{s_p s_p}(i) = K\delta(i) \quad (1)$$

where *K* is a constant which depends on the length *L*, the number of sequences and the value of the elements of the sequences. $\xi_{sp,sp}$ is the aperiodic correlation of the sequence $s_p$.

Additionally, it is said that two or more sets of multilevel sequences are mutually orthogonal if the sum of their aperiodic cross-correlation is zero for all the time shifts.

$$\sum_{p=1}^{N} \xi_{s_p r_p}(i) = 0 \quad \forall i \quad (2)$$

The design of complementary sets of sequences is the base on which new sequences as LS (Loosely Synchronized) or ZCZ (Zero Correlation Zone) are generated [3]. These sequences are employed in Quasi-synchronous CDMA (QS-CDMA) systems, where Multiple Access Interference and Inter-Symbol Interference can be eliminated if the time dispersion of the channel is within an interference free window (IFW) [3].

Figure 1 depicts a multilevel LS sequence, its autocorrelation and the cross-correlation with another multilevel LS sequence. Note that these sequences are noise-like signals.

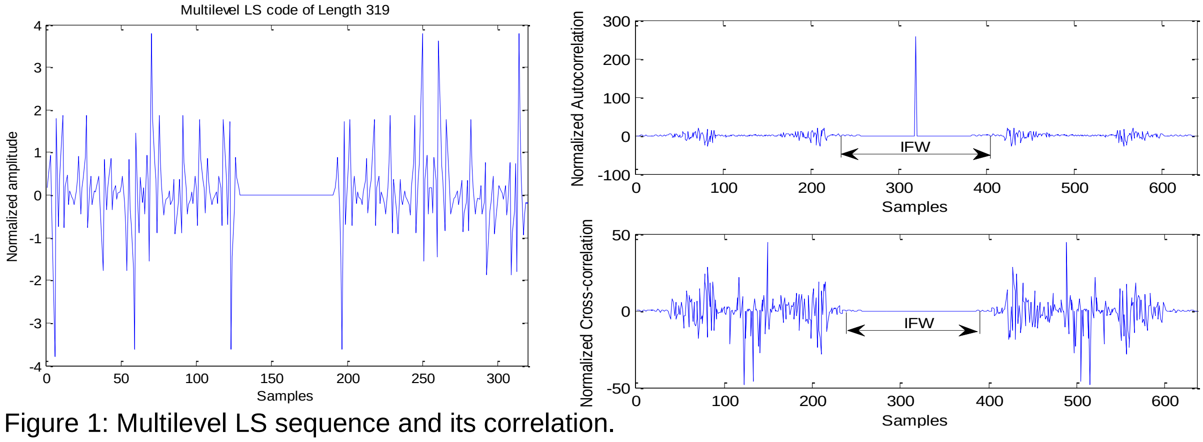


Figure 1: Multilevel LS sequence and its correlation.

## 3 Advantages of the new multilevel sequences

Previous works have demonstrated that multilevel sequences can be used for UWB communications by using chaotic sequences [4]. The receivers of chaotic systems are typically non-coherent [4], so the estimation of the Time of Flight (TOF) is less accurate than others like Matched filter receivers.

As was previously commented, these multilevel sequences are a generalization of the binary ones, and there exist efficient correlators for binary Complementary Sets of Sequences and for binary LS sequences [1][5]. These efficient correlators can be easily adapted for Mutually Orthogonal Complementary Sets of Sequences, being this a great advantage for its practical use. Moreover the estimation of Time of Arrival is less prone to errors due to the existence of the IFW as shows Figure 1.

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## Magnetic Localization

Auditorium D8

Friday, September 17, 08:15 – 09:45

# Position Estimation Using Artificial Generated Magnetic Fields

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## 1 Summary

In this abstract a system is introduced which overcomes the limitations of existing indoor positioning systems by the use of artificial quasi static magnetic fields. The proposed DC magnetic signals show no special multipath effects and have excellent characteristics for penetrating various obstacles. In this contribution the theory of coil-based magnetic fields as well as the basic function principle of the positioning system are described. Furthermore, a prototype that is currently under development is presented. This includes the hardware components, the network and software architectures of the entire system as well as the algorithms for the position and orientation estimation. In addition, the results of first test measurements and the system's calibration in real indoor environments are shown.

## 2 Motivation

Many indoor localization systems developed in the past years are *active systems* based on ultrasound, electromagnetic or optical waves. These systems require a positioning infrastructure to apply time or angle measurements between the reference and a mobile station. For performing the measurements between transmitter and receiver wireless communication technologies are often utilized. As a matter of principle the position estimation of active systems is negatively affected by several issues in indoor scenarios:

- The availability of the systems cannot be guaranteed due to walls, furniture, plants etc. because the signals are not able to penetrate such obstacles or are weakened.
- The systems suffer from multipath, refractions and further wave propagation errors, especially inside buildings. In result the systems are unreliable.
- Because of NLoS (None Line of Sight) errors and due to the used position estimation techniques many of these systems cannot achieve an accuracy better than several meters. Furthermore, these proximate techniques mostly allow only the calculation of 2D position.

On the contrary, *passive localization systems* are independent from any positioning infrastructure. These autonomous systems normally use inertial sensors in combination with pedometer, barometer etc. for position estimation. However, these sensors tend to high drift. This in turn causes inaccurate or unreliable localization so that periodic position updates delivered by other systems are required. The additional use of multiple sensors results in a high complexity and a less mobility of these systems due to the caused weight and power consumption.

## 3 MILPS – Magnetic Indoor Local Positioning System

The indoor positioning system introduced in this text is based on artificial magnetic fields to compensate the disadvantages of existing active and passive systems as described above. It is suggested to utilize alternating DC magnetic signals which show no NLoS errors or multipath effects. Similar to active systems reference stations consisting of electromagnetic coils are applied that generate periodically static magnetic fields. The magnetic field strength B declines with the increasing distance r to the coils, as shown by the following equation:

$$B = \frac{\mu_0 p_m}{4\pi r^3}\left(1 + 3 \cdot \sin^2(\theta)\right)^{\frac{1}{2}}$$ ($u_0$ = magnetic permeability, $p_m$ = magnetic dipole moment; $\theta$ = elevation angle)

For the position determination a mobile station is equipped with a magnetic field sensor. By measuring the field strength of at least three reference coils the 3D position can be determined using trilateration. Utilizing a three-axis sensor, further angles such as the elevation angle can be determined in order to support the position calculation or to decrease the number of coils needed. Besides the static positioning, the system is also intended for position estimation of persons and objects in kinematic applications. By integrating additional passive sensors all six degrees of freedom (6DoF) of the mobile station can be estimated without using antenna arrays. Since the mobile station does not interact proactive with the reference stations, there is no limitation in the number of users. Because of its quasi-static operation, the system radiates electromagnetic waves with very low frequencies (Hz range) and causes no interferences with commercial devices. Thus, it can be applied wherever other positioning systems encounter difficulties, e.g. in mines and tunnels, inside of factories and buildings, etc.

## 4 Prototyping and Experimental Results

First range measurements in real indoor environments with self-made coils and commercial field sensors have shown good results. Figure 1 depicts on the left the raw data of a measurement example at a distance of 4.20 m between coil and sensor.

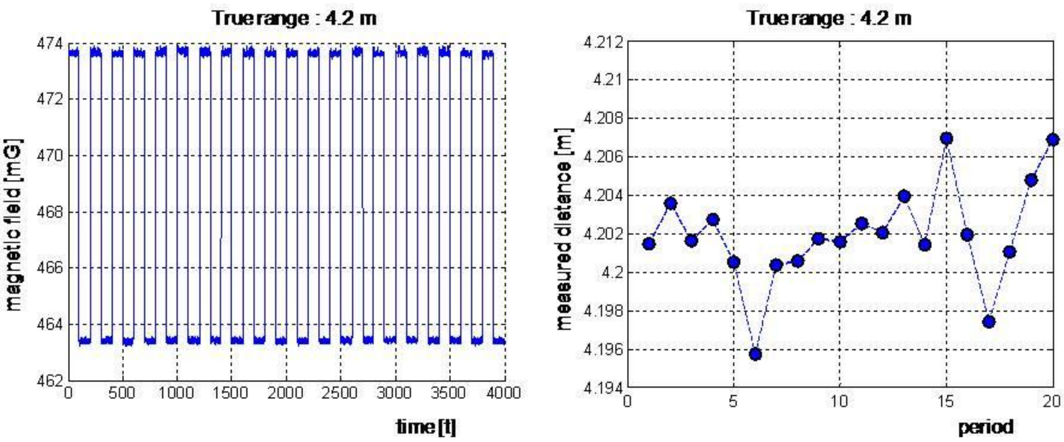


Figure 1: Distance measurement example between coil and magnetic sensor

By changing the current direction periodically and subtracting the period's mean values the influence of the earth's magnetic field can be compensated. In this example the measured distances show deviations of less than 8 cm from true range (Figure 1, right).

## 5 Conclusions and Outlook

Currently, the development of a prototype is in progress and calibration methods for the coils and sensors are developed. Extensive measurement experiments will follow and the algorithms for the position and orientation estimation will be implemented. A further challenge is the development of a method for the elimination of short period interference fields by making use of adaptive filter techniques.

# Multi-targets' Localization and Orientation Algorithm*

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## 1 Summary

To track the movement of multi-targets, a magnetic localization and orientation system is designed. In this system permanent magnets are used as the targets. With the magnetic sensor array, the magnets' magnetic signals can be measured, and the targets' 3D localization and 2D orientation parameters can be computed by an appropriate nonlinear minimization algorithm, e.g. Levenberg-Marquardt (LM) Algorithm. The experimental results show that this system has satisfactory accuracy, high execution speed and high robustness.

## 2 Localization Algorithm Overview

In the localization system, some cylindrical permanent magnets are used as the tracking targets. The length of the magnets is about 12mm and the diameter is about 6mm. Since the distance between the magnet to magnetic sensors is much larger than the size of the magnet, the magnetic dipole model can be used for the computation.

1) Magnetic Dipole Model

Assume that a magnet's position is $(a,b,c)^T$ and the magnet orientation is $\mathbf{H}_0 = (m,n,p)^T$, the magnetic field intensity at the position $(x_l, y_l, z_l)^T$ can be represented as

$$\mathbf{B}_l = B_T \left( \frac{3(\mathbf{H}_0 \cdot \mathbf{P}_l)\mathbf{P}_l}{R_l^5} - \frac{\mathbf{H}_0}{R_l^3} \right) \quad l = 1, 2, \cdots, N \tag{1}$$

where $B_T$ is const parameter related to the magnet size and material, and $\mathbf{P}_l = (x_l - a, y_l - b, z_l - c)^T$, $R_l = \sqrt{(x_l - a)^2 + (y_l - b)^2 + (z_l - c)^2}$, $m^2 + n^2 + p^2 = 1$.

2) Multi-targets' Localization and Orientation

Figure 1 shows schematic of the multi-targets' localization and orientation. There are M magnets, and $(a_1, b_1, c_1)$ ,… , $(a_M, b_M, c_M)$ are the positions, $(m_1, n_1, p_1)$ ,… , $(m_M, n_M, p_M)$ the orientations of the magnets. According to (1), we have

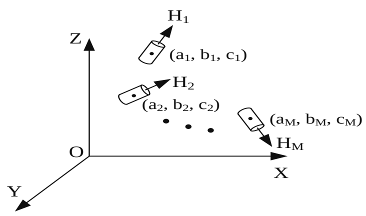


Figure1: Multi-targets Localization and Orientation

$$B_{ix} = \sum_{q=1}^{M} B_{Tq} \left\{ \frac{3\left[m_q(x_i - a_q) + n_q(y_i - b_q) + p_q(z_i - c_q)\right](x_i - a_q)}{R_{iq}^{\ 5}} - \frac{m_q}{R_{iq}^{\ 3}} \right\} \tag{2}$$

* Supported by the grants from Key Lab of Robotics & Intelligent System, Guangdong Province (2009A060800016), the Guangdong/CAS Cooperation Project (2009B091300160), National Natural Sc. Foundation of China (60904031), Shenzhen Sc. & Tech. Research Funds, the Knowledge Innovation Eng. Funds of CAS and the Funds of SRF for ROCS, SEM.

$$B_{iy} = \sum_{q=1}^{M} B_{Tq} \left\{ \frac{3\left[m_q(x_i - a_q) + n_q(y_i - b_q) + p_q(z_i - c_q)\right](y_i - b_q)}{R_{iq}{}^5} - \frac{n_q}{R_{iq}{}^3} \right\} \quad (3)$$

$$B_{iz} = \sum_{q=1}^{M} B_{Tq} \left\{ \frac{3\left[m_q(x_i - a_q) + n_q(y_i - b_q) + p_q(z_i - c_q)\right](z_i - c_q)}{R_{iq}{}^5} - \frac{p_q}{R_{iq}{}^3} \right\} \quad (4)$$

The positions $(x_i, y_i, z_i)$ of these magnetic sensors can be determined in advance and the magnetic signals $\left[B_{ix}\ B_{iy}\ B_{iz}\right]^T$ can be detected by the magnetic sensor arranged at the position $(x_i, y_i, z_i)$. Therefore, equations (2), (3) and (3) can be used to compute the position parameters $(a_q, b_q, c_q)$ and the orientation parameters $(m_q, n_q, p_q)$ $(q=1...M)$ of the magnet by using Levenberg-Marquardt (LM) optimization Algorithm.

## 3 Experiments and Results

For the application in the tracking of the objective inside human body, e.g., the tracking of the wireless capsule endoscope, we designed and built a real magnetic tracking system in a space of $0.5m \times 0.5m \times 0.5m$. Figure 2 shows the system and the real-time tracking interface. This system has 4 sensor planes and each plane has sixteen 3-axes magnetic sensors (total 64 3-axes magnetic sensors). Honeywell AMR (Anisotropic Magneto-resistive) sensor HMC1043 is chosen because of their appropriate sensitivity. Figure 3 shows the localization accuracy, the average position error is around 2mm and the average orientation error is around 2° .

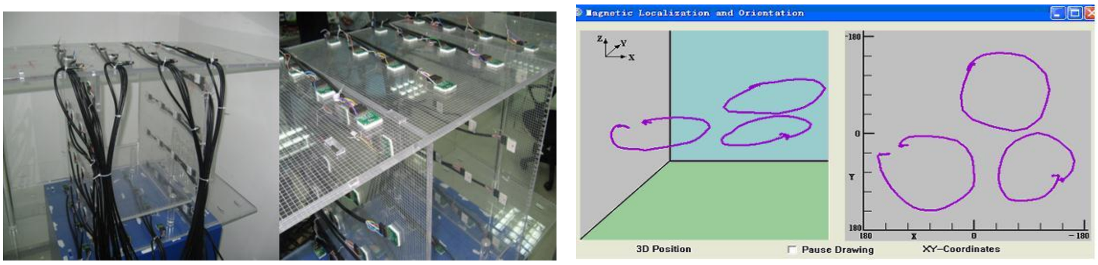


Figure 2: Real Experiment System

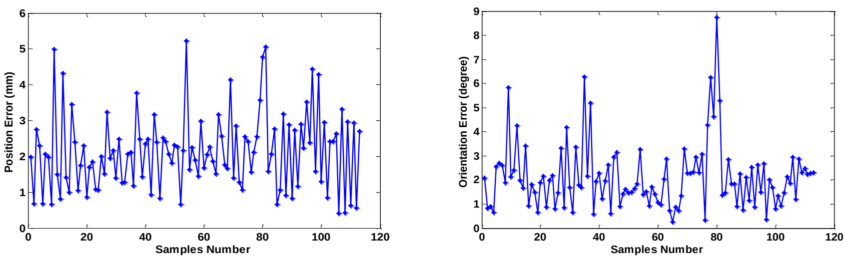


Figure 3: Localization Error and Orientation Error

## 4 Conclusions and Outlook

A real time localization system based on sixty-four 3-axes magnetic sensors has been build. Through the Levenberg-Marquardt optimization algorithm, the multi-magnets' localization and orientation are realized in real time. The results are satisfactory with the localization accuracy about 2mm. The further work will be imposed to improve the system performance, especially the localization accuracy when the magnetic distortion exists as the magnets are too closed each other. We expect that this system can be made to a commercial product and applied to the tracking of the objective inside human body.

## Innovative Systems

Auditorium D8

Friday, September 17, 10:15 – 12:00

# Wireless Acoustic Tracking for Extended Range Telepresence

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## 1 Summary

Telepresence systems enable a user to experience virtual or distant environments by providing visual feedback, e.g., using a head-mounted display (HMD). While most common designs use dedicated input devices like joysticks or a space mouse, the approach followed in the present work takes the user's position and viewing direction as an input, as he walks freely in his local surroundings. This is achieved using acoustic tracking, where the user's pose (position and orientation) is estimated on the basis of ranges measured between a set of wall-fastened loudspeakers and a microphone array fixed on the user's HMD. To allow natural user motion, a wearable, fully wireless telepresence system is introduced. All signal processing, coordinate transform and visualization is performed on-line, aboard the mobile tracking unit. The increase in comfort compared to wired solutions is eminent, as the user's awareness is taken away from distracting cables during walking. Also the lightweight design and small dimensions contribute to ergonomics, as the total of components fits well into a small backpack.

## 2 Motivation

Extended range telepresence implies the ability for a user to explore arbitrarily scalable areas (target environment) while actually moving in a room with limited proportion (user environment). A transformation algorithm is applied to convert between target- and user-space, in order to provide motion compression [1]. The basic principle is to map straight paths in target geometry to curved trajectories in user-space, while still preserving length. Thus, by locally moving in circles, virtually unlimited target areas can be explored.

The intended field of application includes not only virtual environments, but also distant environments, that are established by a mobile teleoperator. The former comprise virtual museum visits, gaming, or educational scenarios. In the latter case, camera images are transmitted in real time to the user as he controls the teleoperator's motion by his own local body movement. Conceivable scenarios are hazardous areas, forbidding places, or remote sites, such as planets' surfaces.

The degree of immersion into those environments depends on the sensory perception covered, such as visual, acoustic, and haptic feedback. As vision is considered the primary sense, the main focus of attention is turned to visual perception. Nevertheless, acoustic and even haptic feedback can be integrated in the existing design as shown in [1].

To provide an optimal experience, reliable and accurate tracking is mandatory. Being tolerant towards occlusions, as they happen frequently in natural user motion, acoustic tracking is chosen. Compared to optical tracking systems, no direct line of sight is required for proper operation. The system is also much easier to install, comprising merely a set of stationary loudspeakers at selected positions and a mobile signal processing unit (see Figure 1), elaborate calibration is omitted. Pose estimation is then obtained by measuring the time of flight (TOF) of specifiable acoustic signals between the stationary loudspeakers and an array of user worn microphones. Given the speed of sound and the loudspeaker/microphone geometry, the user's pose can be estimated from the ranges measured, e.g., by using the closed-form approach in [2].

The performance of the wireless tracking rests with the underlying synchronization between signal emitter and receiver unit. A misalignment in time bases that is not properly handled results in a range offset, which leads to spurious pose estimation. In order to deal with delays, external disturbances and noise, adequate filtering techniques such as state estimation need to be applied.

## 3 Results

A fully wireless telepresence system has been introduced, which is composed of distributed embedded systems. Dedicated, low power hardware features fully digital signal generation and amplification, as well as multi-channel (redundant) signal processing for improved robustness and precision. The challenge of keeping signal emitter and receiver synchronized has been met by periodically transmitting radio pulses, thus neutralizing the time offset. Spread spectrum methods are used to differ between each loudspeaker's signals as they appear at the microphones in additively superposed manner. Finally, global precision in the low cm-range has been achieved, which is sufficient for pose estimation of extended objects. The mobile system runs on battery for at least one hour, after that, a spare battery pack can be easily installed.

Future work could involve the integration of an inertial measurement unit (IMU) to allow higher update rates and to propagate the user's motion in case of defective measurements.

