1st International Conference on Sensing Technology
November 21-23, 2005 Palmerston North, New Zealand

Broadband Indoor Acoustic Location System

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Abstract

The development and implementation of a noise-modulated localisation system using broadband ultrasonic transducers is presented. Such a system offers the possibility of fast self-localisation of multiple targets in an indoor environment, especially in the presence of narrowband interference or situations where high levels of noise are present. The ability of such a system to determine location data from simultaneous transmissions of multiple beacons is demonstrated and its localisation performance evaluated in various circumstances. To process the results, a simple localisation algorithm is derived and a brief analysis performed to determine its validity. The results of trials of the system are detailed and the overall system accuracy determined by least squares methods.

Keywords: Broadband acoustic localisation, pseudo-GPS

1 Introduction

Localisation – the determination of the position of a person or object – is a vital part of everyday life. The ubiquity of GPS technology is an example of the importance we place in knowing exactly where we are. Large-scale localisation of people in many environments can be extremely useful – for example, tracking of doctors within a hospital can help allocate vital resources in emergency situations [1,2]. More exact position determination is also useful as guidance for farm equipment in outdoor agricultural environments [3] and for mining applications [4].

Indoor localisation accurate to within a few centimetres is also becoming more and more important. Advances in automation have vastly increased the number of automated devices operating in domestic and commercial environments. Mines [5], museums [6] and even hospitals [7] all represent commercial enterprises where the use of automation has been employed to aid, guide, or even replace human beings entirely. Within the home, robotic vacuum cleaners [8], and pets [9] are well-publicised examples of the penetration of this technology into everyday life.

In commercial environments, many of these devices are of significant size and mass. It is therefore extremely important that they operate safely and efficiently in the presence of people and fragile or expensive equipment. A major part of this safe operation involves knowing where they are, hence the need for accurate and reliable localisation.

A variety of methods exist for locating objects within a given space. GPS is extremely useful for outdoor use but cannot perform effectively indoors due to multipath effects and partial or complete attenuation of the signals. Systems designed to adapt GPS to indoor environments are typically complex or expensive [10]. Infrared beacons can be used to determine location indoors [11], however they only offer narrowband signalling capabilities. It is also possible to use dead reckoning methods such as wheel encoders to measure the relative position of the object. However, errors in these relative methods will grow with time unless absolute position is measured regularly [12].

The use of acoustic technology is a reasonably cheap and effective way to provide absolute location data. However, a drawback to acoustic methods is the presence of interference due to noise in the environment and from other signals. When similar signals must be sent from multiple beacons, they must negotiate the use of either time or frequency space so as not to interfere with each other. An example of this is the Cricket system [1], where pulses must be broadcast at random intervals to avoid cross-talk between channels.

A solution to this problem lies in the use of broadband (spread spectrum) signals. These allow for the simultaneous non-interfering transmission of multiple signals in the same frequency band. By encoding the signals with specific codes, they can be extracted using appropriate processing techniques [13,14,15,16].

The use of spread spectrum technology to allow differentiation of simultaneous signals is common in everyday devices. Applications include GPS localisation, CDMA telephone networks and many wireless networking standards. Additionally, a large number of niche implementations exist in a variety of fields such as radar [17,18,19] and sonar [20,21]. Use in acoustic ranging systems similar to the one proposed here, along with other applications in robotics, is also common [3,13,14].

The system described here demonstrates the utility of broadband signalling methods by their practical application in an indoor localisation scheme. The concepts are based on the work described in Bortolotto et al. [22]. The scope of the system has been extended from that paper to allow evaluation of the noise immunity between multiple channels, along with the implementation of practical aspects of the localisation process.

Section 2 of this paper introduces the concept of spread spectrum signals and explains how they may be generated and processed. Section 3 describes the implementation of the system and the operation of the localisation algorithm. Section 4 presents the results of testing performed on the system, while the final section summarises the work, with suggestions for further research.

2 Broadband signals

A broadband signal is characterised by the way in which it contains power over a large range of frequencies. By spreading the signal over a wide bandwidth, a large amount of redundant information about the data content of the signal is transmitted [23, p800]. This enables individually coded signals to be more easily detected in the presence of noise or other interfering signals.

