Design of an Ultrasonic Ranging Method for use in an Indoor Location System

MSc ASE Project Report

Simon KingSimon King

A thesis submitted in part fulfilment of the degree of MSc Advanced Software EngineeringMSc Advanced Software Engineering with the supervision of Associate Professor Chris Bleakley.



School of Computer Science

University College Dublin

29 April 2018

Abstract

Indoor localisation has been a widely researched area in recent years. The efforts to create a widely adoptable system for localisation and navigation indoors similar to GPS have increased greatly. While great strides have been made in the area, the problem is still largely unsolved. For these systems to be adopted widely, they require precise location accuracy, scalability, cost effective infrastructure, and should be compatible with available off the shelf technologies. This research intends to explore the various aspects of designing such a system, taking advantage of existing technologies and providing optimal results in an efficient manner.

Table of Contents

[1 Introduction 4](#_Toc512767074)

[2 State of the Art 6](#_Toc512767075)

[3 Measuring distances using audio 8](#_Toc512767076)

[3.1 Time Domain methods with single frequency signals 8](#_Toc512767077)

[3.2 Other methods of measurement 9](#_Toc512767078)

[4 Signal Design 11](#_Toc512767079)

[5 Synchronisation 14](#_Toc512767080)

[6 Localization Algorithms 15](#_Toc512767081)

[7 System Design 16](#_Toc512767082)

[8 Conclusions 18](#_Toc512767083)

[9 Acknowledgements 19](#_Toc512767084)

[10 References 20](#_Toc512767085)

# Introduction

Indoor localisation technologies are a widely researched topic in recent years, with a focus on developing a method for widescale deployment. With the growing availability of advanced mobile devices and wireless infrastructure in public areas, accurate indoor localisation systems, without the need for bespoke hardware, are more feasible than ever. Many applications within places such as hospitals for patient tracking, shopping centres for mapping and context aware notifications, product location in warehousing etc. are already being produced. Although global positioning system (GPS) works extremely well for an open-air localisation, it does not perform effectively in indoor environments due to the inability of GPS signals to penetrate in-building materials. Being able to pinpoint the location of a wireless devices requires higher location resolution for indoor environments than in outdoor applications. We will examine some of the approaches implementing solutions for the indoor localisation problem and some of the main issues in implementing such systems. In order for a system to be adapted on a large scale, it needs to be precise and simple to install, using technologies that are widely available. There is no system that can be used for all applications under all environmental conditions but from the point of view of usability and accuracy, it is preferable to use a system that performs localisation by using the propagation delay time of electromagnetic waves, based on a principle like that used in GPS.

We focus on a solution that uses ultrasonic audio signals to attempt to locate a device with millimetre accuracy. Ultrasonic is a well-known ideal candidate for indoor positioning that relies on the time of flight (TOF) scheme. The key idea is to use an ultrasonic transmitters and receivers to emit and detect ultrasonic signals. For example, ultrasonic waves are used for distance measuring in ultrasound parking assist. An ultrasonic signal is emitted from a transceiver and when it encounters an object and echo is produced. By recording the time it takes for this echo to be received at the source, it is possible to compute the distance given the medium traveling speed. Using to represent the speed of sound in air together with the time of flight, , the distance can be calculated using This system can be expanded on by separating the transmitter and receiver. In mobile positioning systems, the transmitter emits a signal at a known time, and it is detected at the receiver. By calculating the time taken for the signal to reach the receiver, the distance between the two can be calculated. This requires the transmitter and receiver to be tightly synchronised.

Time-difference-of-arrival (TDOA) systems work similarly to the system described above but send both radio wave packets and ultrasonic pulses. The distance between nodes is calculated by the difference in time between the ultrasound signal arriving at the various receivers. As the electromagnetic radio waves travel at speeds much greater than the ultrasonic waves, they effectively are detected at the receiver immediately. Within a localised system, this measurement can be performed between a mobile device and at least three beacons and the position of the mobile device can be found using trilateration. These systems are made up of several fixed nodes, or beacons, and mobile nodes, where the mobile node’s position is calculated based on the known positions of the fixed nodes.

One disadvantage of this system is the considerable amount of fixed position nodes needed, which increases the setup cost. Ultrasound can provide high localisation precision using this system however, it suffers from the line-of-sight restrictions. Given the system requires the mobile device to communicate with at least 3 fixed nodes to get an accurate measurement, the placement of fixed nodes must account for obstacles like desks and chairs to communicate with the mobile devices. Beacon placement thus becomes challenging for ultrasound-based indoor localisation in environments with various obstacles. Determining the node positions also requires manual calibration which is time consuming, since each anchor must be measured individually, and fault-prone, because of inaccurate measurement methods and human error.

Implementing accurate indoor localisation faces several problems technologically to implement. A good solution should be low cost, scalable, robust and easy to deploy. It should also be able to cope with changing environments. The localisation accuracy depends mainly on accuracy of the range measurements, location errors of the anchor nodes and the geometric configuration of the system. There also exist trade-offs among the positioning accuracy, computational complexity, cost and power consumption. A survey conducted in [A survey on wireless indoor Localisation from the device perspective] finds the deployment cost of these various systems to be one of the largest problems to overcome. Out of 22 solutions compared, the average setting and calibration time is 5 hours for two rooms covering 300 square meters. This may be unrealistic and intrusive when deploying these localisation systems in large deployment sites like shopping malls.