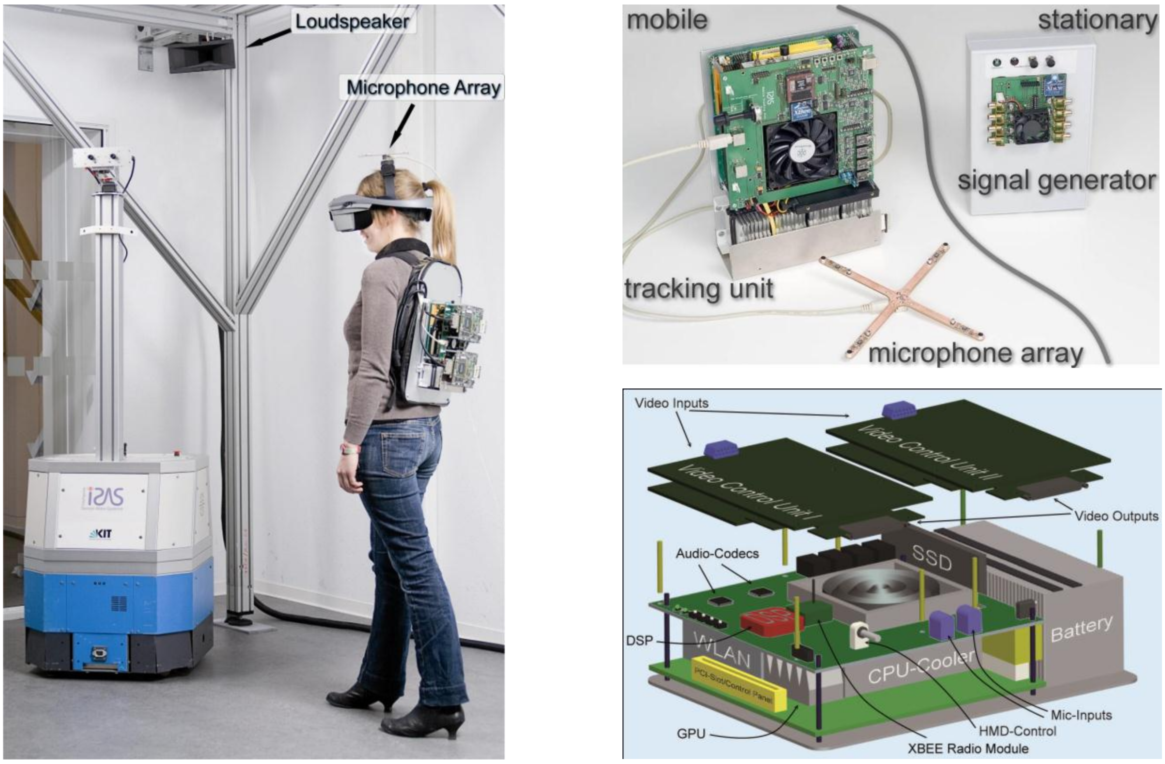


Figure 1: Left – User wearing the tracking system within the telepresence environment, accompanied by a mobile teleoperator. Right (top) – Mobile tracking unit with microphone array attached, signal generator unit. Right (bottom) – Schematic view of the user-wearable tracking unit.

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# Self-Localization Application for iPhone using only Ambient Sound Signals

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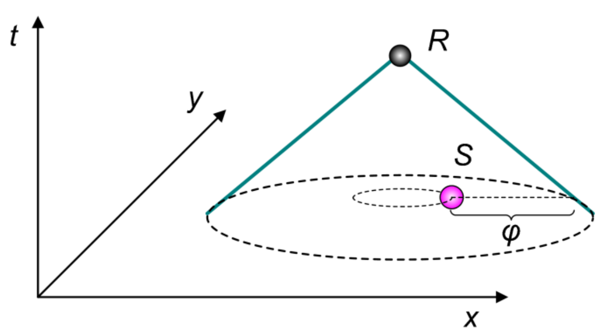
## 1 Introduction

We present a smartphone application to localize a group of devices in a mobile environment without the need of any further infrastructure. Ambient sound signals are the only information source. Time marks are assigned to the recorded audio stream for each distinctive audio event. Then we evaluate the time differences of arrival (TDOA) between devices. The innovation of our approach is, that we need absolutely no positional anchor points in space – neither any predefined smartphone positions nor the positions of the environmental sounds. This stands in contrast to common multilateration approaches. However, we use a WiFi connection to establish a common timebase between the devices and to exchange time marks. In this way the employment in dynamic environments with random sound events is made possible, e.g. in crowded areas like market places or concerts, or for thunderstorm tracking. Especially, the application becomes useful when established positioning systems (e.g. GPS) are too imprecise or fail, as during underwater self-localization of scuba divers. In our experiments we evaluated the audio information and synchronized the devices up to an order of 0.1 ms. This led to a positioning precision in the order of 10 cm.

## 2 Related work

Localization of mobile devices with additional infrastructure has been a broad and intensive research topic. Popular applications include GSM localization [1, 2] and WiFi network fingerprinting [3]. For *known* sender or receiver position information TDOA localization can be addressed in closed form [4, 5, 6] or by an iterative approach [7]. Moses et al. use TDOA with additional angle information (direction of arrival, DOA) to locate both *unknown* sender and receiver positions [8]. This requires expensive microphone arrays or directed microphones. Our approach uses only TDOA information without any further infrastructure.

## 3 Methods




We developed two new methods to address the self-localization problem of both unknown signal senders and receivers [9]. The *Ellipsoid TDOA method* reconstructs the positions for exactly three devices in two-dimensional space for the assumption of infinitely distant sound sources. This can be written in closed form and solved rapidly. Experiments pointed out that the assumption of remote sound sources still holds if the distances of the sound sources are just greater than twice the distances between the devices. The *Iterative Cone Alignment* method generalizes to arbitrary device numbers and no assumptions on the signal origins. It relies on an energy minimization approach implemented in a physical spring-mass simulation. Fundamental is the signal propagation equation

$$\varphi = c\,(t_{R,S} - t_S) - \| R - S \| \qquad (1)$$

where *c* is the signal velocity, *S* and R denote the unknown positions of senders and receivers in two-dimensional space, $t_S$ is the unknown signal time and $t_{R,S}$ is the given sound signal time mark. $\| \cdot \|$ denotes the euclidean distance. Equation (1) describes a cone in (2+1)-dimensional space. The energy minimization approach simulates physical particles *S* and *R* for each signal and receiver (microphone). It attempts to restore valid positions of *S* on the cone surfaces of *R*. Except for symmetries, for a sufficient number of senders and receivers this leads to a globally unique solution of *S* with respect to every receiver and – implicitly – correct distances between pairs of receivers.

## 4 iPhone App


We use the Apple iPhone 3GS as a platform that combines a fast ARM11 CPU with the intuitive multitouch interface making it a good choice for our interactive software. The application ("App") serves both as an experimental platform for the development of our algorithms and as a nice and easy-to-use gadget for the public domain. Both localization schemes are included in our application. The Ellipsoid TDOA method requires three connected iPhones forming a triangle; at least four iPhones are necessary for the iterative method to obtain a unique solution. The algorithms rely upon discrete "timestamps", i.e. the times when short, steep edged audio signals arrive at the devices. The signals are recorded via the built-in microphones and then analyzed by audio processing. Results of the calculations are displayed in an OpenGL visualization which can be rotated and zoomed using multitouch gestures.

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# A Novel Technique for Mobile Phone Localization for Search and Rescue Applications

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## 1 Summary

Recent statistics show an increase in environmental disasters, a fact which is also perceivable to the public as reports of avalanches, earthquakes and landslides mount in media coverage. Search and Rescue with modern localization techniques consequently attracts attention from scientific and industrial sides. This paper introduces one part of the I-LOV project, endorsed by the Federal Ministry of Education and Research in Germany, in which partners from relief organizations, universities and industry investigate enhancements to disaster handling and victim rescue. Future developments in the area of mobile phone detection by field intensity measurements will be addressed in this paper.

## 2 Introduction

In today's search and rescue market there are already several systems based on tags or hand held devices which persons at risk should carry with them. Examples are the RECCO System or LVS equipment for avalanche rescue. These localization approaches are suffering from the fact that only a low percentage of people at risk own such tags. Therefore it is an obvious approach to use the most common handheld device: the mobile phone.

One part of Project I-LOV is to find new approaches on locating mobile phones in search and rescue scenarios. The focus lies here on localization of buried people trapped under collapsed houses after natural disasters like earthquakes or landslides. A survey made by the Federal Agency for Technical Relief, which is the most important partner in this project, shows that about 80% of buried people carry their mobile with them. Of course there are already some approaches used by network providers to fulfil E-911 specifications or to offer other location based services. The predominantly used methods here are cell based like the timing-advance method or propagation time based like the time-difference-of-arrival (TDoA) approach. These techniques achieve only a poor resolution of 100m – 200m which is not suitable for search and rescue applications in our scenarios. Of course more and more mobiles are equipped with global-positioning-system (GPS) chipsets which offer the option of satellite assisted localization. To use GPS the mobile device needs line of sight to at least four satellites which is seldom possible in burying scenarios. Taking everything above into account leads to the need of a new approach which uses the advantages and solves the disadvantages of mobile phone localization.

## 3 The new System Approach

Since 1982 the Global System for Mobile Communications (GSM) was invented and developed as a worldwide standard. And even today in times of 3rd generation (3G) and long term evolution (LTE) GSM is still the most common mobile standard. But GSM has also another advantage besides the wide market spread. The lower the frequency of electromagnetic waves the better the propagation through debris or concrete. GSM offers a communication band around 900 MHz called E-GSM 900 with uplink frequencies from 880 MHz to 915 MHz with good propagation characteristics for use in search and rescue applications.

In this paper a new approach for mobile phone localization will be presented. This System uses both field intensity measurements and a new approach on TDoA in combination. The second will be addressed in a later publication. To locate a mobile by its radiated field strength first of all it has to be forced to send a massage, where this massage has to be repeatable as often as needed in a certain time. To achieve this full control of the mobile to be located is needed. Total control can only be gathered by setting up an own GSM base station. There are GSM base stations (BS) commercially available but those are too big to be portable and too expensive to afford in large numbers by rescue organizations all over the world. Furthermore a standard BS does not provide all functionality needed for localization purposes. Therefore the decision was made to build a customized BS for project I-LOV (Figure 1). The base station first of all performs the jamming of other networks, then catches all reachable mobiles in the area of interest and finally forces the mobiles to send. How this is done will be explained in detail in this paper. Also measurement results from the first field test will be presented. Those measurements show very promising results and proof the concept. A localization accuracy of +- 10 cm has been achieved. Furthermore the difference between debris and concrete blocks in terms of field intensity localization will be examined and further results will be presented.

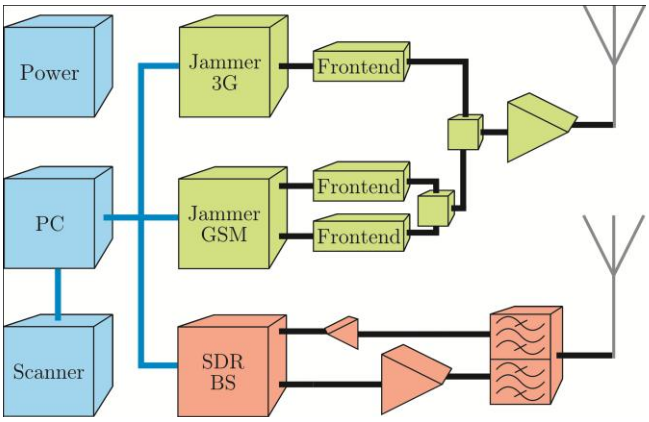


Figure 1: Simplified schematic of I-LOV base station with jammer


Figure 2: One of the testing areas at the first field test.

# Pedestrian Indoor Positioning Method Using Fluorescent Light Communication and Autonomous Navigation

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**Summary** We developed an indoor positioning and footstep-width correction method that is employed while walking. This method employs ordinary indoor illumination apparatuses, i.e., fluorescent lights, as a special visible light communication tool. An experimental system comprises an integrated tri-axis accelerometer and magnetic sensor (Aichi Seiko, AMI603SD), a gyro-sensor, a specially developed visible light sensor, and a PDA. In the experiments, the prepared experimental environment is a rectangular shape corridor. There are 15 signal-transmission-type fluorescent lights installed in the ceiling of the corridor along the experiment route, and the receiving test is conducted 5 times continuously (5 rounds) in the same corridor. When error correction is employed, there is no problem due to the accumulation of the error. The average error is 0.77 m and the maximum error is 3.96 m. In addition, the error in the footsteps is corrected to less than 5% on average (0.03 m).

## 1. Introduction

Recently, it has become possible to apply indoor autonomous navigation technology to practical applications due to the progress in the development of highly precise and miniaturized sensors. However, to counter the existing problems with this technology such as the need to input the initial position data or the effect of integrated measuring errors, the navigation system should be combined with other position measuring technologies. Therefore, we developed an indoor positioning and footstep-width correction method that is employed while walking. This method employs ordinary indoor illumination apparatuses, i.e., fluorescent lights, as a special visible light communication tool. In the following section, a detailed explanation and experimental results in an actual environment are given.

## 2. Method

Figure 1 shows the employed system configuration. The system comprises an integrated tri-axis accelerometer and magnetic sensor (Aichi Seiko, AMI603SD), a gyro-sensor, a specially developed visible light sensor, and a PDA (Personal Data Assistant, HP iPAQ rx4200). A description of the measuring method is given hereafter.

### 2.1 Positioning by dead reckoning

The number of footsteps taken by a pedestrian is calculated using the waveform from the accelerometer. At the same time, the next moving position is estimated successively based on the information of the forward direction, which is obtained from the magnetic sensor and the predetermined single footstep width. In the experiment, the PDA with an accelerometer and magnetic sensor unit are worn over the midriff of the pedestrian.

### 2.2 Fluorescent light

1) Basic method: A specially designed fluorescent light is equipped to send unique positional signals (IDs) using frequency shift keying. Each signal is decoded by an original receiver equipped with photo sensors. The ID is sent to the PDA through a Bluetooth connection, and the present position is estimated by accessing a fluorescent light position database in the PDA.
2) Absolute position correction: The receiving area of the fluorescent light signal is determined based on the receiving angle of the light at the photo sensor. In the experiment, a relatively narrow angle (±10 degrees) photo sensor (Hamamatsu Photonics S5821-01) is used as the

basic receiving element and is combined with three other sensors to achieve a wider angle and to avoid interference. The next correction of the footstep width starts at the time when a new fluorescent light ID is received.

3) Footstep width correction: Using previously detected IDs, we estimate the distance that is equal to the movement range of the pedestrian. The footstep width can be corrected based on the range divided by the number of footsteps. Using this method, the variation in the width or personal footstep width is automatically calculated while the pedestrian walks.

## 3. Experimental Results

The experiment was conducted in a fluorescent light communication environment in a corridor on the $8^{th}$ floor of the Information and Science Technology building in Niigata University. In the experiments, the prepared experimental environment is a rectangular corridor. There are 15 signal- transmission-type fluorescent lights installed in the ceiling of the corridor along the experiment route, and the receiving test is conducted 5 times continuously (5 rounds) in the same corridor. The total length of the course is 274 m.

Figure 2 shows the results of error measurements according to the distance travelled. In the figure, the definition of an error is the difference between the actual distance and estimated total length of all the footsteps. Without any correction, the error of the distance travelled accumulates for each round, and the total error is 38.8 m. On the other hand, when error correction is employed, there is no problem due to the accumulation of the error. The average error is 0.77 m and the maximum error is 3.96 m. In addition, the error in the footsteps is corrected to less than 5% on average (0.03 m).

## 4. Discussion and Conclusion

By using dead reckoning combined with the fluorescent communication system, we studied the indoor positional estimation method and automatic footstep correction. The results showed that it is possible to measure each position within the average error of 0.77 m, which enables practical use in indoor navigation applications. In the experiment, at some particular positions, there was some direction error even after correction. This is due to outside magnetic irregularity affecting the magnetic sensor output. Therefore, we experimented with combining an additional gyro-sensor that detects the actual movement to avoid irregular direction output due to the outside magnetic effects to achieve more precise position measurements. There is another sensing method using radio frequency identification (RFID); however, it requires additional cost for actual machine installation and maintenance of such equipment. Moreover, there are problems with the range of detection caused by variations in the environment. On the other hand, since the fluorescent light system is used as regular illumination equipment and each fixture is set a few meters apart from each other, it is a suitable positioning platform. (Partially supported by SCOPE, Japan)

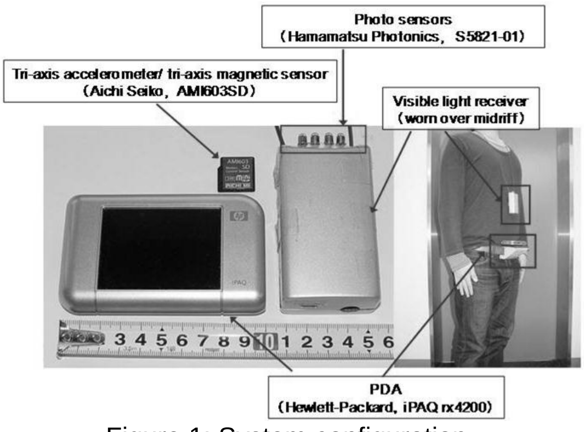


Figure 1: System configuration

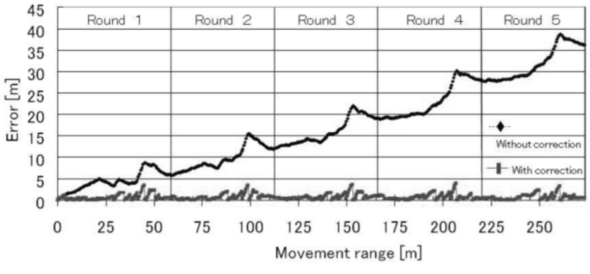


Figure 2: Experimental results of error measurement

# Basic Study of Indoor Robot Control Using Fluorescent Light Communications

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**Summary**

We investigate a robot control method using the location information sent by a fluorescent light communication platform. More specifically, we confirm the operation of the downlink route that acquires location information through fluorescent lights using a specially developed optical receiver, and the uplink route that feeds back in real time to the host computer an acknowledgement signal according to the downlink signal. In the developed system, a miniature LEGO MINDSTORMS NXT robot is used as the target. The actual experimental environment incorporates 22 signal-transmission-type fluorescent light units at Niigata University. The results confirm that the IDs sent through the fluorescent lights were displayed sequentially on the robot LCD over the route that the robot traversed. Moreover, it was confirmed that the infrared communication device was able to transmit information from the robot to the host computer.

## 1. Introduction

To control an experimental type robot in an indoor environment, we initiated research on indoor positioning using fluorescent light communications. This method will be useful for indoor security monitoring or automatic assistance of electric wheelchairs. Therefore, we investigate a robot control method using location information sent by the fluorescent light communication platform. More specifically, we confirm the operation of the downlink route, which acquires the location information through the fluorescent lights using a specially developed optical receiver, and the uplink route, which feeds back to the host computer in real time an acknowledgement signal according to the downlink signal.

## 2. System Configuration

Figure 1 shows the system configuration. In the system, a miniature robot (Afral Co.,Ltd. ,LEGO MINDSTORMS Education NXT Base Set, WRL9797) is used as the target. The actual experimental environment incorporates 22 signal-transmission-type fluorescent light units on the 8th floor of the Information Engineering building in Niigata University. First, in the downlink route, a unique ID (Identification) number that corresponds to the location information is sent to the optical receiver, and it is used to detect the current position of the robot. Second, in the uplink route, optical communications are used. This is especially important in an environment where the use of electric-magnetic waves is prohibited such as in a hospital. In the system, we use a commercially available infrared communication device (ACTiSYS CORP., Intelligent IR Port, ACT-IR100SL-M).

