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High Accuracy Reference-free Ultrasonic Location Estimation

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Abstract

This paper presents a novel reference-free ultrasonic indoor location system. Unlike most previous proposals, the Mobile Device (MD) determines its own position based only on ultrasonic signals received at a compact sensor array and sent by fixed, independent beacon. No Radio Frequency or wired timing reference signal is used. Furthermore, the system is privacy-aware and one-way in that the receive-only MD determines its own position based on ultrasonic signals received from fixed, transmit-only beacons. The MD uses a novel hybrid Angle of Arrival (AoA) - Time of Flight (ToF) with Timing Lock algorithm to determine its location relative to the beacons with high accuracy. The algorithm utilizes an AoA-based location method to obtain an initial estimate of its own location. Based on this, it estimates the Timing Offsets (TOs) between the MD clock and the beacon transmissions. The average TO and the known periodicities of the beacon signals are then used to obtain a second, more accurate, MD location estimate via a ToF method. The system utilizes wideband Spread Spectrum ultrasonic signaling in

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order to achieve a high update rate and robustness to noise and reverberation. A prototype system was constructed and the algorithm implemented in software. Experimental results show that the method provides 3D accuracy of better than 9.5 cm in 99% of cases, an 80% accuracy improvement over the conventional AoA-only method.

Index Terms

ultrasonic, FHSS, location estimation, reference-free, timing lock, AOA, TOA.

I. Introduction

OBTAINING location information indoors is becoming important for many applications, including navigation tools for humans and robots, building mapping, interactive games, resource discovery, asset tracking and location-aware sensor networking [1], [2], [3], [4], [5], [6], [7]. GPS works well outdoors, but fails in indoor environments due to signal attenuation by the building fabric [8]. Development of a robust, reliable and accurate indoor location system is still an open research problem. Many attempts to develop indoor location systems have been reported in the literature. These proposals make use of a range of technologies including lasers, infrared beacons, cameras, Radio Frequency (RF) signals and ultrasonic signals [9], [10], [11], [12]. Of these techniques, ultrasonic systems are distinguished by their ability to estimate location with a high degree of accuracy at low cost. Their accuracy is primarily due to the low velocity of ultrasonic wave propagation in air, allowing high accuracy Time of Flight (ToF) measurement. Typical ultrasonic location systems exploit the difference in the Times of Arrival (ToA) of a narrowband ultrasonic signal and a reference Radio Frequency (RF) pulse emitted synchronously with the ultrasonic signal, to estimate the distance between the transmitter and the receiver based on the known propagation speed of sound in air [13], [14]. Unfortunately, the inclusion of a RF sub-system to provide a timing reference adds significant cost, size, power consumption and complexity to such systems [15].

Herein, a novel hybrid AoA-ToF with timing lock algorithm for ultrasonic indoor location estimation is proposed. The system is reference free in that it does not use a reference signal of any kind for communicating the ultrasonic Time of Emission (ToE) from the transmitter to the receiver or for synchronizing the transmitters. The system is privacy-aware and one-way in that it consists of a receive-only MD which determines its own position based on ultrasonic signals sent by at least three transmit-only ultrasonic beacons. The beacons have known positions and transmit repeating orthogonal, Spread Spectrum (SS) ultrasonic sequences at known, fixed rates. The use of SS signals ensures a high update rate, reduces multipath effects, and reduces interference between beacons. The MD is capable of estimating the AoA and ToA of the received ultrasonic signals. The algorithm exploits the estimated AoA to obtain a coarse estimate of MD-beacon distance using a novel angulation method. The Time of Emission (ToE) of the ultrasonic signals is estimated based on the coarse MD-beacon distance estimates and the estimated Times of Arrival (TOA). These estimated ToEs are used to determine the Timing Offset (TO) of beacon transmission sequences relative to the MD's clock. Since the transmitted ultrasonic signals have fixed known time periodicities, the TO of each beacon is constant relative to the MD's clock. As a consequence, the TO estimates can be averaged over a number of beacon periods. Assuming that the TO estimates at the MD are noisy with mean equal to the true TO, a moving average will converge to the true TO over time. Based on this a more accurate estimate of the MD location is obtained via a conventional ToF method using the measured ToAs and estimates of the ToEs obtained using the converged TO estimate. The advantage of averaging the TO estimates, rather than using the raw AoA estimates, is that the TO estimates are constant, regardless of the position of the MD. In contrast, averaging the raw AoA estimates requires that the MD is stationary. Averaging of the TO estimates ensures that estimation noise is reduced, allowing more accurate ToF-based location estimation. We refer to the process of obtaining a converged TO estimate as acquiring Timing Lock between the Beacon and the MD.

To the author's knowledge, this is the first paper to report a Hybrid AoA-ToF with Timing Lock method for high accuracy reference-free indoor location estimation. The main advantage of the method, compared to previous proposals, is that the need for a reference signal is eliminated [16],[17], that the method only uses one-way communication and that the approach offers high accuracy. The elimination of the reference signal and the use of one-way signalling greatly simplifies the beacon devices in that they only require a single ultrasonic transmitter and do not need an RF transceiver. This has the benefit of also reducing their energy consumption, which is important given that they are typically difficult to access. One-way signalling also means that the system is privacy aware in that the MD determines its own position. The overall system can be implemented at low cost using off-the-shelf components. The algorithm can be implemented digitally in software and in real-time. The system provides absolute 3D location estimates with high accuracy. As will be shown later, the Timing Lock algorithm significantly improves location estimation accuracy relative to location estimation based on the AoA estimates only.

The rest of this paper is structured as follows. Section 2 discusses related work. Section 3 explains the proposed system. Section 4 details the experimental method. Simulation results and experimental results are provided in Section 5. Section 6 concludes the paper.

II. Related work

A small number of previously reported ultrasonic systems exploit the periodicity of transmission to assist in estimation of a MD's location without the need for a timing reference between the transmitter(s) and receiver(s) or between the transmitters [16], [17], [18], [19], [20]. The authors' of [17], [18], [19] proposed elimination a time reference by utilizing Doppler shifts in the arrival times of periodic narrowband ultrasonic signals sent by independent ultrasonic transmitters and received by a MD. The approach allows the deduction of both the location and velocity of the MD but the accuracy of location estimation reported in their work is very poor since the method relies on identifying small Doppler shifts and on dead-reckoning position estimates based on integration of velocity estimates. Moreover, the use of narrowband ultrasonic pulses introduces a number of limitations, specifically sensitivity to noise, low update rate and difficulty in identifying beacons. The average error obtained by the system is 20-30 cm, and the maximum error is 70 cm [17]. In [20], use is made of independent receivers for calculation of the inter-arrival time of ultrasonic pulses emitted periodically from an MD. The system is dependent on the motion of the MD and does not work if the MD is stationary. Again, the use of narrowband ultrasonic signals limits the number of co-existing MDs and means that the system is susceptible to noise and multi-path interference. The overall accuracy of the system has not been stated clearly but from the reported results in the paper the system is subject to high errors (up to 1 meter) specially when the initial estimate is far away from the initial real location. The work described in [16] uses an approach based on the difference of signal arrival times with the assumption of transmission periodicity and a known initial MD location. The main disadvantage of this approach is propagation and accumulation of error from the first location to all subsequent locations.

