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A robust and precise 3D indoor positioning system for harsh environments

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***Abstract*—In recent years there has been a considerable research on the development of indoor positioning systems. Several kinds of technologies such as ultrasonic, UWB, WLAN, optical waves and hybrid solutions were utilized already. However, using these technologies many difficulties arise in indoor environments due to none line of sight (NLoS) and multipath errors. In this paper, the realization and the evaluation of a 3D indoor localization system, which is robust for harsh and NLoS environments is presented. The positioning system is Direct Current (DC) magnetic based, shows no multipath effects and has excellent characteristics for penetrating various obstacles. To eliminate additional interference fields (e.g. earth's magnetic field, electrical disturbances) a differential measurement principle and adaptive noise suppression algorithms are used.**

In the case of the deployment in smaller areas, even smart phones equipped with embedded low cost sensors can be utilized as mobile station. A real time 3D position estimation with an accuracy up to 50 cm is achievable by setting up only three magnetic coils inside or around the building. In order to analyze existing systematic errors, a simple calibration procedure has been implemented. The calibration routine reduces the systematic errors, which leads to improved system's positioning accuracy up to 10 cm.

Keywords-component: Indoor Positioning; Localization; Magnetic Indoor Local Positioning System, Adaptive Filtering

I. INTRODUCTION

In the past years indoor positioning has already attracted increasing interest from both research and industry. With the advent of latest-generation smart phones, it is very supposable that the demand for location based services inside buildings (indoor location services) will increase, which in turn requires mass market indoor localization technologies. The objective of the presented research project is the development of an accurate indoor positioning system based on magnetic fields. The principle of this magnetic indoor local positioning system (MILPS) is based on direct current (DC) artificial magnetic fields, which are generated by magnetic coils. By capturing the magnetic field components of multiple coil fields, the unknown position of a mobile station can be estimated [1]. In many existing infrastructure-based systems, which typically use optical waves, radio or ultrasound, the position estimation is adversely affected by attenuation, fading, multipath or signal delay. However, magnetic fields are able to penetrate commonly used building materials without signal propagation error or multipath effects.

This paper contributes to the fields of indoor positioning by presenting a system which is immune to fading und multipath effects. The outline of the paper is as follows: section II presents briefly related works on magnetic field based positioning systems, section III shortly describes the operation method of MILPS following by section IV picturing the realization of a prototype. The topic signal processing and noise elimination is carried out in section V. In section VI range and accuracy tests are accomplished in a harsh indoor environment. Section VII performs an examination of 2D and 3D positioning while the last section summarizes the presented project and gives a short outlook to further researches.

II. RELATED WORKS

Object tracking by means of artificially generated magnetic fields has been examined occasionally in recent decades [2…5]. Two commercial systems do already exist [6] [7]. The majority of magnetic fields based tracking systems are designed for motion tracking and virtual reality. These systems are mainly used for artistic, industrial and biomedical applications in specially equipped laboratory environments [8] [9]. Magnetic field creation is usually done by using concentric coils or permanent magnets and is limited to small measurement volumes only (typically with a radius less than 3 m) [10…13].

For example, systems that use sinusoidal magnetic fields are described in [2] and [3]. In the receiver the magnetic fields have to be first filtered by frequency. Ref. [10] and [14] describe systems using pulsed DC fields. Here, the fields are generated sequentially. Ref. [4] presents an experimental system, which utilizes 8 small diameter coils giving limited size coverage area of 4x4 m. To distinguish the signals from the different coils a code division multiple access (CDMA) approach has been used. Ref. [8] explores the usage of triaxial magnetometers and a vessel with known magnetic dipole to localize the sensors in underwater environments. Ref. [9] presents a magnetic localization and orientation system for medical diagnoses and treatments to track an object through the human gastro tract wirelessly.

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III. MILPS – MAGNETIC INDOOR LOCAL POSITIONING SYSTEM

The basic idea of our approach is to develop an infrastructure-based indoor positioning system which follows the principle of an active system, but using passive sensor technology at the client side. The system utilizes artificial magnetic fields generated by coils (=active), which serve as reference stations (RSi) in a local reference frame (cf. Fig. 1). By capturing the coils' magnetic field components with a magnetometer (=passive), the unknown 3D position (X_{MS}, Y_{MS}, Z_{MS}) of a mobile station (MS) can be determined by employing the lateration method. In order to distinguish between their magnetic fields, the coils are activated sequentially using real time clocks.