## 3. Method

In the downlink route, we use the robot combined with an infrared type distance sensor (ROBO Product, High Precision Long Range Infrared distance sensor for NXT, RPMS01011) and a gyrocompass (HiTechnic Products, NXT Gyro Sensor, NGY1044) as well as the optical receiver and transmitter. In the experiment, the robot acquires the location information from each fluorescent light one-by-one while autonomously moving forward in the corridor (6.4 cm/sec), and displays the IDs on its LCD. Figure 2 shows the pathway used in the experiment. Each number in the figure indicates a unique ID number transmitted through the fluorescent light. On the other hand, in the uplink route, the robot communicates with the host computer through an infrared-type communication device. More specifically, we prepared five infrared-type communication devices. One is established on the body of the robot and the remaining four devices are established on the ceiling. We confirmed acknowledgement signal transmission from the robot to the host computer.

## 4. Results

Figure 3 shows the LCD output that indicates the received IDs sent from fluorescent lights while the robot moved along the route autonomously. We confirmed the sequential reception of the location information through the fluorescent lights that were on the route shown in Fig. 2. In the next experiment, we confirmed bidirectional connection between the robot and host computer using the infrared communication devices. Communications were established in asynchronous mode at 9600 bps between the robot and the infrared communication device on the ceiling.

## 5. Conclusion

We developed a communication system for indoor robot control using the downlink that received positional IDs from the fluorescent lights and the uplink that transmitted a reply signal from an infrared transmitter to the host computer in an actual experimental apparatus. The results confirmed that the IDs sent through the fluorescent lights were displayed on the LCD sequentially while the robot was moving. Moreover, we confirmed that the infrared communication device can be used to transmit information from the robot to host computer. We are currently preparing firmware for the interface circuit that connects the robot and the infrared communication device.

This research was partially supported by the Strategic Information and Communications R&D Promotion Program, Ministry of the Internal Affairs and Communications of Japan.

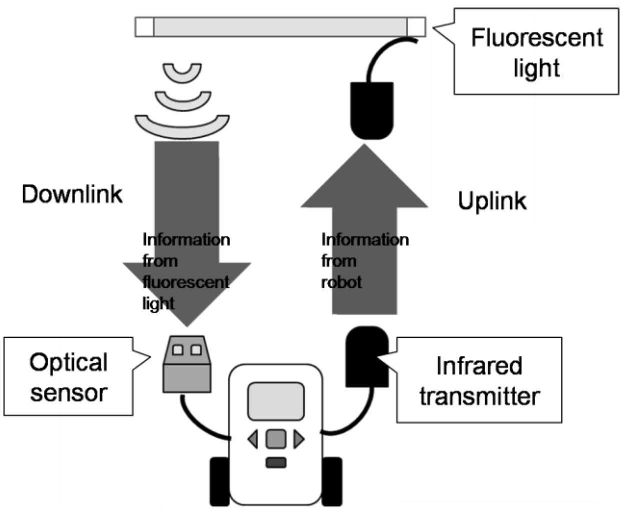


Figure 1: System configuration

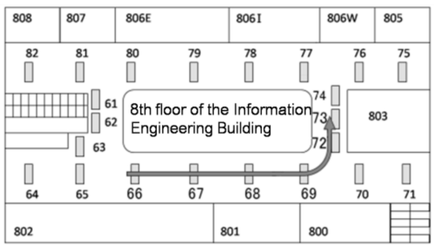


Figure 2: Moving route of robot

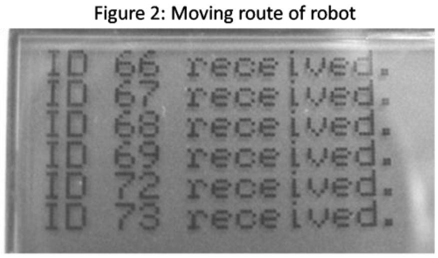


Figure 3: Experimental results
Received IDs on LCD of NXT

# Indoor Location Estimation Using Visible Light Communication: Practicality and Expandability

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**Summary**

We proposed an indoor location estimation method using Visible Light Communication (VLC) and triangulation. According to the performance of the practical VLC system in Niigata University, including the tube type fluorescent light system and the compact fluorescent down light system, we discuss the practicality and expandability on the three components: server component, light component, and receiver component. Several applications based on the presented indoor location estimation method such as a robot control system are suggested. We also give consideration to combining VLC with other technologies such as RFID and mesh networks.

## 1 Introduction

Since ubiquitous computing was proposed in 1988, more and more intelligent communication systems have been developed, and location is considered as the most important parameter for ubiquitous computing. We established an indoor communication system using Visible Light Communication in the past seven years. Lightning instruments are installed in many places indoors, and we found VLC is very convenient for indoor location estimation. As a new location estimation method, the practicality and expandability are very important.

## 2 Location Estimation using Visible Light Communication

Figure 1 shows the Visible Light Communication system in Niigata University. The system concludes three components. In server component, a local network is used to send information to the control boards which are connected to each fluorescent light; in light component, Frequency Shift Keying (FSK) is used as the communication method; in the receiver component, a date receiver (with photo sensor) and a Personal Digital Assistant (PDA) with Bluetooth functionality are used to acquire essential information. Now three practical VLC systems are established in Niigata University: tube type fluorescent light system, compact fluorescent down light system and system for exhibition. LED, which is considered as next generation light source, could also be used for VLC system.

We used triangulation to calculate the position of the target using VLC. Verification experiments were performed using 14 compact fluorescent down lights at 20 measuring points, and 22 tube type fluorescent lights at 39 measuring points. Distance errors of less than 15 cm are achieved.

## 3 Practicality

To make the system universal practical, development in the three components are necessary. (1) In the server component, since the load will become heavy when we send information to a number of VLC lights, intelligent network should be used to update data. (2) In the light component, the employed special designed fluorescent lights are all inverter-type enabling easy signal modulation. (3) In the receiver component, according to our former research, the recommended receiver is a multi-channel multi-directional photo sensor circuit. The present receivers are a 9-channel photo sensor receiver (Niigata University) for VLC system using

fluorescent light and a charge coupled device (CCD) receiver (Keio University) for VLC system using LED lights.
Visible Light Communication Consortium (VLCC) is working on the research, development, plan, and standardization of VLC system with many flagship companies. In addition, IEEE 802.15.7 Visible Light Communication task group is working on the standardization.

## 4 Expandability

This section discusses related technologies and potential applications of VLC.
(1) Related technologies:
Sensor technology: A multi-channel photo sensor receiver is required to obtain the data necessary to perform triangulation calculations for location estimation. Also a gyro sensor and direction sensor technology should be implemented in the receiver component.
Mesh Networks: In Mesh networks, each node acts as an independent router, and this type of networking could be used in the server component to make VLC system more intelligent.
(2) Potential applications:
Robot control: according to the present location estimation experimental results, it is convenient to use VLC for indoor robot control. In 2009, we proposed a LEGO NXT robot control system using VLC in Niigata University.
Combination system: In 2007 we proposed a combination system using VLC, Bluetooth and Radio Frequency Identification (RFID) for indoor guidance; in 2008 we used VLC and infrared communication to establish a both-way communication system. These days, since "Internet of Things" becomes more and more popular, combination system with the applications of different technologies should be an important trend for ubiquitous computing.
In this part, we compare VLC with location estimation systems using ultrasound, IEEE 802.11, RFID, infrared communication, Global Positioning System (GPS) in the aspects of accuracy, scale, cost and limitations. Compared with other technologies, VLC could cover most of the indoor environment with least dead points, it is easy to install and the accuracy is high. This research was partially supported by the Strategic Information and Communications R&D Promotion Program, Ministry of the internal Affairs and Communications of Japan.

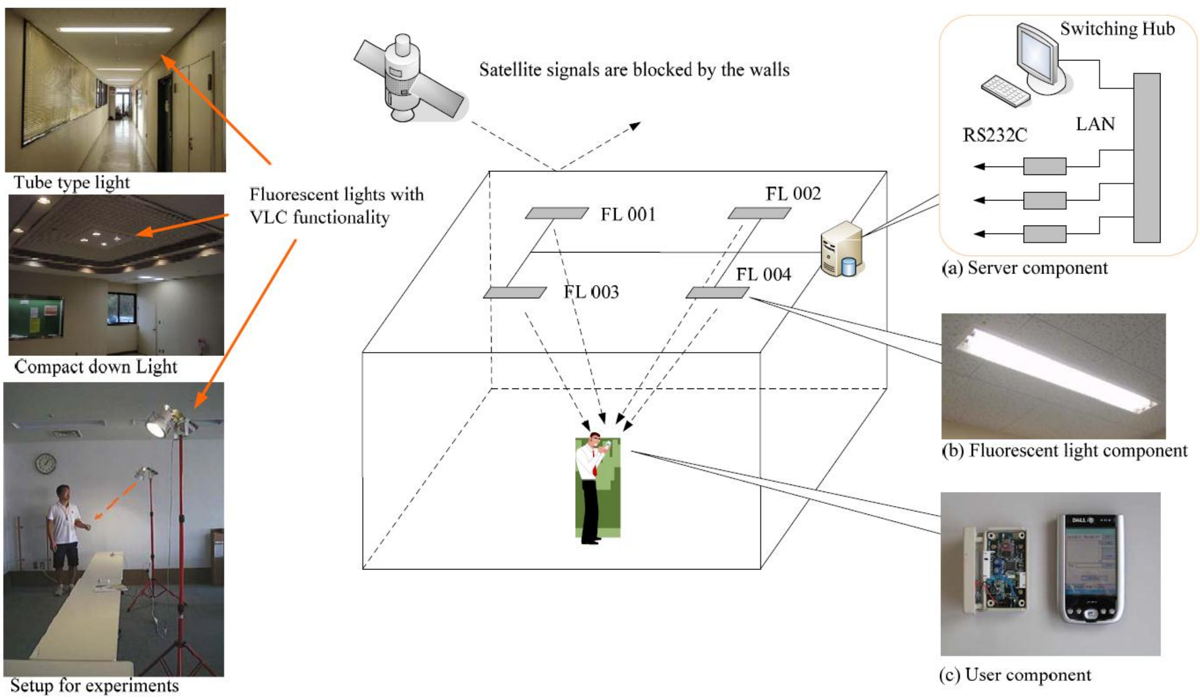


Figure 1 Visible Light Communication System using fluorescent light

# Advances in Thermal Infrared Localization: Challenges and Solutions

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## 1 Introduction

The localization of persons is one of the basic requirements to provide location based services in home environments. However, no solution exists that meets all the requirements arising in the field of home automation and Ambient Assisted Living (AAL). Most available systems are based on technologies like active infrared [1], radio [2], ultrasound [3] or cameras [4] to acquire the necessary measurements for localization. Unfortunately, the majority of these technologies require some sort of active transceiver, often referred to as tag or badge, which has to transmit or receive some kind of reference signal. Technologies that do not require a tag - like camera based systems - depend on the lightning conditions and suffer from a lack of consumer acceptance since privacy is being violated.

Thermal Infrared Localization (ThILo) however follows a different approach. In case of ThILo, no cameras or radio signals, but instead low-resolution thermopile arrays are used. These thermal infrared sensing sensors measure the thermal radiation emitted by any object in its field of view relatively to the ambient temperature. Because the human skin temperature generally differs from the ambient temperature in indoor environments, thermopiles deliver a great opportunity as basis for an indoor localization system.

Every localization system has its challenges. For ThILo, the challenges have been formulated in [5] and over the last few years good progress has been made in solving them. Here, the most important developments will be pointed out and its results are being summarized. In the full paper, the algorithms will be explained in detail and the most informative evaluation results will be presented.

## 2 Challenges and Solutions

By using thermopiles, the only measurable parameter is the thermal radiation. Due to the fact, that people are not the only source of radiation in home environments, additional heat sources influence the measurement signal. These influences can be regarded as sources of disturbance. In general, these disturbances can be divided in four distinct categories: reflection, occlusion, static and dynamic background radiation. Studying these effects in real environments is necessary but time consuming and difficult task. That is why; a real-time thermal infrared simulation environment [6] utilizing state of the art graphics processing unit capabilities has been developed.

Locating persons is difficult due to the stated reasons. When considering the relaxed problem with only static background radiation and only one person to track, well known triangulation algorithms can be applied. Therefore, multiple sensors are deployed throughout the surveillance region each supplying an angle of arrival that is extracted from the raw measurement data [7].

Considering multiple persons in the surveillance region, simple approaches like triangulation are not usable anymore. Consequently, more sophisticated multi-target localization and tracking algorithms need to be employed. Probabilistic Hypothesis Density (PHD) filters yield an elegant and yet efficient way to solve the multi-target localization and tracking problem [ref] and have successfully be applied to ThILo. PHD-filters further implicitly handle the problem of occlusion since missed detections are considered. Analyses of a Sequential Monte Carlo (SMC) - PHD filter variant have shown a localization accuracy of fewer than 25 cm, for data generated by the simulation environment. Real world measurements have also confirmed these results. However, the accuracy is slightly worse with approximately 50 cm when two persons are localized and tracked.

It is a fact that the localization accuracy does not only depend on factors like sensor resolutions but also on the sensor arrangement within the surveillance region and the knowledge of the exact sensor pose. Therefore, a semi automatic human assisted calibration system has been developed that uses the single target localization algorithm as a basis. An over determined nonlinear least squares optimization problem is formulated and solved iteratively with the Newton-Raphson method [8]. Evaluation results yield mean position and orientation errors below 30 cm and 5° respectively.

## 3 Conclusions and Outlook

The recent developments have shown that ThILo is a promising approach for localization in home environments. Several issues have been solved the past years and the solutions were discussed and presented in this paper. However, some issues - like reflection and dynamic background radiation – remain and are in the focus of current research. In order to eliminate the influence of dynamic background radiation in the localization process, preliminary progress has been made.

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# Indoor IR Azimuth Sensor using a Linear Polarizer

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## 1 Summary

We propose an Infrared-Ray (IR) type azimuth sensor system for the use in indoor environments. The feature of this sensor is an adequate conic shaped linear polarizer film. Because of the measurement error is accumulated with time, an azimuth information supplied by the angular velocity sensor (gyroscope) is unreliable. In addition, most indoor environments like an office or a factory are using many iron based materials for furniture or reinforced concrete, it is difficult to measuring the geomagnetism. Our sensor system can produce a position which measured from the non-drift azimuth information only by installing one landmark. We make a prototype of the sensor based on this technique and conduct the measurement experiment.

## 2 Concept

At first, we explain the basic property of linear polarized light. While the polarizer rotates one turn around the light axis, the same polarizing states appear twice as shown in Figure 1. This does not depend on the distance L of two polarizers. The range of an azimuth angle is 360 degrees. On the contrary, the range of a polarizing angle is 180 degrees. This means that between an azimuth of 180 and one of 360 degrees cannot be distinguished. Polarizing planes cannot discriminate the front and the rear surface. Since a linear polarizer is a flat sheet in the original shape, there are some problems when we use it as an angle sensor. For solving this problem, we invented a new form of linear polarizer.

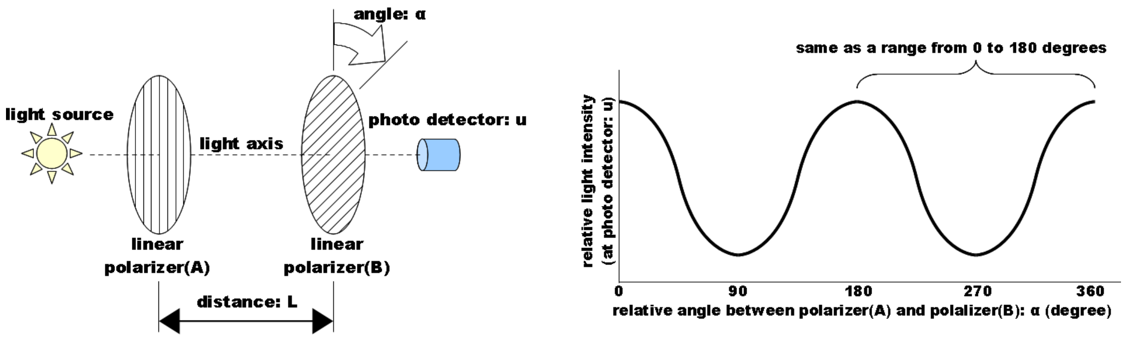
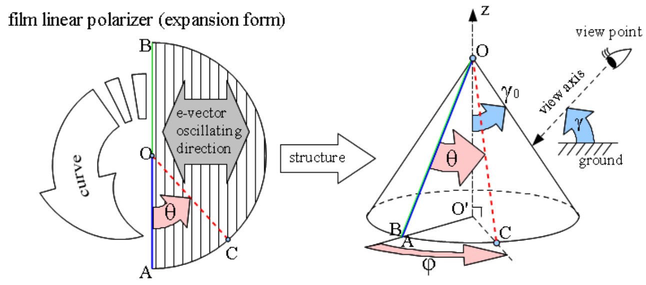



Figure 1: Basic property of linear polarizing light.

So we cut out the semi-circular sheet from the flat sheet of the linear polarizer. We create a cone-shaped linear polarizer from the semi-circular flat sheet by attaching each straight edge mutually around the center of the straight line as shown in Figure 2. We denote the apex of the cone-wise curved surface with point O, the center axis with Z, the angle along the cone from the line OA to an arbitrary position C with θ, the rotating angle of the cone around the Z-axis with φ, the angle between the line of vision (view axis) and the ground with γ, and the inclined angle of the mother line with $\gamma_0$. We can obtain (1a), (1b) and (2) from the above geometrical relation.




$$\cos\varphi = \cos(2\theta). \quad (1a)$$

$$\sin\varphi = \cos(\gamma - \gamma_0)\sin(2\theta). \quad (1b)$$

$$\gamma_0 \equiv 30^\circ . \quad (2)$$

$$\varphi = 2\theta\ ;\ (\text{at } \gamma=\gamma_0.) \quad (3)$$

Figure 2: Structure of a conical linear polarizer.

Hence we can extend the polarizing angle θ in the range of 180° to the rotating angle of the cone-wise polarizer φ in the range of 360°. Since both angles correspond one-to-one, we can determine the azimuth angle uniquely as exemplified in (3). Then we can show that the rotating angle of the cone around the Z-axis can be modulated as the angle of the polarizing plane rotates around the view axis. Considering the application of this sensor for positioning system, we set a light source inside the conical polarizer as a landmark and observe it from outside the cone. The angle around the view axis of the observed polarizing plane is proportional to the rotating angle of the cone φ.

## 3 Experimental Result

The proposed sensor consists of two parts. One is the transmitter which emits polarized-modulating IR. Another is the receiver which demodulates the IR from the transmitter. So we can get the heading of the receiver's azimuth. By using the transmitter as the landmark, we measure a self-position and absolute azimuth of the receiver. A schematic view of an experimental setup is shown in Figure 3. The transmitter is attached to a tripod at a height of H=1500 [mm] from the receiver. The vertical direction of the conic polarizer is downwards. Figure 4 shows the relation with the measured results of the azimuth φ and the settling one. This result is independent of the distance L. If we know the height H and the elevation β in Figure 3, we can easily calculate the distance L. Therefore, we can acquire the receiver's position based on the polar coordinate system.

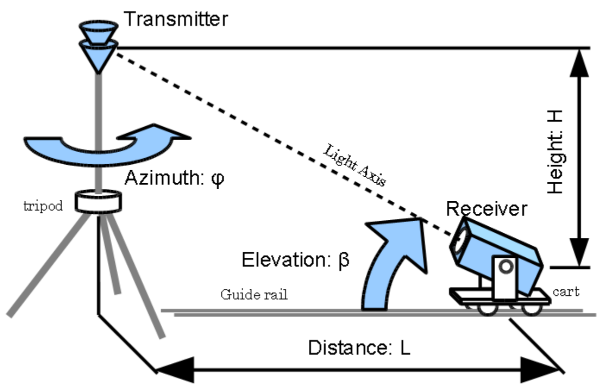



Figure 3: Experimental setup.