A number of systems have used ultrasonic Spread Spectrum signals for location estimation. In [21] a privacy-oriented broadband ultrasonic location system allowing users with mobile ultrasonic receivers to ascertain their position autonomously was proposed. It performs SS ranging using Gold codes to allow simultaneous multiple access. Positioning algorithms were presented for both synchronous and asynchronous receivers, but the transmitters were always assumed to be synchronised. The work in [22] presents a Local Positioning System (LPS) with ultrasonic beacons emitting periodically and simultaneously. Direct Sequence Code Division Multiple Access (DS-CDMA) techniques were used to allow simultaneous emission from several beacons. The absolute position of the receiver is determined by hyperbolic trilateration, using the Differences in Times-of-Arrival (DTOA). The system depends on synchronised beacons in order to estimate DTOA. In [23] Sverre Holm proposed utilizing an ultrasonic indoor data communications system to perform indoor positioning which can rely on ultrasound alone, as no radio, no infrared channel nor any tether is required. The system uses a transmitter tag and a receiver detector and the positioning method operates in a fashion similar to RFID while benefitting from the shielding provided by room walls to ultrasonic signals, the proposed system provides proximity sensing but does not provide the actual 3D position. The use of a broadband ultrasonic signal was also considered in [24], [25], [26], [27]. Both Direct Sequence Spread Spectrum modulation [25], [26], [27] and Frequency Hop Spread Spectrum (FHSS) modulation [24] have been investigated for use in ultrasonic location estimation. In [28], it was shown that FHSS provides better accuracy than both conventional narrowband pulses and DSSS modulation in terms of noise and multi-path interference immunity. The use of an ultrasonic receiver array for determination of AoA was described previously in [29], [24]. However,

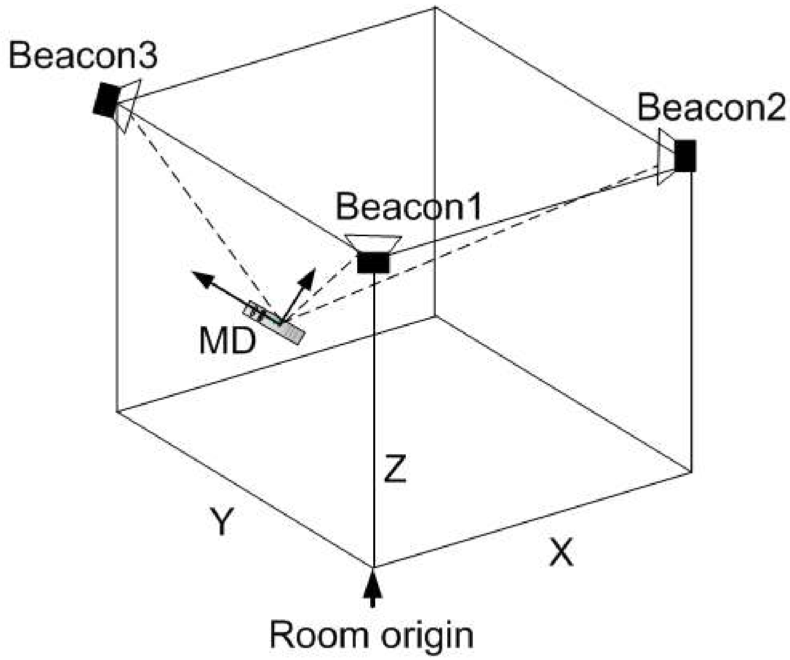


Fig. 1: Proposed system configuration

in these works a reference signal is used in determination of MD location by means of a ToF method. AoA information was solely utilized for estimation of the orientation of the MD. Receiver arrays are typically not used at the MD in RF based location systems due to their size.

III. Proposed System and Algorithm

A. Reference-free System

The proposed system consists of at least three ultrasonic beacons at known locations and a MD whose position is to be determined. The system configuration is illustrated in Figure 1.

Each beacon consists of an ultrasonic transmitter, amplifier, digital-to-analog converter and processing unit. Each beacon sends a unique FHSS modulated ultrasonic signal. FHSS modulation causes the frequency of the carrier to hop between a pre-determined set of hop frequencies. Hops are of duration T_h = 3 milisecond. The hopping duration should be short enough to avoid hop collisions between the direct path signal and reflections from objects close to the MD. The hopping sequences are generated

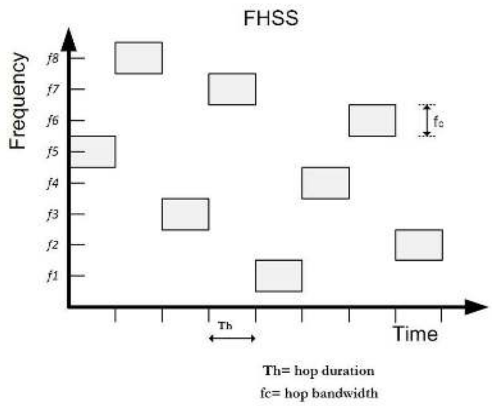


Fig. 2: Frequency Hop Spread Spectrum.

using conventional SS codes such as m-sequence, Gold, Kasami, or Golay codes [24]. The FHSS hopping pattern is unique to the beacon such that the MD can identify the beacon based on it [30], [31]. The hopping sequences are selected so that the sequences are orthogonal and can be separated at the receiver. The sequences are self-orthogonal so that the direct-path signal can be separated from multi-path signals at the receiver. The following equation describing the FHSS signal transmitted by beacon i:

$$S^i(t) = \sum_{j=0}^{N_p-1} G(t - jT_h) \sin(\omega_j t + \phi_j) \tag{1}$$

where $S^i(t)$ is the hopping sequence of beacon i, $G(t)$ is a rectangular window which has a value equal to 1 for the interval $0 \leq t < T_h$ and zero otherwise, ω_j and ϕ_j are the the frequency and phase associated with hop j.

A pseudorandom sequence determines a unique frequency hopping pattern defining the values of ω_j for beacon i ensuring orthogonality and collision avoidance between signals. Figure 2 shows how the carrier hops between different frequencies with time.

The hopping sequences have a period of N_p hops, where N_p is an integer. To avoid confusion between direct-path and reflected signals, the period of the sequence $T_p = N_p T_h$ is chosen to be greater than the reverberation time of the room. This assures that all reflections will be under a certain low power threshold

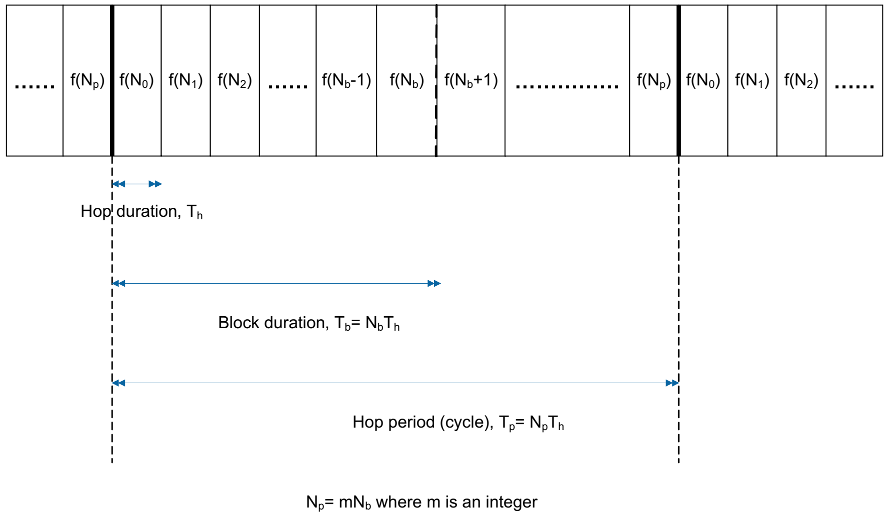


Fig. 3: FHSS signal sequence

when the next cycle of ultrasonic signal is transmitted from the same beacon. All beacons are completely independent of each other and do not share timing reference information between each other or with the receiver unit.