The rest of the chapters are organised as follows:

Chapter 2 examines some of the current indoor localisation systems which are currently available or in development. Chapters 3-6 explore in further detail the various techniques used within indoor localisation systems for measurement and positioning. Chapter 7 details the system design as part of this project and experimental results. Chapter 8 details the overall conclusions and possible future research directions.

# State of the Art

There are many approaches to the indoor localisation problem [Surveys 1 + 2]. For many years Microsoft have been holding a competition to bring together current proposals and compare them in the same space. From here we can see the range of approaches currently being developed. The leading system in terms of accuracy is a LIDAR system [Compact, Real-time Localization without Reliance on Infrastructure] comprising cameras, Inertial Measurement Units (IMUs) and laser scanners, obtaining results accurate to within ±3cms. This system requires no other infrastructure to be in place, however, the due to the bespoke nature of the devices used, widespread adaptation would not be feasible, for now.

Range-based approaches use measured distances or angular estimates between known anchor points to compute a position. Range-free approaches on the other hand typically attempt to match either synthetic or naturally occurring signatures to a particular location. TOA and TDOA systems both require bidirectional coordination between the infrastructure and the device being tracked which generally limits scalability. The systems proposed in [intranav] and [IR-UWB based Indoor Localization System] use ultra-wideband (UWB) signals. UWB based systems have a promising future, but similar to the LIDAR system, the devices required to implement are not widely available. While UWB has been shown to be a good candidate, large manufacturers of smart devices have not yet introduced chipsets into their devices which can be used to implement a system on a large scale.

Lazic et al propose a system that use a combination of ultrasound and Bluetooth to obtain precise localization in small and medium sized areas using a TDOA [lazik-alps]. The system was designed using time synchronized ultrasonic signal. This platform uses a combination of ultrasound and Bluetooth Low Energy (BLE) to obtain precise localization in small and medium sized areas. The system can perform precise localization using TDOA data from ultrasonic transmitters that utilize bandwidth just above the human hearing range but can still be detected by modern smartphones. After performing a simple calibration and mapping process, users were able to map room corners and the beacon positions with an average error of 19.8cm and 16.1cm respectively, without having to manually measure any distances.

This approach of combining BLE with other localisation methods has gained a lot of interest, especially with the emergence of iBeacon. The iBeacon is the Apple's implementation of BLE wireless technology to create a way of providing location-based information services to mobile devices. It acts as an emitter continuously broadcasting Bluetooth signals, which each signal contains a Universally Unique Identifier (UUID) and a Received Signal Strength Indicator (RSSI). The system designed in [A mobile indoor positioning system based on iBeacon technology] uses an RSS-based algorithm as a location-estimation method because it is simple to obtain the RSSI data from iBeacon without requiring any specialized hardware. They obtain results achieving 97.22% accuracy of location classification and accuracy to within 5 meters, which acceptable for tracking the locations of patients in a hospital environment.

RSSI is an indoor localisation system which uses the signal strength of radio communication to estimate the distance between devices. The main idea is to measure a set of signals signatures, known as fingerprints, based on different locations in the area of interest and build a fingerprint database. The location is then estimated by mapping the measured fingerprints against the database. This approach requires a considerable manual effort to build the fingerprint database and the resulting system is relatively inflexible to changing environments. RSSI is not well suited to tracking users in real time, due to the lengthy time taken to calibrate for channel propagation parameters [Indoor localisation using a context-aware dynamic position tracking model]. As we have seen already, RSSI is suited to many different technologies. In the case of [Indoor Localisation Using a Context-Aware Dynamic], the ZigBee/ 802.15.4 wireless communications protocol was used to implement the network. ZigBee is a low data rate wireless communications protocol that can operate on devices with limited computing or power resources. The work carried out in [Gradient-Based Fingerprinting for Indoor Localization and Tracking] improves on the RSSI model by developing a robust gradient-based RSSI map. The gradient-based map is based on differential RSSI measurements, rather than absolute values, making the system more dynamic and adaptive to time-varying signal strength of nodes.

Many of the issues in deploying an ultrasound-based localisation system are described in [Two practical considerations of beacon deployment for ultrasound-based indoor Localisation systems]. In general, ultrasonic wave emission is usually directional, which introduces difﬁculties in orienting the transceiver precisely. Only when the listener is inside the transmitter’s beam pattern, can the listener derive distance measurement value from the beacon. One solution to this issue is described in [TDOA-Based Localization Using Interacting Multiple Model Estimator and Ultrasonic Transmitter/Receiver]. They developed a 2-D isotropic ultrasound transmitter with a beam width of 360° using an array of eight ultrasound transducers placed in a round body. The angle of aperture of one transducer is 45°. By using eight ultrasound transducers, the coverage range can be increased by a factor of 8. However, a system like this would not be practical for widespread adaptation.

Another issue determined in [Two practical considerations of beacon deployment for ultrasound-based indoor Localisation systems] is that the number of beacons required to provide full coverage grows linearly with the size of the area of interest. This means for widespread adaptation, the design of the beacons needs to be relatively cheap.

In [Design and Implementation of a Fully Distributed Ultrasonic], an indoor localisation system which is realized with as few initial references as possible is proposed. This is based on the idea of iterative multilateration. When such a localisation method is used, deterioration of localisation accuracy due to no line-of-sight signals and to accumulated errors is a problem. To overcome this, a method is employed to detect and eliminate non-line-of-sight (NLOS) signals from distance measurements and in an implementation experiment using 24 nodes, a localization accuracy of about 17cm was demonstrated. The NLOS problem is also dealt with in [INDOOR LOCATION BASED ON IEEE 802.11 ROUNDTRIP TIME MEASUREMENTS WITH TWO-STEP NLOS MITIGATION] using a statistical model and previously known measurements. In this work, a complete location scheme based on return trip time (RTT) measurements is proposed, and has been taken as RTT measuring system, and an IEEE 802.11 wireless infrastructure, already deployed, has been used as indoor wireless technology.