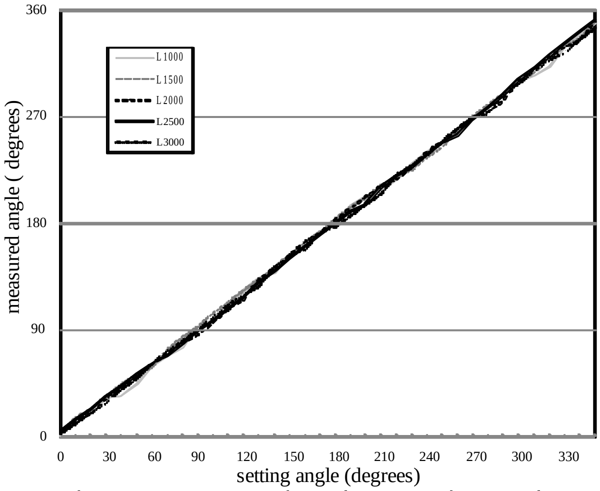



Figure 4: Measured angle vs setting angle.

## 4 Conclusions

Our sensor system can measure the azimuth in indoor environments using linear polarized IR. It has advantages in indoor environments which is difficult to measure the self-position by GPS or the other sensors that the position of the receiver is obtained by the azimuth with installation of only one landmark.

**Ultra Sound Systems**

Auditorium J6

Wednesday, September 15, 10:30 – 11:45 & 13:15 – 15:30

# Indoor Position Sensing Using Broadband Ultrasound

Mohammed Alloulah, Mike Hazas, Computing Department, Lancaster University

## 1 Introduction

A variety of methods have been proposed for sensing the positions of tags, devices and sensor nodes indoors. Practicable, fine-grained positioning has been accomplished using ultrasonic signaling, with typical accuracies on the order of centimetres. Ultrasonic localisation has been applied in sensor networks [1, sect. 4], mobile computing and augmented reality [2]. In these types of positioning system, ultrasonic pulses are sent between devices (or *nodes*). Receiver nodes record the times-of-arrival (TOAs) of incoming pulses. In a system where there are multiple receiver nodes with known location, the TOAs can be used to estimate the position of a transmitting node. The accuracy of the positioning system relies upon the receiver nodes' ability to reliably estimate pulse times-of-arrival.

Recently, there has also been emphasis on ad hoc, infrastructureless systems, because they tend to be less expensive and time-consuming to deploy. In such systems which use accurate, fine-grained ultrasonic localisation [3], it is common for each transmitter node to emit an RF signal to trigger nearby receiver nodes, prior to sending its ultrasound pulse. This allows receivers to directly calculate TOAs (and thus ranges) from the difference of the arrival times of the RF signal and the ultrasonic pulse. As the number of nodes in such a system increases however, they must negotiate to share the RF channel [4].

Broadband ultrasonic transducers, signalling and processing can be used to vastly improve the noise robustness, the number of concurrently trackable users, and the operating range [5]. Further, acoustic simultaneous multiple access makes possible an ad hoc deployment scenario wherein only a single broadcast-style RF trigger would be needed to indicate the start of a ranging time interval for a group of co-located nodes. No additional RF traffic would be incurred by adding nodes to the system. To date however, broadband ultrasonic location systems have relied upon offline post-processing on workstation-class computers. *The implementation of a low power, real-time, embedded signal processing for broadband ultrasound location systems is crucial for their realisation in practical sensor networks and mobile computing*. However, ad hoc positioning over a broadband ultrasonic channel essentially requires each node to incorporate the functionality of an *asynchronous basestation* (to borrow a term from RF communications).

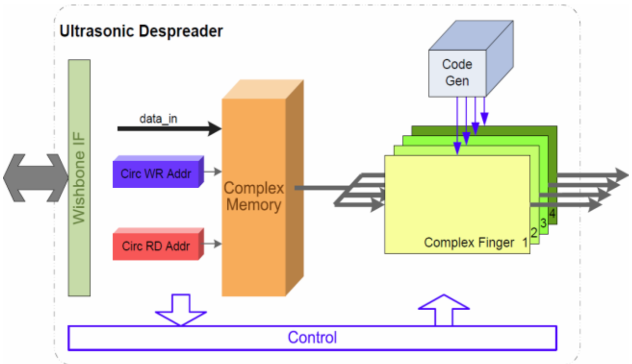
## 2 The Airborne Broadband Ultrasonic Modality for Ad Hoc Indoor Localisation

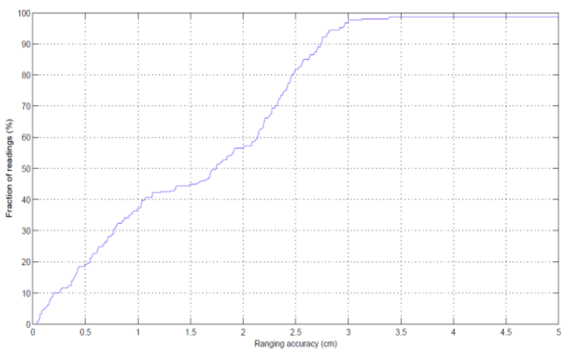
The airborne acoustic channel in ultrasonic frequencies is characterized by a different decay profile to that of RF. Absorption alongside the inverse-square law result in a 6dB attenuation in a signal's sound pressure level (SPL) as its distance from the source doubles [6]. Thus, multipath arrivals from far away are not expected. Nevertheless, short multipath exists, for example due to indoor reflective surfaces such as smooth glass (e.g. monitors and windows). Also transmitter-receiver phase variations due to mismatch and/or mobility affect both of the carrier and code frequencies (both typically in the tens of kilohertz). Therefore, most established RF spread spectrum receiver signal processing methods necessarily fail if one were to attempt to apply them to broadband ultrasound.

Besides pseudoranging and its immediate applicability to ad hoc localization, we posit that broadband ultrasound is a promising modality for indoor context sensing. The term context refers to the physical conditions of the object emitting the acoustic signal with respect to the receiver, be it its distance, orientation when sampled spatially, or even velocity when on the move. Not only these physical quantities are enriching from a user interaction perspective, but also they can be fused to further inform the final location solution. The caveat, however, is increased computational complexity. Therefore, we argue that jointly-designed, custom algorithms and their corresponding hardware realisations are crucial to truly unlock what the broadband ultrasonic modality has to offer. We can envision a rapidly deployable, ad hoc system whose nodes have reconfigurable fabric (e.g. an FPGA) which can be tailored to an application's needs. For example, a node might be configured to dynamically track fast-moving transmitters using Doppler-compensated array processing, or to monitor relatively static transmitters using a simple low-power matched filter, maximising device battery life.

Our ongoing work aims at devising a reconfigurable transceiver with three modes of operation; namely *static*, *Doppler-tolerant*, and with *angular resolution*. In the case of severe Doppler distortion resulting from motion, the *Doppler-tolerant* mode tackles sending a packet in place of a single PN burst. The packet consists of a number of unmodulated codes that would train the receiver adaptively in joint range-speed estimation. In this mode the maximum node separation would be dictated by the code length and acquiring timing readily derives range in subchip resolution. Adaptive training also produces chip-rate phase variations as a byproduct of coherent processing which can be used to estimate velocity. Despite fundamental differences between the two media (e.g. propagation speed) and hence required processing, adaptive methods from spread spectrum underwater acoustic communications perfectly underscore this concept. These coherent algorithms rely heavily on chip-rate adaptation wherein despreading (encountered also in ranging and beamforming) is performed on a per chip basis [7].

Initial results identified a recurring processing kernel in all modes. Using reconfigurable fabric (a Xilinx Virtex 4 device), we have implemented and mapped this algorithm, depicted as a block diagramme, below left. Using a dataset gathered in a real deployment of broadband ultrasound nodes [5], we have characterised its TOA accuracy to be within 3 cm, as shown in the cumulative error distribution, below right. We have also designed a chip-spaced linear array and we will employ this for direction estimation and spatial diversity.

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# *LOSNUS*: An Ultrasonic System Enabling High Accuracy and Secure TDoA Locating of Numerous Devices

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## 1 Summary

Indoor positioning systems based on transmission of ultrasonic (US) signals are mostly directed at the tracking of mobile devices or persons. On the other hand, US locating can also offer significant advantages for systems containing numerous static sensor/actuator devices. An important example is a wireless sensor network (WSN) with numerous nodes. WSN application can be significantly improved by node locating, e.g. network integration of nodes, supplying node locations to application programs, supervising locations with respect to accidentally dislocating, detecting faking of node locations. For delivering these services, the indoor positioning system should be permanently installed demanding cost saving solutions of system structure and components. It has to provide both locating of mobile and static nodes and has to deliver high location accuracy for coping with numerous concentrated nodes. As presented in this paper, the indoor US locating system *LOSNUS* (Locating Sensor Nodes with UltraSound) is designed to meet these demands [1, 2].

## 2 Design goals of the indoor US locating system *LOSNUS*

*Low cost installation*: Locating based on an optimized sequence of US signals delivers medium locating speed in conjunction with reduced signal interferences. Rooms are equipped with minimum five to six broadband US transmitters (Polaroid 600) on the walls next to the ceiling. The transmitters are activated in a well-defined sequence (Fig. 1) where each transmitter sends a signal frame containing a precise time mark (chirp coded signal) and an individual transmitter code (Fig. 2). Only one activation unit is used supplying the room transmitters with differently coded signals. The sequence of US frames is stored in the activation unit which amplifies the signals to an appropriate signal level and transmits each frame by means of a signal demultiplexer and an individual cable to an US sender.

*Low cost node equipment*: US receivers of network nodes need minimal additional analog and digital hardware (Fig. 3). This hardware includes a microphone, an amplifier and filter, and two comparators. Digitized frame bits can easily be read via a synchronous shift register of the microcontroller. Time stamps of the local clock mark the start of frame receptions. The

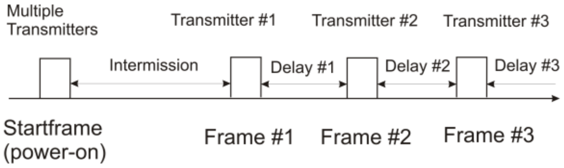


Figure 1: Sequence of transmission with start-frame (only single cycles) and non-overlapping reception of transmitter identifying frames

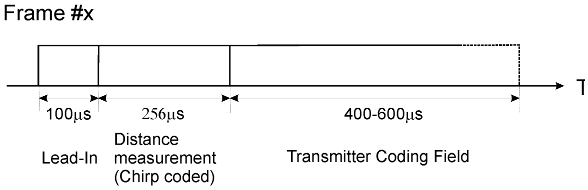


Figure 2: Setup of a transmitted frame consisting of lead in, constant chirp and transmitter coding time slot (used frequency band 35 kHz – 65 kHz)

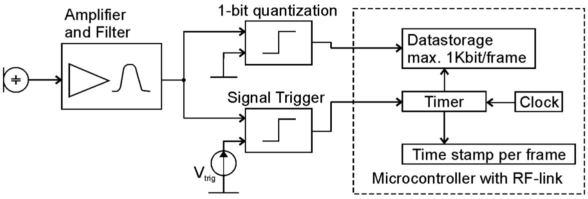


Figure 3: US receiving device with local data storage of frames which are sent after a location cycle by RF link to the locating server: Microcontroller with additional microphone, amplifier and filter, one-bit quantization of US signal with 1 Mbit/s, signal trigger for roughly marking the local time of frame reception

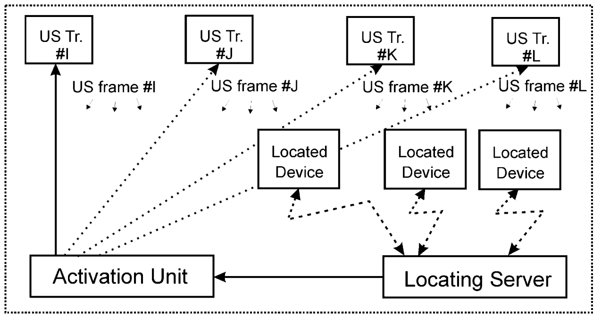


Figure 4: System overview: Sequential sending of US frames by the transmitters, communicating of received frame data by the devices to the locating server which is calculating the device locations

microcontroller stores portions of received signals enabling computing high resolution TDoA. US frame receiving nodes are not enabled for calculating their own locations. Instead of that, received frame data (0.1~1 kbit/frame) are transferred to a central location server which calculates node locations and is also responsible for functional services, especially node integration into the network, and security checks.

*Location server, security of locating*: Node locations are evaluated by the location server which also controls the locating sequence (Fig. 4). Omitting any RF start information, locations have to be calculated by a TDoA algorithm considering the given transmitter delays of the transmission sequence. The currently used resolution of the receiver time stamps of 1µs (~0.33mm) typically leads to position shifts of localized nodes of <1cm. Calculated node locations are delivered back to the nodes. Each node features an individual activity rate which is also used for periodically taking part in current locating cycles. For path tracking of mobile nodes the locating rate can be realized up to about 10 cycles/s. For many applications sensor node locations are crucial parameters which have to be checked up on legality. To prevent delivering faked static node locations, US locating sequences and transmitter coding can be changed frequently or permanently which enables fake detecting.

## 3 Methods providing high accuracy and robust frame detection

*High accuracy*: The uniform chirp coded part of each frame delivers high time resolution and fast recognition of transmitter codes. Additionally, a calibration of local receiver clocks with respect to the unique clock of the activation unit is performed. Each frame of a sequence is repeated after a short well-defined delay. By scaling the measured frame delays of a receiver to the given values, an effective clock calibration of the receiver clock is achieved.

*Frame delays*: The defined frame delays are adjusted for guaranteeing a non-overlapping reception of line-of-sight (LoS) transmitter signals. In case of overlapping of a LoS signal with an echo of a former transmitted signal, a mostly perfect decoding of the larger LoS signal is resulting. E.g. considering delays in a medium sized room of about 30 $m^2$, the locating cycle time using six transmitters is anyhow < 50ms. If sending pairs of locating sequences for applying clock calibration, 10 cycles/s, each with 12 frame transmissions can be performed.

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# Accurate indoor positioning for mobile phones using ultrasound

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## 1 Introduction

Currently outdoor Location Based Services (LBS) have the advantage of reliable positioning via GPS (also Wi-Fi and GSM) and a defined business model for the delivery of content to the user. This has led outdoor LBS to greatly expand in recent years, though indoor locationing technologies and methods have yet to fully mature on mobile devices. In the current state of the art in indoor LBS, merging accurate indoor positioning and context-sensitive services is still an outstanding problem. Existing systems such as employee tracking [1] using RFID/Wi-Fi tags or badges are relatively cheap to implement, but no development path for mobile device RFID currently exists in Europe. For context-sensitive services, such as a virtual tour guide, factors such as device cost, functionality and service provision are still stumbling blocks to effective implementation of solutions. A frequent example would require the user to point a device at a tag or enter an exhibit's number manually. Such approaches are time consuming, complex and require user focus (thus distracting them from the exhibits). In addition, inability to provide effective user navigation (e.g. how to find an exit) and lack of rich media multimodal interfaces has led to a disparity between device capabilities (where media delivery is a de facto standard) and quality user focussed services.

Although approaches such as computer vision [2] are viable for indoor locationing, the most straightforward approaches use signal propagation with Radio Frequency (RF) or sound. Currently it is impossible to achieve accuracy below one meter [3] using RF-based technologies present in mobile phones such as GSM, Wi-Fi and Bluetooth [4-6]. Time-of-arrival does offer robust performance [7], however for RF this requires specialised equipment, which is why less direct approaches using signal strength and bit error rate have to be used. Sound, being significantly slower than RF, is easily localised to a few centimetres (due to longer time of arrival). Borriello et. al. [8] showed that it is possible to emit 21 KHz (just above the human hearing range) signal from a mobile phone speaker and successfully receive with a conventional microphone. In a separate study Peng et. al. [9] showed that it is possible to utilize sound in order to measure the distance between two mobile phones using time-of-arrival. These two principles are combined in our method that involves trilateration of an inaudible ultrasound signal using a static microphone array.

## 2 Proposed Solution

The proposed approach is to generate a simple sine tone ultrasound signal using inbuilt mobile phone speakers. The signal is then received by up to four matched DPA microphones, each located in one corner of the test laboratory, and processed using a Pro Tools HD system. Live audio streams from the four microphones are then analyzed in real time by DSP filters tuned to specific ultrasound frequencies. The arrival time at each microphone is then used to calculate the position of the signal source using trilateration. The derived position can then be combined with accelerometer (pitch and roll) and magnetometer (yaw) readings (which are now standard on many smartphones) in order to obtain the position and orientation of the device. This combination of position and azimuth can then used for directional querying of points of interest (POI) within the environment. The concept of functional area is introduced in order to describe the size and shape of the area in which the device can effectively operate. To the best of our knowledge the concepts of functional area and ultrasound trilateration of a mobile phone have not been attempted in other work, and thus represent novel contributions to the field.

## 3 Test Design

Test 1: A test tone emitted from a loudspeaker is used to calibrate the detection algorithms relative to the output of several current smartphones (e.g. Android, iPhone, Nokia). This will lead to an initial definition of the concept of functional area, specifying the size and shape of an area a device can effectively be located within using ultrasound.

Test 2: An emitted tone from a device is detected and processed for intensity and is then repeatedly measured by emitting the same tone from the device at discrete distance intervals on both x and y planes (height is maintained to keep the z dimension static). These intervals will be defined relative to the functional area for each device, as determined in experiment 1.The comparison of these results will lead to the definition of location for the x and y axis of the test environment using trilateration. This will then be compared to randomised locationing signals to determine how effectively the algorithm can position the source in a given environment by using the test data to predict the current position of the device.

## 4 Conclusions

This paper presents two new concepts: ultrasound trilateration of a mobile phone and functional area in the context of such positioning system. The first test illustrates the concept of functional area, which we consider important to practical application of ultrasound locationing within a given environment. The second test illustrates the concept of ultrasound trilateration using mobile phone hardware, which is essential to solving the problem of accurate indoor positioning using a mobile device.

Future work will consider the use of larger calibrated arrays of microphones to determine azimuth of the signal source. In so doing, the concept of multiple trilateration points will be investigated to further refine the locationing accuracy of the method. In addition, the notion of azimuth (direction) of the source will also be investigated using such larger arrays, to determine whether signal strength (and accelerometers) can be used to determine the current direction of the device.


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# Robust ultrasonic indoor positioning using transmitter arrays

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## 1 Summary

As time-delay based ultrasound positioning often is noise sensitive, the goal of the research reported here is to achieve sub-room ultrasound positioning with other methods. By combining a portable ultrasound receiver which measures signal strength and Doppler shift with a transmitter array that sends steered, coded beams inside a room, the tag can determine which beam it is located in and carry out fine-positioning. The concept is demonstrated in an experiment using a 40 kHz system with 4-7 transmitter elements.

## 2 Introduction

Ultrasound positioning systems can be classified according to the need for RF, i.e. whether they are based on ultrasound alone (1), or hybrid, combining ultrasound and RF (2). They can also be classified according to the positioning principle: time-delay based (A) or based on other parameters such as the ability to communicate, signal level and Doppler shift (B).

We have previously developed ultrasound systems using only the ability to communicate as a positioning criterion (class 1B). These systems have the capability to indicate in which room a transmitter is located [Holm et al, ICASSP 2005, and Holm, IEEE Ultrason. Symp 2005]. It is now used commercially for tracking of assets and personnel [Greenemeier, Scientific American, 2008]. Nevertheless it has some shortcomings, the primary one is a relatively low update rate resulting in a chance to miss items if several objects are to be located in a short time. A second disadvantage is that portable ultrasound transmitters may expose human bearers to levels that are near the maximum recommended levels, due to proximity to the ears. We therefore focus here on a hybrid system with a reversed flow of ultrasound, so that the portable tag only contains an ultrasound receiver and no transmitter. In addition there is an RF unit for communicating the data [Holm, IEEE RFID, 2009].