IV. SYSTEM OVERVIEW

Following computer simulations concerning the required magnetic field strength with regard to the desired building-wide coverage, an experimental system has been developed. The system consists of three coils with 140 turns of wire wrapped on 50 cm diameter core, current sources and relay units for each coil and a commercial magnetic field sensor (Honeywell HMR2300). The magneto-resistive sensor is able to measure all three components of the magnetic field vector $\boldsymbol{B}$. The measurement range is +/- 2 G with a resolution of 67 µG.

Fig. 2 shows the experimental system connected to a laptop computer using a parallel port for controlling the current sources and a serial interface for reading the sensor data. The sensor data are captured with a sampling rate of Ts = 6.5 ms.

V. SIGNAL PROCESSING AND NOISE SUPRESSION

For 3D position determination the slope distances between the centers of the reference coils and the magnetic field sensor of the MS are needed. The distance r between coil center and magnetometer is calculated by the following equation [5] [15]:

$$r = \sqrt[3]{\frac{\mu_0 NIF\sqrt{1+\sin(\varphi)}}{4\pi B}} \qquad (1)$$

In this context N describes the number of turns of wire, I is the current running through the coil, F expresses the base area of the coil, B is the measured magnetic field, φ the elevation angle between coil and sensor and μ_0 the magnetic constant. In order to mitigate natural magnetic noises such as the earth's magnetic field as well as the artificial magnetic fields, which are caused by the electrical appliances, a differential measurement principle has been developed. Therefore, during the measurement the current direction between the individual measurements is switched in polarity. The overlaying magnetic interference fields with frequencies higher than the switching frequency (direct component in the signal) are eliminated subsequently by calculating the difference (cf. Equation 2) between the measured magnetic field B over two successive periods (high pass filtering).

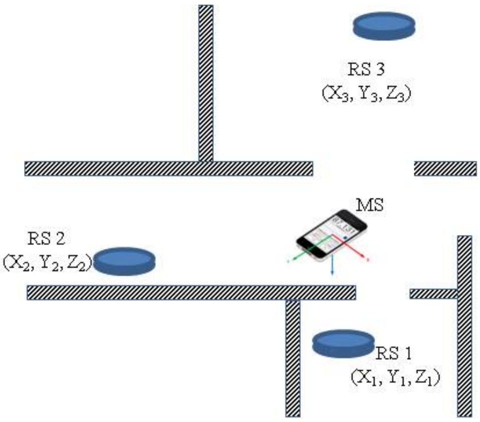

Figure 1: System architecture of MILPS with multiple reference

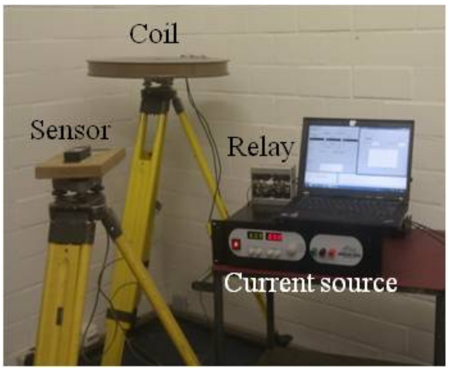

Figure 2: Experimental system

Fig. 3 shows an observed signal (blue) at a distance of 12 m from the coil's center. The coil's magnetic field B can be estimated by using the following relation, where B_t is the median of cluster at point in time t:

$$B = \frac{B_{t+1} - B_t}{2} \qquad (2)$$

In addition to the individual clusters, which result from the switching of the current direction described above, periodic noise components can be recognized in the depicted example signal. To reduce these noise components, a digital Finite Impulse Response (FIR)-Filter with a cutoff frequency of 1 Hz is used. Fig. 3 shows the filtered signal (red) in comparison to

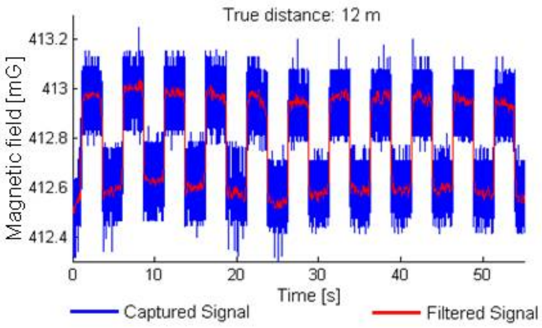

Figure 3: Signal filtering by a FIR low-pass filter

the input signal. It can be clearly seen that the high-frequency noise components can be significantly filtered. The output signal is quite similar to the original transmitted square wave signal.