While the research into the various approaches of Indoor Localisation is extensive, the problem had still not been resolved. Some of the outstanding problems with most systems being developed are highlighted in [lessons learned ]. The deployment efforts and costs of infrastructure based systems remain high. Deploying systems to cover or profile even a relatively small area takes extensive manual effort and in real world deployments, these efforts would be intrusive, time consuming and labour intensive. The systems have also not been proven to adapt well to changes in the area of interest, such a furniture being moved or introduced. Recent improvements to widely available network infrastructures, as well as technological improvements, will mitigate some of these issues, but the topic of indoor localisation is still very much open.

# Measuring distances using audio

Measuring distance using ultrasonic signals offers an inexpensive solution to the indoor localisation problem. Measurements of the distance of an object from fixed landmarks can be used to calculate the precise location of that object. The basic idea is to send an acoustic signal through the air from a transmitter to a receiver. The time it takes for the signal to reach the receiver is known as the time of flight (TOF), which can be used to measure the distance by the following equation:

Where is the distance, is the time of flight and is the speed of sound in air. Many ultrasonic applications use a single transducer, which both emits and receives, to calculate the distance to an object by emitting a signal and measuring the time it takes for an echo to be received. The distance is calculated similarly to the calculation above, but having the result, as the signal has travelled the distance to the object and back;

For this comparison, we will consider the measurements are using the second technique, which allows us to know when the signal was sent, although in more complex ranging systems that use independent transmitters and receivers, synchronisation becomes an important factor, which we will examine later.

The accuracy of the distance measurement depends on the accuracy of the measurements of the TOF and the speed of sound in air. Choosing the measurement technique of the TOF depends on a number of factors such as cost, ease of implementation, environment. We will examine some common methods used for these TOF measurements [3]. Methods are usually compared by the accuracy, or error in the distance measurement, repeatability, or the variance in repeated measurements, cost of implementation and performance under noise.

## Time Domain methods with single frequency signals

The first method we look at is thresholding. A signal is sent, and the time of flight is the time it takes for the amplitude of the echo signal to surpass a certain threshold. The threshold is usually selected to be well above the noise standard deviation. This method is relatively straightforward and does not require complex circuitry or calculations, and can be implemented with inexpensive transducers. Its limitation is it naturally introduces a bias into the measurement. If the threshold level is set to low, noise interference can cause false positive to be detected. Increasing the threshold will improve detection of real echoes, however the time it takes for the incoming signal amplitude to surpass the threshold will be delayed further. This is especially true if too low a sampling frequency is chosen. Although noise and sampling frequency selection are issues that all TOF measurements must deal with.

Curve fitting is a method of TOF estimation that attempts to fit a parabolic curve to the echo signal envelopes leading edge to provide a measurement without bias. This uses threshold estimate as above, but then fits a parabolic curve in the form where is the estimation of the result of simple thresholding and is estimated from a second derivative approximation around this threshold point. A nonlinear least-squares method is then applied to fit the curve, and the vertex of the parabola is used as the measurement of the TOF.

Sliding window is a method that can be used to make detection more robust. A window of length N is slid through the echo signal one sample at a time. As the window slides through the sample, it counts the number of samples which exceed the threshold value. If this count exceeds second threshold the signal is considered present and the TOF estimate is produced.

Cross-correlation is an unbiased measure of TOF. The echo signal is correlated with a matched filter that contains the waveform and the delay will be the peak. This method has a few drawbacks in comparison with those outlined above. In real-time processing, the entire echo must be observed before the correlation process can being which can add a significant delay to producing the estimate. It is also computationally much more complex than the previous methods. However, this method should significantly reduce noise interference.

A study performed by [Fast processing techniques for accurate ultrasonic range measurements] shows that Correlation gives by far the best results in terms accuracy, which is what would be expected, however the less complex methods offer some acceptable performance results at much lower cost. Curve fitting performing best when it came to bias and total error, whereas sliding window performed best with standard deviation.

### Correlation

Correlation can be used to the measure of how similar two signals, x and y, are to each other. Mathematically, it can be defined as follows:

When dealing with signals that are zero valued up to sample n=0, and zero values for all samples greater than N-1, we can rewrite the equation as:

Autocorrelation is simply the cross correlation of a signal with itself. When dealing with one dimensional, real sequences, autocorrelation will have a peak at a lag of zero, and its size will be the signal energy. Autocorrelation has some interesting properties for use in digital signal processing. The autocorrelation of a periodic function is itself periodic, with the same period. This can be used to determine frequencies or pitches of musical tones. In a noisy waveform, autocorrelation can be used to reduce the effects of that noise.

## Other methods of measurement

Time difference of arrival (TDOA) can be used as part of a multilateration system to predict the location of an object. A transmitter sends a signal which is received at receiver stations 1 and 2, which are at known locations. When both receivers have received the signal, the can cross-correlate them to determine the time shift between the two waves which is the difference in time it took the signal to at each station. This time shift can be used in the first equation above to get a measure of distance. As both stations are fixed, we now have an infinite number of points along a curve that satisfy the transmitters location. If we had a second pair of stations, we would get a second curve of possible locations that intersects the first. This produces a small number of locations that the transmitter could be.

