Spread Spectrum Ultrasonic Positioning System

Omar A. M. Aly and A.S. Omar

University of Magdeburg, Chair of Microwave and Communication Engineering FEIT-IESK
Postfach 4120, 39016 Magdeburg, Germany, e-mail: oaly@iesk.et.uni-magdeburg.de

Abstract – Many mobile applications can be greatly enhanced when provided with the locations of people and devices. Indoor ultrasonic positioning system provide fine-grained position data for such applications. This paper describes an ultrasonic tagging system developed for monitoring the location of a moving target. Use of spread spectrum in ultrasonic location system allows the system to work at a noisy environment. In the same time it solves the problem of signal collisions when more than one transmitter transmit at the same time. Test results demonstrate that the system is able to locate the position of a moving target with high accuracy.

1 Introduction

Ubiquitous computing applications require context information in order to blend seamlessly into the environment and to unobtrusively aid people in their everyday lives. A particularly important component of context is the location of people and the objects they interact with. Numerous ubiquitous applications utilizing location information have been developed [1].

Various methods exist for determining the location of a people or object. All of them involve gathering data by sensing a real-world physical quantity, and using it to calculate or infer a position estimate. The data can be gathered via a number of physical media. Previously developed location systems have used infrared light [2,3,4], ultrasound [5,6,7], and wireless LAN-based radio [8,9].

The desirable property of ultrasonic location system is that they have the capability to be fine-grained, meaning they can estimate location with a high degree of resolution. This is because the speed of ultrasound in air is sufficiently slow to allow the time-of-flight of a signal to be accurately measured between a fixed unit in the environment and a mobile unit functioning as a tag on a person or object. Previous ultrasonic location systems have employed narrowband signals. This makes them susceptible to noise, and their update rate is limited due to the fact that signal collisions must be avoided. In [10,11] a broadband spread spectrum techniques has been used to overcome these two limitations, facilitating multiple-access location systems which are robust in the presence of noise. As reported in [10] both the transmitter and the receiver are too large and bulky to be used as mobile tags. In the same time the power drawn by the unit is over 1 w. For these reasons this system is unsuitable for mobile devices.

In this paper we present a spread spectrum ultrasonic location system based on a commercially available narrowband ultrasonic sensor. Use of such a sensor will reduce the cost of the system. In the same time it can be used as mobile tag regarding to the small size and the low power that is required for the transmitter. In the next sections we will give the details of the hardware structure of the system and the measurements result of its location accuracy.

2 Hardware structure

This section describes the design and properties of the transmitter and receiver hardware. The system is designed to work at frequency 40 kHz with bandwidth of 2 kHz. These parameters are selected based on the commercially available ultrasonic sensors.

The transducers used in this work rely on piezo-electric ceramics as its active elements. These kinds of transducers are inexpensive, small, rugged, and have a high sensitivity. However, they are highly resonant, and in most cases have a usable bandwidth of less than 5 kHz. Fig. 1 indicates the measured transfer function of the used ultrasonic transducer. From the measurements of the transfer function of the sensor we found that the sensor has a resonance frequency 40.2 KHz and a 3dB bandwidth 1.7 kHz

