# Design and Implementation of Spread Spectrum Ultrasonic Location System

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## Abstract

This paper proposes an ultrasonic location system based on the spread spectrum principle. Compared with the existing ultrasonic location systems, the proposed system combines the spread spectrum and amplitude modulation principles. As a result, the proposed ultrasonic location system is advantageous in that it can improve positioning accuracy and detection sensitivity by the spread spectrum principle, it simplifies transmitter and receiver circuits by the amplitude modulation, and it is easy to upgrade its performance by the software functionalities. The advantages and performance of the proposed location system are demonstrated by experiments.

**Keywords:** Spread Spectrum, Ultrasonic Location System.

## 1. Introduction

In the near future, it is anticipated that indoor location systems would produce diverse application areas including home robot navigation, management of ubiquitous sensor network, and human interface for interactive games. Due to its potentialities, various indoor location systems have been developed utilizing infrared sensor, Radio Frequency IDentification (RFID), Wireless Local Area Network (WLAN), Ultra Wide Band (UWB), and ultrasonic sensor technologies.

The infrared location system relies on periodic pulse signals between the transmitter and the receiver [2]. The RFID location system identifies the proximity condition of the reader and tag pair when they are located close to each other [3]. Both of these systems usually utilize the known location of the fixed unit which has its own unique ID. When the fixed unit detects the mobile unit's existence within its neighborhood, the mobile unit's position is estimated as the known location of the closest fixed unit. As a result, the precision of the position estimate heavily depends on the granularity of the known fixed units.

The WLAN location system utilizes signal strength measurements [4]. This system typically shows the low accuracy of about three meters. The Ubisense location system utilizes UWB technology [5]. This system consists of the UWB base stations and the small UWB transmitters carried by users. It shows the accuracy within 15cm.

As explained before, there are many sensor technologies with different characteristics. Thus, it is difficult to say that one specific technology is the best among the many techonologies. The ultrasonic sensor technology is an attractive choice in terms of accuracy and cost. Typically, the sound speed ($3.4\times10^2$ m/s in normal air condition) is much slower than the light speed ($3\times10^8$ m/s). Therefore, the ultrasonic system requires simpler hardware and smaller processing capacity than the RF-based location systems.

Currently, Active BAT [6], Cricket [7], and Broadband Ultrasonic Location System [8] are the mostly well-known examples of ultrasonic location systems. Active BAT requires users to wear small badges. The small badge transmits an ultrasonic pulse when a radio signal is triggered by the network. The system determines time-of-flight from the badge to the receivers on the ceiling. The network calculates the 3-dimensional position of the badges. Cricket consists of beacons and listeners. Each beacon sends RF-signals and ultrasonic pulses in response to the listener's request. The listener receives the RF-signals and ultrasonic pulses and calculate its distance to the beacons. Since each listener computes its own position, the maintenance of user privacy can be effectively considered. Broadband Ultrasonic Location System utilizes transducers to increase data transmission rate. Its wideband modulation scheme, however, requires high transmission energy and costly DSP techniques to demodulate the signals.

This paper proposes a new type of ultrasonic location system. Compared with the existing ultrasonic location systems, the proposed system combines the spread spectrum and amplitude modulation principles. As a result, the proposed ultrasonic location system is advantageous in that it can improve positioning accuracy and detection sensitivity by the spread spectrum principle, it simplifies transmitter and receiver circuits by the simple amplitude modulation principle, and it is easy to upgrade its performance by the software functionalities.

In the following section, the transmitter and receiver hardware of the proposed ultrasonic location system is described. The final section demonstrates the advantages and performance of the proposed system by several experiments.

## 2. Design of the Ultrasonic Location System

The proposed location system consists of two parts; the transmitter part and the receiver part. The transmitter part consists of multiple ultrasonic transmitters and and a controller to create modulated signal as shown in Fig. 1. The receiver part consists of an ultrasonic sensor and a digital signal controller to demodulate received signals and compute position estimates as shown in Fig. 2.

### 2.1 Transmitters

The signal to be transmitted is at first modulated by the spread spectrum code or Pseudo Random Noise (PRN). The spread signal is modulated again by the amplitude modulation principle. The proposed system adopts the Time Division Multiple Access

(TDMA) for multiple transmitter because the ultrasonic sensor has single frequency 40 kHz. It allows multiple channels to share the same frequency by dividing it into different timeslots. Among the multiple channels, one channel is assigned a timeslot of a 0.1 seconds. Thus, if there are five transmitters nearby, for example, one repetition of all the channels' signal broadcast corresponds to 0.5 seconds. As a result, the receiver's position update rate becomes 2 Hz.

