Robust Ultrasonic Spread-Spectrum Positioning System using a AoA/ToA Method

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Abstract **– This paper proposes a novel hybrid Time of Arrival (ToA) and Angle of Arrival (AoA) based system for 3D indoor location using ultrasonic spread spectrum signals. The proposed system differs from previously proposed hybrid systems in several ways - the mobile devices determines its own position, the consequent orientation problem is solved and the system uses spread spectrum techniques to improve robustness to noise and multipath. The system uses an inclinometer to allow the mobile to determine its own position. This paper compares the performance of the proposed hybrid system with that of a conventional ToA-only system. The hybrid system is found to reduce the number of base stations needed for 3D location of the mobile device, from three to two, and to provide more accurate location estimates under conditions of typical noise and room reverberation.**

Keywords **– Spread Spectrum, Time of Arrival, Angle of Arrival, Image Method, ultrasonic, location systems.**

I. INTRODUCTION

The problem of estimating a mobile device's 3D location has been widely studied. Ultrasonic location systems have been proposed for use in indoor applications because of the advantages that they possess over RF based systems - lower carrier velocity, negligible wall penetration, lack of regulatory control, suitability for use in hospitals, low cost, etc. However, the performance of previously reported ultrasonic systems has been shown to degrade significantly under conditions of noise and typical in-room acoustic reverberation [14]. The emergence of new array signal processing algorithms, together with rapid growth in the performance of Digital Signal Processors, has opened a range of new possibilities for solving these problems.

The system proposed in this paper makes use of array processing to determine a mobile device's location based on Angle of Arrival (AoA) and Time of Arrival (ToA) estimation. AoA estimation requires use of an antenna array and computationally complex Digital Signal Processing at the receiver. The advantage of using ToA and AoA information is two-fold. The first advantage is that 3D location may be estimated with Line Of Sight (LOS) to only two Base Stations. In contrast, traditional ToA-only methods require LOS to, at least, three Base Stations (BSs). A reduction in the number of beacons required by the system increases robustness to occlusion events, a significant issue in practical location systems, and so can reduce the cost of infrastructure installation. The second potential advantage of hybrid systems is increased accuracy under conditions of noise and reverberation. Since hybrid systems require less Base Stations, the amount of self-noise is decreased. Furthermore, the hybrid systems may also be more robust since they combine two separate positioning techniques which degrade in different ways.

The system considered herein differs three previously published hybrid AoA-ToA systems in two ways. Firstly, the mobile device determines its own position rather than relying on the infrastructure to estimate the mobile device's location. This allows the system to be used in privacy-aware ubiquitous applications. It also significantly reduces the cost of infrastructure installation. Secondly, Mobile Station (MS) location introduces a new problem that does not exist in infrastructure location, i.e. the MS must determine the deviation of its reference frame from that of the BSs. The algorithm proposed herein solves this problem using AoA and ToA information from two BSs and data from an inclinometer within the MS. This approach is made possible by recent advances in MEMs technology, which have significantly reduced the size and cost of inclinometer devices [18]. Thirdly, the system differs in that Frequency-Hopped Spread Spectrum (FHSS) modulation is used for robust ToA estimation.

In this paper, we compare the accuracy of the proposed hybrid system with that of a conventional ToA-only system under conditions of noise and reverberation. In addition, we analyze the impact of transducer directionality on accuracy.

The paper is structured as follows. Previous related work is described in Section 2. A theoretical study of the issues is provided in Section 3. Section 4 describes the proposed hybrid location algorithm. Section 5 describes the method of performance assessment. Section 6 gives the results and discusses their implications. Section 7 concludes the paper.

II. RELATED WORK

Indoor ultrasonic location systems for pervasive computing were first studied in the Bats [3] and Crickets [2] systems. The Bats system employs Base Station location with impulsive signaling. In response to an RF pulse, the mobile Bat device transmits an ultrasonic pulse which is detected by receivers on the walls and ceiling. The infrastructure then estimates the position of the Bat. The Crickets system utilizes transmitting beacons and a receiving mobile device. Again, a simple ultrasonic pulse with RF synchronization is used for ToA estimation. The accuracy of the systems is reported to be 10 cm with an orientation accuracy of 3 degrees in low noise environments. The update rate of the systems is limited since time must be allowed for the reverberation of the impulses to decay before re-sending.