Phase modulation is a particularly effective way to spread the bandwidth of a signal [16,23]. Changing the phase of the signal by 180˚ according to a specific binary code sequence, known as binary phase shift keying (BPSK), introduces large phase discontinuities into the signal. Figure 1 shows how the phase of the carrier is modulated according to a binary data sequence, generating a large number of phase discontinuities at the switching points.

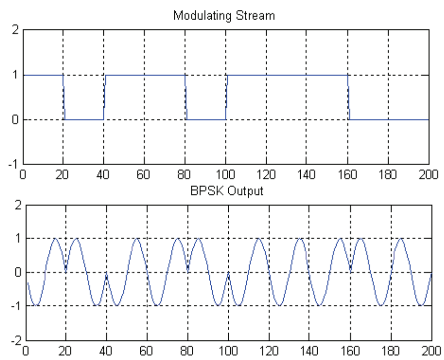

Figure 1: Data and corresponding BPSK signal

The modulation process is equivalent to convolving the spectrum of the binary sequence with the narrow spectrum of the pure carrier sinusoid [24, p117]. Figure 2 shows both the unmodulated (impulse) and BPSK modulated (flat) spectra of a 50 KHz carrier.

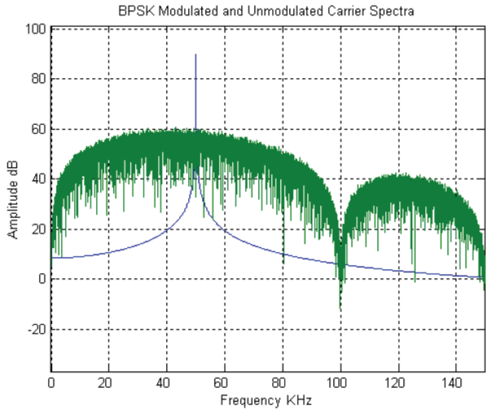

Figure 2: Sinusoid before and after spreading

The selection of the sequences used by each transmitter in the system is therefore the key parameter in determining to what extent the narrow bandwidth of the original frequency is spread. Because this encoding is also the mechanism that allows the channel transmissions to be separated, careful selection of the codes is vital for the system to function correctly.

Separation is achieved by the use of codes that do not exhibit any common trends with the other codes over time. Codes that are entirely dissimilar in their time series are referred to as being orthogonal. The degree of orthogonality of two codes may be tested by correlating the codes – sliding one along the other and evaluating how similar they are at each alignment. This process is shown in the diagram below:

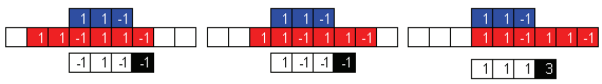

Figure 3: The Correlation Process

The total correlation is the number of equal bits less the number of unequal bits. Two orthogonal codes will have a low cross-correlation. When a code is correlated with itself, it has a high peak correlation, equal to the bit length of the code.

For the system considered here, two requirements are important. Firstly, codes must be found that have low correlation values with each other. Secondly, the autocorrelation of each code should have a high main peak when fully aligned, with low values at all other points. The narrow width of this peak ensures that its time of arrival can be determined accurately. Figure 4 shows these correlation requirements graphically.

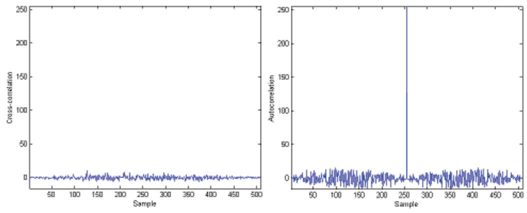

Figure 4: Ideal Cross-correlation (a) and Autocorrelation (b) for 256-bit code sequences

Due to their extensive use in digital communications, a number of code sets have been found that have these correlation properties [16]. Gold or Kasami codes are commonly used in GPS, while a variety of others, such as Walsh codes, are common in communications systems. These codes all exhibit highly peaked autocorrelation, differing mainly in their cross-correlation properties.