The receiver contains an internal clock that is used to extract the Time-Of-Arrival (TOA) from each transmitter. The receiver's clock is not synchronized with the transmitters' clock. Thus, it needs to hear at least four TOAs to calculate its position estimate. If the receiver receives three TOAs, two dimensional position estimate can be computed.

The selection of spreading code plays an important role in extracting accurate TOA. The TOA accuracy is restricted by the PRN code's length and chipping rate conditions. The proposed system generates the PRN code which is similar to that of the C/A code of the Global Positiong System (GPS). The GPS C/A code belongs to the family of PRN codes known as the Gold codes. The signals are generated from the product of two 1,023-bit PRN sequence G1 and G2 registers. Both G1 and G2 are generated by a maximum-length linear shift register structure of 10 stages. The proposed location system utilizes the maximum-length linear shift register of 7 stages. Selection of code is decided by the chipping rate of ultrasonic data and the time slot interval.

## 2.2 Receiver

It is useful to model the modulated ultrasonic signal as follows [9].

$$v_1(t) = V_0 t^m e^{-t/h} \cos(\omega_c t + \theta) \tag{1}$$

The values for $m$ and $h$ express the received ultrasonic signal envelop. The phase shift $\theta$ is transducer dependant constant and $\omega_c$ is angular frequency of the ultrasonic signal. Figure 4 illustrates an exemplified waveform based on the received ultrasonic signal.

The proposed location system utilizes the signal envelops to detect the digitalized level of signals. Based on Eq. (1), the equation of the received signal envelope can be modeled as

$$v_2(t) = V_0 t^m e^{-t/h}. \tag{2}$$

To detect the digitalized signal level, the proposed system utilizes the following variable threshold level.

$$V_t = \begin{cases} C & (if \quad V_t \le C) \\ \left( \sum_{i=1}^{N} v(t-i)/N \right) - N/10 & (otherwise) \end{cases} \tag{3}$$

In Eq. (3), $C$ is the constant for detecting the noise level. $N$ is the sampling count during one chip interval. As a result, $V_t$ is approximately the average signal level during the previous one chip-length interval if the previous signal's digital level is not zero. On the contrary, if the previous level is zero, $V_t$ is kept constant.

Based on Eq. (3), the receiver decides the digital signal level by comparing the input ADC value and the variable threshold value. In the upper plot of Fig. 5, the solid line is the envelop of the input ultrasonic signals. The dotted line corresponds to the variable threshold values. In the lower end of Figure 5, digital signal '1' is black area. The dotted line is PRN code generated in the receiver.

The positions are calculated by the four or more measured pseudoranges. In figure 6, it is correlation data between measured digital value and generated PRN code in a channel data interval.