Use of spread spectrum modulation for improving the robustness of ToA based systems was investigated in [7]. It was found that Frequency-Hopped Spread Spectrum (FHSS) modulation outperforms Direct Sequence Spread Spectrum (DSSS) in terms of accuracy under conditions of noise and reverberation. Methods based on both spread spectrum modulations show a significant improvement in robustness over impulsive systems [2], [3].

Hybrid AoA/ToA systems were proposed previously in [8],[5],[6]. The authors of [5] propose a location method utilizing two angles of arrival and two range estimates to obtain a location estimate. The paper reported the results of simulations but did not take into account the orientation problem. This problem appears when location estimation is performed by the mobile device. Clearly, a device can be placed in any position, with any orientation. Hence it is necessary to estimate orientation as well as location, otherwise the device's location could be anywhere on a circle of points which are equidistant from both beacons. Other hybrid systems, such as [6] use Time Difference of Arrival (TDoA) with AoA measures, which allow translation of the reference frame to obtain a set of simple equations. However the method requires LOS to, at least, three beacons.

The authors of [17] describe a theoretical study comparing the Cramer-Rao Bound with ToA/RSS and TDOA/RSS schemes. The results are interesting but the work does not consider the effects of practical issues discussed in this paper, e.g. the directionality of the transducers and the problems arising from the unknown orientation of the Mobile Station. In [16] the benefits of using a hybrid system in a mobile network are assessed. Unlike this work, the paper focuses on RF systems.

III. THEORY

A. Problem Statement

The problem addressed herein may be formulated as follows: "Determine the 3D location of a mobile device based on ultrasonic signals received by the mobile device from a set of fixed beacons, whose position is known a priori, under conditions of noise and room reverberation. Independent time synchronization of the mobile device and beacons is available."

The following two sub-sections describe the ToA and AoA techniques used within the proposed system. The third and fourth sub-sections describe the techniques used in this work to model room reverberation and transducer directionality.

B. Time of Arrival

For impulsive systems, the ToA of the transmitted pulse is calculated as the delay of the peak of the received signal relative to an independent synchronization signal.

Direct Sequence Spread Spectrum systems use a spreading signal that comprises a pseudorandom sequence of binary pulses +1,-1 (spreading code) at a high rate (chipping rate). The spreading codes used by the beacons are orthogonal so that the signals can be separated at the receiver. The data signal is multiplied by the spreading code and used to modulate a carrier signal at the desired center frequency. The received signal is cross-correlated with the known transmitted sequence used by each beacon. The delay of the peak of the cross-correlation is taken as the ToA estimate for each beacon. This modulation can be represented as:

$$s_1(t) = Ap(t)\cos(2\pi f_c t + \theta) \tag{1}$$

where A is the signal amplitude, *p(t)* is the spreading waveform, f_c is the carrier frequency, and θ is the phase at time *t=0*.

In Frequency-Hopped Spread Spectrum systems, the transmitted signal hops between a set of frequencies according to a pseudorandom code. Again, the delay of the peak of the cross-correlation between the received signal and the known transmitted signals is used for ToA estimation. This modulation can be represented as:

$$s_2(t) = A\cos(2\pi f(t) + \phi) \tag{2}$$

where $f(t)$ is the pseudo-randomly modulated carrier frequency, and ϕ is the phase angle. In all cases, the ToA estimate is converted to a range estimate based on the speed of sound in air.

C. Angle of Arrival

Angle of Arrival systems estimate location based on the angle of incidence of the ultrasonic signal at an antenna array. These techniques estimate AoA based on the information received by the array, usually from the covariance matrix of the signals received at the array *R*. The method employed herein determines the elevation and azimuth angles associated with the steering vector, *S*, which maximizes the power of the shaper output given by:

$$P(S) = \frac{1}{S^H R^{-1} S} \tag{3}$$

assuming that:

$$R = \alpha S S^H + R_o \tag{4}$$

where α is the power received from the beacon at the angle given by the steering vector *S* and R_o is due to the other beacons and noise. For more information, see [9] [10].