The received signal at the MD is segmented into N_b hops, where N_b is an integer. Herein, we refer to an N_b hop segment as a block. Blocks have a fixed period $T_b = N_b T_h$ but different frequency hopping patterns. A diagram illustrating a beacon FHSS signal sequence is provided in Figure 3.

The MD consists of an ultrasonic receiver array, associated analog-to-digital converters and a processing unit. To allow for AoA estimation, the receiver array must consist of at least 3 receivers placed in an triangle. This configuration allows estimation of 2D AoA, that is, elevation and azimuth. Additional redundant receivers, such as in a Uniform Circular Array, can be used to improve performance by averaging. To avoid phase ambiguity problems, either the spacing of the elements must be less than half that wavelength of the maximum carrier frequency or a phase disambiguation algorithm must be applied [32], [33]. The centre of the receiver array defines the origin of the MD's coordinate system.

B. Hybrid AoA-ToF Algorithm with Timing Lock

High accuracy reference-free location estimation is performed at the MD using a hybrid AoA-ToF algorithm with Timing Lock. The algorithm consists of five steps: (1) Signal Acquisition; (2) AoA-

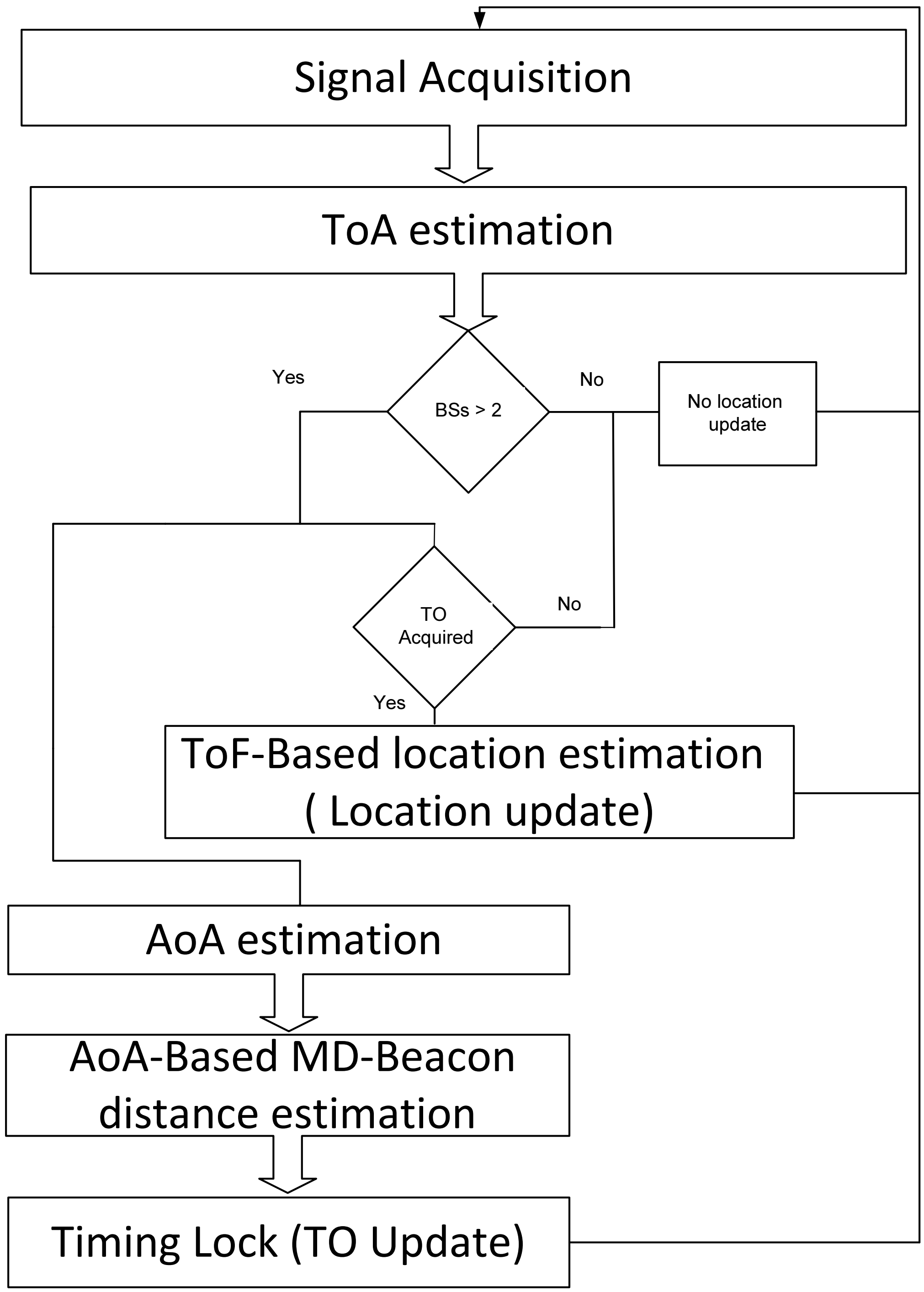


Fig. 4: Block diagram of the proposed algorithm

based MD-beacon distance estimation; (3) ToA estimation; (4) Timing Lock; and (5) ToF-based location estimation. A block diagram of the algorithm is presented in Figure 4.

1) Signal Acquisition: The MD is provided with the locations, FHSS hopping sequences $S_i(t)$, hopping period N_p and hop duration T_h of the beacons *a priori*. Initial FHSS code acquisition is performed using four dedicated pilot channels. Each beacon transmits a start of sequence symbol followed by the beacon *id* using DBPSK. The receiver detects activity on these channels by integrating the output of a pass band filter centred on the pilot channel centre frequency. It then decodes the beacon *id*. In this way the receiver can synchronise to the start of the beacon sequence and identify the beacon *id* so it can segment the received signal into individual hops [34].

2) AoA-based MD-beacon distance estimation: The received signal at the MD is segmented into individual hops and the Discrete Fourier Transform (DFT) of each is calculated. The phase differences between the DFT outputs for each receiver at the bins associated with each hop are then obtained. These phase differences are averaged over all hops in one signal block i.e. (N_b hops), to reduce the effects of noise.

The estimated time-difference between sensor 1 and sensor 2, $\hat{\tau}_{12}$, is given by:

$$\hat{\tau}_{12} = \frac{1}{N_b} \sum_{j=0}^{N_b-1} ang(X_{1,j}(\omega) X^*_{2,j}(\omega))/\omega_j \tag{2}$$

where *ang*. denotes the complex angle operation, ω is the radian frequency which is assumed to be discrete, $X_{1,j}(\omega)$ and $X_{2,j}(\omega)$ are the Discrete Fourier Transforms of the j^{th} hop received at sensor 1 and sensor 2 respectively, and * denotes the complex conjugate operation.

Outliers, due to collisions between hops from different beacons, are rejected prior to averaging. The mean phase difference is used to calculate the AoA of the signal from each beacon.

