ACCURACY OF SPREAD SPECTRUM TECHNIQUES FOR ULTRASONIC INDOOR LOCATION

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ABSTRACT

This paper presents an assessment of the accuracy of impulsive and spread spectrum based algorithms for indoor ultrasonic location. Ultrasonic location systems have been proposed for pervasive computing applications. Previous systems have focused on the use of impulsive and Direct Sequence Spread Spectrum (DSSS) signalling. The use of Frequency Hopped Spread Spectrum (FHSS) signalling has not been previously studied for ultrasonic location. It is shown herein that FHSS outperforms DSSS and impulsive signalling under conditions of noise and reverberation. The accuracy of location for FHSS is shown to be twice that of DSSS under typical conditions. FHSS also provides opportunities for simplified transducer construction.

Index Terms— Ultrasound, spread spectrum, multilateralization, image method, multipath.

1. INTRODUCTION

In recent years, interest in location systems has increased significantly. Location is an essential element of context - a key requirement for context-aware, pervasive computing systems [1], [7]. The explosive development of GPS based navigation systems together with wireless computing and communication technologies, such as PDAs and 3G, is changing the way we live and work. One of the disadvantages of GPS systems is that, due to the attenuation of RF signals, they do not provide indoor location estimates. A number of systems have been proposed to address this problem including WLAN location, dedicated Radio Frequency (RF) location and ultrasonic location systems. [12] [13].

This paper considers the problem of accurate, robust indoor ultrasonic location. Ultrasonic location systems have three advantages over RF based systems. Firstly, the lower speed of propagation of ultrasonic systems facilitates accurate ranging. Secondly, ultrasonic signals do not propagate through walls and so are easier to model and control. Thirdly, RF systems are prohibited or unusable in certain situations, for example in hospitals, on ships and underwater.

The paper focuses on privacy-aware mobile device location, that is, a mobile device receives signals from placed beacons and estimates its own position [14]. Alternative infrastructure location systems utilize a transmitting device. Receivers on the walls and ceiling receive and estimate the position of the device. The advantages of device location systems are two-fold. Firstly, only the mobile device knows its own position - important for personalized, pervasive applications. Secondly, the infrastructure is much cheaper and simpler to install since no 'back haul' is required.

The paper presents an assessment of the accuracy of impulsive and spread spectrum signalling techniques for ultrasonic location. Location is by multilateralization based on Time Of Arrival (TOA) estimates from multiple beacons. Independent time synchronization between the mobile device and the beacons is assumed. This can be achieved using an RF signal. Improved techniques will be the subject of future work. The impulsive technique utilizes a simple pulse emitted by each beacon in turn. The spread spectrum techniques studied are Direct Sequence Spread Spectrum (DSSS) and Frequency Hopped Spread Spectrum (FHSS) [8][10]. The spread spectrum techniques allow for simultaneous transmission by all beacons. In the case of DSSS, the signals are made orthogonal by multiply with a pre-determined pseudorandom binary sequence. In the case of FHSS, orthogonality is provided by a pre-determined pseudorandom sequence of frequency hops at particular time instants. The signal from each beacon may be recovered at the receiver by cross-correlation of the received signal with the known pseudorandom sequences. Spread spectrum techniques have the advantage that the recovered signal is, in effect, averaged over a large number of samples. Hence, it is expected that they will be more robust to noise than impulsive signalling. The paper assesses the accuracy of the systems in estimating indoor 3D location by means of simulation. The simulations model the acoustic reverberation present in a typical room. The impact of noise

and transducer location on accuracy is investigated.

This paper is structured as following. Previous related worked is described in Section 2. A theoretical study of the issues is in Section 3. Section 4 describes the assessment method. Section 5 details and discusses the results. Finally, Section 6 concludes the paper.

2. RELATED WORK

Indoor ultrasonic location systems for pervasive computing were first studied in Bats[1] and MIT [6] Crickets[2] systems. The Bats system employs infrastructure location with impulsive signalling. In response to an RF pulse, the mobile 'Bat' 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 and an orientation accuracy of 3 degrees in low noise environments. The accuracy of the systems deteriorates rapidly in noise. It has been reported that ultrasonic noise in typical office environments is less than 40db/Hz dB[15] so this measure was done within industrial environment. The update rate of the systems is limited since time must be allowed for the reverberation of the pulses to decay before re-sending.

Use of DSSS signalling for ultrasonic location has been investigated previously. In [3], the authors describe construction of a wideband ultrasonic transducer. The transducer was found to have a response of 20 kHz - 100 kHz. The author's report that a location system using the transducer has an accuracy of just over two cm under conditions of typical noise. There are other systems, like [4], where the authors uses a transducer with a response of 4KHz-100 KHz and an accuracy of 2cm. To the authors' knowledge, use of FHSS for ultrasonic positioning has not be studied previously.