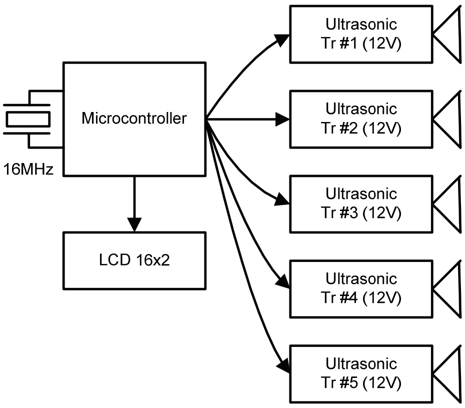

Figure 1. Configuration of transmitters

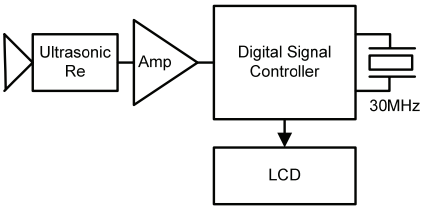

Figure 2. Configuration of receiver

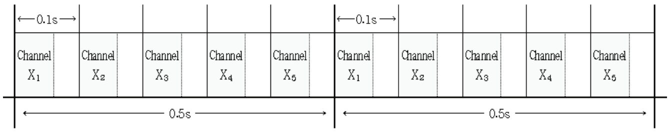

Figure 3. Time division structure for multiplexing

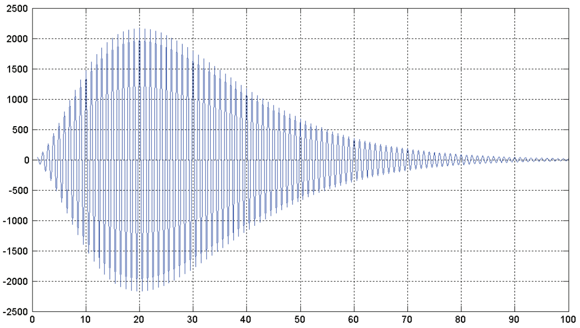

Figure 4. Modeled profile of received ultrasonic signal

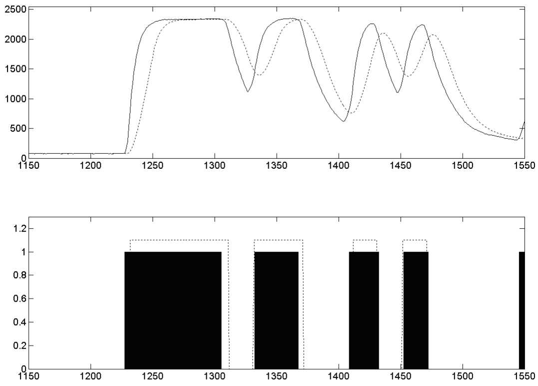

Figure 5. Input ultrasonic signal and adapted threshold value (upper plot) and transmitted and decided digital signal level (lower plot)

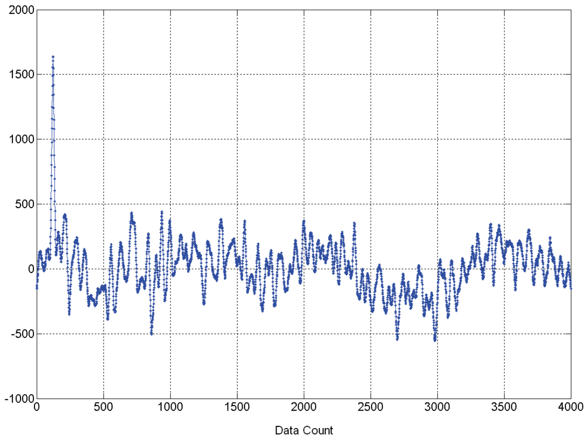

Figure 6. Correlation profile

## 3. Experiments and Results

To demonstrate how the spread spectrum amplitude modulation improves signal sensitivity and positioning accuracy, experiments were performed in a space of 1.96 × 1.8 × 2.18 meters in size. Two experiments were performed to verify the performance of the proposed system.

The first one is the static positioning test and the second one is the dynamic functionality test. The experimental setup consists of five ultrasonic transmitters and a signal controller in a space 1.96 m × 1.8 m × 2.18 m in size as show in Figure 7. The position of the five transmitters are (0.98 , 0.90, 1.675), (-0.98, 0.90, 1.675) , (-0.98, -0.90, 1.675), (0.98, -0.90, 1.675), and (0, 0, 2.175) meters. It should be noted that an ultrasonic transmitter is installed at different height value as compared with others. Each position of ultrasonic transmitter sensors is measured manually by floor grid lines and a ruler. Thus, each of them may bear the inaccuracy of around 1 cm.

### 3.1 Static condition

For static accuracy experiment, the receiver is located at the origin of the local coordinate system. In Figure 7, the origin is indicated by a thick point. The receiver measured the pseudoranges from all the transmitters and calculates its position. During the experiment, total 200 sets of pseudorange measurements are received.

Figure 8 and Table 1 shows the static position error. In Figure 8, the horizontal axis corresponds to the count of data set..The receiver updates its position by 2 Hz rate. Thus, the entire static test required 100 seconds. 100 second is the product of 200 by 0.5. The vertical axis of Figure 8 is absolute error between the true position and the computed position.

Table 2 provides the mean and variance of the position errors. The X- and Y- axis errors are ranged within 2 cm. It corresponds the horizontal position error. The Z-axis error or the vertical error is within 7 cm. Thus, from the result, it can be seen that the vertical error is much larger than the horizontal error. It is well-known that the vertical inaccuracy is due to the Dilution Of Precision (DOP). The DOP is caused by the form of the observation matrix in the measurement equation and the observation matrix parameters are determined by the geometry of multiple transmitters.