The AOA, as viewed from the centre of the baseline of sensor-1 and senor-2, is calculated as:

$$\hat{\phi}_{12} = \arcsin\left(\frac{c\hat{\tau}_{12}}{\Delta_{12}}\right) \tag{3}$$

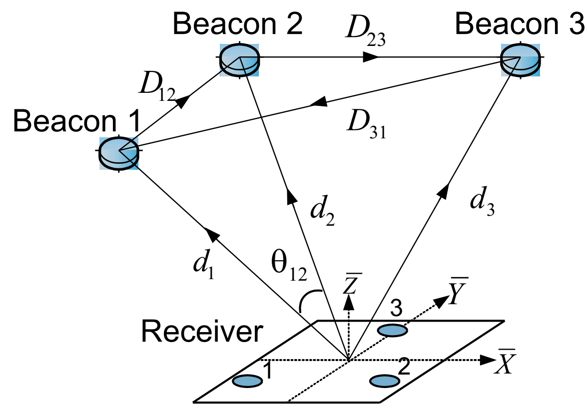


Fig. 5: AoA-based MD-beacon distance configuration

where c is the speed of sound in air and Δ_{12} is the fixed distance between sensor 1 and sensor 2.

Using 3 receivers placed in an triangle configuration, the same procedure is applied to each pair of receivers. As we are only interested in calculating the angle between the vectors pointing to the beacons from the MD, we do not need to calculate the absolute angle of arrival with reference to the global coordinate system, which requires the knowledge of the MD orientation, we only calculate the angle with reference to the local coordinate system of the MD. These estimated AoA are used to determine the distances between the MD and the beacons using a novel angulation method. The method is based on a previous proposal described in [35]. Considering the configuration in Figure 5, the known distance between Beacon 1 and 2, D_{12}, is given by:

$$D_{12}^2 = d_1^2 + d_2^2 - d_1 d_2 \cos(\theta_{12}) \tag{4}$$

where d_1 is the distance between the MD and Beacon 1, d_2 is the distance between the MD and Beacon 2, and θ_{12} is the angle between the vectors from the MD to Beacons 1 and 2.

According to the method, Eq.(4) is expressed for all three inter-beacon distances. The inter-beacon distances are known and the angle between the vectors can be calculated from the AoA estimates obtained previously. This gives three equations with three unknowns. These equations are solved to obtain the three MD-beacon distances.

A coarse estimate of the MD location can now be obtained by tri-lateration. Herein we refer to this as the AoA-only location estimate. Note that, the MD may be moving, so the location estimates may change with time, as well has being subject to measurement noise. The AoA method is sensitive to noise in that a small change in phase difference can lead to a significant change in the location estimate provided by the system. The output of step 1 is an AoA-based MD-beacon distance estimate for every beacon after every block i.e. (N_b hops)

3) ToA estimation: The ToA of the ultrasonic signal blocks from each beacon are determined by finding the delay associated with the peak of the cross-correlation of the received signal block, at a reference array element, with the known transmitted signal block [36]. This provides an estimate of the ToA with sample-level accuracy for each beacon signal block.

This ToA estimate can be refined by adjusting the ToA estimate according to the phase difference between the carrier of the received signal and the carrier of the reference signal delayed by the sample-level ToA estimate [37]. This phase adjustment leads to a ToA estimate with sub-sample accuracy. Since the ToE of the signal blocks are not known at the MD at this stage, the ToA cannot be directly used for location estimation.

The output of step 2 is a sub-sample ToA estimate for each beacon associated with each received signal block. The length of the block N_b is an important design parameter as it trades off between the resolution and accuracy of the AoA and ToA estimates and the update rate of the system, the longer the block length the higher resolution and accuracy and the lower the update rate.

4) Timing Lock: A key feature of this work is obtaining an accurate estimate of the ToE of the ultrasonic signals from the sub-sample ToA estimate and the AoA-based MD-beacon distance estimates using a Timing Lock method. This step is now explained in detail.

Consider the MD-beacon distance estimates and ToA estimates arising from applying step 1 and step 2 to block n of the signal arriving from beacon i. Based on the distance estimate $d_i(n)$ from the MD to beacon i and the sub-sample accuracy ToA estimate $a_i(n)$ of the received signal block n from Beacon i, an estimate of the ToE $e_i(n)$ of the transmitted signal block n can then be calculated as follows:

$$e_i(n) = a_i(n) - d_i(n)/c \tag{5}$$

where c is the speed of sound in air.

Since the transmitted signal blocks are periodic in time with a fixed known period T_b, a MD local prediction of the ToE of block n from Beacon i, $r_i(n)$, can be expressed relative to some unknown fixed Timing Offset R_i established at the MD as:

$$r_i(n) = R_i + nT_b \tag{6}$$

Figure 6 shows a time diagram for beacon i and the MD clarifying different time points and intervals between the two time frames.

An estimate of the Timing Offset $\hat{R}_i(n)$ can be obtained for each block n transmitted by Beacon i as follows:

$$\hat{R}_i(n) = e_i(n) - nT_b \tag{7}$$

Since the Timing Offset of each beacon is fixed, the MD can obtain an improved Time Offset estimate $\hat{\hat{R}}_i(n)$ by averaging over a window including the current and previous n blocks:

$$\hat{\hat{R}}_i(n) = \frac{1}{n+1}\sum_{j=0}^{n}(e_i(j) - jT_b) \tag{8}$$

Assuming that the ToE estimates $e_i(j)$ are noisy but unbiased, the average Timing Offset estimate converges to the true value as n increases. Since the actual Timing Offset is determined by the beacon, it does not change when the MD moves. Hence, the output of the averaging process is independent of the movement of the MD.