3. THEORY

3.1. TOA Estimation

For impulsive systems. the TOA of the transmitted pulse is calculated as the delay of the peak of the received signal relative to a independent synchronization signal.

DSSS uses a spreading signal that comprises a pseudo-random sequence of binary pulses +1,-1 (spreading code) at high rate (chipping rate). The spreading codes are chosen to be orthogonal so that they may be separated at the receiver. The data signal is multiplied by the spreading code and used to modulate a carrier signal at the desired centre frequency. The received signal is cross-correlated with the known transmission sequence for each beacon in turn. The delay of the peak of the cross-correlation is taken as the TOA estimate for that beacon.

In FHSS, the transmitted signal hops between a set of frequencies according to a pseudo-random code. Again, the delay of the peak of the cross-correlation between the received signal and known transmitted signals is used for TOA estimation.In all cases, the TOA estimate is converted to a range estimate based on the speed of sound in air.

3.2. 3D Location

The range estimate for each beacon must be converted to a 3D location estimate based on the known positions of the beacons. There are two main algorithms for location estimation based on multiple range estimates.Linear Least Squares (LLS) is a simple method that provides reasonable accuracy at low computational cost [9]. Its a simple method that have a pretty low computational cost but give a very poor accuracy.Non-linear Least-Squares (NLLS) is an iterative method that requires an initial estimate of location which can be provided by the LLS algorithm.

3.3. Reverberation Model

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 [5]. 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 signal received from each source is determined by time lagging and attenuation due to the source-receiver distance and further attenuation due to the number of wall reflections.

4. METHOD

The performance of the systems was assessed by implementation and simulation using Simulink MATLAB. The systems are comprised of three sub-systems. The modulation sub-system calculates the signal transmitted by each beacon. The channel sub-system convolves the impulse response for the particular beacon-device configuration with the signal transmitted by the beacon, sums the signals received from all beacons and adds Gaussian, white noise. The receiver sub-system cross-correlates the received signal with the known transmissions, estimates the range of each beacon and performs multi-lateralization to estimate the 3D location using NLLS seeded by LLS.

It was decided to use signals in the frequency range 20 - 40 kHz so the sample frequency chosen was 80 KHz, double the maximum frequency. Acoustic signals below 20 kHz are audible. This is clearly not desirable. Attenuation increases with frequency, reducing range. Hence, it was decided to limit signals to below 40 kHz. For DSSS, a data rate of 1 KHz and chipping rate of 20 were chosen. BPSK modulation was used with a center frequency of 30 KHz. The configuration was designed to use the entire available spectrum. For FHSS, a signal of 20/M kHz was used with an M-ary frequency synthesizer and a separate between frequencies of 20000/M in order to utilize the same bandwidth as in the DSSS case. No averaging was applied between estimates.

The system used the Image Method to simulate the impulse responses of the room. The room was 6x6x4 meters with walls, ceiling and floor having a reflection coefficient of 0.35. This was selected so as to be representative to a typical office environment. The beacons were placed in the next three positions: [3,0,4], [3,6,4] and [6,3,4].Omni-directional transmitters and receivers are assumed. This was to eliminate a source of variability in the comparisons. [11] describes construction of omni-directional ultrasonic transducers.

The performance of the systems was established using a Monte Carlo method across multiple random mobile receiver positions under varying degrees of noise. For each iteration, the error in 3D location was determined relative to 'ground truth'. The average SRR(Signal to Reverberation Ratio) was estimated in -3.45 db.