The ultrasonic waves from a small mobile device with an ultrasonic transmitter are received by the receiver array. The ultrasonic receiver array and the mobile device are synchronized by a wireless connection. The listener can then derive the distance from the beacon by multiplying the ultrasound propagation time by the speed of sound. Since the location of the receiver is known when the mobile device was deployed, the listener must be located at the surface of a sphere that is centred at the beacon and with a radius of the derived distance from the beacon to the listener [Analysis of the frequency offset effect on Zadoff–Chu sequence timing performance]. By multiplying the measured propagation delay time by the speed of sound, the distance between the mobile device and each of the ultrasonic receivers is derived. Since the locations of the individual receivers are accurately given beforehand, the location of the mobile device can be derived three-dimensionally by solving a set of simultaneous equations involving the measured distance to each receiver and the locations of the receivers. [Design and implementation of a fully distributed ultrasonic positioning system] However, this does require the system to be synchronised for accurate measurements between devices.

Another approach using TDOA is described in [Improving the accuracy of ultrasound-based localisation systems]. Distance is measured using the difference in time-of-ﬂight of RF signals and US signals. A RF and US signal are sent simultaneously from a transmitter to a receiver. The RF signal travels much faster than the US signal. Over a distance of 10m, the radio signal takes ~30ns and the ultrasound signal, will take ~30ms. As the RF signal is much lower, the TDOA can be measured as the difference in time from when the RF signal arrives to when the US signal arrives.   
Unfortunately, the speed of sound is not constant. Indoors it varies mainly with temperature and can be approximated using where T is the temperature in degrees Centigrade.

The multilateration approach is popular in indoor localisation systems, however its accuracy is dependent on many factors such as the devices in the system being synchronised, interference from noise or multi-path interference, inaccuracies in the measurement of the locations of the fixed devices.

Angle of Arrival (AOA) is used to determine the direction a received signal arrives at an array of sensors. It is measured by taking the phase difference between elements within the array. For example, let’s consider an array of two microphones separated by half the wavelength of an incoming sinusoidal wave. If the wave was emitted from directly in front of the array, there would be no phase difference between the two measured waves. However, if the wave was emitted from the right of the array, the microphones would receive the signals half a wavelength apart, resulting in a phase difference on 180. If this was used alongside a multilateration system, we could immediately disregard many of the values of the curve produced. However, this requires a more complex receiver to collect measurements.

# Signal Design

When generating the ultrasonic signal that will be used for the ranging measurements, there are a number of characteristics the signal should have. The signal is limited by a lower bound of approximately 20kHz, as this is the upper limit if the human hearing range. The upper limit is confined by the limitations of the devices being used as nodes within the system. Sample rates on many commercially available mobile phone devices support sample rates of 44.1kHz and 48kHz, which would set the maximum frequency at 22-24kHz, according the Nyquist sampling theorem. More specialized sound cards are available with sample rates up to 192kHz, but this work uses a 48kHz sampling rate. To try and avoid introducing noise from aliasing, the signal frequencies should not be too close to the upper limit imposed by the sample rate. Within a system using a single US tone the frequency can safely be anywhere for 20-23.5kHz. It has also been shown in [FIND THE PAPER WITH THE SLOPED TONE SHAPE], that gradually sloping the amplitude of the beginning and end sent signals removes an unwanted audible clicking which is produced with sharp changes in amplitude. The ideal ultrasonic signals generated by the system must be able to provide accurate ranging information, support multiple access and encode data to identify the transmitter.

Another characteristic the signal should have is good autocorrelation properties. Signal detection in real world environments is susceptible to noise, so simple methods like threshold detection tend to product a lot of false positives. The cross-correlation between a transmitted signal and the delayed received signal produces a maximum peak when the original signal overlaps directly with the delayed version of itself. By finding the lag time of this maximum, we can determine the propagation delay between sender and receiver. The cross-correlation of narrowband signals have a distinctive ‘triangular’ shape, with wide sidebands around the peak value. However, in noisy environments, it is possible for erroneous local maxima to be detected. By using a frequency modulated signal, such as a linear chirp, we can improve the shape of the autocorrelation result, which allows for better detection, even in noisy environments. Comparing the narrowband correlation result with that of the linear chirp, we see the peak value is the same, but the side bands have been greatly reduced. This process is known as Pulse Compression. The approach proposed in [Lazik-indoorPsuedo] uses a modulation scheme similar to Chirp Spread Spectrum (CSS). A chirp is a linearly frequency modulated pulse that increases or decreases over time between two frequency ranges. Chirps benefit from Pulse Compression, which increases the SNR at the receiver by a factor over a sinusoidal signal at equal transmission power, where T is the signal duration and is the bandwidth. This improves both the range resolution as well as the SNR of the data symbols for better detection. The ultrasound ranging signals used in [lazik-alps] consist of a 50ms up-chirp between 20kHz and 21.5kHz followed by an orthogonal 50ms down-chirp between 21.5kHz and 20kHz.

This chirp system can be expanded to be used in multiple access systems, as shown in [Time-varying multi-chirp rate modulation for multiple access systems]. This introduces the use of chirp-rates as a mechanism to assign uniquely modulated chirp signals to users. This approach decomposes each chirp into two interconnected chirps with different frequency rates that change at the halfway points of the symbol. Each different waveform is correlated with the received signal to extract the embedded sequences of data. Each transmitter is provided with a unique ID, which is encoded as a series of up-chirps, each representing two bits.