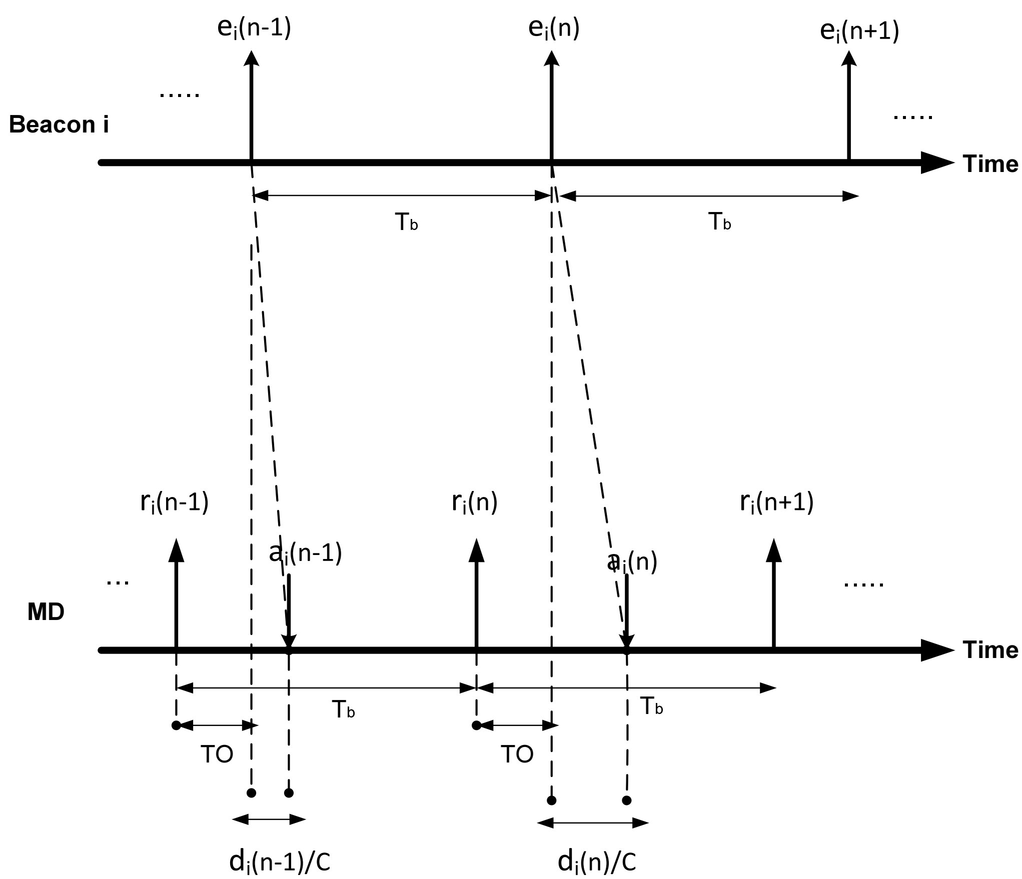


Fig. 6: Time diagram for beacon i and the MD

5) ToF-Based Location Estimation: The average Timing Offset estimate obtained in step 3 is used to determine the location of the MD using a ToF method.

The average Timing Offset estimate can be used to estimate the ToE of each block. The ToF of the signal can then be calculated as the difference between the estimated ToE and the sub-sample ToA estimate obtained in step 1. This estimated ToF can then be used to determine the distance between the MD and the beacon based on the speed of sound in air. Overall, the distance from the MD to Beacon i at reception of block n is given by:

$$\hat{d}_i(n) = (a_i(n) - \hat{\hat{R}}_i(n) - nT_b)c \tag{9}$$

Finally, the MD-beacon distance estimates are provided to a conventional tri-lateration algorithm for calculation of the MD location [38]. Since the Timing Offset is obtained by averaging over the current and previous n blocks, the ToF-based location estimate is much more accurate that the AoA-based estimate which only uses information from the current block. The averaging process removes the random error associated with the estimated TOs. This random error is mainly due to propagation of AoA estimation noise to the TO estimates. The clock drift between the transmitter and the receiver also introduces a systematic error that is not removed by averaging. Fortunately this error is not significant due to the low speed of sound in air provided that the averaging time is not very long. For example with a typical clock drift ($\varepsilon = 10^E - 6$) and an normal averaging time ($nT_b = 1$ minute), the error is around 1 cm.

It worth noting that the orientation of the MD can also be determined based on the final ToF location estimate and the AoA estimates [24], [35].

C. Computational complexity

The ToA estimation and ToF-Based location estimation steps are the same as used in previous ultrasonic 3D location systems, e.g. Cricket, Bats. The MD-Beacon distance estimation and timing lock steps are new but have very low computational complexity. Therefore, the main increase in computational complexity

TABLE I: Overview of the computational coplexity of the algorithm

Algorithm step	Required operation	Number of points	Values
AoA estimation	Real FFT	$NR * N_b * N_s$	7680
	Phase difference	$NB * N_b$	20
AoA-based distance estimation	Angulations	$NB * N_i$	40
ToA estimation	cross-corrilation	$W * N_b * N_s$	128000
	Peak search	W	50
Timimg Lock	Averaging	NB	4
ToF-based location estimation	Trilateration	$NB * N_i$	40

arises due to the AoA estimation step. AoA estimation method is based on the FFT. Therefore, it is reasonably computationally efficient. In any case, the update rate of the AOA-derived Timing Offset estimates can be adjusted independently of the update rate of the ToF-Based location estimates in order to reduce the computational complexity of the system so as to meet real-time constraints. For example, the ToF update rate may be 20 Hz while the AoA might be 5 Hz. This will increase the time to TO convergence but, once the TO estimate has converge, performance will be unaffected.

ToA and AoA are estimated for each received signal block, the length of this block as well as the sampling frequency is an important design parameter that can be used to trade off between update rate, computational complexity, and accuracy. Longer block length and higher sampling frequencies provides better accuracy but in the other hand reduces update rate and increases computational complexity. Table I gives an idea about the order of computational complexity of the algorithm different steps assuming the following parameters: NB=number of beacons=4; NR= number of receiver sensors=3; N_b = number of hops per block = 5; N_s = number of sample per hop = $T_h * F_s$= 512; W = cross correlation window length (-W/2:+W/2)=50; N_i=number of iteration=10.

IV. Experimental Method

The performance of the proposed algorithm was evaluated using Matlab prior to building the prototype. The image method [39] was used to obtain synthetic impulse responses for a 4x4x4 m room with reflection coefficients for walls, ceiling and floor equal to 0.65 and a Signal to Noise Ratio (SNR) equal to 20 dB, unless otherwise stated. A FHSS signal was designed with 14 frequency slots in the band between 36-45 kHz with 750 Hz separation between adjacent frequencies. The signal consists of 14 hops; each hop occupies a time slot of 3 milliseconds. Orthogonal FHSS signals were synthesized for the three beacons. Figure 7 shows the auto- correlation and cross-correlation of signals transmitted from beacon 2 and beacon 3, the auto- correlation of beacon 2 signal appears in blue while the cross correlation of beacon 2 and beacon 3 signals appears in red. Actual experiments were performed using the same signal applied in a prototype location estimation system. A total of three transmitter units were used in the tests. Each transmitter was connected to a separate interfacing circuit. The transmitters used were the E-152/40 wideband ultrasonic transducers from Massa [40]. This type of transducer has a bandwidth of 15 kHz between 35-50 kHz and a total beam angle of 75^o. SPM0204 ultrasonic sensors were used as receivers [41]. These microphones are based on CMUT technology and have a nearly flat response between 10 and 70 kHz. The MD has three ultrasonic sensors fixed in a triangle configuration with distance of 2.1 cm between each pair of sensors. A Digital Signal Processing (DSP) board from Sundance, model 361A was used for signal acquisition [42]. It includes a C6416 DSP from Texas Instruments with two daughter boards, a SMT377 with 8 independent Digital to Analog Converters (DACs) and a SMT317 with an 8-channel Analog to Digital Converter (ADC). Coaxial cables were used to connect the daughter cards to the transmitter and receiver boards. The sampling frequency used was 168 kHz which is greater than $2F_c$ where F_c is the highest carrier frequency, in this case 45 kHz. The prototype was installed in a typical office room with dimensions 350x285x270 cm. The beacons were placed at the corners of the office. The MD was moved between 13 positions and around 100 valid readings were recorded. Sound velocity was assumed to be constant during the experiments. The effect of variations in temperature and humidity on sound velocity were assumed to be negligible since the experiments were conducted over a short period of time. Figure 8 shows photographs of the prototype system.