D. Image Method

One of the sources of inaccuracy in ultrasonic location systems is reverberation. The transmitted signal is reflected from the surfaces of the room. These reflections are correlated with the original signal and so can be more damaging to accuracy than random noise. For these experiments, we chose to model reverberation using the Image Method [1]. The Image Method is used for simulating the impulse response between two points in a small rectangular room. The method considers that each wall is an acoustic 'mirror'. Reflected images of the actual sound source can be considered as virtual transmitters. The impulse response is determined as the sound received at the transducer when the actual transmitter and all of the virtual transmitters send an impulse at time zero. The contribution of the actual and virtual sources is determined based on the source-receiver distance and the reflection coefficients of the walls, ceiling and floor.

E. Transducers Response

Ultrasonic transducers can be highly directional. This can limit the performance of a location system. Herein, the directionality of the transducers is modeled using the formulation given in [4]:

$$D_N(f,\phi) = 2\frac{J_1(\frac{2\pi a}{\lambda}\sin(\phi))}{\frac{2\pi a}{\lambda}\sin(\phi)} \tag{5}$$

where J_1 is the first-order Bessel function of the first kind, *f* is frequency, λ = *c/f* is wavelength, *a* is the transducer radius and ϕ is the elevation angle of the direction vector.

IV. LOCATION ALGORITHM

The focus of this investigation is the use of two different sources of information to obtain a correct location estimate. In theory, it is possible to estimate position using a solid angle estimate and a range estimate (a solid angle being azimuth and elevation). In practice, the problem is more complex if the mobile device estimates its own position, without knowing its orientation. The orientation problem has three axis to estimate (x, y, z). A planar array antenna is able to estimate two angles, so a 2-axis inclinometer is used to determine the third, missing, variable.

In this work we determine the location of the Base Stations in the reference frame of the Mobile Station. The deviation of the MS reference frame with respect that of the BS is then determined. Finally the 3D location of the MS in the reference frame of BSs is found.

The problem is illustrated for the 2D case in Fig. 1. The variable α_{or} represents the deviation of the MS reference frame with respect to the BS reference frame. $\hat{\alpha}$ is the measured AoA at the MS of the signal from BS 1. The AoA of the signal within the BS reference frame is then $\alpha = \hat{\alpha} + \alpha_{or}$.

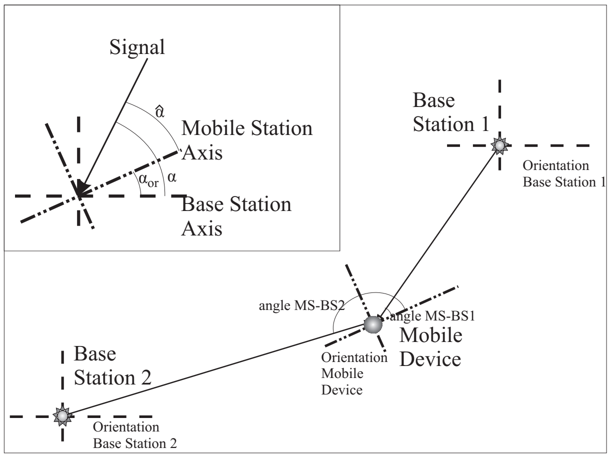

Fig. 1. ORIENTATION PROBLEM AND SOLUTION WITH 2 BASE STATIONS

Location estimation then proceeds as follows. We assume that all the BSs are placed in the ceiling. This assumption, an inclinometer that measures tilt relative to the *x*-*y* plane, means that the *y* variable is not necessary in the equations. The algorithm takes as input a set of *M* BS positions (x_m, y_m, z_m), estimates of the ranges from each BS_m to the MS, L_m, and the AoA of the signals from each BS_m, θ_m, ϕ_m.

Let the position of the MS in the BS frame of reference *r* be:

$$r = [x_{MS}, y_{MS}, z_{MS}] \tag{6}$$

Then let *Ar*=*b* where:

$$A = \begin{bmatrix} (x_1 - x_m) & (y_1 - y_m) & (z_1 - z_m) \\ \tan(\theta_m) & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{7}$$

$$b = 0.5 \begin{bmatrix} (L_m^2 - L_1^2 + K_1 - K_m) \\ 2(x_m \tan(\theta_m) - y_m) \\ 2(L_m \sin(\phi_m) - z_m) \end{bmatrix} \tag{8}$$

$$K_m = x_m^2 + y_m^2 + z_m^2 \tag{9}$$

The first row is derived from the Time of Arrival information. The next two rows are derived from the given that $\theta_m = \arctan \frac{y-y_m}{x-x_m}$ and $\phi_m = \arcsin \frac{z-z_m}{L_m}$. Hence we can solve for r given A and b

