Title	Ultrasonic Orientation-Location Algorithm based on ToA and AoA Measurements
Authors(s)	Gonzalez-Hernandez, Juan, Bleakley, Chris J.
Publication date	2008-08-28
Publication information	Gonzalez-Hernandez, Juan, and Chris J. Bleakley. “Ultrasonic Orientation-Location Algorithm Based on ToA and AoA Measurements.” IEEE, 2008.
Conference details	International Symposium on Spread Spectrum Techniques and Applications (ISSSTA), Bologna, Italy, 25 - 28 August, 2008
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/7029
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Publisher's version (DOI)	10.1109/ISSSTA.2008.156

Ultrasonic Orientation-Location Algorithm based on Time and Angle of Arrival Measurements

Juan Ramon Gonzalez
School of Computer Science
and Informatics, University
College Dublin, Belfield,
Dublin 4, Ireland.
juanragonz@gmail.com

C.J. Bleakley
School of Computer Science
and Informatics, University
College Dublin, Belfield,
Dublin 4, Ireland.
chris.bleakley@ucd.ie

***Abstract*—This paper proposes a novel system providing 3-axis orientation and 3D location for a Mobile Device based on Time of Arrival (ToA) and Angle of Arrival (AoA) measurements using ultrasonic signals. Robustness is provided to the system by using a Slow Frequency-Hop Spread Spectrum modulation and a robust 2D AoA estimation method using a Uniform Circular Array. In simulations, the system shows an orientation accuracy of 1.7 degrees and location accuracy of 1cm in 95% of cases under conditions of noise and reverberation.**

***Index Terms*—ToA, AoA, orientation, location, ultrasound**

I. INTRODUCTION

Ubiquitous Computing is defined as a model of human-technology interaction in which information processing has been integrated with people everyday live [11]. A person using this technology engages with devices and systems in their daily activities without being aware that the technology is there. For this paradigm location-aware technologies are essential. One approach to providing accurate and reliable location estimates is to use ultrasonic signals to infer position.

Ultrasonic location systems have been focused on estimating the location of a Mobile Device (MD) with the smallest error possible. Several ultrasonic location systems such as [1], [2] and [3] have been shown to provide good accuracy. However, most lack robustness to noise, reverberation and transducer directionality. Furthermore, almost all provide no estimate of device orientation, a key for understanding user intent.

In this paper, a Spread Spectrum modulation, specifically Slow FH-SS, and a close-form AoA measurement algorithm, UCA-ESPRIT, are used to provide robust estimates of the orientation and location. In order to estimate this orientation, an accurate model is necessary to describe it. The proposed algorithm uses Euler's Angles [12], a common representation in aerospace and robotic applications.

The paper is structured as follows. Previous related work is described in Section 2. A theoretical study of the measurement techniques employed is provided in Section 3. Section 4 describes the proposed location orientation algorithm. Section 5 explains 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 [8] and Crickets [1] 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 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.

There are several indoor systems, such as [5] and [6] that track orientation by subtracting the current location estimate from previous ones. This procedure introduces errors because it estimates movement orientation, not estimation device orientation.

One of the most important orientation systems was presented in [4] where a set of sensors were added to Cricket system to support orientation estimation. Other systems for orientation estimation include specific hardware to estimate the orientation of the device. In [7] orientation specific hardware is built, with TILT technology. The method proposed herein avoids the need for extra hardware, reducing the cost and complexity of the device.

Use of Spread Spectrum modulation for improving the robustness of ToA based systems was investigated in [9]. It was found that Frequency-Hopped Spread Spectrum (FH-SS) modulation outperforms Direct Sequence Spread Spectrum (DS-SS) in terms of accuracy under conditions of noise and reverberation. Methods based on Spread Spectrum modulation show a significant improvement in robustness over impulsive systems as can be seen in [8] and [1].

III. ANALYSIS

From previous studies [9] indoor ultrasonic environments are characterized mainly by a significant multipath interference. Spread Spectrum (SS) modulations are one of the most successful tools to mitigate these problems. A brief introduction to SS, focused on the modulation used herein, as well as a brief introduction to EigenVector Decomposition (EVD) methods to AoA estimation is provided below

A. FH-SS Modulation

For impulsive systems, the ToA of the 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 pseudorandom sequence of binary pulses +1,-1 (spreading code) at a high rate (chipping rate) to comprise the data. 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 with respect to the RF synchronization is taken as the ToA estimate for each beacon.