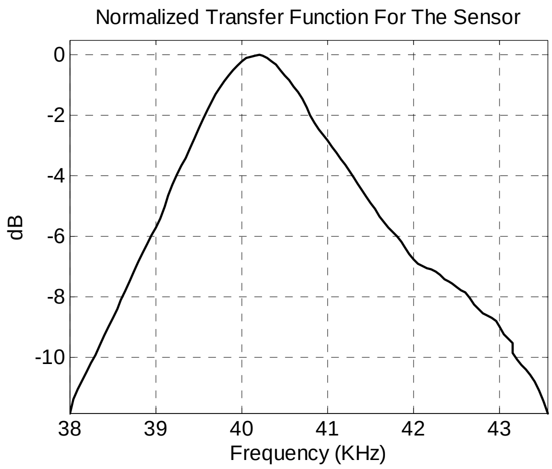

Fig. 1 Normalized transfer function of the ultrasonic sensor

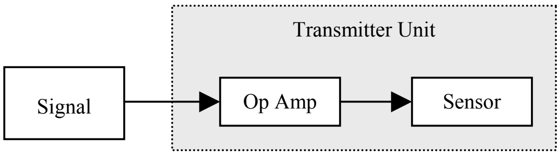

Fig. 2.a Transmitter block diagram

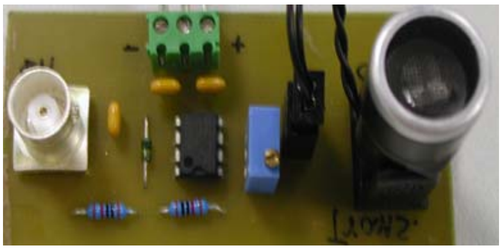

Fig. 2.b Transmitter board

As shown in Fig. 2.a, the transmitter is designed to convert an electrical voltage signal into an ultrasonic one. The transmitter unit is shown in Fig. 2.b. The same circuit can be used also as the receiver unit by changing the input output terminals.
The signal for the transmitter was synthesized digitally on a PC, to allow the structure of the ranging message to be changed easily in software. The signal was sent out through the sound card, which performs digital-to-analogue conversion, and carried to the transmitter unit via coaxial cable.
Using coaxial cable, the signal outputs of the receiver units were connected to data acquisition cards at a PC. The PCI data acquisition card performs analog-to-digital conversion. A sampling rate of 100 KHz, which is larger than twice the highest frequency in the signal, was chosen for each receiver. The converted signals are then processed using c++ program running on a PC. This method allows flexibility when conducting experiments with our prototype system, as signals can be analysed in real time using a variety of methods, implemented as c++ software.

3 Signal Structure and Processing

A direct sequence spread spectrum (DSSS) signal structure was applied in order to achieve multiple-access properties and robustness towards noise.

3.1 Signal Generation

The ranging messages used in the measurements consisted of a 40.2 kHz carrier wave, modulated by M-sequence pseudo random code of length 63 bits. The clock rate of the code was selected to be 1 kHz, which leads to a bandwidth of 2 kHz. The transmitted signal s(t) can be described as follow.

$$s(t) = p(t).\cos(w_0 t) \tag{1}$$

Where p(t) is the M-sequence pseudo random code and w_o is the carrier frequency. Fig.3(a) indicates the generated M-sequence pseudo random code and Fig.3(b) indicates the power spectral density (PSD) of the transmitted signal.

3.2 Digital Signal Processing

The location of transmitter unit (T) was estimated using the following steps.

1. The time-of-flight for the T mobile ranging message were measured by correlating the receivers' signal against the expected signal. The time-of-flight was defined as the time between the triggering time and the first peak in the correlated data.
2. The time-of-flight is converted to distance using the speed of sound in air.
3. Using the accurately surveyed positions of the receivers and the transmitter-to-receivers distances, Location was estimated by employing the multilateration algorithm described by [12].

Since the receivers are coplanar, a minimum of two distances are needed to estimate the 2D transmitter position.