A. Adaptive Filtering

The method of digital filtering provides a powerful method to separate the measurement signal from the noise. The drawback of regular FIR filters is their invariancy in respect to the absolute time. If the requirements for the “optimal” coefficients change over time (non-stationarity) due to changing conditions in the surrounding environment caused by suddenly arising interference fields (e.g. in factories), they are not able to adjust their operating characteristics. To prevent this in the case of non-stationary signals, adaptive filters are deployed [16] [17].

The adaptive filter as shown in Fig. 4 is used to find the optimal coefficients $\boldsymbol{\omega}$ of a variable filter for extracting an estimate of the desired signal, which is in the present case the uncorrupted magnetic field at a reference sensor located in a known position. The adaptive filter is driven by the input signal x[k] (corrupted magnetic field signal at reference sensor) and outputs y[k] an estimate of the desired signal. The objective is to adapt the coefficients of the filter in a way, that the variance of the error signal e[k] becomes minimal. Therefore the Least Mean Square (LMS) algorithm is utilized. The computed adaptive filter coefficients are then used to filter the signal of every sensor in the proximity of the reference sensor in real time.

Fig. 5 shows the captured signal in comparison with its filtered version using LMS adaptive algorithm. Although the signal was in an electrically noisy environment (elevator, power supplies, electrical devices,…) and traversed five walls, the original signal can be extracted very properly even at a distance of 17 m away from the coil. At the beginning the algorithm requires some transition time for converging to the optimal solution, because the start value has been first set to zero. To reduce the transition time, in future runs the last filter coefficients can be stored and used as new start value.

VI. RANGE AND ACCURACY TESTS

After the implementation of signal processing algorithms various range and accuracy tests have been carried out. With an experimental scenario in the University building the system’s performance can be demonstrated.

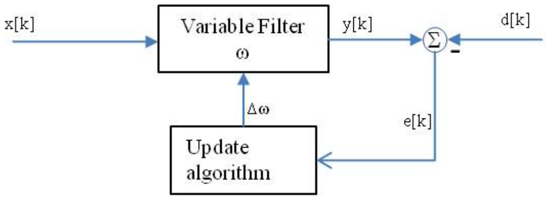

Figure 4: Set up of adaptive filtering

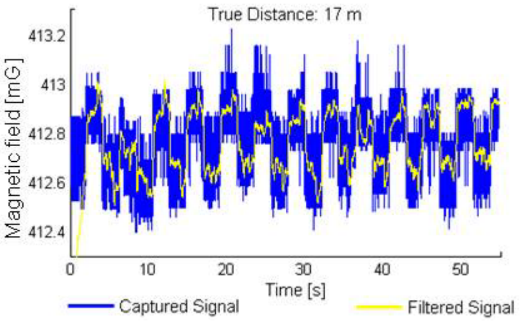

Figure 5: Adaptive filtered signal

In this scenario the magnetic coil is located near the stairs and the sensor (HMR2300) is placed in different sensing points along a straight, horizontal measurement line (cf. Fig. 6), in such a way that the elevation angle in (1) is equal to zero. As shown in Fig. 6, miscellaneous obstacles exist in the measurement line. In this scenario, at a distance between 2 m and 4 m the coil and sensor are separated by a 27 cm reinforced concrete wall. At distances between 6 m and 9 m the sensor is placed in the vicinity of the home electrical equipments and furthermore the coil and the sensor are separated by an additional 24 cm brick wall. In order to apply the adaptive filtering method described in section V, two reference sensors are placed at a distance of approximately 6.7 m and 12.3 m to the coil in an orthogonal distance of 3 m to the measurement line.

For evaluation of the system’s maximum range the signal-to-noise ratio (SNR) is gathered at every sensing point. In this scenario the coil’s signal could be reliably detected and evaluated up to a distance of about 15 m, despite the presence of electrical disturbances and obstacles.