5. RESULTS
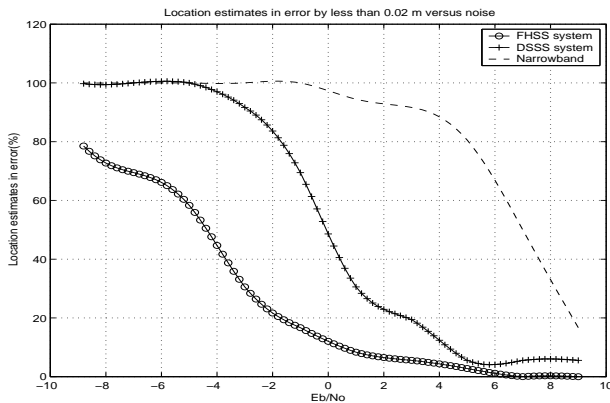
**Fig. 1**. Location estimates in error by less than 0.002 meters

The accuracy of the systems under varying levels of noise with reverberation was determined. Fig. 1 shows how the percentage of location estimates in error by less than 2 mm varies with SNR. Under all noise conditions, FHSS is more accurate than DSSS which is more accurate that impulsive location estimation. The improvement in accuracy of FHSS relative to DSSS is larger at lower Signal to Noise Ratios.
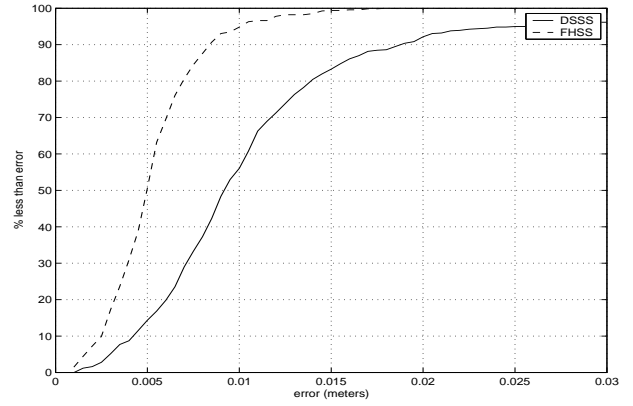
**Fig. 2**. Accuracy estimation

The accuracy of the FHSS and DSSS systems was assessed at a SNR of 0 dB (Fig.2). The percentage of location estimates in error by less than a particular value is shown in Fig.2 . Again, FHSS outperforms DSSS. In terms of accuracy at this noise level, FHSS is roughly twice as accurate.

The distribution of errors with mobile device location was assessed. A contour map showing variation of the peak error in location accuracy across the room is shown in Fig. 3 and 4. The map for FHSS shows that the errors are distributed fairly evenly across the room with peaks in the extremes of the room. The map for DHSS shows much larger errors along the walls. These peaks are at the points where the mobile device is close to at least one beacon and far from at least one beacon. In these cases, the signal from the 'near' transmitter dominates that of the 'far' transmitter. This is a manifestation of the classic near-far problem associated with DSSS based wireless communication systems. FHSS avoids this problem by ensuring that no two beacons transmit at the same frequency at the same time. This effect leads to the improvements in accuracy seen for FHSS. The floor cannot be seen in this map, but in others plots is clear that FHSS performs better across almost all locations.
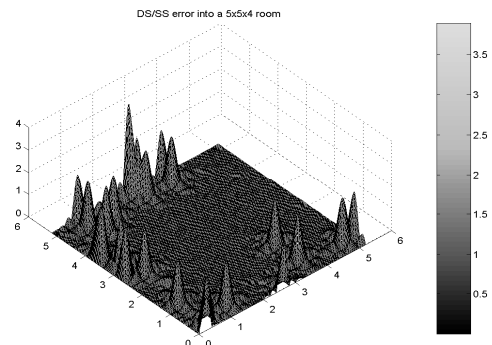
Fig. 3. Location error DSSS

A further benefit of an FHSS ultrasonic system is in the
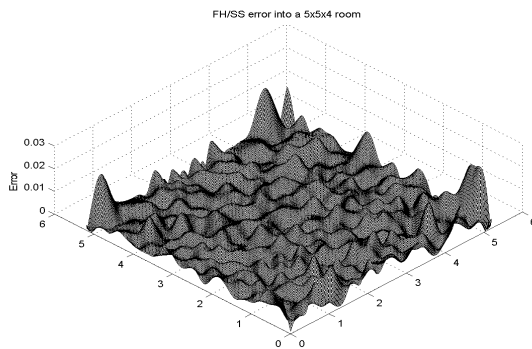
Fig. 4. Location error FHSS

design of the transducers. As shown in [5], designing a wide-band ultrasonic transducer is difficult. In the case of FHSS, multiple (M) transducers can be utilized - each at a different centre frequency. In this way, conventional ceramic ultrasonic transducers may be utilised within a spread spectrum system.

6. CONCLUSIONS AND FURTHER WORK

The paper describes an investigation of the accuracy of impulsive and spread spectrum ultrasonic location systems. The performance of the systems was assessed by Monte Carlo simulation. The results of the simulations indicate that FHSS outperforms DSSS and impulsive systems in terms of location accuracy. The FHSS based system provides twice the accuracy of the DSSS system under typical noise conditions. To the authors' knowledge FHSS has not been previously applied to ultrasonic location.

Future work includes investigation of further signal processing techniques to improve ranging, extraction of Angle of Arrival (AOA) information, beamforming and virtual imaging. A hardware prototype will be constructed to determine the accuracy of the system by experiment.

7. ACKNOWLEDGMENTS

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