One of the simplest sequence sets are maximal length, or pseudo-noise (PN) codes, also known as pseudo-random codes. These can be easily generated with hardware [16] or software [25]. While their properties as a set are not as optimal as other code sets [16], this is only important when the number of interfering transmissions becomes large.

For the system described in this paper, the three sequences required were chosen specifically for their optimal cross-correlation properties. The codes chosen were selected using Matlab to check the peak cross-correlations for all codes in a large set, using the three codes that were observed to have the lowest combinations of cross-correlation. The length of the codes used in this implementation was 256 bits – while this length was sufficient in this situation, superior performance could be obtained from the use of longer codes [16 p10.20].

3 System Operation

The operation of the system is similar to GPS, in that a number of 'satellites' are placed at known locations around the room. When a synchronisation signal is received, each satellite begins to transmit a uniquely identifiable code. At the same time, any receivers in the room begin to listen for incoming signals, correlating the received signal with stored versions of each of the transmitted codes. When the correlation reaches a peak for each channel, the time of receipt for that particular channel is recorded. The time of flight of each signal – and thus the distance to each transmitter – can then be established and used to calculate position.

Synchronisation of the system is achieved by the transmission of a radio-frequency (RF) pulse from one of the transmitters, designated as the master transmitter. Because of the fast propagation speed of RF waves, it is assumed that they travel instantaneously over short distances. Thus each transmitter will begin to transmit and the receiver will begin to count all at the same time. This concept is known as time difference of arrival and is reasonably well-known [1,2,26,27].

When the signal from three or more transmitters has been received, the distance to each transmitter can be calculated. This is combined with the known position of each transmitter, providing estimates of the position of the object relative to three points in the room, as shown in Figure 5.

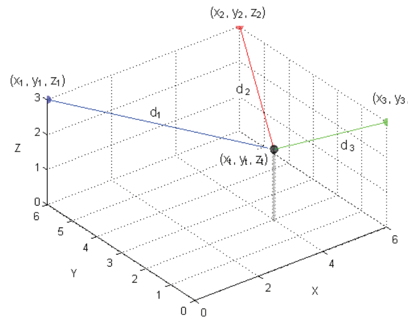

Figure 5: Distances of transmitters to receiver

A solution can be obtained from these three constraints to solve for position in space, a process known as trilateration. This is the same principle used in GPS to provide location, albeit on a much smaller scale. By consideration of the second transmitter as the origin of the frame of reference, the relative transmitter locations are given by:

$$(x_1,0,0)\ (1),\quad (0,0,0)\ (2),\quad (0,y_3,0)\ (3)$$

The signals propagate from the transmitters as three spheres with radii equal to the time of flight from each transmitter. By solving for the intersection of these spheres, three simultaneous equations result,

$$(x_t - x_1)^2 + (y_t)^2 + (z_t)^2 = d_1^2 \qquad (4)$$

$$(x_t)^2 + (y_t)^2 + (z_t)^2 = d_2^2 \qquad (5)$$

$$(x_t)^2 + (y_t - y_3)^2 + (z_t)^2 = d_3^2 \qquad (6)$$

yielding the following position equations:

$$x_t = \frac{x_1^2 + d_2^2 - d_1^2}{2x_1} \quad (7)$$

$$y_t = \frac{y_3^2 + d_2^2 - d_3^2}{2y_3} \quad (8)$$

$$z_t = \sqrt{d_2^2 - x_t^2 - y_t^2} \quad (9)$$

Assuming that the speed of sound can be calculated accurately, errors in the distance measurements will be due mainly to timing discrepancies in the electronics. If it is assumed that the error in each measurement is normally distributed, then the error inherited in the calculation of the position variables has certain properties. For a normally distributed distance *d*, the d^2 term will have identical chi-squared distributions [28]. The difference of the d^2 terms used to calculate the *x* and *y* variables will have an expected value of zero, and these two variables will be unbiased estimators.