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:

$$s_2(t) = A\cos(2\pi f t + \phi) \tag{1}$$

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.

Two kinds of FH-SS modulation exist, Slow and Fast FH [13]. In Fast FH-SS each data bit hops several times, while Slow FH-SS uses several bits per frequency hop. Both modulate the signal using a PSK or FSK modulation to next, spread the signal in frequency. As can be inferred, Fast FH is more robust to interferences, but the bandwidth requirements may exceed the actual ultrasonic transducer bandwidth and the electronic necessary to modulate and demodulate signals is more complicated and expensive. Slow-FH provides less multipath mitigation than Fast-FH, but the bandwidth requirements are less strict and the implementation cost is smaller.

From a previous study, presented in [9], the performance advantages of FH over DS were shown. It was demonstrated than for smaller bandwidth, FH modulation provides greater mitigation of multipath interference, one of the most important sources of error in indoor environments. Hopping over a set of frequencies allows discrimination of interferences in time and frequency, providing better performance than DS spreading under the same reverberation conditions.

The proposed algorithm uses Slow FH-SS modulation. As data a Golay code [14] was chosen, using a BPSK modulation. It has been shown that this configuration provides very good performance as can be seen in Section 6.

B. Angle of Arrival Estimation

Estimation the Angle of Arrival (AoA) of plane waves is a problem in many applications. In all cases, a planar array is required for 2D estimation of the source azimuth and elevation. A Uniform Circular Array (UCA) is a common configuration because its 360 degree azimuth coverage. The UCA-ESPRIT algorithm [10] yields the AOA estimates directly. In contrast, other methods perform searches in 2D, at high computational cost. The angles are provided by eigenvalues whose form is $\mu = sin(\phi)exp(j\theta)$ where ϕ and θ are the elevation and azimuth angles.

This algorithm provides paired source azimuth and elevation angles by a close-form procedure, but the accuracy in azimuth is far better than the elevation accuracy.

Close-form solutions for AoA estimation were developed initially for Uniform Linear Arrays (ULAs). These are only able to estimate a 1D angle, but the special characteristics of their elements allow better solutions than for other array shapes. Estimation of AoA with UCA uses a property of Bessel's functions to transform a UCA-type steering vector to a ULA type steering vector in order to apply the close-form solutions developed for it. Consider:

$$\left.\begin{array}{l} {}^{i}\left[a\left(\phi\right)\right]_{UCA} = e^{-j\frac{2\pi d}{\lambda}\cos\left(\phi - i\frac{\pi}{4}\right)} \\ {}^{i}\left[a\left(\phi\right)\right]_{ULA} = \left(e^{-j\frac{2\pi d}{\lambda}\cos\left(\phi\right)}\right)^{i} \end{array}\right\} i = 1\ldots N \tag{2}$$

where the exponent is the number of the element, i, d is the distance between sensors, λ the wavelength and ϕ the desired angle. This relation between elements allows use of centro-Hermitian matrices [15], which is the basis of ULA methods and ESPRIT estimation methods. Premultiplying the UCA steering vector with a special beamformer, a similar expression can be provided. While the expression is not exactly the same, it maintains the form with *i* in the exponent. The new steering vector is equivalent to a virtual linear array of the same size, and ULA specific methods (closed-form solution instead of iterative search over the space) can be applied, such as Root-MUSIC or ESPRIT.

IV. ORIENTATION-LOCATION ALGORITHM

Assuming a set of *M* Base Stations (BS) with known positions $[x_{BSi}, y_{BSi}, z_{BSi}]$, each transmitting a signal to a Mobile Station (MS) that receives them and measures Time of Arrival (ToA) and Angle of Arrival (AoA). Synchronization between BSs and MS is assumed, so the measurements of ToA are absolute distances, allowing for spherical localization.

The inputs to the location algorithm are the set of *M* distances and *M* 2D angles:

$$\begin{array}{l} d_i \quad i = 1\ldots M \\ [\theta_i, \phi_i] \quad i = 1\ldots M \end{array} \tag{3}$$

where azimuth $\theta = \arctan\left(\frac{z}{\sqrt{x^2+y^2}}\right)$ and elevation $\phi = \arctan\left(\frac{y}{x}\right)$.