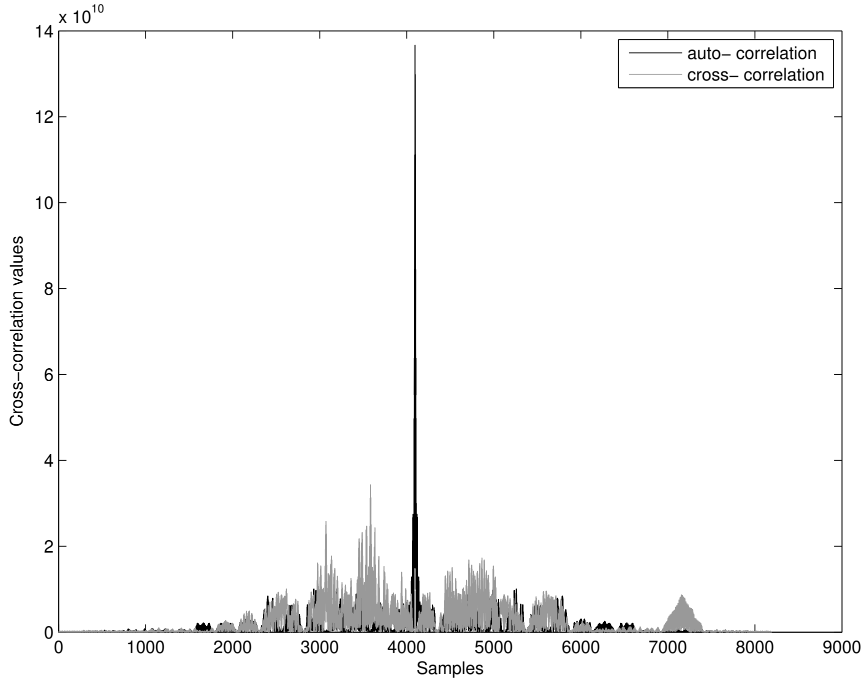
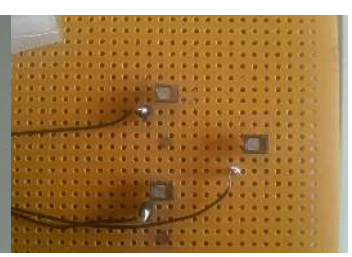


Fig. 7: auto- correlation and cross-correlation of FHSS signals

(a) Office room

(b) Transmitter



(c) Receivers

Fig. 8: Photographs of the prototype system

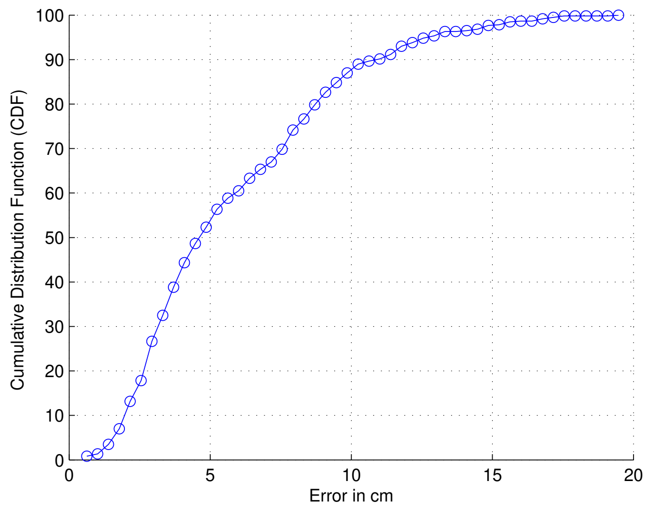


Fig. 9: Cumulative error of the location estimates when using AoA-only method

V. Results

In order to evaluate the performance of the proposed method, simulation and experimental results were obtained.

A. Simulation results

Simulations were performed to model three ultrasonic transmitters sending FHSS ultrasonic signals (as described in Section IV) and located at the corners of the room. The MD was moved over 600 different locations in the room. At each location, the received signal was processed and the AoA-only method and the proposed AoA-ToA algorithm were applied.

Figure 9 shows the cumulative error in the estimated MD location obtained using the AoA-only method for all 600 locations in a typical office environment (SNR=20 dB and reflection coefficient=0.65). Figure 10 shows the cumulative error in the estimated MD location obtained by applying the proposed Hybrid AoA-ToF with Timing Lock algorithm for the same 600 locations.

Comparing Figure 9 and Figure 10, it can be seen that the location estimates obtained using the proposed Hybrid AoA-ToF with Timing Lock algorithm is more accurate than the location estimates obtained using AoA-only method.

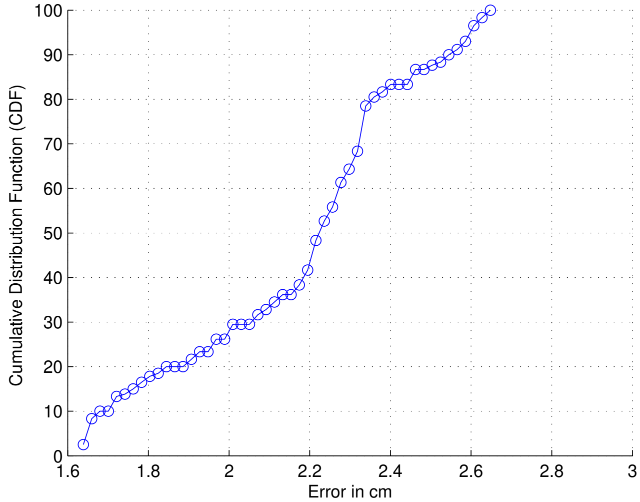


Fig. 10: Cumulative error of the location estimates when using proposed Hybrid AoA-ToF with Timing Lock algorithm

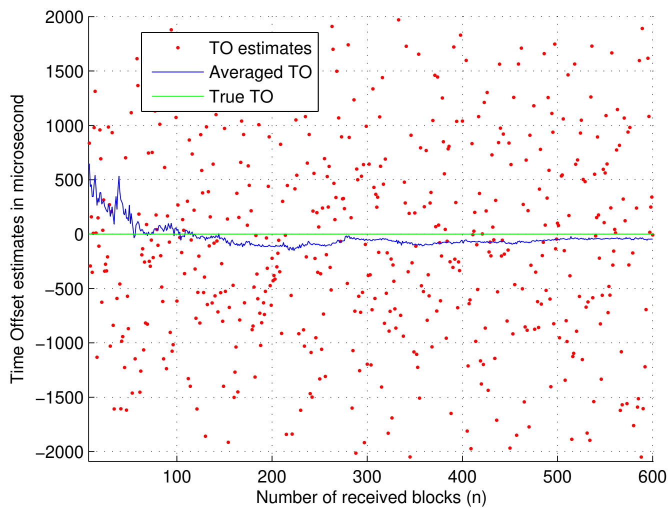


Fig. 11: Time Offset estimates and averaged Time Offset estimate

Figure 11 shows the Time Offset estimates and how the averaging process reduces error over time. The averaged Time Offset estimate converges towards the true Time Offset as the number of received blocks (n) increases. The final error is 30 μs corresponding to a bias error of 1 cm.

Figure 12 and Figure 13 show the actual and estimated locations of the MD using the proposed AoA-ToA method when $n = 20$ and $n = 100$, respectively. The beacons locations and room walls are also highlighted in the figure. It is clear that as the value of n increases, the accuracy of the estimates increases.