### 3.2 Dynamic movement

The second experiment was performed to assess the characteristics of the proposed system under dynamic movements. The results are illustrated in Figure 9 as the 2-dimensional plot. The receiver is located at start position of (0, -0.51, 0.61) meters, circled twice at counterclockwise direction, and stopped near the start position. As shown in Figure 9, it can be seen that two different circles corresponding to the two different revolutions almost overlap to each other.

As the performance indication value, the distance between the origin and the receiver's position is computed. The true radius of the circular path was 0.51 meters. By subtracting the true radius from the computed radius, the distance errors were extracted and stored. Table 2 shows the mean value of the distance errors. This result shows that the proposed location system performs effectively under the receiver's movements.

## 4. Conclusions

This paper proposed a prototype ultrasonic location system that combines spread spectrum principle and amplitude modulation principle. By the two experiments, it was shown that the proposed system performs well under both the static and dynamic conditions. It was shown that the achievable static accuracy is within a few cm.

The proposed ultrasonic location system is easy to upgrade its performance since most of its functionalities can be easily modified only by software. Our future work includes the enhancement of accuracy by the addition of Kalman filter algorithm and detection range by modifying the PRN modulation scheme.

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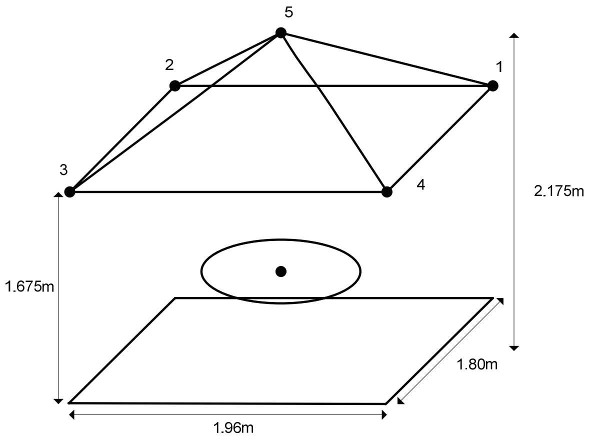

Figure 7. Installation configuration of receiver and transmitters

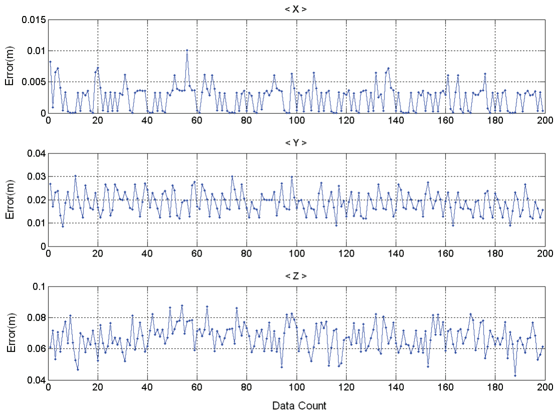

Figure. 8. Static position error profile

Table 1. The position errors of origin point

| | Mean (cm) | Variance (cm) |
|---|---|---|
| X | 0.2453 | 0.0420 |
| Y | 1.8694 | 0.2203 |
| Z | 6.7243 | 0.7250 |

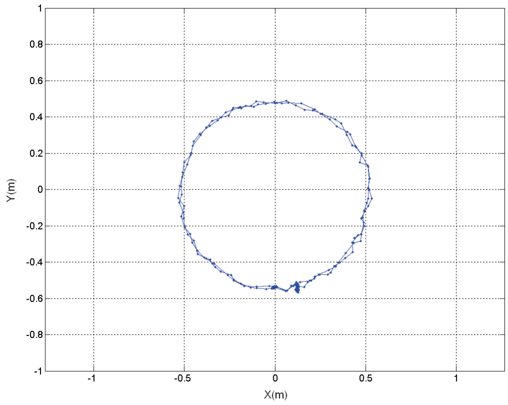

Figure 9. Computed 2-dimension trajectory under circular movement

Table 2. The distance error in circle moving

| | Mean (cm) |
|---|---|
| Distance Error | 2.7841 |