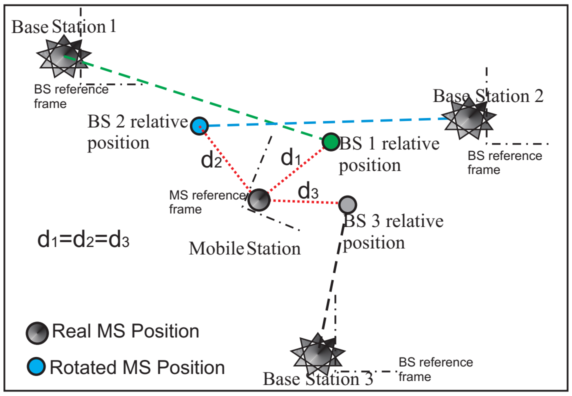

Fig. 1. 3 BS location estimation under orientation variation

Assuming a MS orientation (x_{or}, y_{or}, z_{or}), defined by Euler Angles and a Rotation Matrix as follows:

$$\underline{\underline{R}} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \tag{4}$$

$$\begin{aligned}
a_{11} &= \cos\left(y_{or}\right)\cos\left(z_{or}\right) \\
a_{12} &= \cos\left(y_{or}\right)\sin\left(z_{or}\right) \\
a_{13} &= -\sin\left(y_{or}\right) \\
a_{21} &= \sin\left(x_{or}\right)\sin\left(y_{or}\right)\cos\left(z_{or}\right) - \cos\left(x_{or}\right)\sin\left(z_{or}\right) \\
a_{22} &= \sin\left(x_{or}\right)\sin\left(y_{or}\right)\sin\left(z_{or}\right) + \cos\left(x_{or}\right)\cos\left(z_{or}\right) \\
a_{23} &= \sin\left(x_{or}\right)\cos\left(y_{or}\right) \\
a_{31} &= \cos\left(x_{or}\right)\sin\left(y_{or}\right)\cos\left(z_{or}\right) + \sin\left(x_{or}\right)\sin\left(z_{or}\right) \\
a_{32} &= \cos\left(x_{or}\right)\sin\left(y_{or}\right)\sin\left(z_{or}\right) - \sin\left(x_{or}\right)\cos\left(z_{or}\right) \\
a_{33} &= \cos\left(x_{or}\right)\cos\left(y_{or}\right)
\end{aligned} \tag{5}$$

MS rotation provides contamination in the MS measured angles, so $\hat{\theta} \neq \theta$ and $\hat{\phi} \neq \phi$. The first step to determine the MS location is to know the MS orientation.

For each set of measurements from a BS_i, $\left(\hat{d}_i, \hat{\theta}_i, \hat{\phi}_i\right)$ with known position $[x_{BSi}, y_{BSi}, z_{BSi}], i = 1...M$ one MS position estimate can be obtained as $[x_{MSi}, y_{MSi}, z_{MSi}], i = 1...M$.

If we rotate all of the MS estimates, using as a center the associated BS position, we will find one rotation that provides the same $[x'_{MSi}, y'_{MSi}, z'_{MSi}]$ for all the BSs

$$[x'_{MSi}, y'_{MSi}, z'_{MSi}] = [x_{MSi}, y_{MSi}, z_{MSi}]\underline{\underline{R}} \tag{6}$$

The rotation has to be defined using the BSs positions as center. An example in 2D is showed in Figure 1 where 3 BSs estimate the same MS location with an orientation error. As can be seen, the rotation is performed using the BSs positions as centers, so Eq.6 can be rewritten as follows:

$$\begin{bmatrix} x'_{MSi} \\ y'_{MSi} \\ z'_{MSi} \end{bmatrix}^T = \left[\begin{bmatrix} x_{MSi} \\ y_{MSi} \\ z_{MSi} \end{bmatrix} - \begin{bmatrix} x_{BSi} \\ y_{BSi} \\ z_{BSi} \end{bmatrix}\right]^T \underline{\underline{R}} + \begin{bmatrix} x_{BSi} \\ y_{BSi} \\ z_{BSi} \end{bmatrix}^T \tag{7}$$

where $[x_{MSi}, y_{MSi}, z_{MSi}]$ is the MS position estimated by BS_i.