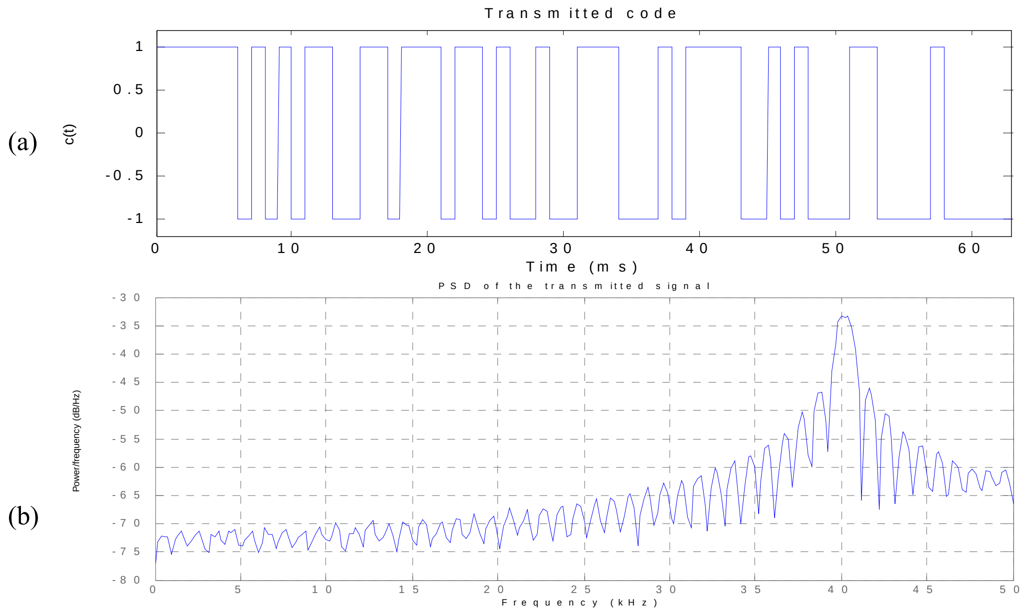

Fig.3 (a) The transmitted code (b) the PSD of the transmitted signal

3.2.1 Distance measurements Processing

The distance between the transmitter and the receiver is calculated by measuring the time-of-flight for the T mobile ranging message.

The time-of-flight is measured by calculating the correlation between the received signal and the reference signal. The received signal can be described as a summation of delayed copy of the transmitted signal which was described by Equation (1). Using Equation (1) we can describe the received signal by:

$$z(t) = \sum_{k=1}^{p} A_k s(t - \tau_k) \tag{2}$$

where p represents the number of multi-path reflections, including the direct path between the transmitter and receiver, A_k is the amplitude of the k path and τ_k is the time-of-flight for the k path. Substituting for s(t) from Equation(1), Then Equation(2) can be written as:

$$\begin{aligned} z(t) &= \sum_{k=1}^{p} A_k p(t - \tau_k) \cos(w_o(t - \tau_k)) \\ &= \sum_{k=1}^{p} A_k p(t - \tau_k) \cos(w_o t - \theta_k) \end{aligned} \tag{3}$$

where $\theta_k = w_o . \tau_k$. The time τ_k can be calculated by calculating first the correlation between the received signal z(t) (after demodulation by the carrier) and the transmitted code p(t). Two-channel demodulator was used to overcome the problem of the phase shift θ_k between the received carrier and the reference carrier. Fig.(4) indicates the block diagram of the two-channel correlator receiver.
After demodulation the received signal can be written as:

$$z_I(t) = \sum_{k=1}^{p} A_k\, p(t-\tau_k)\cos(\theta_k) \tag{4}$$

$$z_Q(t) = \sum_{k=1}^{p} A_k\, p(t-\tau_k)\sin(\theta_k) \tag{5}$$

where $z_I(t)$ is the in-phase signal and $z_Q(t)$ is the qudrature signal. By using the reference code p(t) the correlation can be calculated. The correlation was calculated using FFT (Fast Fourier Transform) as follows

$$RI = IFFT(\, Z_I(f).\, conj(\, P(f)\,)\,) \tag{6}$$

$$RQ = IFFT(\, Z_Q(f).\, conj(\, P(f)\,)\,) \tag{7}$$

Where $Z_I(f)$, $Z_Q(f)$ and $P(f)$ are the Fourier transforms of $z_I(t)$, $z_Q(t)$ and $p(t)$ respectively and IFFT denotes the Inverse Fourier Transform. The total correlation was calculated as shown by the block diagram of Fig. (4). Fig.(5) indicates the correlations for the received signal.