As was explained previously, the MS deviates from that of the BSs by both θ and ϕ. Let $\theta = \hat{\theta} + \theta_{or}$ and $\phi = \hat{\phi} + \phi_{or}$ where $[\hat{\theta}, \hat{\phi}]$ are the MS estimated elevation and azimuth respectively and $[\theta_{or}, \phi_{or}]$ the deviation from the BS frame reference, assuming a third angle estimated by an inclinometer. From the previous matrix:

$$z_{MS} = L_m \sin(\hat{\theta}_m + \theta_{or}) - z_1 \tag{10}$$

$$x_{MS} = L_m \sin(\hat{\phi}_m + \phi_{or}) - x_1 \tag{11}$$

With a set of at least 2 Base Stations, we can obtain a set of equations where z and x are eliminated to obtain:

$$L_m \sin(\hat{\theta}_m + \theta_{or}) - L_{m+1} \sin(\hat{\theta}_{m+1} + \theta_{or}) = (x_m - x_{m+1}) \tag{12}$$
$$L_m \sin(\hat{\phi}_m + \phi_{or}) - L_{m+1} \sin(\hat{\phi}_{m+1} + \phi_{or}) = (z_m - z_{m+1}) \tag{13}$$

An iterative 3 step method is used. Firstly search with an accuracy of 10 degrees for the best solution; next, search around that value, with an accuracy of 1 degree; and finally search with an accuracy of 0.1 degrees.

The estimated values θ_{or} and ϕ_{or} can then be used to obtain values for θ and ϕ. With it and the inclinometer estimation, the three angles of orientation are obtained.

V. METHOD

The performance of the system was assessed in simulation using MATLAB.

The hybrid system used two base stations and an antenna array of six elements. The array was configured in two circles each with three sensors, one at 0.5 λ and the other at 1 λ using for λ the carrier frequency. The accuracy of the hybrid system was compared with that of a TOA system using conventional multilateralization over three base stations. The inclinometer was simulated to an accuracy of 0.1 degrees, which is typical accuracy for modern inclinometers. For example, the SPECTROTILT family [18] has an accuracy below 0.02 degrees over a range of 90 degrees.

In a previous study [7], the benefit of using FHSS over DSSS for this application was demonstrated. DSSS has better characteristics in noisy channels but when the channel has a large degree of multipath interference, FHSS outperforms DSSS in terms of accuracy. Hence FHSS was chosen as the modulation for this study. The simulations were conducted using a random data sequence. An ultrasonic carrier frequency of 30 KHz and a separation between frequency slots of two times the data frequency were selected and a Slow Frequency-Hopped modulation, using 1 hop per data bit. The data and chipping rates were both chosen to be 10 KHz.

The channel, which was generated using the Image Method, has 80 interferers per transmitter in a room of 6x6x4 meters. Room humidity was 50 and temperature 20 degrees. The walls have an reflection coefficient of 0.4 and floor and ceiling 0.6. The beacons were placed at the corners [6,6,4];[0,0,4] of the room. The third beacon, used in the conventional ToA-only multilateralization system, was placed at the corner [0,6,4].

Simulations were conducted in two sets - one using omni-directional transducers and one using directional transducers. For reference, the Quantelec SQ-40 40KHz transducer has a beam angle of nearly +/- 30 degrees [12]. Twelve directional transducer models were tested with beam angles varying from 20 degrees to 180 degrees.

The performance of the systems was assessed across noise levels in the range -12 dB to +10 dB SNR. Location accuracy at each noise level was determined by averaging the error over 100 repetitions using randomly placed receiver positions and orientations. In each case, the signal consisted of 500 PN pulses at a data frequency of 10 kHz giving an update rate of 0.05 seconds, sufficient for tracking normal movement.

VI. RESULTS

The first set of experiments investigated the accuracy of the hybrid and ToA-only systems using omni-directional transducers. The percentage of location estimates in error by less than 2.5 cm is shown in Fig. 3. The results show that the hybrid system provides more accurate location estimates that the ToA-only system. At an SNR of 0 dB, the ToA method is accurate to within 2.5 cm in 67% of case whereas the hybrid model achieves equivalent location accuracy in 90% of cases.