To estimate the rotation that provides the same MS location for all the BSs measurements an estimates of $\underline{\underline{R}}$ called $\hat{\underline{\underline{R}}}$, is necessary. From Eq. 7 and Eq. 5 we have:

$$\left[\begin{bmatrix} x_{MSi} \\ y_{MSi} \\ z_{MSi} \end{bmatrix} - \begin{bmatrix} x_{BSi} \\ y_{BSi} \\ z_{BSi} \end{bmatrix}\right]^T = \begin{bmatrix} x_{rel\_i} \\ y_{rel\_i} \\ z_{rel\_i} \end{bmatrix} \tag{8}$$

$$\begin{aligned}
x'_{MSi} - x_{BSi} &= x_{rel\_i}a_{11} + y_{rel\_i}a_{12} + z_{rel\_i}a_{13} \\
y'_{MSi} - y_{BSi} &= x_{rel\_i}a_{21} + y_{rel\_i}a_{22} + z_{rel\_i}a_{23} \\
z'_{MSi} - z_{BSi} &= x_{rel\_i}a_{31} + y_{rel\_i}a_{32} + z_{rel\_i}a_{33}
\end{aligned} \tag{9}$$

Each equation from Eq. 9 defines a system of M equations (M being the number of BSs available) allowing solution for 3 of the $\underline{\underline{R}}$ coefficients.

We have from Eq. 9, 3 system of equations, each with 4 variables to solve, 3 orientation coefficients and one MS position coordinate. Four BSs would be necessary to solve the system In order to minimize the number of BSs, it is necessary to eliminate a variable from Eq. 9. The best way to do it is to eliminate$[x'_{MSi}, y'_{MSi}, z'_{MSi}]$.

It was explained previously that, for each BS, a set of $\left(\hat{d}_i, \hat{\theta}_i, \hat{\phi}_i\right)$ exists. With $M \geq 3$ BSs, the position can be solved for any trilateration method, for example by Taylor Series [11]. Using the position as a initial location estimate, the variable $[x'_{MSi}, y'_{MSi}, z'_{MSi}]$ becomes known, and regrouping terms, the system can be solved by:

$$\begin{gathered}
A = \begin{bmatrix} (x_{rel\_1}) & (y_{rel\_1}) & (z_{rel\_1}) \\ (x_{rel\_2}) & (y_{rel\_2}) & (z_{rel\_2}) \\ (x_{rel\_3}) & (y_{rel\_3}) & (z_{rel\_3}) \end{bmatrix} \\
B = \begin{bmatrix} x'_{MS1} - x_{BS1} \\ x'_{MS2} - x_{BS2} \\ x'_{MS3} - x_{BS3} \end{bmatrix}
\end{gathered} \tag{10}$$

which with only 3 BSs provides a set of 3 or more lineally independent equations, but relies on a initial location estimation.

When $\underline{\underline{R}}$ is estimated, in order to calculate the angles that generate that matrix, the next equations are used:

$$\begin{aligned}
y_{or} &= -\arcsin\left(a_{13}\right) \\
z_{or} &= \tfrac{1}{2}\mathrm{ar}\cos\left(\tfrac{a_{11}}{\cos(y_{or})}\right) + \tfrac{1}{2}\arcsin\left(\tfrac{a_{12}}{\cos(y_{or})}\right) \\
x_{or} &= \tfrac{1}{2}\mathrm{ar}\sin\left(\tfrac{a_{21}}{\cos(y_{or})}\right) + \tfrac{1}{2}\mathrm{ar}\cos\left(\tfrac{a_{31}}{\cos(y_{or})}\right)
\end{aligned} \tag{11}$$

V. METHOD

In order to test the proposed algorithm and provide a reliable simulation, several parameters were characterized. As modulation parameters Slow FH-SS was used, modulating a 32 bits Golay code with a BPSK modulation and 10 cycles per chip. The spreading was done using a hopping pattern of one hop per 4 chips. A carrier frequency of 30KHz and a sampling frequency of 160KHz were chosen, to allow for typical ultrasonic transducers. A bandwidth of 20 KHz was used to modulate the signals. A antenna array of 7 elements placed in a circular shape was simulated. As interference,