One of the properties of Additive white Gaussian noise (AWGN) is that the auto-correlation values for any non-zero delay, i.e. where the signals do not align perfectly, is effectively zero. It also has zero cross-correlation with any other AWGN waveform. This is a very useful property in peak detection. Pseudo-random (PR) sequences display similar autocorrelation properties. At zero time-delay there is a peak, and at non-zero time-delays the values are very small. These PR signals also carry timing information as well, which is extremely useful in distributed systems to coordinating device transmissions.

In wireless transmission, a PR sequence is used in setting up connections to detect and synchronise devices. A wireless access point will transmit a synchronisation signal. A matched filter in devices check incoming frames for this PR sequence and aligns its local clock to the access point’s and sends back a signal, which the access point then scans for the PR sequence, detecting the devices timing and instructs the device to adjust its transmit timing to account for round trip propagation.

So far, we have determined that a sequence with good autocorrelation properties are useful in time-of-arrival detection. However, another useful property of these sequences is having zero or very low cross-correlation with the same signal at any delay. A complex PR sequence has a periodic autocorrelation of where N is the period of the PN sequence. Therefore, cyclically shifted PN sequences have a correlation with the original sequence.

Barker codes are a class of well-known codes that possess the required correlation properties. The disadvantage of Barker codes is the limited maximum code length of 13 chips. [Improving the accuracy of ultrasound-based localisation systems] discusses the problem of improving the position update rate by coordinating beacons and by using orthogonal sequences that allow the ultrasound signals to be sent completely concurrently. This method introduces high computational overhead and also, because the length of the sequences, the benefits are questionable.

A Gold code, also known as Gold sequence, is a type of binary sequence, used in telecommunication and GPS. Gold codes have bounded small cross-correlations within a set, which is useful when multiple devices are broadcasting in the same frequency range. A set of Gold code sequences consists of 2n − 1 sequences each one with a period of 2n − 1. Gold codes are used in [Ultrasonic multiple-access ranging system using spread spectrum and mems technology for indoor localization] A Gold code is modulated on a carrier using binary phase shift keying (BPSK). Both Frequency Hopping Spread Spectrums (FHSS) and Direct Sequence Spread Spectrums (DSSS) are compared in single and multiple-access systems for ranging.

A Zadoff-Chu (ZC) Sequence is a complex-valued sequence with some very useful properties in signal transmission [Polyphase codes with good periodic correlation properties]. It is given by the equation

where is the length of the sequence.

When is odd, the sequence is periodic. If is prime, the Discrete Fourier Transform of a ZC sequence is another ZC sequence conjugated, scaled and time scaled. When applied to radio signals they give rise to an electromagnetic signal of constant amplitude, whereby cyclically shifted versions of the sequence imposed on a signal result in zero correlation with one another at the receiver.

The orthogonal nature of the ZC signals means that multiple cyclically shifted signals can be combined and sent simultaneously in a single transmission. If each receiver had a matched filter to look for the signal with a particular phase shift, the other signals in the transmission would not be detected. The generalized cross-correlation properties of ZC Sequences are explored in more detail in [Generalized Cross-Correlation Properties of Chu Sequences].

ZC sequences are used in the 3GPP LTE air interface in the Primary Synchronization Signal, random access preamble, uplink control channel, uplink traffic channel and sounding reference signals. They are also widely used in many indoor localisation systems for synchronisation and ranging.

# Synchronisation

The earlier discussions on measuring time delays when calculating distance assumed that the signal was sent from a single transceiver, that both sends and receives the signal on a single circuit. In the localisation solutions, it is more likely the transmitters and receivers are distributed. This presents a new issue. For accurate measurements of TOF, we need to be confident that each module in the distributed system is synchronised to within a reasonable degree of accuracy.

In a distributed system, each node has its own physical clock. These clocks are based on crystal oscillation counters which generate many interrupts per second. The clock in the node will tick on each timer interrupt.

The issue is that two devices will hardly ever agree, as the clocks will oscillate at slightly different frequencies. If we take UTC time, , to be the perfect clock, the physical clock on nodes, , usually run faster or slower. This is known as drift and can be measured using the . Ideally, which means the clock is perfectly in sync with UTC time. If , the clock is fast, and , the clock is slow. When we read two disagreeing clocks at the same time, the difference in values is known as the skew. The aim of synchronisation is to keep the skew between clocks bound to within an acceptable constant of drift, , such that . As we are attempting to use the time difference in signals to measure distance, even a skew of 1ms could lead to errors in measurement of around 0.35m. To ensure the time difference between any two clocks in the system never exceeds a maximum value of , The clocks need to be synchronised every seconds.

There are several methods of achieving system wide synchronisation.

External synchronisation requires each node to synchronise its clock with an authoritative external source. The MSF is a 60kHz radio signal which is dedicated to broadcasting the current UTC which can be decoded by radio-controlled clocks for synchronisation. Similarly, GPS receivers can be used to synchronise with UTC. These solutions, do provide accurate measurements, but are not a practical solution for simple distributed systems.

A much simpler solution is to have a dedicated time server within the system, which all other devices can synchronise with. Each node can ask the time server for an accurate time periodically, and adjust its clock accordingly. This requires an accurate measure of the round-trip delay for the node to receive the updated time.