For analysis of the ranging accuracy repetitive measurements and comparisons with true distances were performed. As shown in Fig. 7, in this scenario an accuracy of about 50 cm has been achieved in short range (0-8 m) and approximately 1 m in the vicinity of the maximum range. By the use of two reference sensors and the adaptive filtering method the ranging accuracy could be improved to less than 20 cm for short ranges and below 40 cm for far ranges (8-15 m). The empirical standard deviation as indicator for the ranging precision could also be improved to approximately 1 cm and 10 cm in the short and far range respectively by applying the adaptive filter method.

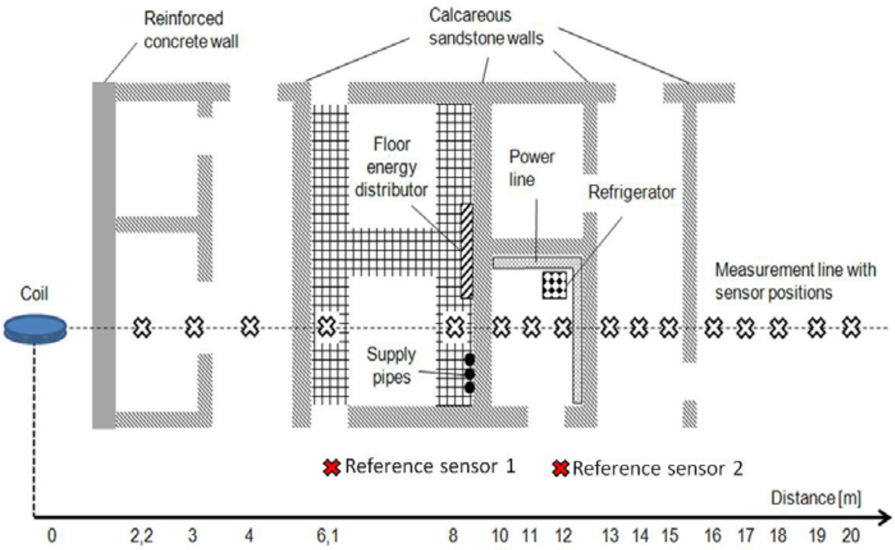

Figure 6: Magnetic coil and sensor locations for the sample measurements

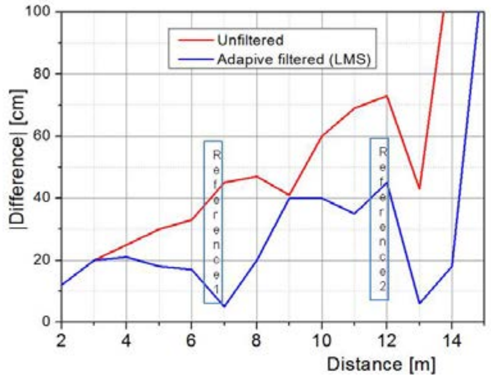

Figure 7: Accuracy comparison between filtered and unfiltered mesurements

VII. POSITIONING

One of the obstacles for the application of indoor localization in practice is the lack of mass market technologies, because most positioning systems require specific sensor components. In our case the mobile station is to be equipped with a three-axis magnetic field sensor only, which is already embedded in many today's smart phones. For that purpose, the evaluation of MILPS for 2D and 3D positioning has been performed not only with the HMR2300 magnetic sensor, but also with two smart phones and their embedded magnetic sensors: iPhone 4 (iOS 5.1.1) and Samsung Galaxy Nexus (Android 4) (cf. Fig. 8). For positioning tests the coils were placed at known points in a local reference frame, which enfolds three different rooms and a corridor inside the building. It was assured that the configuration of the coils positions ensure a practical geometry for the position determination.