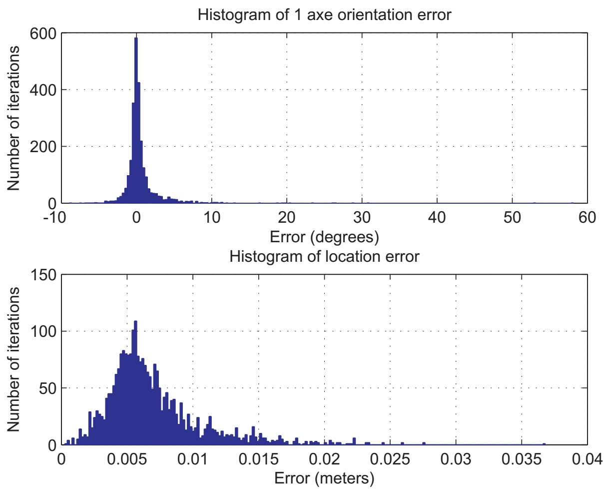

Fig. 2. Histogram of orientation and location error

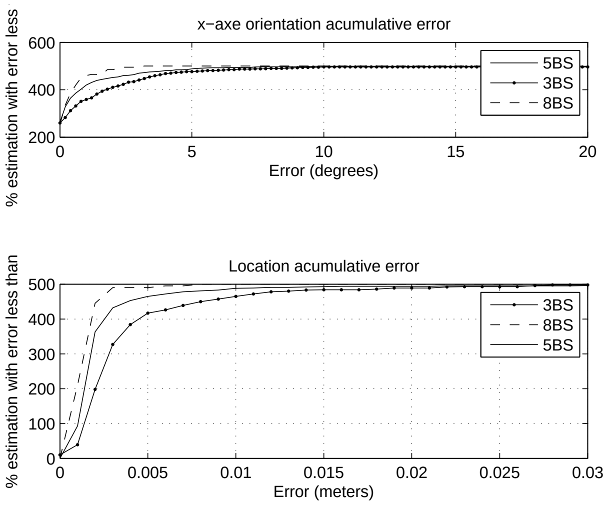

Fig. 3. Orientation Location Accumulative error vs number of BSs

white Gaussian noise was added with a SNR of 10 dB. A set of 80 multipath interferences were generated per beacon using the Image Method [12]. A 6x6x4 meters simulated room was used with a reflection coefficient of 0.6 for the walls and 0.4 for ceiling and floor.

Omnidirectional receivers were assumed. There are several ultrasonic and acoustic receivers which are close to omnidirection in practice [16]. Ultrasonic transmitters are not so ideals, so beam response was simulated with a beam response of 50 degrees using the next equation:

$$D_N(f,\phi) = 2\frac{J_1(\frac{2\pi a}{\lambda}\sin(\phi))}{\frac{2\pi a}{\lambda}\sin(\phi)} \tag{12}$$

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

VI. RESULTS

Performance was assessed over 1000 randomly chosen orientations and positions in the room. The results of the simulation can be seen in Figure 2. Most location estimates have error of less than 1 centimeter and orientation error of less than 1.5 degrees.

The second study was done using a grid of 200 positions in the room with a beacon on each corner, except at the position [6,6,4]. Figure 3 shows the orientation and location accumulative error for different number of BSs. It is clear that the more number of BSs the more accurate the results. With the minimum number of BSs, the system provides location estimate accuracy of under 1 centimeter and orientation error of less than 2 degrees.

A more detailed orientation study was performed. The results are plotted in Figure 4 where the orientation error for different BS configurations can be seen. In all the cases the number of BSs simulated was 4. The configuration called ”Corner” was performed using 4 BSs placed one in each corner of the ceiling. ”Half-wall” uses 4 BSs placed in the ceiling of the room, each one in the middle of the wall. ”x-axis” and ”y-axis” are two examples of bad configurations where all the BSs were placed following a line in the x-axis or y-axis. Figure 4 shows that the system performs better with well placed BSs and the error increase significantly when the BSs have a bad configuration. For well placed BSs the system provides an error less than 1 cm in 95% of cases, and for a bad configuration an error less than 9 cm in 95% of cases for x-axis.

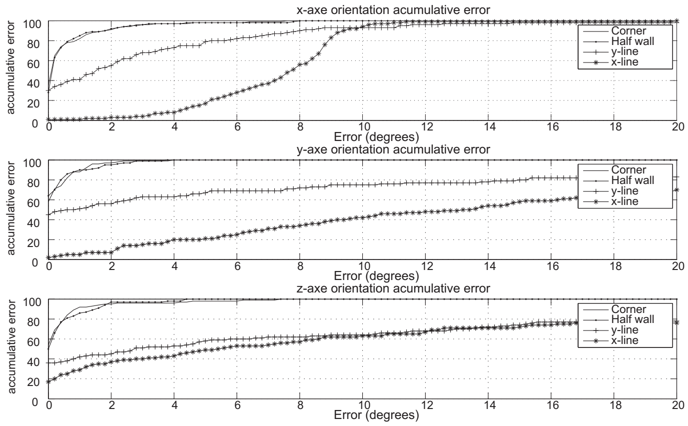

Fig. 4. Accumulative Orientation error vs BS position.