Table II lists the bias and standard deviation of the AoA estimates, AoA-only location estimates and

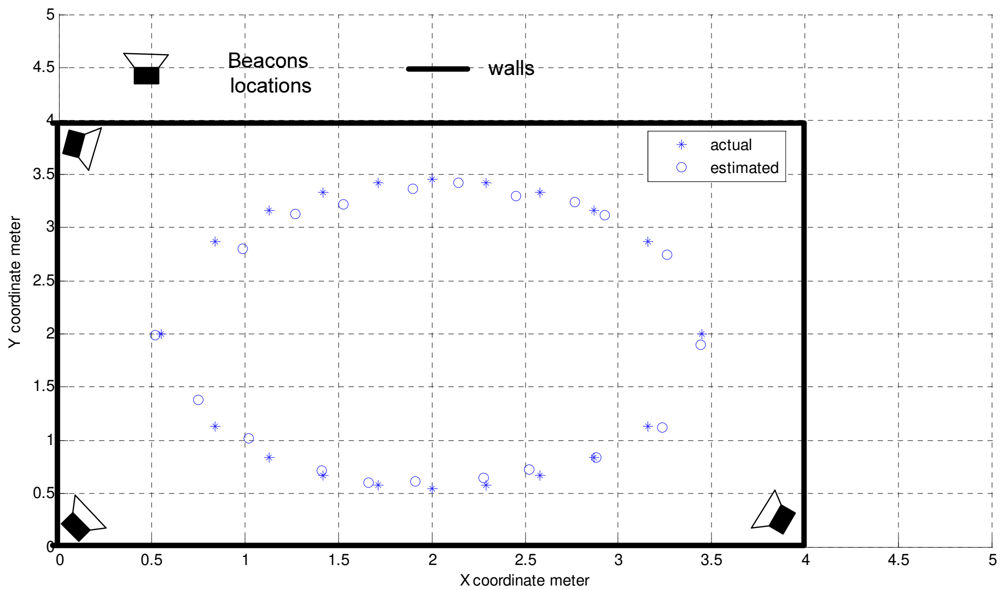


Fig. 12: MD location estimates for n=20

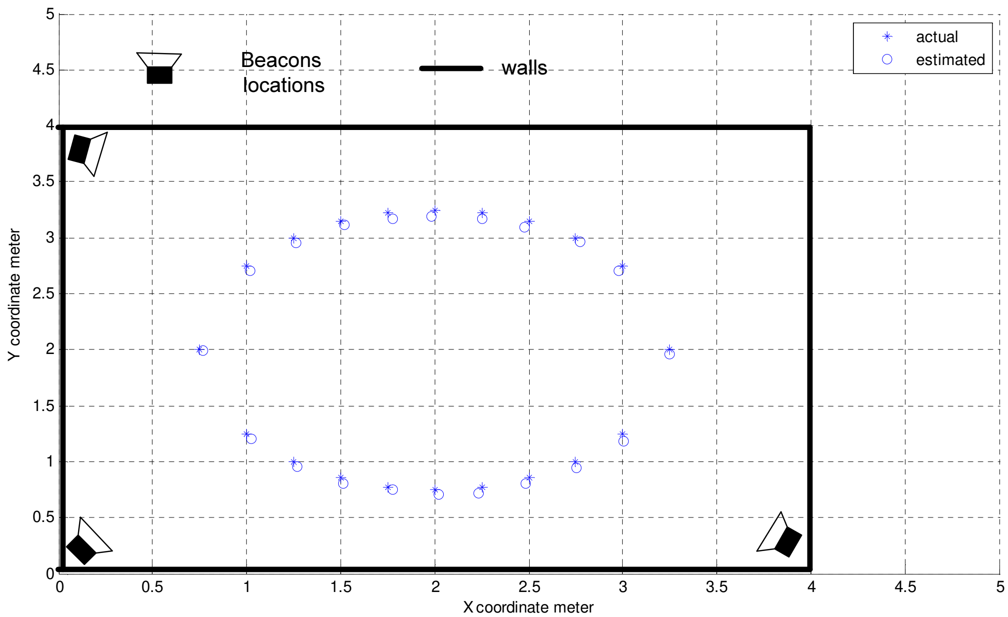


Fig. 13: MD location estimates for n=100

TABLE II: Bias and standard deviation of AoA estimates, AoA-based location estimates and Hybrid AoA-ToF with Timing Lock location estimates vs. Signal to Noise Ratio.

	SNR dB	30	20	15	10	5	0
AoA estimates	Bias degrees	-0.01	-0.40	0.18	-0.81	-0.83	-4.81
	σ degrees	4.2	6.1	7.3	9.9	13.5	23.6
AoA-Only location estimates	Bias cm	4.3	7.2	20	92	61	133
	σ cm	6	7	42	57	73	98
Hybrid AoA-ToF location estimates	Bias cm	2.5	2.7	7.7	2.9	26.4	26.1
	σ cm	0.63	0.69	0.46	2.4	22	29

TABLE III: Error of location estimates and percentage improvement vs. Signal to Noise Ratio.

	SNR dB	30	20	15	10	5	0
AoA-Only location estimates	50% cumulative error cm	4.5	4.9	10	24	27	89
	99% cumulative error cm	20	34	120	250	300	396
Hybrid AoA-ToF location estimates	50% cumulative error cm	2.7	5.3	7.8	17	20	22
	99% cumulative error cm	5.3	6.8	9	28	40	47
Improvement(%)	50% cumulative error	40%	41%	22%	29%	26%	75%
	99% cumulative error	74%	78%	93%	89%	87%	88%

Hybrid AoA-ToF with Timing Lock algorithm location estimates obtained for various Signal to Noise Ratios.

Table III gives the 50% and 99% cumulative error points for the AoA-based location estimates and the Hybrid AoA-ToF with Timing Lock location estimates and calculates the percentage improvement for various Signal to Noise Ratios.

The results provided in Tables II and III show that the proposed method improves the accuracy of location estimation. It also illustrates the robustness of the proposed algorithm to degradations in SNR. The error in the AoA estimates increases as SNR decreases. This error directly propagates to the location estimates when using AoA-only method, while the proposed AoA-ToA method reduces the effects of these errors giving accurate location estimates.

Table IV states the 50% and 99% cumulative error points for the AoA-based location estimates and the Hybrid AoA-ToF with Timing Lock location estimates and gives the percentage improvement for various values of AoA standard deviation, assuming zero mean guasian AoA noise and zero mean guasian ToA noise with standard deviation equal to 1 mm.

Table V lists the 50% and 99% cumulative error points for the AoA-based location estimates and the Hybrid AoA-ToF with Timing Lock location estimates and states the percentage improvement for various

TABLE IV: Error of location estimates and percentage improvement vs. standard deviation of AoA

	σ degrees	0.1	0.5	1	2	3	4	5	6
AoA-only location estimates	50% cumulative error cm	0.8	4.2	9	18	26	35	39	51
	99% cumulative error cm	4.8	17.8	34.2	66	87	120	144	175
Hybrid AoA-ToF location estimates	50% cumulative error cm	0.2	0.4	0.8	1.8	3.2	3.5	5.7	9
	99% cumulative error cm	0.7	1.1	1.3	2.3	4.2	4.9	6.4	11.2
Improvement (%)	50% cumulative error	75%	90%	91%	90%	88%	90%	85%	82%
	99% cumulative error	85%	94%	96%	96%	95%	96%	95%	94%

TABLE V: Error of location estimates and percentage improvement vs. bias of AoA

	Bias degrees	0.1	0.5	1	2	3	4	5
AoA-Only location estimates	50% cumulative error cm	8.5	9	9	13.8	19	183	69
	99% cumulative error cm	31	33	38.2	57.6	71	213	219
Hybrid AoA-ToF location estimates	50% cumulative error cm	0.4	2.7	6.2	13.5	20.5	28.5	42
	99% cumulative error cm	1.2	3.8	9.2	19.5	29.8	41.3	65
Improvement (%)	50% cumulative error	95%	70%	31%	−2%	−7%	84%	39%
	99% cumulative error	96%	88%	76%	66%	58%	88%	70%

values of AoA bias assuming non zero mean guasian AoA noise with standard deviation equal to 1^o and zero mean guasian ToA noise with standard deviation equal to 1 mm.