Figure 8: Customized Applications for MILPS measurements running on Samsung Galaxy (left) and iPhone 4 (right)

A. 2D positioning

1) 2D positioning algorithm

In order to determine the two dimensional position of an unknown point by means of lateration, the mathematical principle of intersection is used. To get a unique solution the distance observations to at least three different coils are required. Generally the intersection of two circles delivers two solutions such that a third distance measurement is needed. By using all these information, the unknown position can be estimated by method of least squares. The mathematical relationship for distance can be described by the following equation, where d_i is the distance to one specific coil i, (X_P, Y_P) is the MS position and (X_i, Y_i) are the coordinates of the reference point:

$$d_i = \sqrt{(X_P - X_i)^2 + (Y_P - Y_i)^2}\ , \qquad i = 1\ldots \qquad (3)$$

Due to the non-linearity of the equations, the Gauss-Newton algorithm is utilized. For the linearization approximate values as initial guess are required. These values can be directly calculated by using the distance information to at least three different reference points. Since the two dimensional intersection yields generally two different solutions, the one that is compatible to distance measurement to a third reference point is selected. By using this method at all combinations of intersection, based on three different coils, only three solutions are remaining.

Fig. 9 shows the results of intersections in three different combinations. The blue crosses describe the correct solutions. To get a more accurate approximation all these three solutions are averaged. In the next step an optimal solution is computed by using least squares method applied on the linear system equation derived from (3) and the estimated approximate value. Since during a measurement period several distances are collected, it is possible to estimate not only the specific distance, but also its variance. These values yields to statistical information, which can be used in a Gauss-Markov model to get an optimal new position as best linear unbiased estimate (BLUE) [18].

The position is determined by solving the equation system:

$$\boldsymbol{d} + \boldsymbol{v} = \mathbf{A} \cdot \Delta\boldsymbol{x} \qquad (4)$$

Where $\boldsymbol{d}$ describes the vector of distance measurements d_i from sensor to fix point i, $\boldsymbol{v}$ is the vector of observation corrections v_i, $\mathbf{A}$ includes the derivations of d_i in respect to the unknown point coordinates, linearised on the point of aproximation and $\Delta\boldsymbol{x}$ describes the vector of parameter addition [18].

$$\begin{pmatrix} d_1 \\ d_2 \\ \cdot \\ d_n \end{pmatrix} + \begin{pmatrix} v_1 \\ v_2 \\ \cdot \\ v_n \end{pmatrix} = \begin{pmatrix} \frac{\delta d_1}{\delta X_P} & \frac{\delta d_1}{\delta Y_P} \\ \frac{\delta d_2}{\delta X_P} & \frac{\delta d_2}{\delta Y_P} \\ \cdot & \cdot \\ \frac{\delta d_n}{\delta X_P} & \frac{\delta d_n}{\delta Y_P} \end{pmatrix} * \begin{pmatrix} \Delta X_P \\ \Delta Y_P \end{pmatrix} \qquad (5)$$

2) 2D positioning with magnetic field sensor:

According to the experimental system, which is described in III and IV, a 2D position determination has been carried out by using the magnetic field measurements of three different coils at a MS in the University building (cf. Fig. 10). Beside MS, which was again placed along a straight line, a reference sensor was placed on a known point in order to use the method of adaptive filtering. Fig. 10 shows the location of the coils as well as the MS and the reference sensor in different rooms. Furthermore the comparison between the priori known and the calculated positions is shown.

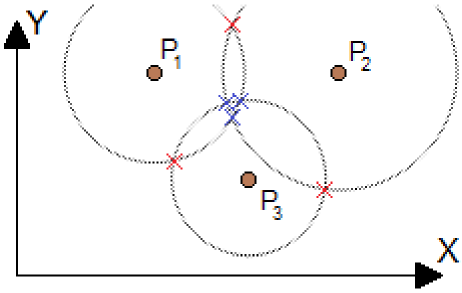

Figure 9: Two dimensional intersection of every combination

Firstly the “calculated positions” are computed based on distances to three different coils. From calibration measurements in an electrical noise free environment a trend function with a linear regression approach has been derived describing the systematic ranging errors. The line in Fig. 11 depicts the differences between computed and true values as regression function of the known distance. The “positions with correction” are calculated from an evaluation using this simple calibration procedure. As it can be seen in Fig. 10, it is possible to determine the two dimensional position inside a building by using artificial magnetic fields. The positions which are enhanced through the calibration routine are often closer to true positions than to the ones that are not treated via the calibration routine. While the accuracy in the first case stands in the range of 50 cm, the accuracy in the second case with simple calibration is less than 10 cm.