# Localization Algorithms

Perhaps the most complex aspect of developing an indoor localization system is the algorithm that uses the distance measurements between the beacons and mobile nodes and calculates the position of the nodes. An efficient algorithm for calculating the objects position must be of low computational complexity, and highly robust. There are many approaches to determining node positions and, depending on the approach used in the measurement of distance between nodes and the infrastructure used, some become more appropriate than others. In this section, we will briefly examine some of the techniques used, their applications and limitations. For simplicity we should assume the positions of the beacons in this system are fixed and the relative positions of the beacons are known within the system. The three main techniques for computing positions are triangulation, trilateration and multilateration [A Novel 3D Multilateration Sensor Using Distributed, A Survey on Secure Localization in Wireless, Localization algorithms research in wireless sensor network based on Multilateration and Trilateration techniques, Moving sound source localization based on triangulation method, Quality of Trilateration- Confidence-Based Iterative Localization, Sensor Placement for Triangulation-Based Localization].

Triangulation is based on AOA measurements between the mobile node and three or more beacons. Using some simple geometric relationships between the fixed nodes, the position of the mobile node can be calculated.

Trilateration refers to positioning an object based on the measured distances between the mobile node and three fixed reference positions. It can be expressed as the problem of finding the intersection of 3 circles, each of which has a radius equal to the respective distance from the mobile node. These distances can be measured using a TOF method.

Multilateration uses TDOA measurements between a mobile node emitting a pulse and three or more fixed beacons with known positions. Each TDOA measurement between a pair of beacons gives a hyperboloid from which the mobile node could lie. Introducing a third beacon would give a second independent hyperboloid, and the mobile node is located at one of two points on the curve of the two intersecting hyperboloids. To locate the mobile node in a 3-dimensional space, a fourth beacon needs to be introduced giving a third independent measurement. Enhanced accuracy can be obtained by adding more beacons. Multilateration can also be performed by taking measurements at the mobile device. By allowing the beacons transmit at known time intervals, or simultaneously using multiple frequencies or using orthogonal codes to avoid interference. The advantage of using a TDOA approach is the beacons and mobile nodes do not have to be synchronised to perform calculation [Asynchronous Ultrasonic Trilateration for Indoor Positioning of Mobile Phones].

When more than four beacons are used, a least squares method can to be used to reduce the errors [Asynchronous Ultrasonic Trilateration for Indoor Positioning of Mobile Phones, An Efficient Least-Squares Trilateration Algorithm for Mobile]. This allows for some tolerance for errors in measurements caused by noise, blocked signals and other sources of error.

# System Design

A number of ongoing experiments with the various methods mentioned above are ongoing. The current system is being developed on a Raspberry Pi [56], a low cost computer which is widely available. Although it is low cost, it is powerful with processing and memory capabilities comparable of modern smartphone, but with the versatility of being able to expand functionality by adding additional components using the USB and GPIO connections. It also has ethernet, wireless and Bluetooth connectivity built in, which makes it ideal for selection in its use in a distributed, interconnected system such as the indoor localisation system.

This project is using a single Raspberry Pi 3 initially, which is the latest, most powerful iteration, but does not cost much more than the earlier models available. In addition, a PiFi audio expansion board is being used to for additional audio capability. For the final system, an array of ultrasound transmitters and receivers will be used for the devices, but for early development and testing, audible frequencies are being used. A USB microphone acting as a receiver and a standard speaker connected by auxiliary cable as the transmitter.

The code is being developed using Python. Python is a widely adopted, open source, general purpose programming language with the quick development process that is possible when using interpreted languages that are focused on signal processing applications [14]. Programming in Python offers access to many open-source libraries which can provide functionality for most applications at a broad level, which can then be tailored to suit the needs of the developer. For example, MATLAB is a widely used program in digital signal processing, but using libraries such as NumPy [57], SciPy [58], and MatPlotLib [59], a lot of the features can be implemented in Python freely.

Playing audio can be done in many ways. The most straightforward is to create an array with audio data, and use the SoundDevice [60] and SoundFile [61] libraries to transmit the signals. These libraries are built on the PortAudio [63] and provided simple and convenient methods for basic processing. Solutions for the Time of Arrival and Time Difference of Arrival methods are currently in development. The Time of Arrival measurement can be made by generating a short, single channel sinewave signal. This signal is played over the speaker and recorded simultaneously by the microphone. The recorded wave is then cross-correlated with the original wave and using these results the lag position is found. This lag position represents the time delay between the signal being sent and is then multiplied by an approximated speed of sound to give the distance measurement.

The Time Difference of Arrival uses a similar approach, however this time, the output signal is split using a 3.5mm splitter. The audio is sent to the speaker where the signal is recorded by the microphone as before. The signal is also sent to an input jack on the soundcard to give a second waveform. The Time of Arrival is calculated for both of the recorded waves. As the signal is sent directly to an input via a wire, we can assume the signal arrives instantly from the output. We can then assume that the time difference between the wire input and the microphone input is more representative of the true distance measurement as it alleviates any propagation delays in the hardware before the output is transmitted. One of the main issues with this however, is that the SoundDevice libraries do not allow inputs from multiple sources on the same stream. Two input streams, which will almost certainly never be exactly in sync, must be created and processed which introduces uncertainty in the measurements and erroneous behaviour. Ongoing work is being done to modify the code which SoundDevice uses to provide a more reliable measurement.

Using the RPiTx [62] library is it possible to transmit FM signals from the Raspberry Pi. All that is required to attach a wire to the GPIO18 pin to act as an antenna. Early local tests have been able to transmit signals which are received using a standard FM radio. Further investigation in the areas of improving the power of the sent signal is ongoing.

Future development looks to modify the systems above to use Ultrasonic signal transmitters and receivers for accurate range measurements. Use a second device as a transmitter, synchronize transmissions and measure distance from receiver. Develop a reliable synchronisation system that ensures the accuracy of the range measurements. With additional devices, locate the receiver in a 1D space between 2 transmitters, and a 2D space between 3 or more transmitters.