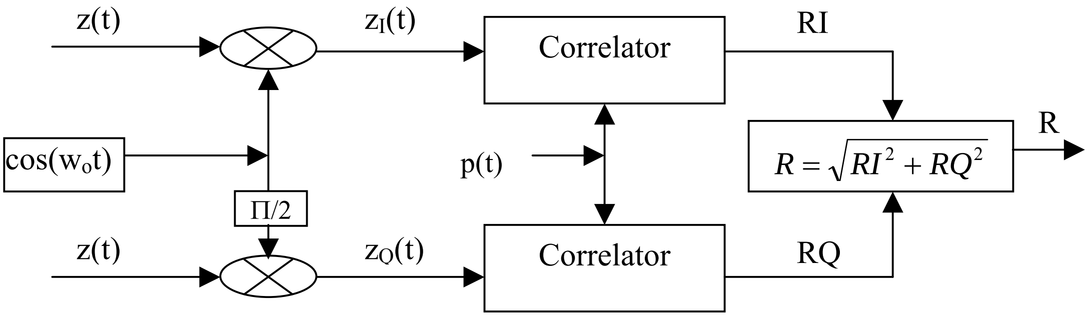

Fig. 4 Two Channel Correlator Receiver.

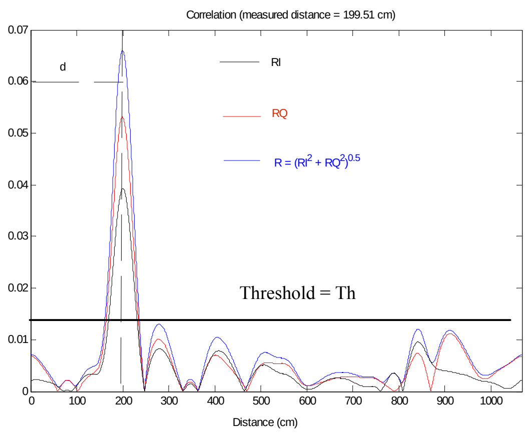

Fig. 5 The correlation for the measured signal at distance (200 cm).

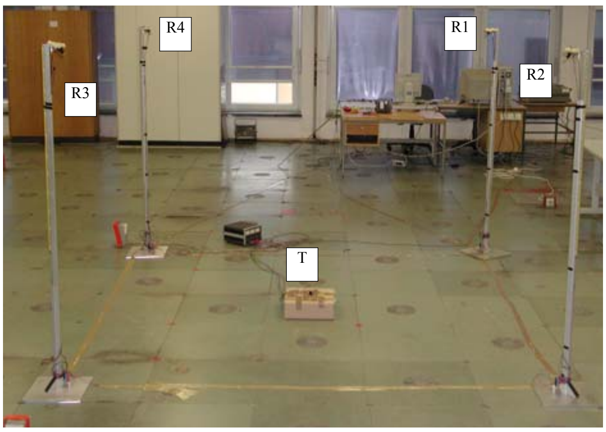

Fig.6 Ultrasonic Location System Lab

At first the correlation is passed through a threshold to remove the effect of noise and side loops. There are different methods for calculating the value of the threshold. In this work the value of the threshold was calculated based on the average value of the correlation as.

$$\text{Th} = a.\ \text{mean}(\text{R}) + b \tag{8}$$

Where a and b are constants calculated based on the observed values of the correlation.
The time-of-flight between the transmitter and receiver τ_1 was taken as the time of the occurrence of the first peak in the correlation curve (the short path is the direct path between the transmitter and receiver). Using the speed of sound in air (c = 341 m/s) we can calculate the distance between the transmitter and receiver by:

$$\text{d} = \tau_1 .\ \text{c} \tag{9}$$

3.2.2 Position Finding

In this paper we present a two-dimensional (2D) positioning system. To find the unknown 2D position (x, y) of the target we need two distances to be measured between the transmitter and a well-defined receivers position (x_i,y_i) (we assume that the target is inside the test area). By knowing the height of the receivers (h) and the measured two distances (d_1, d_2) between the transmitter and receivers we can find the x-y position of the target by solving the following equations.

$$(x - x_i)^2 + (y - y_i)^2 = r_i^2 \qquad \text{where} \qquad i = 1,2 \tag{10}$$

Where $r_i^2 = (h^2 + d_i^2)$ and h again is the height of the receiver.