Many hybrid systems of class 2A have been developed, such as Active Bat, Cricket and Dolphin. They have a high accuracy in the cm-range, but often a very low robustness to external noise. The experience is that they easily break down in real life. In our view this is due to the large (+/- 30 dB) variation in the background noise level, see [Holm, IEEE RFID, 2009] for a link budget analysis.

## 3 Array based system

The goal of our research is to determine how accurately a system can perform in a real-life environment without relying on time-delay estimation. The required components are a portable tag with an ultrasound receiver which outputs the Received Signal Strength Indicator (RSSI) value and the velocity as described in [Holm, IEEE RFID, 2009], and one or more stationary, array-based ultrasound transmitters.

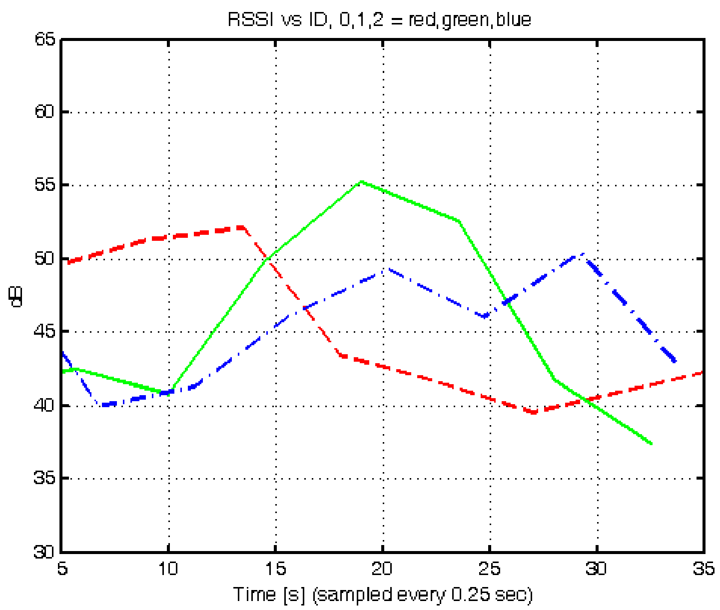
The new feature of this paper is the array-based transmitter, which can be either 1- or 2-dimensional. The 1-d array is usually oriented in the horizontal plane, e.g. high up on a wall. Such an array will send out a beam of approximate width $\lambda/D$ (radians), where $\lambda$ is the wavelength and D is the total aperture.

The array is configured to transmit data and steer its beam electronically in the array plane. In this way sectors may be formed, typically 3-7, to cover a medium sized room. The transmitter first sends its data into sector 1, then shifts its beam to sector 2, and so on, and may repeat this pattern continuously. The transmitted data may consist of an optional room ID + sector IDs. The array is used in combination with RSSI and Doppler measurements in the movable receiver. By comparing the RSSI-values, the tag will know in which sector it is located. For example two arrays mounted on perpendicular walls may be used to form a grid of about 1 m. In addition, the Doppler shift may be used for estimation of the velocity vector.

## 4 Results

We have done RSSI measurements on horizontally steered beams from a 40 kHz array. The experiments were done in a relatively narrow room of size 2.8 x 8 x 2.3 (height) meters. The array was high up in a corner, and every second a new beam with a new ID was sent. We compared two arrays, both with a horizontal beamwidth of 0.25 radians or 14 degrees. The difference was that the first array (4 elements in a single row), had a vertical beamwidth of +/- 40 degrees, while the second one (7 elements arranged in two rows) had half this value.

The figure shows the RSSI measured from the 7-element array, as the tag is slowly moved across the beams at a distance of 4 meters. From 5 to 14 seconds it is in the beam with ID=0 (-15 deg, dashed), from 14 to 26 seconds it is in the central beam with ID=1 (solid) and for the rest of the time it is in the ID=2 beam (15 deg, dash-dot). Thus, from a simple comparison of RSSI the sector number can be found.




The array with the wider vertical beam gives similar results but the contrast is smaller, i.e. the distance in dB between the actual beam in a certain direction and the other beams. This is believed to be due to the increased number of reflections via the ceiling and the floor.

## 5 Conclusions

Our first results demonstrate the feasibility of horizontal beam steering for positioning. The stronger the direct beam compared to reflections from surfaces above, below and to the sides, the better the concept will work. This means that the larger the room the better, but even in our narrow lab the concept worked well. The influence from the reflections from the ceiling and floor were reduced with a narrower vertical beamwidth.

# Fast and Accurate Ultrasonic 3D Localization Using the TSaT–MUSIC Algorithm

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## 1 Summary

In this paper, a fast and accurate indoor localization technique using the MUSIC (multiple signal classification) algorithm is described. The MUSIC algorithm [1] is known as a high-resolution method for estimating DOAs (directions of arrival) or propagation delays. One of the critical problems in using the MUSIC algorithm for localization is its computational complexity. Therefore, we devised a novel algorithm called TSaT–MUSIC, which can rapidly identify DOAs and delays of multicarrier ultrasonic waves from transmitters. Computer simulations have proved that the computation time of the proposed algorithm is almost constant and is shorter than existing methods that use the MUSIC algorithm, because the computational complexity of the latter increases in proportion with the number of incoming waves. Experiments in real environments revealed that the standard deviation of position estimation in a 3D space is less than 10 mm, which is a satisfactory accuracy level for indoor localization.

## 2 The TSaT–MUSIC Algorithm

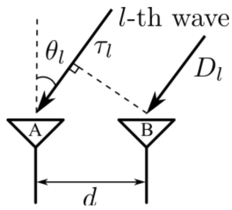


Figure 1. Relation between two sensors

A method for localizing a transmitter in a 2D space estimates its distance (propagation delay) and orientation (DOA) from a static receiver. The MUSIC algorithm itself can identify either the delay or DOA, but not both simultaneously. Extended MUSIC algorithms, such as TST–MUSIC [2] or 2D–MUSIC [3] integrate the spatial MUSIC (S-MUSIC) for estimating DOA and the temporal MUSIC (T-MUSIC) for estimating the delay. However, these existing algorithms consume much computation time and thus are not always suitable for applications such as human motion tracking that require real-time localization. The TSaT–MUSIC algorithm, on the other hand, can rapidly determine the pairing of the DOAs and delays. The TSaT–MUSIC algorithm uses multicarrier ultrasonic waves and estimates their DOAs and delays with S-MUSIC and T-MUSIC, respectively. When the number of incoming waves is *L,* their DOA and delay values are described as $(\theta_1, \theta_2, ..., \theta_L)$ and $(\tau_1, \tau_2, ..., \tau_L)$ at sensor A, as shown in Figure 1. By using T-MUSIC again at sensor B, delays can be estimated as $(D_1, D_2, ..., D_L)$. The path length of the $l$-th incoming wave that arrives at the sensor A is $d\sin\theta_l/c$ longer than that arriving at sensor B, where $c$ is the sound velocity and $d$ is the distance between the two sensors. Therefore, when we plot $L^2$ points as possible DOA–delay pairs in the $(d\sin\theta, c\tau)$ space, as shown in Figure 2, the following equations must be fulfilled:

$$c\tau_l - d\sin\theta_l = cD_l \ (l = 1, \cdots, L)$$

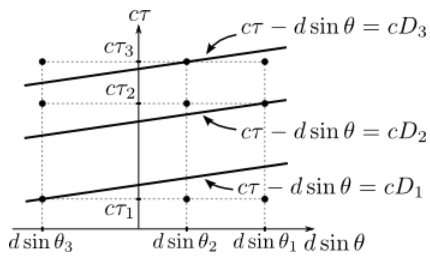


Figure 2. Candidate DOA–delay pairs and path difference lines on the $d\sin\theta - c\tau$ space

The equations drawn in the $(d \sin \theta, c\tau)$ space are called "path difference lines". Theoretically, only one point that represents a correct DOA–delay pair must be on each line. In real environments, however, the correct point is not always on the line because of noise. Hence, we calculate the distance $\mid c\tau_j - d \sin \theta_i - cD_l \mid / \sqrt{2}$ between each candidate point $(d \sin \theta_i, c\tau_j)$ and the path different line $c\tau - d \sin \theta = cD_l$, and select the point with the minimum distance.

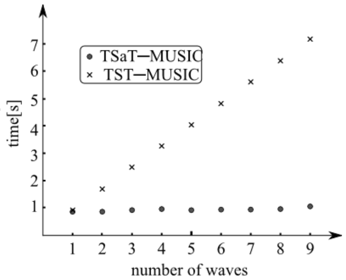

Figure 3. Computation time of TSaT–MUSIC and TST–MUSIC algorithms

The computational complexity of the TSaT–MUSIC algorithm can be estimated as $\max(\mathrm{O}(K_T^3), \mathrm{O}(g_T K_T^2))$, where $K_T$ is the number of subcarriers and $g_T$ is the number of searches conducted along the time-delay axis. On the other hand, the computational complexity of the TST–MUSIC algorithm is $\max(\mathrm{O}(LK_T^3), \mathrm{O}(Lg_T K_T^2))$. We have compared the TSaT–MUSIC and TST–MUSIC algorithms through computer simulations by varying the number of incoming waves $L(L = 1, 2, \cdots, 9)$. From Figure 3, the TSaT–MUSIC algorithm can estimate DOAs and delays in almost constant time, whereas the computation time of the TST–MUSIC algorithm linearly increases as $L$ increases. This remarkable feature of the TSaT–MUSIC algorithm is useful for rapidly estimating positions of multiple transmitters.

## 3 Experimental Results and Future Work

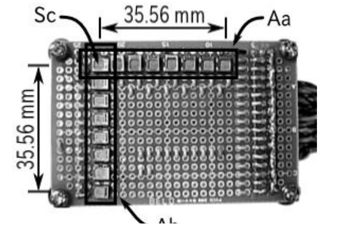

Figure 4. Ultrasonic receiver

We used an ultrasound transmitter (PIONEER PT-R4) and receiver where 15 ultrasonic sensors (SPM0204UD5 from Knowles, Figure 4) are arranged in an *L*-shaped manner and conducted localization experiments in real environments. The frequencies of six subcarriers were 34~39 kHz (their interval was 1 kHz). Two angles, $\theta_a$ and $\theta_b$, and one time delay $\tau_c$ were estimated by using two sensor arrays Aa and Ab, and the sensor $S_c$, respectively. As shown in Figure 5, the position of the transmitter from $S_c$ is described as:

$$(x_0, y_0, z_0) = (c\tau_c \cos \theta_a, c\tau_c \cos \theta_b, c\tau_c \sqrt{1 - (\cos^2 \theta_a + \cos^2 \theta_b)})$$

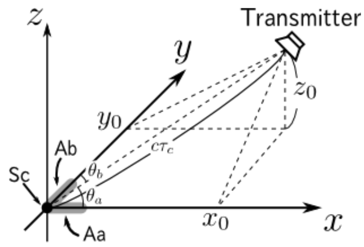

Figure 5. The position of the transmitter

3D positions of two transmitters ($L$ = 2) placed at points Ta (200, -350, 1000) and Tb (-500, 250, 1400) (unit: mm) were estimated simultaneously. The result gained through 10 times measurements was that the average position estimates of Ta and Tb were (192.94, -370.10, 1037.60) and (-478.03, 263.28, 1441.36), and their standard deviations were (9.39, 3.89, 3.17) and (5.94, 3.61, 2.18), respectively. This proved that the accuracy level of the proposed algorithm is satisfactory for indoor 3D localization. One of our future works is to apply the algorithm to several applications such as robot tracking and navigation.

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# A tag-free solution to unobtrusive indoor tracking using wall-mounted ultrasonic transducers

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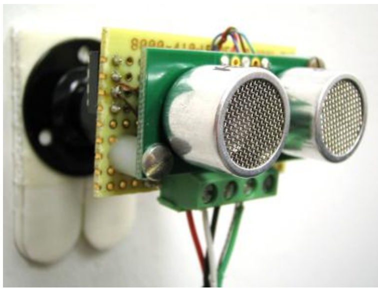
## 1 Summary

Methods for indoor tracking typically require a person to carry some type of a body worn tag. A novel *tag-free* solution is presented that utilizes low cost wall-mounted ultrasonic transducers. The active ultrasonic transducers capture analog echoes, which are then digitized and analyzed in order to calculate the 1D range of the moving person. The tracking algorithm utilizes a number of signal processing techniques including band-pass filtering, Hilbert transformations, and background subtraction to remove interference from other objects in the room. The range data from multiple sensors are treated as observations in a Bayesian framework using the sigma-point Kalman smoother (SPKS) to determine a person's 2D position and velocity. The SPKS also performs "self-calibration" or simultaneous localization and mapping (SLAM) to determine the location of the wall-mounted transducers. The indoor tracking accuracy of the tag-free system is better than 0.5 meters.

## 2 System and Method Overview

Indoor tracking systems rely on a variety of sensors and approaches, ranging from RFID, infrared, ultrasonic transducers, received signal strength indication (RSSI), to ultra-wide-band (UWB) time-of flight-measurements. All these approaches require the user to carry some type of physical device or tag. In some applications (e.g., monitoring activities of daily living of seniors in independent living facilities), wearing a tag may be seen as undesirable or simply a nuisance. Unfortunately, unobtrusive tag-free tracking options are quite limited. Arrays of infra-red (IR) motion sensors may be employed to determine region level location, but are expensive and complicated to install. Video based tracking draws from advances in automated surveillance and can often be very effective, though performance may degrade with complicated background clutter and other non-ideal environments. However, privacy is a major concern as people don't want video cameras in their home, constantly monitoring their activities. In this study, we evaluate the feasibility of achieving the unobtrusive tag-free tracking using a system based on wall-mounted ultrasonic transducers.



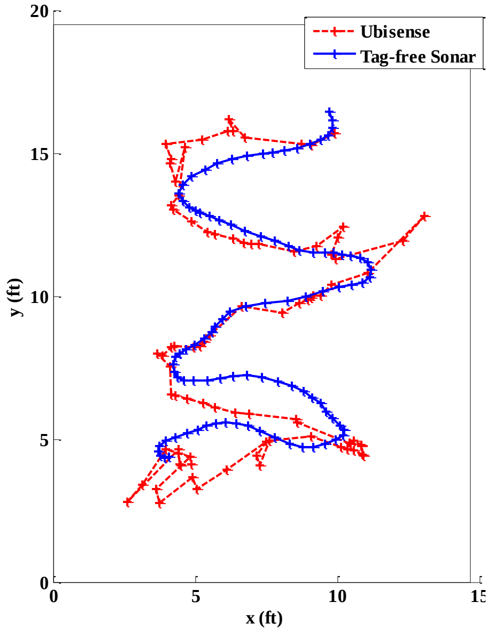
Wall-mounted sonar module

Hardware: Wall-mounted "sonar-modules" were constructed by re-purposing active ultrasonic sensors typically used for robot localization. Specifically, we use a low cost unit manufactured by Devantech Inc., which has two separate transducers for transmitting the ultrasound and for listening to the corresponding echo. The transducers operate at 40 kHz and have a range from 3cm to 4m. An array consisting of six sonar-modules was mounted on the walls of a room. Much of the Devantech circuitry was bypassed using a custom pre-amp to sequentially trigger the sonar-modules. A multi-channel DAQ digitizes the received signals for real-time recording using a PC and the MATLAB data acquisition toolkit. The specific sonar-module that emits an ultrasonic signal and records the primary echo is referred as the "active" unit. The other 5 sonar-modules act as "passive" units and record indirect reflections or shadows coming from the active unit. All 6 sonar units are sequentially triggered and signals recorded at a 2 Hz cycle.

Signal Processing: A number of signal processing steps are carried out on the received signals in order to estimate range data. Simplistically, the range corresponds to the timing at which the maximum energy from an echo is received. A signal is first band-passed and then processed using the Hilbert transformation in order to extract its instantaneous envelope. A background subtraction process using an autoregressive time-averaging technique is applied on the envelope to remove echoes from static objects (e.g., chairs in the room). An adaptive threshold is then used to determine the locations of strong echoes. Finally, clustering is performed to determine several candidate range estimates. These candidate range estimates provide the observations for the subsequent tracking algorithm.

Tracking Algorithm: Core to our system is the use of the sigma-point Kalman filter (SPKF) The SPKF is a recursive Bayesian estimation approach that has recently become a popular better alternative to the extended Kalman filter (EKF). For tracking purposes, we use a Rauch-Tung-Striebel sigma point Kalman smoother (RTSSL-SPKS), which works as a fixed-lag smoother.

The SPKS fuses a predictive model of a human walking with multiple range measurements from the ultrasonic sensors to track 2D position and velocity. A coordinated turn (CT) model is used to mimic human walking. Observations correspond to all range estimates from the processed active and passive sonar-modules. A *gating* technique is also used to avoid confusion from multiple potential range candidates. Instead of performing an offline sensor calibration, "self-calibration" is achieved using simultaneous localization and mapping (SLAM), corresponding to simultaneously estimating the state of the person (position and velocity) and the parameters of the observation model. Parameters correspond to the 2D sonar module locations along with a correction factor for the speed of sound to account for multipath and other measurement errors. Two filters are run simultaneously; one SPKS to track the person given the current estimated parameters, and a second SPKS to estimate the parameters given the current estimated location of the person. Convergence of the SLAM is usually within 5-10 seconds of tracking.



Tracking Performance

## 4. Result and Conclusion

Testing was performed in a 6x5 m lab used to develop assistive technologies for the elderly. A number of trials were conducted in which different subjects followed random trajectories. For benchmarking, we compared performance to an accurate commercial tag-based system developed by Ubisense, which uses UWB for time difference of arrival (TOA) localization. A comparison is shown in the figure above. Performance of our tracking system based on 50 trials gives an average accuracy to within .41 meters.

# An Accurate Technique for Simultaneous Measurement of 3D Position and Velocity of a Moving Object Using a Single Ultrasonic Receiver Unit

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## 1 Summary

An ultrasonic localization system is described in the paper. To the best of our knowledge, this is the first system that can simultaneously identify not only the 3D position [1], but also the velocity of a moving object. The proposed system uses an original and innovative method called "extended phase accordance method" (EPAM) that can precisely identify the distance between an ultrasonic microphone and a moving transmitter by rapidly estimating the frequency shift of the transmitted signal. One remarkable feature of the proposed system is the use of a single compact receiver unit, which will reduce deployment labor and costs. Experiments proved that the proposed system shows the 3D position and velocity estimation with sufficient accuracy.

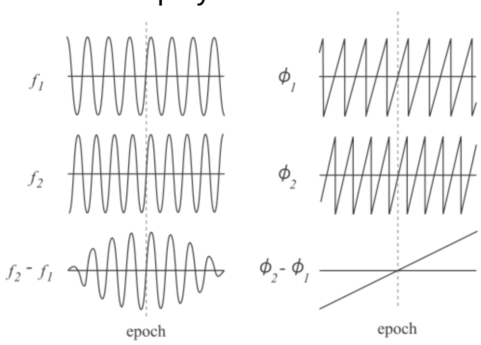

Figure 1: Sync pattern and epoch

## 2 The Proposed System

### 2-1 Extended Phase Accordance Method

EPAM is an extended version of the phase accordance method (PAM) for localizing a moving object. In PAM, a burst signal called "sync pattern" composed of two ultrasonic waves with different frequencies is sent from a transmitter, as shown in Figure 1. To identify the time of arrival (TOA) of a sync pattern, an epoch at which the phase difference of the waves becomes zero is set at the transmitter and is precisely detected at the microphone [2]. When a transmitter moves, the frequencies of the transmitted waves change because of the Doppler effect and PAM does not work properly. Despite the Doppler effect, the amplitude of the signal from the transmitter does not change. When the frequency shift is unknown, the amplitude is not correctly estimated by using quadrature detection. However, when the frequency shift is known, the correct amplitude can be found through quadrature detection using a sinusoidal wave of any frequency. This means that by conducting quadrature detection with two waves with different frequencies and assuming that the amplitudes obtained through them become equal, the frequency shift of the received signal is correctly estimated. In our current implementation, we used two different reference frequencies (39.75 and 40.25 kHz) and confirmed that this unique method can rapidly and accurately identify the frequency shift of the transmitted signal [3].