# Conclusions

This is clearly a load of shite. Apologies.

# Acknowledgements

This report was completed as part of the MSc Advanced Software Engineering with the supervision of Associate Professor Chris Bleakley. I would like to acknowledge and thank Chris for his efforts in guiding me while working on this project.

I would also like to acknowledge and thank Dr. Mel Ó Cinnéide for allowing me the opportunity to participate in this program.

Finally, I would like to thank all the lecturers, teaching assistants, and classmates in this program for their help, support and guidance throughout the course.

# References

[1] K. Wu, J. Xiao, Y. Yi, D. Chen, X. Luo, and L. M. Ni, “Csi-based indoor localization,” IEEE Transactions on Parallel and Distributed Systems, vol. 24, no. 7, pp. 1300–1309, 2013.

[2] J. Xiao, Z. Zhou, Y. Yi, and L. M. Ni, “A survey on wireless indoor localization from the device perspective,” ACM Computing Surveys (CSUR), vol. 49, no. 2, p. 25, 2016.

[3] M. Minami, H. Morikawa, and T. Aoyama, “Design and implementation of a fully distributed ultrasonic positioning system,” Electronics and Communications in Japan (Part III: Fundamental Electronic Science), vol. 90, no. 6, pp. 17–26, 2007.

[4] H. Piontek, M. Seyffer, and J. Kaiser, “Improving the accuracy of ultrasound-based localisation systems,” Personal and Ubiquitous Computing, vol. 11, no. 6, pp. 439–449, 2007.

[5] J. Moutinho, D. Freitas, and R. E. Ara´ujo, “Indoor global localisation in anchor-based systems using audio signals,” The Journal of Navigation, vol. 69, no. 5, pp. 1024–1040, 2016.

[6] L. Segers, J. Tiete, A. Braeken, and A. Touhafi, “Ultrasonic multiple-access ranging system using spread spectrum and mems technology for indoor localization,” Sensors, vol. 14, no. 2, pp. 3172–3187, 2014.

[7] C.-C. Hsiao and P. Huang, “Two practical considerations of beacon deployment for ultrasound-based indoor localization systems,” in Sensor Networks, Ubiquitous and Trustworthy Computing, 2008. SUTC’08. IEEE International Conference on, IEEE, 2008, pp. 306–311.

[8] J. Xu, M. Ma, and C. Law, “Performance of time-difference-of-arrival ultra wideband indoor localisation,” IET science, measurement & technology, vol. 5, no. 2, pp. 46–53, 2011.

[9] R. Zhang, F. H¨oflinger, and L. Reindl, “Tdoa-based localization using interacting multiple model estimator and ultrasonic transmitter/receiver,” IEEE Transactions on Instrumentation and Measurement, vol. 62, no. 8, pp. 2205–2214, 2013.

[10] B. Barshan, “Fast processing techniques for accurate ultrasonic range measurements,” Measurement Science and technology, vol. 11, no. 1, p. 45, 2000.

[11] V. R. V. Remya B Ashish Francis, “An efficient zadoff-chu based communication system,” International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering, vol. 4, no. 9, 2016.

[12] J. C. Glover, V. Lazzarini, and J. Timoney, “Python for audio signal processing,” 2011.

[13] T. E. Oliphant, A guide to NumPy. Trelgol Publishing USA, 2006, vol. 1.

[14] P. Lazik, N. Rajagopal, O. Shih, B. Sinopoli, and A. Rowe, “Alps: A bluetooth and ultrasound platform for mapping and localization,” in Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems, ACM, 2015, pp. 73–84.

[15] C Anjana, S Sundaresan, T. Zacharia, R Gandhiraj, and K. Soman, “An experimental study on channel estimation and synchronization to reduce error rate in ofdm using gnu radio,” Procedia Computer Science, vol. 46, pp. 1056–1063, 2015.

[16] G Piccinni, G Avitabile, and G Coviello, “An improved technique based on zadoff-chu sequences for distance measurements,” in Radio and Antenna Days of the Indian Ocean (RADIO), 2016 IEEE, IEEE, 2016, pp. 1–2.

[17] O. Edfors, M. Sandell, J. v. d. Beek, D. Landstrom, and F. Sjoberg, An introduction to orthogonal frequency-division multiplexing, 1997.

[18] L. Segers, D. Van Bavegem, S. De Winne, A. Braeken, A. Touhafi, and K. Steenhaut, “An ultrasonic multiple-access ranging core based on frequency shift keying towards indoor localization,” Sensors, vol. 15, no. 8, pp. 18 641–18 665, 2015.

[19] M. Hua, M. Wang, K. W. Yang, and K. J. Zou, “Analysis of the frequency offset effect on zadoff–chu sequence timing performance,” IEEE Transactions on Communications, vol. 62, no. 11, pp. 4024–4039, 2014.

[20] J. Blumenstein and M. Bobula, “Coarse time synchronization utilizing symmetric properties of zadoff-chu sequences,” IEEE Communications Letters, 2018.

[21] K. F. Chen and S. L. Mei, “Composite interpolated fast fourier transform with the hanning window,” IEEE Transactions on Instrumentation and Measurement, vol. 59, no. 6, pp. 1571–1579, 2010.

[22] J.-C. Yoo and T. H. Han, “Fast normalized cross-correlation,” Circuits, systems and signal processing, vol. 28, no. 6, p. 819, 2009.