However, the expected value of the z-error will be the square root of the (non-zero) mean of a single chi-squared distribution, less the expected values of the *x* and *y* variables, both of which have an expected value of 0. The reason that this bias occurs only in the z-plane is explained by the fact that all the transmitters are aligned at the same height (*z* coordinate), while their *x* and *y* coordinates differ. This arrangement allows for a simple position algorithm to be used. Further simulation and testing showed that this bias was small in terms of other sources of error in the system and thus would not adversely affect results.

A prototype system was constructed using common electronics. Using a garage door controller for the RF link, a Microchip PIC12f629 microcontroller was used to monitor the link and generate the transmitter sequence when the synchronisation signal was received. The sequences were transmitted by a Polaroid 6500 series ultrasonic transducer, driven by a step-up transformer from the PIC, as shown in Figure 6:

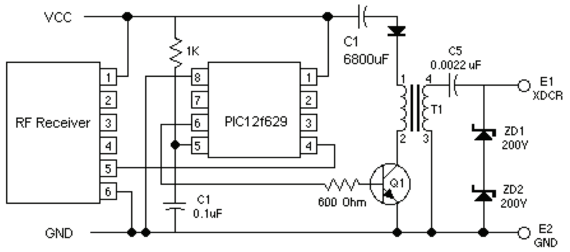

Figure 6: Transmitter Hardware

This particular transducer was chosen for its broadband response, meaning that it could transmit effectively over a range of frequencies. This is a property of the non-resonant electrostatic transducers. Compared to common piezoelectric transducers, electrostatic devices are more sensitive and have a wider frequency response. However, the trade-off for this sensitivity is that they require a bias voltage of several hundred volts to transmit or receive effectively.

It was found during testing that a short-duration sinusoidal pulse applied to the receiver's transducer was required to ensure its sensitivity to ensuing acoustic transmissions. Experimentation showed that the shortest possible pulse duration that would prime the receiver was eight cycles of a 50 kHz wave; longer pulses would introduce unnecessary noise into the system. It is important to note that further reduction in noise might be necessary with multiple receivers. This could be achieved by shifting the priming pulse to a frequency outside the efficient transmission band of the transducers but at which the DC bias capacitor would still be charged effectively.

The receiver circuitry is similar to that of the transmitter, with some additional hardware to process the signal. Use was made of the demonstration board provided with the transducers for this purpose. The output was monitored with an oscilloscope at pin 4 of the analogue processing chip, using the RF synchronisation pulse as its trigger. The data were then transferred to a PC for analysis and correlation. The connections used during this evaluation are shown in Figure 7:

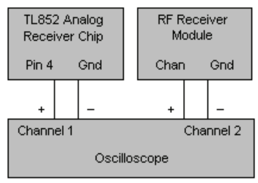

Figure 7: Receiver Setup

4 Experimental Results

Testing with single transmissions demonstrated the efficacy of the orthogonal coding at distinguishing each channel. Individual channels showed peaked autocorrelation on that channel, with simultaneous low cross-correlation for that signal in the other two channels. Figure 8 shows results for the first code; the results are similar for all channels:

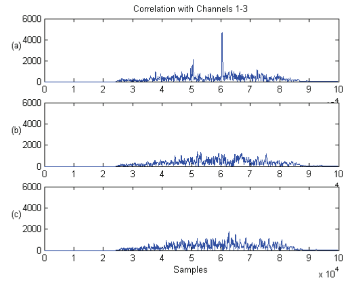

Figure 8: Code 1 correlation with Channels 1-3

Two-channel testing at a distance of 1m showed that the 256-bit codes provided good rejection. This is possibly the worst-case noise scenario, as the pulses will overlap and interfere with each other over their entire length. The separability of the channels is shown in Figure 9:

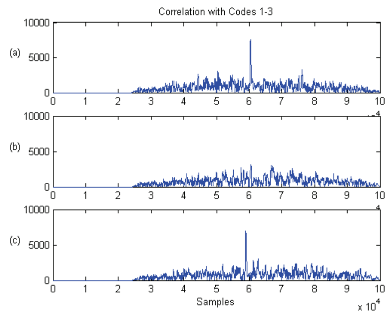

Figure 9: Simultaneous Correlation of Two Channels

As with the single channel testing, the results for the other combinations of channels were similar. However, cross-channel interference was significantly higher than predicted by theory. It was suspected that the close transmitter proximity might have been causing receiver saturation.