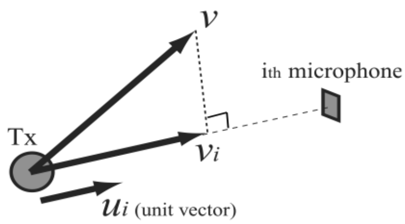

Figure 2: Geometric relation between Tx and the $i^{th}$ microphone

### 2-2 Estimating 3D Position and Velocity

In TOA-based ultrasonic localization, theoretically, the 3D position of an object (e.g., transmitter) is calculated as an intersection point of three spheres whose centers (e.g., microphones) are at different fixed points. In reality, however, the measured distance between a transmitter and a microphone includes errors. 3D positioning errors can be reduced by making the baselines between the microphones longer. On the other hand, we designed a compact receiver unit by mounting microphones with a small baseline, because EPAM performs accurate distance measurements. In our current implementation, four microphones (baseline 76.2 mm) on the unit were used to detect distances to the transmitter and estimate its 3D position. The velocity vector of the transmitter was obtained so that the equations $v \cdot u_i = v_i \ (i = 1,2,3,4)$ are satisfied, as shown in Figure 2, where $v$ is the velocity vector, $u_i$ is the unit vector directed from the transmitter to the $i^{th}$ microphone, and $v_i$ is the detected velocity at the $i^{th}$ microphone based on frequency shifts of transmitted signals from the transmitter.

## 3 Experiments and Conclusions

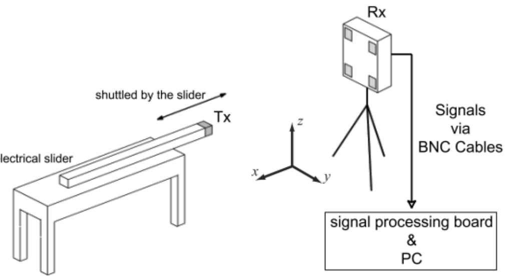

Figure 3: Experimental setup

The experimental setup is shown in Figure 3. The receiver unit whose size is $80 \times 80 \times 60$ mm contains four ultrasonic microphones (SPM0404UD5 by Knowles Acoustics Corporation) as shown in Figure 4. The electrical slider mounts one transmitter (T40-16 by NIPPON CERAMIC Corporation) transmitting a sync pattern composed of 39.75 and 40.25 kHz sinusoidal waves, and moves back and forth perpendicularly to the receiver unit. The distance between the transmitter and the receiver unit varied constantly between 1000~1800 mm. The velocity of the slider was set to 0.1, 0.5, 1.0 and 1.5 m/s. The update rate of the 3D position and velocity estimations was set to 5 Hz. Measurements were conducted about 1500 times at each velocity. Table 1 shows that the 3D positions of the transmitter were estimated with high accuracy; standard deviations (S.D.) were less than 22 mm at each velocity. The measured velocity results are shown in Table 2, which also proves that the system can accurately estimate the velocity of the moving transmitter. We are now applying filtering methods, such as the extended Kalman filter (EKF), by integrating measured positions and velocities for more accurate estimations.

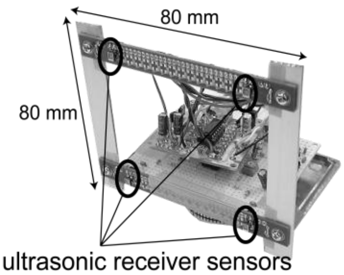

Figure 4: Ultrasonic receiver unit

Table 1: Results of 3D position estimations

| v [m/s] | average error [mm] | S.D. [mm] |
|---|---|---|
| 0.1 | 36.0645 | 18.2219 |
| 0.5 | 34.7328 | 18.5544 |
| 1.0 | 45.2873 | 21.2573 |
| 1.5 | 46.7585 | 20.3769 |

Table 2: Results of 3D velocity estimations (for the same coordinate system as shown in Figure 3)

| v [m/s] | average velocity [m/s] | S.D. [m/s] |
|---|---|---|
| 0.1 | (0.1011, 0.0803, 0.1569) | (0.0197, 0.1345, 0.2118) |
| 0.5 | (0.4913, 0.0512, 0.1502) | (0.0242, 0.1613, 0.2644) |
| 1.0 | (0.9809, 0.0528, 0.1211) | (0.0284, 0.1854, 0.3270) |
| 1.5 | (1.4873, –0.0083, 0.1609) | (0.0311, 0.2308, 0.4056) |

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# Ultrasonic LPS: architecture, signal processing, positioning and implementation

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## 1 Summary

An ultrasonic Local Positioning System (LPS) is presented, based on five transmitting beacons to be placed in the environment, whereas a receiver is located onboard a mobile robot. The ultrasonic transmissions have been encoded by Kasami sequences to improve system performances and immunity to noise. A Field-Programmable Gate Array (FPGA)-based implementation of the receiver is proposed to achieve real-time computing in determining the Differences in Times-Of-Arrival (DTOA) and derive the position coordinates.

## 2 Global overview

The developed LPS is based on five beacons that are placed at the ceiling as shown in Fig. 1.a. Every beacon consists of a cylindrical PVDF emitter by MSI Inc. and of a conical reflector, which is used to increase the covered area in the environment. A Kasami code $c_i$ of length $L$ is assigned to each beacon, since the suitable properties of auto- and cross-correlation among them allow simultaneous emissions from all the beacons every 100ms. The Kasami code $c_i$ is BPSK modulated to focus the transmission $m[n]$ in the maximum spectral response of transducers (1):

$$m[n] = \sum_{k=0}^{L-1} c_i[k] \cdot s[n - k \cdot N_c \cdot M] \quad (1)$$

In (1) $c_i[n]$ is the Kasami code; $L$ is the length of the sequence and $s[n]$ is a symbol formed by $N_c$ periods of the carrier ($f_c = 1/T_c$), with $M$ samples per period. The parameter $M$ is also the ratio between the carrier frequency $f_c$ and the acquisition $f_S$, so $M = f_S/f_c$.

Regarding the receiver, it is based on the Panasonic electret microphone WM-61B and on the FPGA-based Nexys2 platform by Digilent, Inc. As can be observed in Fig. 1.b, the signal received by the microphone is amplified and acquired by ADCS7476, and then processed in Xilinx XC3S1200E FPGA, both are included in the platform mentioned before. The acquired signal $r[n]$ is BPSK demodulated first according to

$$d[n] = \sum_{k=0}^{N_c \cdot M - 1} r[k+n] \cdot s[k]. \quad (2)$$

In (2) $d[n]$ is the output from the demodulation stage; $r[n]$ is the input signal coming from the acquisition stage and $s[n]$ is the symbol of the demodulation, formed by $N_c$ periods of the carrier, each one represented by $M$ samples. Note that the parameter $M$ is again $M = f_S/f_c$.

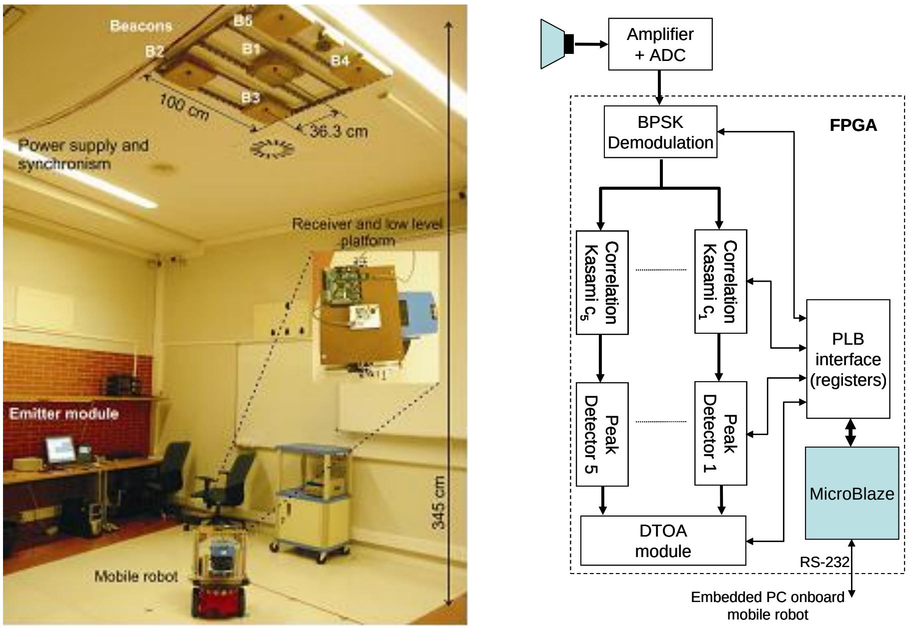


Fig. 1. a) Global view of the developed LPS. b) Block diagram of the proposed receiver.

The demodulated output *d*[*n*] is correlated in order to search for possible emissions coming from the different beacons existing in the environment, as described in (3).

$$t[n] = \sum_{k=0}^{L-1} d\left[k\cdot\left(N_c \cdot M\right)+n\right]\cdot c_i[k], \quad (3)$$

where $t[n]$ is the correlation output; $d[n]$ is the demodulation output; $c_i[n]$ is the Kasami code emitted by a beacon $i$; and $L$ is the length of the mentioned code. Finally, a peak detector for each beacon is used to determine the instant of arrival of the corresponding transmissions, so the DTOA module can determine the Differences in Times-Of-Arrival (DTOA) among the different beacons. These DTOAs are measured from the arrival of the first transmission within a maximum analysis window limited by the beginning of the next emission cycle.

All these processing blocks proposed for the determination of DTOA are connected to a Xilinx MicroBlaze processor as a peripheral device through a PLB bus, so the processor can access the registers in order to configure the processing modules and read the DTOAs that are obtained every emission cycle. Furthermore, a hyperbolic Cayley-Menger bideterminant-based algorithm is C programmed in the MicroBlaze processor to obtain the position of the mobile robot in the area covered by the LPS. These position coordinates are sent to the embedded PC onboard the mobile robot by a RS-232 link.

## 3 Conclusions

A real-time implementation of an ultrasonic LPS has been presented. Apart from the autonomous beacons placed in the environment, a suitable computing platform has been proposed for processing the ultrasonic transmissions, determining the Differences in Times-Of-Arrival (DTOA) and computing the position coordinates of a receiver onboard a mobile robot. The proposed solution is based on a FPGA development, where some processing tasks have been implemented in specific hardware modules, whereas the positioning algorithm has been programmed in a software processor core, due to the high complexity of its calculations.

# Analysis of the Performance of an Ultrasonic Local Positioning System based on the emission of Kasami codes

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## 1 Summary

This work presents a thorough performance analysis of an Ultrasonic Local Positioning System (ULPS). The system is composed of four beacons, placed in the upper corners of a rectangular room, that emit orthogonal Kasami codes BPSK modulated with a carrier frequency of 50 kHz. These emissions are detected by the receiver by pulse compression, giving the system a centimetric precision. A complete model of the system has been built to conduct this study, considering effects such as the ultrasonic transducers response, signal attenuation in air, multipath propagation, reflection coefficient of walls and floor and receiver response. This model helps to identify critical zones where the self-induced noise generated in the cross-correlations masks the main peaks of the auto-correlations, making it difficult to obtain reliable Time-of-Flights from which the receiver's position is determined. Also, the dependence of these critical zones with different parameters integrated in the model is investigated.

## 2 Model description

The proposed model is based in four linear stages that simulate the different phenomena described above to obtain the impulse response of the system as:

$$h(t) = h_1(t) * h_2(t) * h_3(t) * h_4(t) \qquad (1)$$

where $h_1(t)$ stands for the impulse response of the ultrasonic transducer (beacon); $h_2(t)$ represents the response of the air channel; $h_3(t)$ models the multipath propagation effect and $h_4(t)$ is the impulse response of the ultrasonic microphone (receiver). When modelling the impulse response of the beacons, both their frequency response and the filtering associated with the emission pattern have been taken into account. The impulse response of the air channel models geometric spreading and the frequency dependant atmospheric absorption. The effect of multipath propagation introduced by $h_3(t)$ (room impulse response) has been calculated using a simple image method and finally, the impulse response of the receiver $h_4(t)$ takes into account the same effects than that of the emitters. These responses ($h_1$ and $h_4$) have been modelled from the information provided by the manufacturer.

The signals emitted by our system are four orthogonal 255-bit Kasami sequences that have been BPSK modulated with a 50 kHz carrier. A modulation symbol of one cycle has been used thus obtaining a 5.1 ms emission duration. These emissions are convolved with the impulse response *h(t)* and added together to give the received signal *r(t)*. This signal is then processed by a reception stage based on two main blocks, as represented in Fig. 1. First, four correlators search for the reception of the transmitted signals. Then, peak detectors perform the estimation of Time-of-Flights (TOFs) for each emitter. The four estimated TOFs are finally provided to a spherical positioning algorithm based on the Cayley-Menger determinant to obtain the receiver location.

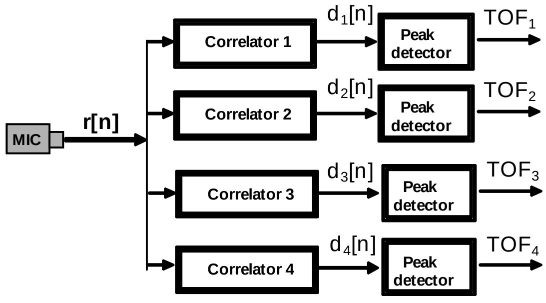


Fig. 1. General block diagram of the reception stage.

## 3 Results

Figure 2 shows the type of results generated by the proposed simulator when the receiver is at the position x = 0.8 m, y = 1.2 m and z = 1 m. As can be seen, the correlation peaks for each emission can be clearly indentified. In this case, the position estimated by the algorithm was x = 0.77 m, y = 1.24 m and z = 1.07 m.  A complete analysis of the results obtained at different positions let us to conclude that the proposed system is capable to reliably estimate the position with a centimetric precision except in the surroundings of the room's corners, where the Sidelobe-to-Mainlobe ratio increases above permissible values.

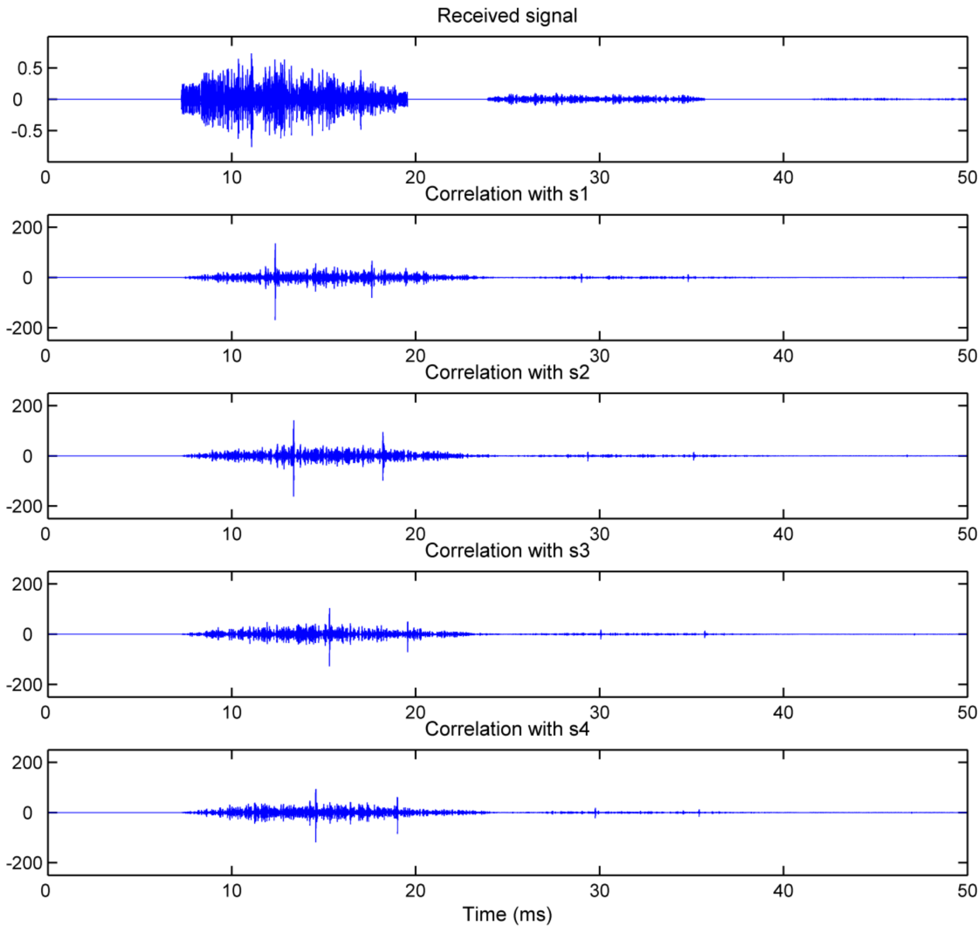


Fig. 2. Received signal and correlators output at the position x = 0.8 m, y = 1.2 m, z = 1 m.

# Ultrasonic LPS: Autocalibration and mobile robot navigation

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## 1 Summary

This paper presents an algorithm for mobile robot positioning and navigation using both, the relative positioning obtained by the on-board dead reckoning and the absolute positioning computed using an ultrasonic LPS (Local Positioning System). At the beginning of the process the dead reckoning is used for robot positioning and LPS autocalibration and, after a predetermined time, the system merges, with an H-∞ filter, the LPS and the dead reckoning information to navigate. The method has been applied in a configuration of the LPS in which there are areas with and without LPS coverage. In such a case the algorithm can consider for positioning the mobile robot both, the dead reckoning and the LPS or only the dead reckoning. The cumulative error of the dead reckoning is reset each time the LPS is discovered by the mobile robot in its trajectory.

## 2 Introduction

In recent years, the research in Local Positioning Systems (LPS) has become important because of the different applications they facilitate in smart spaces. One of these applications deals with mobile robot navigation. In most of the systems the positions of the beacons that compose the LPS are assumed to be known, that is, the coordinates of every beacon (with respect to the origin of reference) have been previously measured or calculated and introduced into the system. These calibration process usually needs a long time and several people taking measurements, making this type of systems slightly portable and adaptable. For that reason, autocalibration techniques, that allow the system to compute automatically the position of beacons or fixed devices, are interesting.

In the system presented here, a mobile robot is used to perform the autocalibration at the same time that it follows a predetermined trajectory. This method takes advantage of the fact that at the beginning of a trajectory the odometry data are precise and not corrupted by cumulative errors. The system merges, using a H-∞ filter, the data obtained by the robot odometry and the distances to the beacons measured with the LPS system. The influence of each kind of data in the positioning algorithm is dynamically adjusted depending on the time (if the system is in the phase of autocalibration/navigation or only navigation) and on the context (if there is –or not- LPS coverage).

## 3 System overview

The general description of the system and variables shown in Fig. 1 will be used. To apply the H-∞ filter it is necessary to know both the robot dynamics and the positioning performed with the LPS.

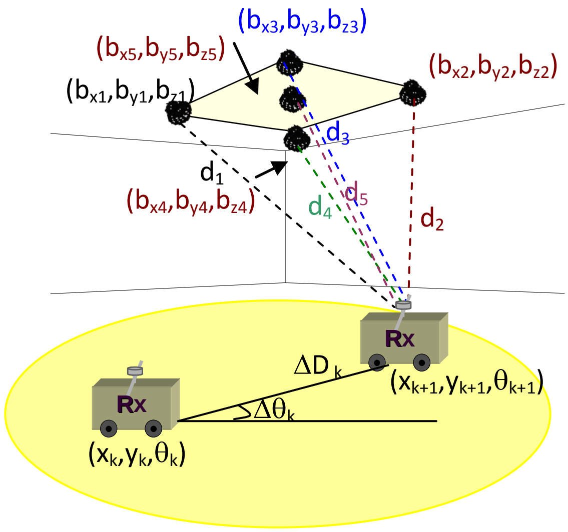


Figure 1: Mobile robot and LPS description.