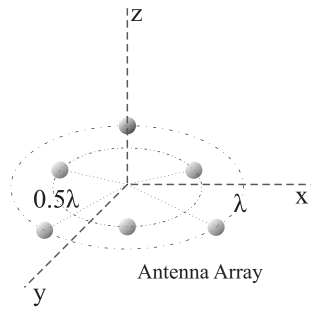

Fig. 2. ANTENNA ARRAY WITH 6 SENSORS

Fig. 4 shows the percentage of location estimates having less than a given error at an SNR of 10 dB. As can be seen, the hybrid

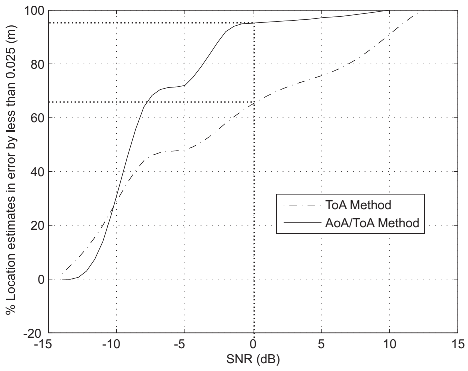

Fig. 3. LOCATION ESTIMATES IN ERROR BY LESS THAN 0.025 METERS, OMNI-DIRECTIONAL TRANSDUCERS

system is more robust than the ToA-only system. This is due to the reduced number of transmitters which decreases the self-noise in the system. The location errors also arise in regions of low signal strength, which lead to incorrect range estimates.

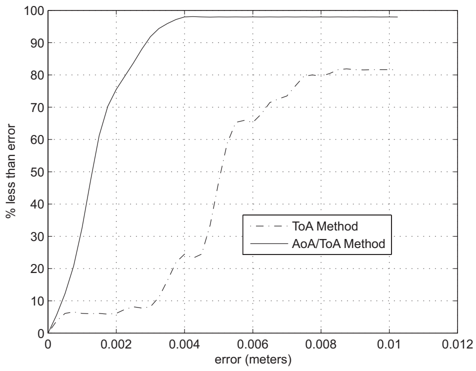

Fig. 4. LOCATION ESTIMATES WITH ERROR OF LESS THAN X METERS AT 10 DB SNR, OMNI-DIRECTIONAL TRANSDUCERS

Fig. 5 shows the distribution of location errors obtained for the two systems operating at an SNR of 10 dB. Only location inaccuracies of greater than 0.003 m are considered as errors. Again, the robustness of the hybrid system, as compared with the ToA-only system, is evident. The mean error is reduced from from 0.006 m to 0.004 m. Additionally, the errors are more tightly clustered around the mean.

A second set of experiments was conducted to determine the effects of using directional transducers in the beacons assuming a omnidirectional receiver. The channel was configured with an SNR of 10 dB. The results are provided in Table 1 and Fig. 6. It can be seen that the results are better when more omni-directional transducers are used. This is due to a reduction in the number of blind spots. Due to the use of FHSS modulation, the system is immune to the consequent increase in interference.

Fig. 7 shows a three dimensional plot of the variation of mean error with mobile device XY (floorplan) location for directional transducers with a beam of 40 degrees. As can be seen, the worst errors occur close to the beacons. This occurs due to

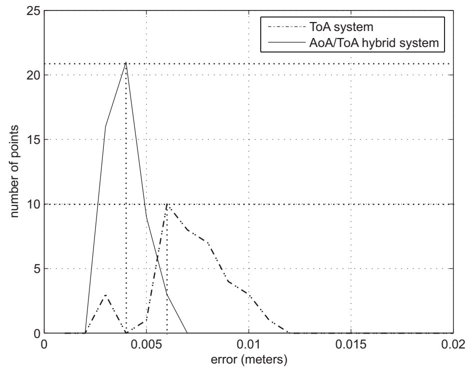

Fig. 5. ERROR ESTIMATION INTO A 10DB SNR ROOM, OMNI-DIRECTIONAL TRANSDUCERS

TABLE I.
LOCATION ESTIMATION STATISTICS FOR DIRECTIONAL TRANSDUCERS WITH A 10DB SNR

Sensor Beam Angle (degrees)	Mean error (meters) ToA system	Hybrid system	% error less 0.01 meters ToA system	Hybrid system
180	0.0122	0.0042	78.0	99.0
140	0.0438	0.0168	71.0	94.0
120	0.0410	0.0221	70.0	90.0
100	0.0665	0.0470	62.0	77.4
80	0.1245	0.0650	56.3	62.3
60	0.1791	0.0872	51.0	59.7
50	0.2025	0.1012	47.1	56.1
40	0.2702	0.1370	45.0	50.7
20	0.3263	0.1441	40.2	49.2
10	0.3320	0.2465	38.1	43.7

the directional transducer response which significantly degrades location accuracy in certain positions and at certain orientations.