Problems with oscillator accuracy in the PICs was observed and it seems likely that this was also affecting the correlation. This was evidenced further in three-channel testing, where one transmitter produced inconsistent results while the other two obtained good correlation. The results for this testing with the transmitters at 1, 1.18 and 1.27m are shown in Figure 10:

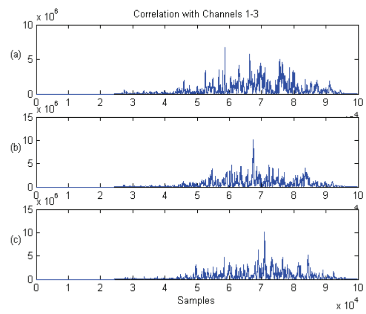

Figure 10: Simultaneous Correlation of Three Channels at different ranges

The best results with simultaneous transmissions were observed when the distance from the transmitters was greater than 800mm. This supports the theory that saturation was degrading the short-range correlation. As the automatic gain control of the receiver was internally fixed, it could not be easily adjusted. While the overall gain of the module could be changed, long-range testing demonstrated deterioration in the received signal strength. Thus, any possible gain change would require a trade-off between near and distant operation. However, saturation would not occur in a realistic system, as the transmitters would be placed at ceiling level and ground-based receivers would not encounter problems due to transmitter proximity.

Evaluation of the overall accuracy of the system was achieved by placing the transmitters at fixed locations and moving the receiver to locations at known distances. Analysis of this data was performed to see if a relationship between the correlation peak and the expected distance could be established. A regression on the recorded data showed some variation between transmitters. However when they were combined, the path that the object had followed could be reconstructed with reasonable accuracy, as shown in Figure 11:

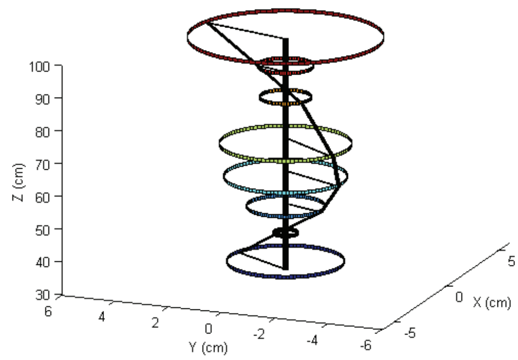

Figure 11: Actual (straight) vs measured path at height 30-100cm; deviations highlighted by circles

The average error in each individual distance was approximately 3%, with the maximum error observed during this testing being 6% of the actual distance to the transmitter. While limited in scope, these results are reasonably promising, indicating that the system can provide localisation data for a target by the differentiation and timing of simultaneous signals.

5 Conclusions

This paper has presented details of the development and testing of a system designed to provide location data for one or more target devices. By using broadband transducers and signals, simultaneous transmissions can be distinguished from each other and used to measure distances to known points. These distances can be easily processed to provide position estimates, with testing demonstrating the function of the entire process.

During the development of this system, it has become evident at a number of points that alternative methods would have been more suitable to the ones chosen and should be considered in further work. The intermittent problems with correlation on certain channels suggest that more reliable or accurate oscillators should perhaps be used. This would help avoid spreading or degradation of the correlation peak due to oscillator drift in the transmitter.

Generation of the code sequences could also be optimised. Instead of hard-coding the sequences in the PIC, a hardware generator or software algorithm could be easily implemented. This would facilitate the evaluation of different code lengths and combinations.

Finally, adjustment could be made to the automatic gain control inputs of the processing module. By increasing the gradient of the gain curve, the receiver would not saturate at early time intervals. Simultaneously, the long-range operation would be improved, as the gain at later time steps is insufficient to account for the corresponding decrease in signal strength over distance.

6 References

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