It is necessary to obtain the mobile robot and the beacon positions, so if there are 'n' beacons, the state vector at time k is:

$$\mathbf{q}_k = [x_k \quad y_k \quad \theta_k \quad bx_1 \quad \cdots \quad bz_n]^T$$

And for the time k+1 can be obtained as:

$$\mathbf{q}_{k+1} = [x_k + \Delta D\cos(\theta_k), y_k + \Delta D sen(\theta_k), \theta_k + \Delta\theta_k, bx_1, ..., bz_n]^T$$

The set of equations of the filter is:

$$\hat{\mathbf{q}}_{k+1} = \hat{\mathbf{q}}_k + \mathbf{K}_k(\mathbf{y}_k - \mathbf{C}\cdot\hat{\mathbf{q}}_k)$$
$$\mathbf{L}_k = (\mathbf{I} - \gamma\mathbf{Q}\cdot\mathbf{P}_k + \mathbf{C}^T\mathbf{V}^{-1}\mathbf{C}\cdot\mathbf{P}_k)^{-1}$$
$$\mathbf{K}_k = \mathbf{A}\cdot\mathbf{P}_k\mathbf{L}_k\mathbf{C}^T\cdot\mathbf{V}^{-1}$$
$$\mathbf{P}_{k+1} = \mathbf{A}\cdot\mathbf{P}_k\cdot\mathbf{L}_k\mathbf{A}^t + \mathbf{F}\cdot\mathbf{W}\cdot\mathbf{F}^T$$

Where:

- $\hat{\mathbf{q}}_k$ is the vector that contains the estimated variables (the robot pose and the beacon coordinates).
- $\mathbf{K}_k$ is the filter gain.
- $\mathbf{y}_k$ is the vector that contains the measurement distances to the beacons.
- **A** y **C** are the dynamic robot and ultrasound Jacobian matrix, respectively.
- **V** y **W** are the matrix related with the odometry and ultrasonic LPS errors.
- **I** is the identity matrix.
- $\mathbf{P}_k$ is the covariance filter matrix.
- $\gamma\mathbf{Q}$ is a parameter of the filter.

The system gives the beacon and mobile robot positions in 3D, although in Figure 2 it is showed only the (x,y) positions obtained after following a circular trajectory under the LPS (the beacons are on the ceiling). It is important to note that the system considers point (0,0,0) at the beginning; and that is the only *apriori* data needed for the process.

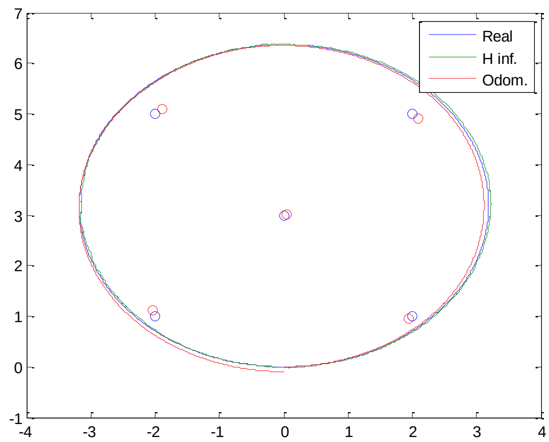


Figure 2: LPS autocalibration and navigation following a circular path.

## 4 Conclusions

The algorithm has been tested with different trajectories and some conclusions can be derived:

- H-∞ filter did not have problems of convergence in situations in which a Kalman filter did.
- It is preferable some kinds of trajectories with abrupt changes of orientation to perform better LPS calibrations.
- The error standard deviation in the mobile robot position and LPS beacon positions is between 1 and 3cm.

# Study of Blue Whale: The Novel Methodology for Indoor Positioning

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## 1. Motivation and Background

Due to the need of precise positioning nowadays in many applications, e.g. in households and in industries as well as in laboratories, extended research is being carried out in this field. Several ultrasonic based indoor location aware systems, such as Active Bat and Cricket, have been developed for precise indoor object localization. Cricket achieves a distance measurement accuracy of 4-5 cm within an $80^o$ cone from a given beacon. It has a limitation on the information update rate of 1 Hz [1]. As a consequence it is not adequate for cases where the target is highly mobile. Active beacons allow a high sampling rate but incur high costs in installation and maintenance. The accuracy of ultrasound-based systems suffers greatly from the multipath problem. We propose a novel methodology for indoor positioning in [2] which is expected to provide low cost, highly accurate position sensing, less susceptible to the multipath problem and can be readily apply to highly mobile target. The system is named 'Blue Whale' due to its resemblance with the blue whales in using sonic signal for localization.

## 2. Summary

This paper presents the results obtained by simulation as well as experiments carried out for the verification of the proposed method. The Blue Whale technology for sensing positions is vulnerable to false readings due to multipath as mentioned in [2]. Here, in this paper, we describe our latest findings on its inherent ability to reduce the multipath problem. The multipath signal loses its strength during each cycle due to its absorption by the reflected surface, thereby forming a weaker composite signal than that formed by the Line of Sight (LoS) signal. In [2] we have mentioned its advantages over the conventional ultrasonic based systems such as higher accuracy and longer range. In this paper the empirical results of our investigation is provided. In order to calculate the distance of MT from BP, displacement alone is not enough, the direction at which this displacement take place is also essential. In this paper we also have introduced a new method for direction detection. The test results of this Direction Detection method have also been included in the paper.

## 3. Results

Here two scenarios of MT movement are considered. The first scenario (Fig. 1(i)) the MT is following the direction of multipath and in Fig. 1 (ii) directed towards BP.  5% of the total incident energy is absorbed by the reflected surface in scenario (i). The variation in amplitude of the resultant signals shown with the change in distance d, for both signals in Fig 2(a) & 2(b). The proposed method has been verified in real test measurements. We have varied the distance between MT and BP with transducers directly facing each other. The frequency we have used in this experiment is of 6 kHz. Ten sets of data are collected and the average value is shown in Table 1.

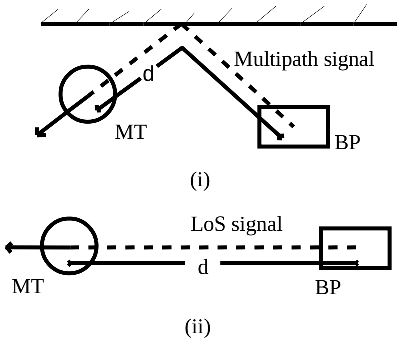


Fig 1. Two scenarios of MT movement ((i) and (ii))

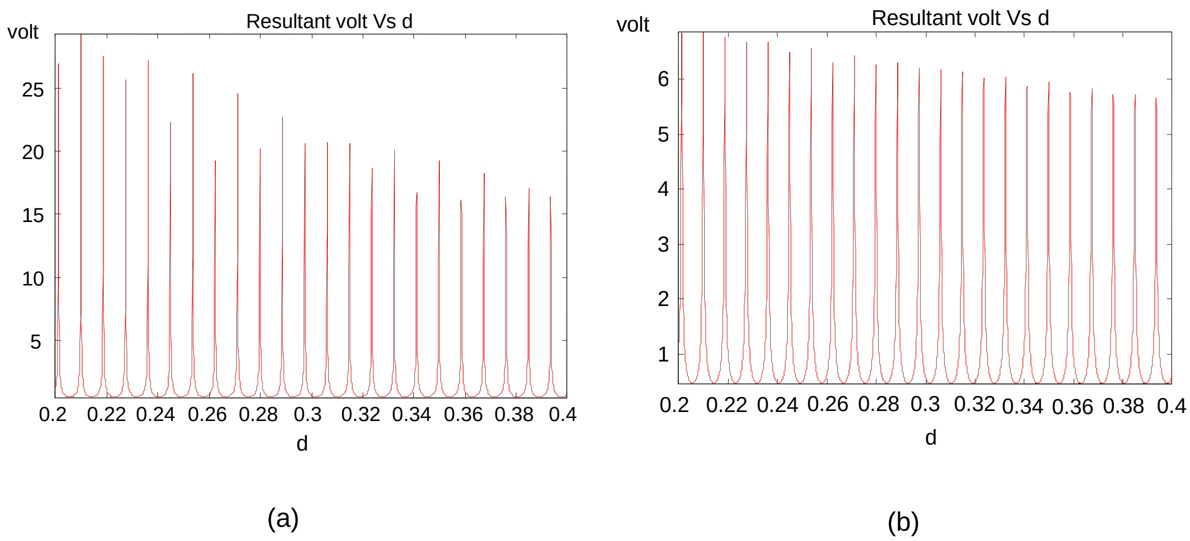


Fig. 2. a) Variation of Resultant signal in scenario (i) b) and in scenario (ii) with distance d

Table: 1

| Distance in cm (Average value) | Displacement in cm |
|---|---|
| 38.30 | |
| 44.35 | 6.05 |
| 50.10 | 5.75 |
| 55.90 | 5.80 |
| 61.85 | 5.95 |
| 67.75 | 5.90 |
| 73.40 | 5.65 |
| 79.05 | 5.65 |
| 85.35 | 6.30 |
| 90.95 | 5.60 |
| 96.80 | 5.85 |
| 102.95 | 6.15 |

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# The iLoc ultrasound indoor localisation system with interactive badges


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## 1 Summary


iLoc is an ultrasound ranging based indoor localisation system which is deployed at the iHomeLab laboratory. For example, the system can be used for visitor tracking: Visitors get an electronic name badge comprising an ultrasound transmitter. This badge can be localized with an average accuracy of less than 10 cm deviation in its spatial position, by means of reference nodes distributed in the lab rooms. In this paper we report on the system itself and on the interactive badges. The badges are equipped with a cholesteric display thus forming an ultra low power locatable tag with a radio controlled information display. Depending on the position update rate, a small battery may suffice for several month of tag operation. Other advantages when compared to existing ultrasound ranging systems (like CRICKET, CALMARI, BAT) are for example the simple deployment with its 2 wire "IPoK" bus system.


## 2 iLoc System Overview

The system (Fig. 1) comprises badges (name tags), detector nodes and a position server. The name tags are equipped with a microcontroller, a radio transceiver and an ultrasound transmitter. The tags emit ultrasound pulses with a rate of about 1 Hz, and are synchronized by radio messages. The badge is equipped with a buzzer, an accelerometer, and a cholesteric LCD graphic display, thus enabling interaction with the user.

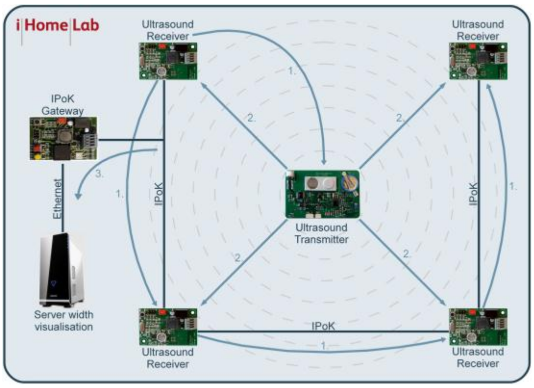


Figure 1: System Overview

The reference nodes also comprise a micro-controller, a radio transceiver to send and receive time synchronization messages, and an ultrasound receiver. The nodes record the reception times of ultrasound bursts transmitted by the badges. The nodes are connected to an IP gateway with a 2 wire bus to communicate data packets for synchronization of the nodes and ultrasound reception timestamps. A server calculates position estimates from the received data by multilateration and averaging / range value selection schemes. The position data is used among others for visualisation of the visitor positions in the lab (see Fig. 2).

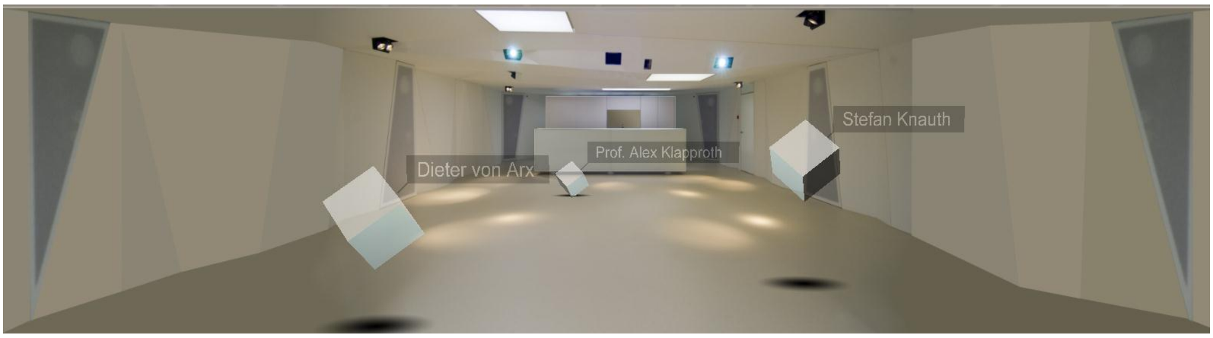


Figure 2: 3D visualisation of visitor positions in the iHome Lab

## 3 Deployment in the iHomeLab

The maximum range of the iLoc ultrasound signal is about 16 meters. Principally, 3 range measurements from 3 different reference positions allow the determination of the tag position. These conditions would be fulfilled when deploying the reference nodes in a lattice with a spacing of about 10 meters. Practically, the density of reference nodes should be much higher such that the distance to the further-most node does not exceed approximately 5 meters. Then every point in the room is in the ultrasound range of more than 5 reference nodes, increasing the stability of the system against ultrasound interfererence. The ultra-sound signal needs a line-of-sight for propagation, which can get lost by a shading caused by the body of the wearer of the tag or by other visitors in the same room. In the lab, 50 nodes (Fig. 4) are arranged in 6 IPoK bus lines.


Figure 3: Name badge with transceiver, ultrasound transmitter and cholesteric LCD

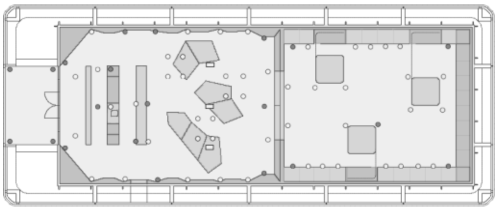

Figure 4: Node positions in the lab rooms

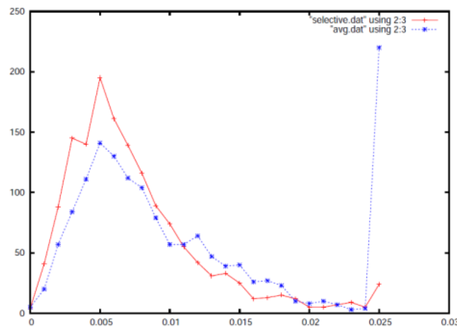


Figure 5: Observed position error
X-Axis: Meter, Y Axis: Number of results

## 4 Results / Outlook

Fig. 5 shows data from a set of about 1500 subsequent measurement cycles, with at most 8 out of 9 reference nodes reporting timestamps. The rightmost values include all measurements lying outside of the graph's X-Axis. During the recording of the observations, the sound propagation was intentionally disturbed by noise, i.e. people walking around thereby shielding the ultrasound reflectors. The high overall accuracy of the reported position values (95% within < 2 cm) has been achieved by careful determination of the sound velocity and position data of the reference nodes. Under less optimal adjusted conditions, the positioning error is still well below 10 cm. The installation of the system is possible with moderate effort in typical indoor housing, warehouse or laboratory environments. The development includes not only the basic ranging electronics, but also system aspects and application software. Current applications of the system are visitor tracking and fall detection. The locatable radio tag with cholesteric LCD might also be used for logistics. The iLoc system is installed at the iHomeLab (www.iHomeLab.ch) at Lucerne University of Applied Sciences.

# Radar Systems

Auditorium J6

Wednesday, September 15, 16:00 – 18:00

# Use of Homodyne Methods of Microwave Phase Measurements in a Task of Precision Indoor Positioning

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## 1. Summary

Microwave indoor propagation offers a good opportunity for object positioning. The use of the pulse radar method for measuring distances and angles are quite unsuitable for indoor applications. The resolution of this method is too low and there is a minimal distance requirement of the pulse radar measurement that is usually higher than the room size. In this paper the phase method of multipoint distance measurements is presented. The microwave phase progression was used for these measurements. The resolution of the phase method of distance measurements is determined by the microwave length. Depending on the wavelength one can reach an accuracy of 10 mm and better [1] and [2]. No doubts, the phase method causes an ambiguity because the phase measurements can only have values in an interval between 0 - 2π. In this paper the way of bypassing this problem is shown.

## 2. Approach to a problem

Realizing the homodyne method of microwave phase measurements and consequently distances determination, we offer to place the radio beacons in the corners of a room or in the middle of an extended wall. The transponder is placed on the object that is to be located. The positioning of object is characterized by the distances $d_i$ from the object to each of beacons.

The beacon radiates the microwave signal that can be described as

$$U_1(t) = U_0 \sin[\omega_0 t + \varphi_0]$$

The microwave, propagated along the distance $d_i$, obtains the attenuation $A_i$ and phase progression $kd_i$

$$U_2(t) = A_i U_0 \sin[\omega_0 t + kd_i + \varphi_0] \ ,$$

where $k = 2\pi/\lambda$ is propagation constant, $\lambda$ is the wavelength.

The transponder receives this signal, shifts the frequency and phase of the received microwave signal on values $\Omega$ and $\varphi_{LF}$ by means of a controlled phase shifter

$$U_3(t) = A_i U_0 \sin[(\omega_0 + \Omega)t + kd_i + \varphi_0 + \varphi_{LF}] \ ,$$

and reradiates this frequency-phase transformed microwave signal back in direction of the beacon. The secondary microwave signal that is received in the beacon will be

$$U_4(t) = A_i^2 U_0 \sin[(\omega_0 + \Omega)t + kd_i + k^1 d_i + \varphi_0 + \varphi_{LF}] \ ,$$

where $k^1$ takes into account the frequency shift $\omega_0 + \Omega$. If the frequency shift $\Omega$ is much lower than the initial frequency $\omega_0$, then $k^1 \approx k$. This secondary received signal is mixed with the original microwave signal and at the mixer's output the low-frequency signal of difference is selected and amplified up to a certain limit. This low-frequency signal will be

$$U_5(t) = U_0 \sin[\Omega t + 2kd_i + \varphi_{LF}] \ .$$

The initial frequency and initial phase of origin microwave signal both are subtracted in a mixer. The only double phase progression of the microwave signal is of interest for the distance definition.

A low-frequency signal is obtained on the output of each mixer of each beacon, but the phase shift will be unique for each beacon and will be determined by the each distance $d_i$. These signals are delivered to the signal processing unit and the phases of these signals are compared with the phase of low-frequency signal reference with the same frequency $\Omega$. Generally it is possible to measure a phase difference between 0 and 2π. The phase progression $kd$ will be represented as $2\pi n + k\Delta d$, where $n$ is integer. In order to avoid this problem we serially change the operating frequency of each beacon and we measure the phase differences. After that we calculate the distance as

$$d_i = \frac{(\Delta\varphi_1 - \Delta\varphi_2)}{2(\omega_1 - \omega_2)} c \ .$$

Certainly, these calculations yield the rough results of distance determination. These calculations let us obtain the number of phase cycles $n$ and the possibility to determine the distance in terms of integer numbers of wavelengths. The exact value of distance $d$ can be obtained by measuring the phase difference $k\Delta d$. Taking into consideration the accuracy of phase measurements in 1.4° (8 digits) and possible wavelength in 0.2 m, the resolution in distance determination will be about 1 mm. We must understand the measured distance will be conditional distance, taking into account antennas' phase centers and all feeders' lengths. Further, as each beacon operates as stand alone unit, there is a possibility to measure the phase difference between beacons' mixers' output signals. Mentioned opportunity let us improve the accuracy of coordinate's determination, as it was pointed out in [3] and [4].