3) 2D positioning with smart phones

In addition to the high quality (HMR2300) sensor, the ability of determining a local position in an indoor environment has been accomplished with an iPhone 4. Due to the lower

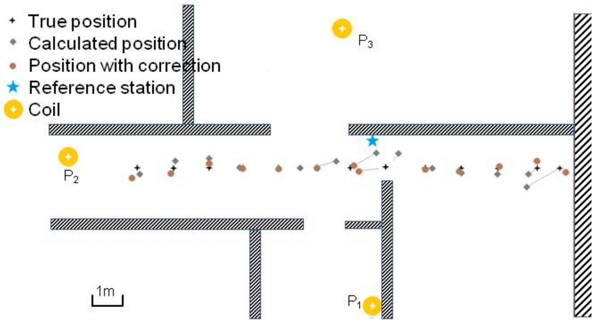

Figure 10: 2D position results for HMR2300

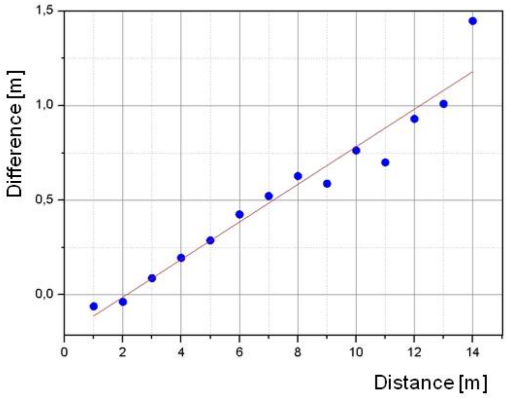

Figure 11: Linear regression of distance measurements to one special coil in an electrical noise free environment

resolution of the embedded sensors the coil's signals can be reliable detected up to the range of 6 m according to own ranging tests. Hence, the positioning experiments have been performed in 7x7 m test field. Fig. 12 shows the position plan of a localization experiment with iPhone 4 as MS. The MS and all coils have been placed in the same horizontal plane to get a two dimensional position using the algorithm explained before. Table I shows the iPhone 4 positioning results. Pointed out are the differences between computed and true values in respect of X- and Y-coordinates. At three locations (1, 5 and 8) it was not possible to get a unique solution, since not all three coils could be reliable detected. In all other cases the accuracy of the coordinates stand in the range of around 0.5 m (excluded Y coordinate of location three), which demonstrate a satisfactory result for indoor positioning with a low-cost sensor.

Summarizing, it can be noted that it is possible to use smart phones (here iPhone 4) for user localization in an indoor environment. The accuracy strongly depends on the signal quality of the coils magnetic fields. If the range between sensor and reference point is too large (for iPhone 4 > 6m), the precision of the position estimation decreases rapidly.

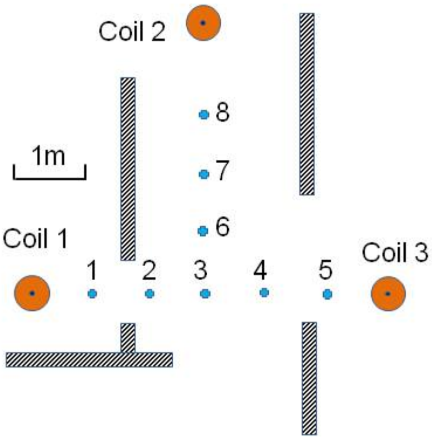

Figure 12: Magnetic coils and sensor locations for iPhone 2D positioning test

TABLE I.
RESULTS OF SMART PHONE MEASUREMENTS

Location	dX [cm]	dY [cm]
1	-	-
2	52	3
3	12	76
4	-24	4
5	-	-
6	-9	-27
7	-9	-19
8	-	-

B. *3D positioning*

Besides the 2D positioning, currently a 3D position estimation algorithm is developed. One approach which is described already in [4] and [5] bases on the solution of the three magnitude equations:

$$|B_i| = k\,\frac{\left(3(z-z_i)^2 + r_i^2\right)^{\frac{1}{2}}}{r_i^4} \qquad (6)$$

Where $k = \frac{\mu_0 NIF}{4\pi}$, i (i= 1...3) identifies a particular coil, B_i is the measured magnetic field vector at the sensor location (x,y,z), (x_i, y_i, z_i) describes the position of the coil i and r_i is the distance to it.