The results provided in Tables IV and V show the effects of the proposed method in reducing the standard deviation and bais of AoA estimation error. The proposed method has high immunity to random errors, but can not remove bias errors. This is due to the averaging process used in the Timing Lock algorithm.

Simulations were carried out to investigate the effect of doppler shift on TOA estimation and to quantify the range of admissible velocities for the MD. Results show that only 20% of TOA estimates have error greater than 5 cm with MD speeds up to 2 m/s.

B. Experimental Results

The prototype described in section IV was used to evaluate the proposed algorithm in a real office environment. Three transmitters were fixed at the corners of the office and their locations were calculated with reference to a local coordinate system for the office. The MD was moved between 13 different locations in the office and around 100 location estimates were calculated. The true values of the locations were measured manually using a meter tape with reference to the same local coordinate system.

Figure 14 shows the cumulative error of the estimated locations using the AoA-only method. Figure

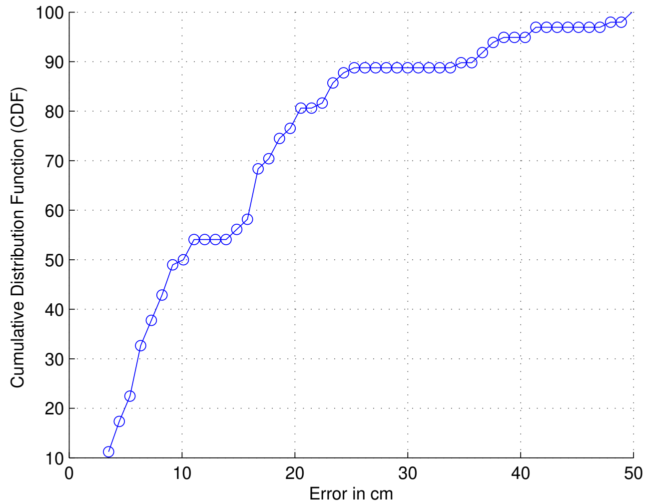


Fig. 14: Cumulative error of location estimates when using AoA-only method

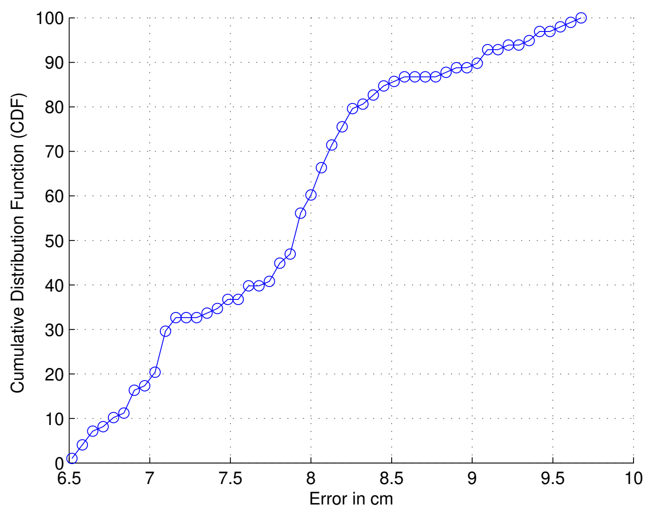


Fig. 15: Cumulative error of location estimates when using proposed Hybrid AoA-ToF with Timing Lock algorithm

15 shows the cumulative error of the estimated locations when applying the proposed Hybrid AoA-ToF with Timing Lock algorithm.

Figure 16 show the actual and estimated locations of the MD using the proposed AoA-ToA method. Experimental setup is also shown in the figure where beacons locations, walls and office furniture is highlighted.

Table VI summarize the values of bias and standard deviation of the AoA estimates, AoA-only method location estimates and Hybrid AoA-ToF with Timing Lock algorithm location estimates calculated from

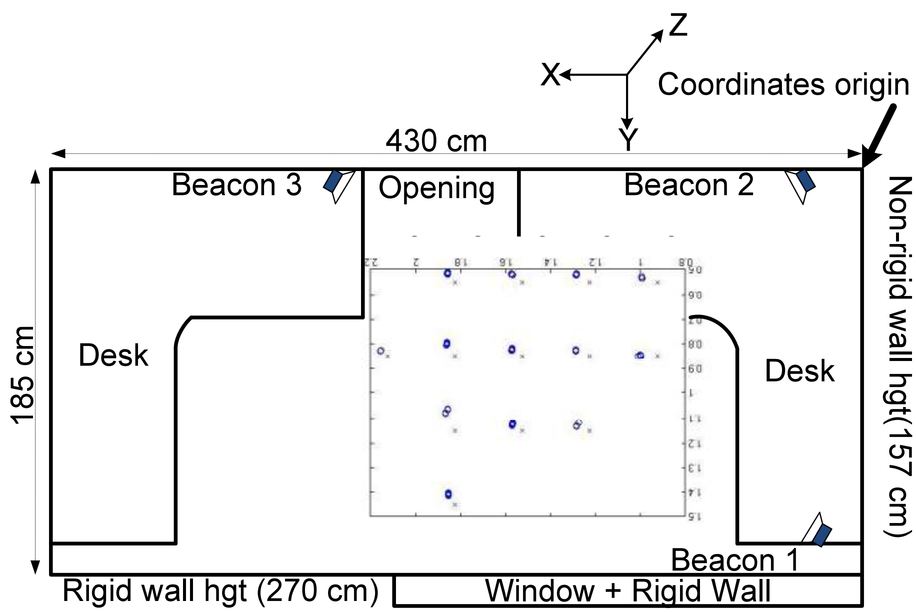


Fig. 16: Experimental setup and MD actual and estimated locations

the real data collected in the experiment.

Experimental results confirm that proposed method provides location estimates with high accuracy. The improvement in location estimates obtained using proposed Hybrid AoA-ToF with Timing Lock algorithm compared to those obtained using AoA-only method is significant.

TABLE VI: Bias and standard deviation of AoA estimates, AoA-only method location estimates and Hybrid AoA-ToF with Timing Lock algorithm location estimates

AoA	Bias degrees	0.2
	σ degrees	2
AoA-based location	Bias cm	14
	σ cm	132
Hybrid AoA-ToF location	Bias cm	7.8
	σ cm	0.64

VI. Conclusion

A novel reference-free ultrasonic indoor location system with high accuracy was presented. The system applies a novel algorithm that uses a Hybrid AoA-ToF with Timing Lock method. The primary advantage of the system is that the need for a timing reference signal is eliminated. The system provides absolute 3D location estimates with high accuracy. Simulation and experimental results show a significant improvement in location estimation accuracy and robustness when applying the proposed method, as compared to an AoA-only method. The main advantage of the system over previous ultrasonic location systems is that it greatly simplifies the location infrastructure while maintaining good accuracy. The system has applications in indoor robotics navigation, museum exhibitions, and interactive games. In future we plan to investigate the effectiveness of the approach in underwater location systems.

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