A plot of the error variation obtained using omnidirectional transducers is shown in Fig. 8. As can seen using omnidirectional transducers, the problems of blind points do not exist, and the entire data set has an error of less than 1 cm. Clearly the system works better at locations close to the center of the room and generally degrades close to the walls, as can be seen in Fig. 7 and Fig. 8.

The largest errors for the directional system occur near to the beacons. This arises for two reasons. Firstly, due to the beacon configuration, the signal from one beacon is weak when the MS is close to other beacon. Secondly, there are significant blind spots close to, but below, the transducers. This problem could be mitigated by placing transducers in all corners in order to reduce the number of blind points.

VII. CONCLUSIONS AND FURTHER WORK

The benefits of using Angle of Arrival techniques, in addition to Time of Arrival methods, in ultrasonic location estimation systems has been clearly shown. The proposed hybrid system has been shown to be more robust to noise and room reverberation. It also benefits from reduced self-noise arising

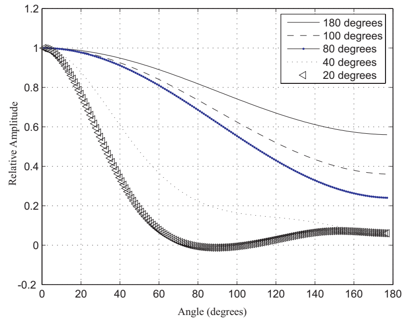

Fig. 6. Transducers Directional Response

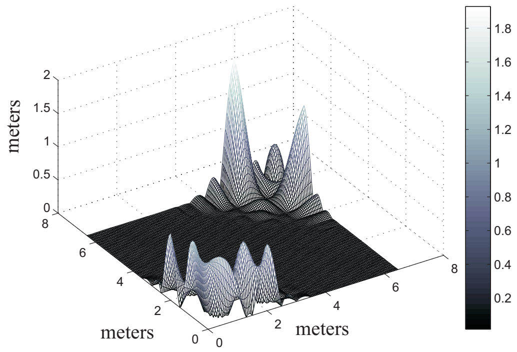

Fig. 7. Error surface for a 6x6x4 meters room with directional transducers

from a reduction in the number of Base Stations. In addition, the decreased Base Station requirement reduces system installation costs. However, mobile device costs are increased due to the need for an antenna array. It is worth noting that a single location infrastructure can support both high accuracy location devices with antenna arrays and cheaper, lower accuracy devices with single transducers.

A realistic set of simulations was performed, showing that use of directional transducers leads to blind points. Unfortunately, ultrasonic omnidirectional transducers are expensive and difficult to implement.

Future work includes investigation of alternative AoA estimation algorithms and post-processing methods, such as Kalman filters. The main problem with AoA techniques, in general, is that if a noise source exists, with similar received power to the beacon, then angle estimation can be erroneous. A further issue arises from Non-Line Of Sight due to occlusion. Techniques for mitigating these problems will be developed and assessed. It is planned to test the performance of the proposed algorithms in a system prototype.

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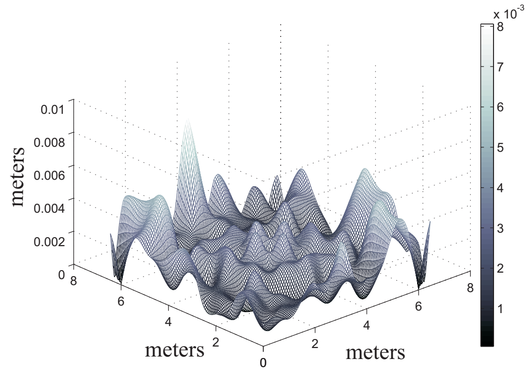

Fig. 8. Error surface for a 6x6x4 meters room with omni-directional transducers

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