The equation system (6) can be solved by using again the Gauss-Newton method [19]. The initial estimation of the solution is derived by solving the following approximate equations for (6) [4] [5]:

$$B_i = k\,\frac{1{,}5}{r_i^3} \qquad (7)$$

The approach has been evaluated on a set of 7 locations with respect to the 3D position accuracy at the corridor of the University building (cf. Fig. 13). In this case the coils are closer to each other to enable signal detection by both smart phones. Table II shows the results of our experiments as deviations between the determined and the priori known coordinates. As expected, the HMR2300 gives the best performance with accuracy in the cm-range. Using low cost magnetic sensors embedded in smart phones, accuracies in the dm-range can be expected. In this scenario the iPhone 4 device provides better positioning accuracy than the Samsung Galaxy Nexus, probably because of a more sensitive magnetic sensor. Furthermore, it can be seen due to the coil's vertical configuration that the accuracy of measurement, along the Z-axis is less than along the X and Y axes.

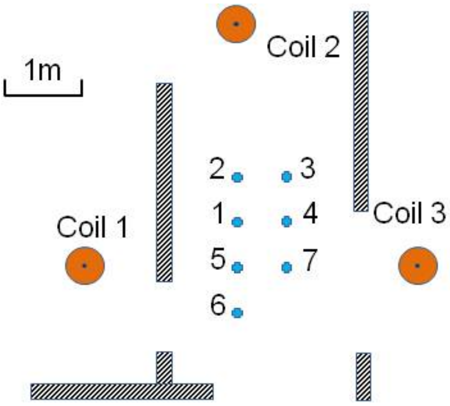

Figure 13: Magnetic coils and sensor locations for 3D positioning

TABLE II.
3 D POSITIONING RESULT

	HMR2300			iPhone 4			Samsung Galaxy Nexus		
Location	dX [cm]	dY [cm]	dZ [cm]	dX [cm]	dY [cm]	dZ [cm]	dX [cm]	dY [cm]	dZ [cm]
1	-2.5	-0.1	-19.0	-3.2	-2.0	45.7	9.0	-8.6	-141.3
2	-3.4	0.0	11.4	1.8	-12.3	-82.0	6.9	-26.3	-129.9
3	-4.5	-2.7	-14.5	-5.5	-4.1	44.5	-1.8	-20.4	-119.0
4	-4.3	-0.9	13.5	-5.7	0.4	45.0	-13.4	0.3	96.3
5	-3.1	-0.5	9.8	-3.1	2.8	61.7	10.3	-11.3	-143.2
6	-0.8	-6.4	-99.6	5.2	-13.5	-131.4	11.6	10.5	-141.6
7	9.5	-8.0	-56.5	-9.6	-3.3	51.7	-12.0	8.3	81.5

VIII. CONCLUSION AND OUTLOOK

A method for determining the position of mobile user based on artificially generated magnetic fields even in NLoS indoor environments was presented. In the testbed deployment, an experimental system has been built on the basis of low-cost coils and commercial magnetometers including low cost sensors embedded in modern smart phones. Currently, 2D positioning accuracies of less than 0.5 m can be achieved by using three magnetic coils and a magnetic sensor in measuring range of 15 x 15 m. By using a simple calibration approach the accuracy could be improved to less than 0.1 m. By means of digital signal processing the influence of interference fields can be minimized. Consequently, the accuracy of position estimation can be improved significantly. Similarly in a 7 x7 m field the 2D positioning accuracies were less than 0.8 m using an iPhone. In a smaller 4 x 4 x 3 m measuring volume, 3D positioning accuracies of less than 0.2 m in X- and Y-coordinate and 1.5 m in Z-coordinate could be achieved by using an iPhone 4 and Samsung Galaxy Nexus.

Currently, system refinements are carried out, e.g. the 3D positioning algorithm is further improved and the distance dependence of the adaptive filter is analysed. In the course of the project the development of a 3D calibration method is intended as well as the enlargement of the system’s (maximum) range by using larger coils and higher currents. The latter has already been implemented successfully with another coil: the signals were detected up to a distance of 45 m in a corridor building. In addition, we are working on the use of the system for mass market applications through the evaluation of modern smart phones as a mobile station and the development of a framework for implementation of location-based indoor applications.

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