In this paper the design of the equipment and the algorithm are discussed. The problem of phase synchronization of low-frequency oscillators is discussed as well.

## 3. Conclusion

Having defined distances to the object from several beacons (not less than two) and knowing the exact coordinates of each beacon, by means of the simple software we will calculate exact coordinates of the object in a room. The time of the object's coordinates determination will be derived from the time of the phase difference measurement at consecutive iterations. One iteration can last tens or hundreds of milliseconds. The time of the PC computation cannot be taken into account. We can reduce the measurements and the calculations accordingly to a minimum by using a tracking mode.

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# Power Level Surveillance for an FMCW-based Local Positioning System

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## 1 Introduction

In the frequency modulated continuous wave (FMCW) based local positioning system LPM the time of flight distance is determined by evaluating the frequency difference between the down converted chirp signal of a reference transponder (RT) and the measurement transponder (MT) inside every base station (BS). In a typical LPM setup several BSs surround the measurement field whereas the RT is located around the center of the setup. Both, the BSs and RT are located at known positions, while the MT is movable. A schematic of an exemplary LPM setup is depicted in Figure 1. For a more detailed explanation of the LPM working principle the reader is referred to [1]. The LPM system also provides the power level (PL) value of the received signals which can be used for monitoring the quality of the current measurement. In this contribution, a signal model for the received signal powers is derived with respect to the antenna characteristics, the hardware parameters of the LPM system and the Friis equation for the line of sight (LOS) path. This information can be used as a weighting factor for the pseudo-ranges in the position estimation process which is shown on real measured data.

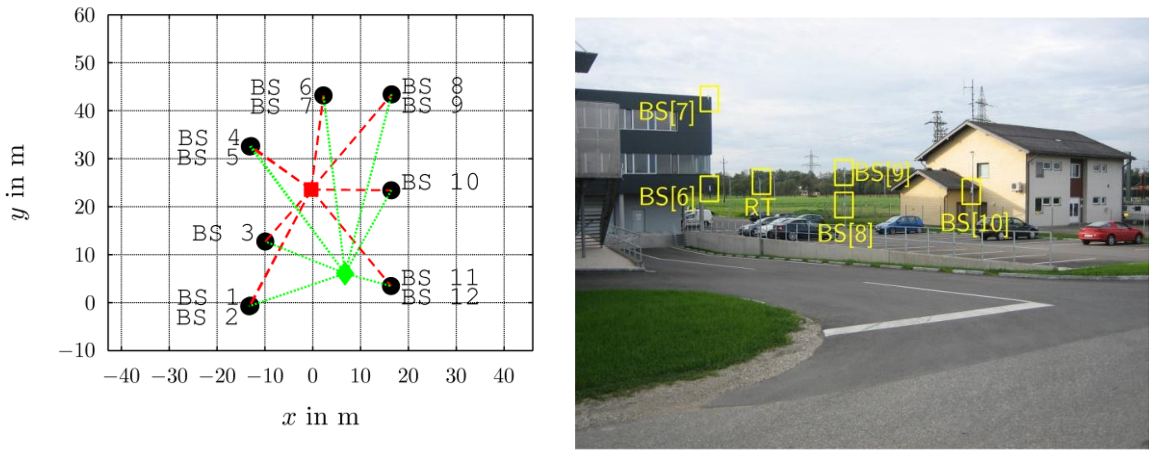


Figure 1: Schematic and photograph (point of view around BS 2) of an LPM setup with 12 BSs (circles) for a 3D measurement scenario at the LPM test site in Regau, Austria. The RT (square) is at fixed position located approximately in the middle of the setup, whereas the MT (diamond) is mobile. The lines mark the LOS path from the RT (dashed), and MT (dotted) respectively, towards the BSs.

## 2 Method and signal model for PL estimation

The basic model for the received PL can be defined as

$$P_{\mathrm{R}}[m,n]=\eta_{\mathrm{SP,HW}}\,\gamma_{\mathrm{CL}}\,\eta_{\mathrm{BA}[n]}(\theta[m,n],\varphi[m,n])\,\xi[m,n]\,\kappa_{\mathrm{TA}[m]}(\theta[m,n],\varphi[m,n])\,\xi_{\mathrm{CL}}\,P_{\mathrm{T}}, \qquad (1)$$

where $P_R[m, n]$ denotes the measured PL from the *m*th transponder (TP) in the *n*th BS, where $P_T$ is the transmitting power of each TP. Since position estimation in the LPM system is strictly restricted to LOS paths, the path loss is modeled with the well-known Friis equation [2] in $\xi[m, n]$. Moreover, hardware parameters such as the antenna gains $\eta_{BA[n]}$ and $\kappa_{TA[m]}$, the cable attenuations $\xi_{CL}$ and $\gamma_{CL}$ as well as the signal amplification of the BSs $\eta_{SP,HW}$ have a major effect on the PL. The PL of the MT ($P_R[1, n]$) is highly influenced by the BS antenna gain towards its position, which is dependent of the azimuth and elevation angles of the incident signal. Since the antenna characteristics provided by the manufacturer are often limited to a measurement of one azimuth/elevation plane, this paper will present a method to interpolate this information over the whole unit sphere.

## 3 Simulation and measurement results

As depicted in the left plot of Figure 2, an arbitrary movement with a remote-controlled vehicle (RCV) equipped with an MT was performed. For the estimated positions, the PLs of an arbitrarily chosen BS (here BS 12) were simulated. The right plot of Figure 2 shows that the simulated data fits the measured values, except in the regions where the RCV leaves the field of view of BS 12. Note that the displayed PLs are scaled by an internal factor $P_0$. For a schematic of the setup of the BS and RT, see Figure 1.

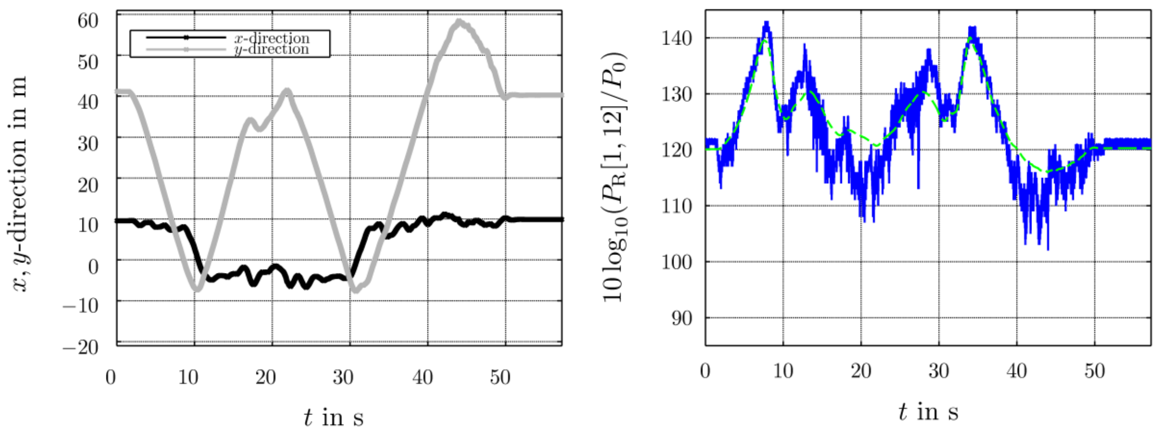


Figure 2: (Left) Test movement of an MT mounted on the RCV. (Right) Simulated (dashed line) and measured (solid line) PLs of BS 12.

## 4 Conclusion

In this contribution the feasibility of precise PL estimation for the LPM measurement system is shown, which can be used to monitor the measurement quality of the BSs. This additional measurement information can then be used in an Extended Kalman filter to weigh the pseudo-ranges depending on the deviation from the predicted PL.

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# Non-Stochastic Multipath Simulations for an Indoor Local Positioning System

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## 1 Summary

The measurements of an active pulsed reflector in an indoor local positioning system revealed that multipath propagation has a large influence on the positioning accuracy. In this study, a channel model is developed, which calculates the multipath components based on base station and reflector positions in a room. This model allows identifying correlations between the reflector position and the distance error. The distance error is correlated to the channel damping due to multipath propagation with a correlation factor of 0.59. By comparing the distance errors of one reflector measured by 17 base stations, the reflectors with the largest standard deviation are close to a wall. The standard deviation of 3400 simulations is 17.19 cm. This is comparable to the measurement results, which resulted in a standard deviation of 26.6 cm.

## 2 Introduction

An active pulsed reflector can be used as a backscatter in a FMCW radar based indoor positioning system [1]. The base stations measure the round-trip time-of-flight by detecting the frequency difference in the spectrum (Figure 1a). The measurement results revealed that multipath propagation has a large influence on the positioning accuracy. This paper presents multipath simulations for the active reflector system and evaluates the influence of the position of the reflector to the 1D distance error.

## 3 Channel Model

In wide-band channel models, the propagation channel is modelled with stochastic parameters. For the simulation of the accuracy of 3D indoor positioning system, these channel models are not suited, because the propagation channels from different base stations are correlated. Our channel model assumes a 10x10x3 $m^3$ large room. With the known position of the base station and the reflector, the multipath and line-of-sight (LOS) components are calculated. In this paper, we present results for an empty room. This approximation is valid e.g. for interactive guiding in a museum. With non-empty rooms, the channel model can still be used, but the calculation of the multipath components will be more elaborate.

## 4 Simulation Results

The multipath simulations were conducted with 17 base stations and 200 random reflector positions. This results in a total of 3400 different propagation channels. For each of these propagation channels, one distance measurement was simulated. This includes the multipath propagation, the start-up behaviour of the reflector, and the down-conversion in the base station with a subsequent zoom-FFT. Figure 1a illustrates the base band spectrum with and without multipath propagation. The detected distance error has a standard deviation of 17.19 cm. The distance error is correlated to the channel attenuation due to constructive and destructive interference from multipath components. The correlation factor is 0.5946. The largest distance errors occur close to the two opposite walls. However, the error is not correlated to the distance to the wall, only the standard deviation of the distance errors measured from several base stations is. Figure 1b illustrates the 60 reflector positions with the highest standard deviations. All of these reflectors are less than 2 m away from the closest wall.

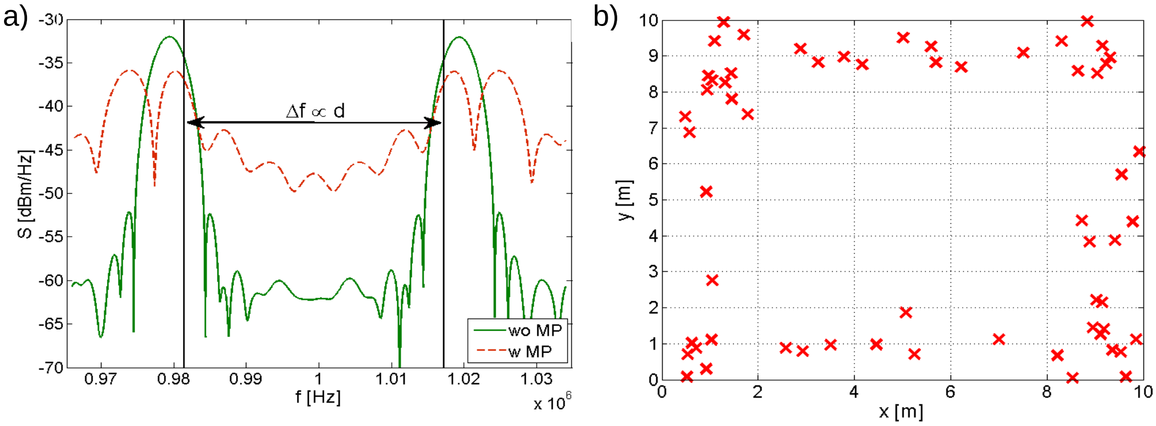


Figure 1.a: Base-band spectrum without and with multipath propagation. The frequency difference between the peaks is proportional to the distance d from the base station to the reflector. b: This plot illustrates the 60 reflector positions of 200 with the largest standard deviation of the distance error.

## 5 Comparison with Measurement Results

The measurement results for the active reflector in a strong multipath environment were presented in [1]. The measured standard deviation of the 1D distance error is 26.6 cm. This value is comparable to the simulated standard deviation of 17.19 cm. The simulation underestimates the error, because it uses a simple multipath model, neglecting multiple reflections and reflections at objects inside the room. Moreover, the laboratory room was smaller and the doors and part of the walls were metallic. Nevertheless, the measured and the simulated spectra are very similar. Thus, the simple channel model enables us to predict the distance error due to multipath propagation and allows testing of the detection and positioning algorithms.

## 6 Conclusions and Outlook

The presented channel model allows estimating the influence of multipath propagation for indoor positioning systems. The multipath propagation has the highest influence on reflectors close to a wall due to the smallest multipath delay time. The results can be used to find the optimal position of the base stations.

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# Input Amplifier for Sensitivity Improvement in an M-Sequence Radar Front-End

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## 1 Summary

In this paper, a new input amplifier is presented which is intended to improve the dynamic range of an M-sequence radar front-end. The latter is part of a sensor array and at the current state its dynamic range is confined by spurious tones caused by cross-talk. Owing to the advantageous characteristics of the M-sequence device it is possible to predict the receive signal by digital signal processing and thus to compensate for spurious tones. For this purpose an additional input is provided by the amplifier which is used for signal subtraction.

## 2 Extension of the basic M-sequence principle

**Figure 30** depicts a principal block level schematic of the M-sequence system (solid lines) and the intended extension for sensitivity improvement (dashed lines). Due to the steep clock slopes in this system driven by a square pulse source, jitter is kept low and sampling is absolutely equidistant so that sophisticated digital signal processing is feasible.

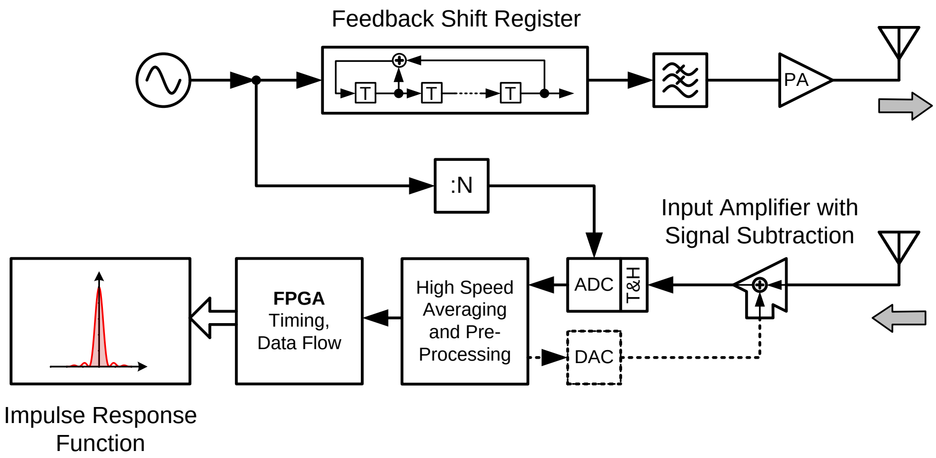
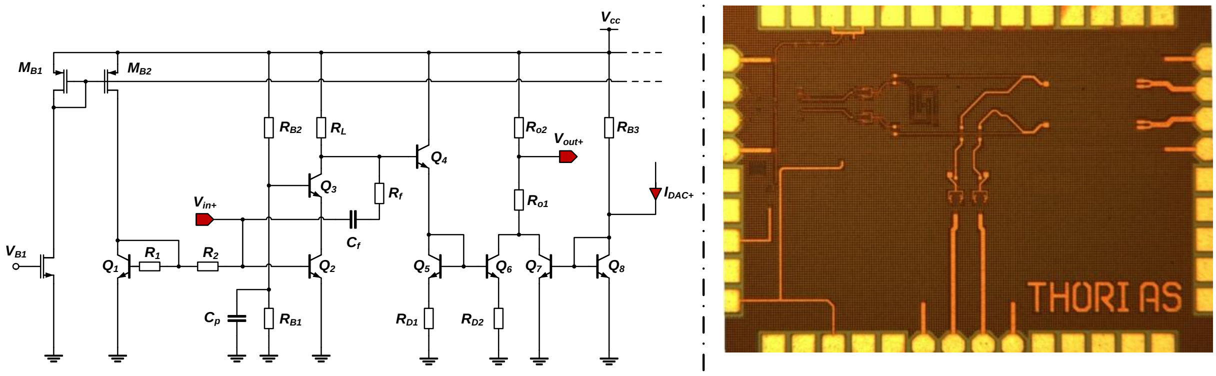



Figure 30: M-sequence system

As the scene under test varies slow compared to the clock rate and wave propagation, samples of the same chip in consecutive sequences can be averaged to generate a prediction signal. Also, the data rate transferred to the FPGA can be reduced by such a high speed processing without significant loss in accuracy and thus be adapted to the capabilities of the FPGA. The digital prediction signal is then converted to an analogue representation and fed into the second input of the designed input amplifier. This way it is subtracted from the input signal and only the difference signal, usually of small amplitude, is sampled and converted by the ADC. In section 3, the design of such an input amplifier is examined in more detail and first measurement results of the fabricated chip are shown.

## 3 Input Amplifier with Integrated Signal Subtraction

Focussing the schematic in **Figure 31** (a), the principle of operation of this input amplifier can be explained. The signal from the main branch $V_{in+}$ is amplified by a cascoded common emitter amplifier while input matching is achieved by resistive feedback. The second input signal $I_{DAC+}$ is provided by a current steering DAC which implies signal subtraction in the current domain. As the amplifier is driven by a differential signal, subtraction can be performed by two current mirrors $Q_5$-$Q_6$ and $Q_7$-$Q_8$ which share a common output node. To ensure output matching, the biasing resistor is split in two portions, $R_{o1}$ and $R_{o2,}$ presenting the required impedance to the load.




(a) (b)

Figure 31: Half circuit schematic (a) and chip photo (b) of the amplifier with signal subtraction

**Figure 31** (b) shows a chip photograph of the amplifier produced in IHPs 250 nm SiGe:C BiCMOS technology. Measurement results for this chip are presented in **Figure 32** in which 1 and 2 are considered to be the differential input and output of the main branch, respectively.

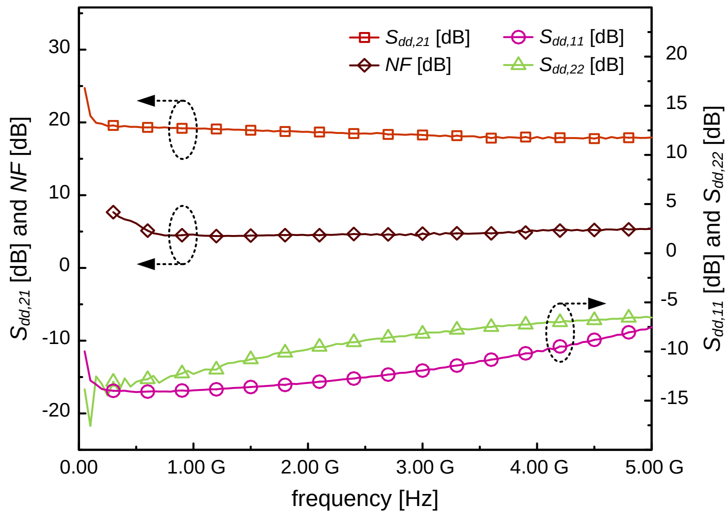



Figure 32: Transfer characteristics and noise figure for the amplifier with signal subtraction

## 4 Conclusion and Outlook

In this abstract a new input amplifier for dynamic range improvement of an M-sequence radar front-end is presented. Its main branch is characterized by first measurement results. They show the desired gain curve progression and encourage further tests within the target system.