4 Test System Configurations

The system was installed in an area of 2.5 m x 2.5 m. Four receivers R1 to R4 (Fig. 6) were installed on stands in the corners of this area. The heights of the stands are 2.0 m. A mobile transmitter unit (T) was attached to a moving object within this area. As indicated in the previous section, we need only two receivers to find the x-y position of the target. In the proposed system we installed four receivers to overcome the problem of reflections which can lead to large errors in measuring the distance when there are obstacles exist between the transmitter and receiver. From the four-measured distances we use only two to calculate the position. The roles of selecting the two distances are.
1- the difference between the two distances should be less than that between the two receivers.
2- the sum of the two distances should be larger than that between the two receivers.
3- each distance should be larger than h and smaller than the maximum distance within the test area.

5 Experimental Results

Tests were conducted in order to assess the accuracy of the location system. Fig. (7) indicates the histogram of the measured distance error. This figure was obtained by varying the distance between the transmitter and receiver from 1m to 6 m with a step of 1 m and measures the distance at each point 1000 time. From Fig. (7) we found that 85 % from the measurements have a distance error less than 0.5 cm. The theoretical accuracy of the system is ± 3.4 mm, which is determined by the sampling frequency of the A/D converter. From Fig. (7) we can conclude that the accuracy of measuring the distance is within ± 0.5 cm. Fig. (8) indicates the measured 2D position of a moving target.

6 Conclusions

In this paper, we have proposed a spread spectrum Ultrasonic location system using narrowband commercially available ultrasonic transducers. Using such a sensor can reduce the cost of the system.

The experiments show that our system is able to locate the 2D position of a moving target within an accuracy of ± 0.5 cm.

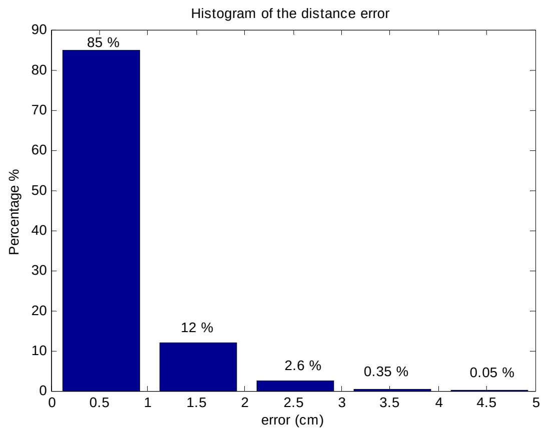

Fig. 7 Histogram of the distance error.

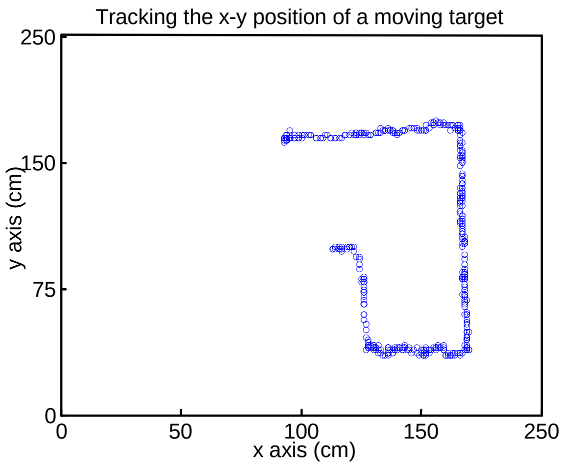

Fig. 8 Measured location (x,y) of a moving target

7 References

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