A simulation for various levels of noise was performed, using SNR values between -4 and 14 dB. As can be seen in Figure 5, the system performs well for all tested values. Because of the robust modulation used, FH-SS, multipath and noise rejection allows correct estimates for typical noise values, allowing accurate estimates with a SNR under 0. It can be seen that this robustness is only provided to the location estimates, that is because the AoA estimation method uses

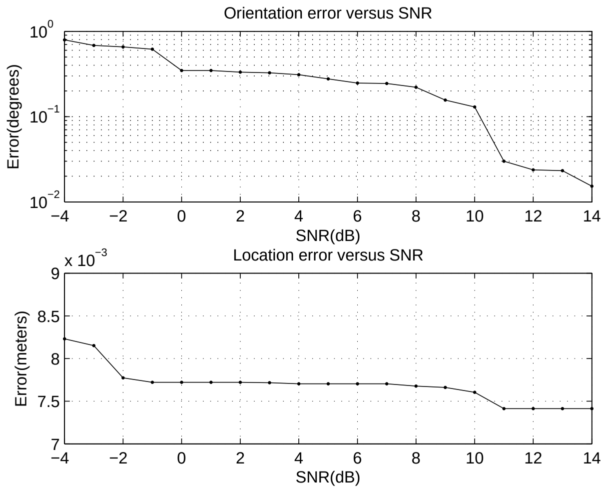

Fig. 5. Orientation and Location error vs SNR

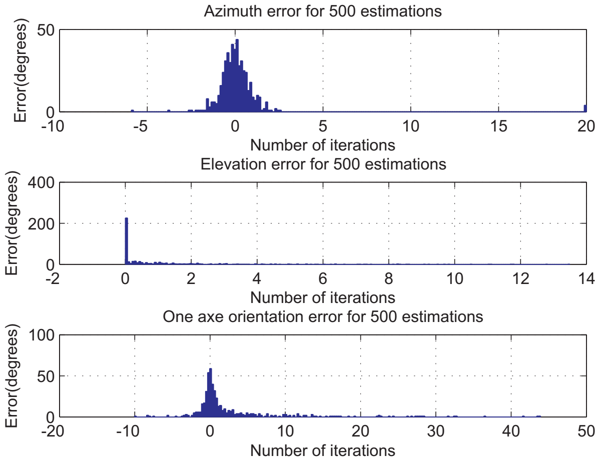

Fig. 6. Histogram of orientation error and Elevation and Azimuth error

received signals, and the benefits of SS modulations are not available if the signals used are not demodulated.

The error in the orientation estimation is not increased because the initial position estimates are good enough to limit the possible orientation error. If a robust modulation technique was not used, the location estimates would suffer from great errors, and orientation estimates would be very less accurate.

Finally, an study using 500 points in a grid in the room showed azimuth estimated with an error of under 2 degrees in 95% of cases, while in the elevation errors are less than 10 degrees in 95% of cases.

VII. CONCLUSIONS

This paper shows simulated results for a novel orientation-location algorithm. The robustness of the system to noise and interference has been shown. The system performs well in most of the tests. The algorithm fails at very low SNR or when the BSs are badly configured. A further study will be performed, to mathematically characterize the Geometrical Dilution of Precision (GOP) due to bad-configured BSs.

The work has developed an orientation and location estimation system which provides orientation accuracy of 2 degrees and location accuracy under 1 cm in 95% of cases. To the author knowledge, no previous orientation system provides such good accuracy. Cricket Compass system is the most similar work done in orientation estimation. They provide an azimuth error from 0.57 degrees in the best case to 21.8 degrees, depending on the estimated angle, being the mean error 5.4 degrees with the data provided in [1].The authors consider the proposed system a great improvement in accuracy and improving the azimuth estimation to 3-axis estimation.

ACKNOWLEDGMENT

The work presented in this paper is supported by a research grant from Science Foundation Ireland.

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