[23] C. G. Priya and A. Vasumathi, “Frequency synchronization in ofdm system,” Journal of signal and Information Processing, vol. 4, no. 03, p. 138, 2013.

[24] J. W. Kang, Y. Whang, B. H. Ko, and K. S. Kim, “Generalized cross-correlation properties of chu sequences,” IEEE Transactions on Information Theory, vol. 58, no. 1, pp. 438–444, 2012.

[25] Y. Shu, Y. Huang, J. Zhang, P. Cou´e, P. Cheng, J. Chen, and K. G. Shin, “Gradientbased fingerprinting for indoor localization and tracking,” IEEE Transactions on Industrial Electronics, vol. 63, no. 4, pp. 2424–2433, 2016.

[26] F Hammer, M Pichler, and C Hesch, “Sound based localization system for safety applications in underground mining,”

[27] M. A. N. Shukur, K. Pahwa, and H. Sinha, “Implementing primary synchronization channel in mobile cell selection 4g lte-a network,”

[28] R. G´orak, M. Luckner, M. Okulewicz, J. Porter-Sobieraj, and P. Wawrzyniak, “Indoor localisation based on gsm signals: Multistorey building study,” Mobile Information Systems, vol. 2016, 2016.

[29] A. Bahillo Martinez, S. Mazuelas Franco, J. Prieto Tejedor, R. M. Lorenzo Toledo, P. Fernandez Reguero, and E. J. Abril, “Indoor location based on ieee 802.11 roundtrip time measurements with two-step nlos mitigation,” Progress In Electromagnetics Research, vol. 15, pp. 285–306, 2009.

[30] P. Lazik and A. Rowe, “Indoor pseudo-ranging of mobile devices using ultrasonic chirps,” in Proceedings of the 10th ACM Conference on Embedded Network Sensor Systems, ACM, 2012, pp. 99–112.

[31] A. Ens, L. M. Reindl, T. Janson, and C. Schindelhauer, “Low-power simplex ultrasound communication for indoor localization,” in Signal Processing Conference (EUSIPCO), 2014 Proceedings of the 22nd European, IEEE, 2014, pp. 731–735.

[32] D. Lymberopoulos, J. Liu, X. Yang, R. R. Choudhury, S. Sen, and V. Handziski, “Microsoft indoor localization competition: Experiences and lessons learned,” GetMobile: Mobile Computing and Communications, vol. 18, no. 4, pp. 24–31, 2015.

[33] F. Perez-Cruz, C.-K. Lin, and H. Huang, “Tdoa-based localization using enhanced multilateration,”

[34] B Remya and A. Francis, “Ofdm systems using zc sequences,”

[35] H. Minn, M. Zeng, and V. K. Bhargava, “On timing offset estimation for ofdm systems,” IEEE Communications letters, vol. 4, no. 7, pp. 242–244, 2000.

[36] M. O. Khyam, S. S. Ge, X. Li, and M. Pickering, “Orthogonal chirp-based ultrasonic positioning,” Sensors, vol. 17, no. 5, p. 976, 2017.

[37] D. Chu, “Polyphase codes with good periodic correlation properties (corresp.),” IEEE Transactions on information theory, vol. 18, no. 4, pp. 531–532, 1972.

[38] M. M. U. Gul, S. Lee, and X. Ma, “Robust synchronization for ofdm employing zadoff- chu sequence,” in Information Sciences and Systems (CISS), 2012 46th Annual Conference on, IEEE, 2012, pp. 1–6.

[39] L. Kong, G. Bauer, and J. Hale, “Robust wireless signal indoor localization,” Concurrency and Computation: Practice and Experience, vol. 27, no. 11, pp. 2839–2850, 2015.

[40] S. Tripathy and S. Jakonen, “The fourier transform of rectangular function,” International Journal of Mathematics, Game Theory, and Algebra, vol. 24, no. 4, p. 289, 2015.

[41] J. C. Jackson, R. Summan, G. I. Dobie, S. M. Whiteley, S. G. Pierce, and G. Hayward, “Time-of-flight measurement techniques for airborne ultrasonic ranging,” IEEE transactions on ultrasonics, ferroelectrics, and frequency control, vol. 60, no. 2, pp. 343–355, 2013.

[42] M. M. U. Gul, X. Ma, and S. Lee, “Timing and frequency synchronization for ofdm downlink transmissions using zadoff-chu sequences,” IEEE Transactions on Wireless Communications, vol. 14, no. 3, pp. 1716–1729, 2015.

[43] O. Onalaja, M. Adjrad, and M. Ghavami, “Ultra-wideband-based multilateration technique for indoor localisation,” IET Communications, vol. 8, no. 10, pp. 1800–1809, 2014.

[44] P. Lazik, N. Rajagopal, B. Sinopoli, and A. Rowe, “Ultrasonic time synchronization and ranging on smartphones,” in Real-Time and Embedded Technology and Applications Symposium (RTAS), 2015 IEEE, IEEE, 2015, pp. 108–118.

[45] M. H. AlSharif, M. Saad, M. Siala, T. Ballal, H. Boujemaa, and T. Y. Al-Naffouri, “Zadoff-chu coded ultrasonic signal for accurate range estimation,” in Signal Processing Conference (EUSIPCO), 2017 25th European, IEEE, 2017, pp. 1250–1254.

[46] M. Zivkovic and R. Mathar, “Zadoff-chu sequence based time-domain snr estimation for ofdm systems,” in Signal Processing Advances in Wireless Communications (SPAWC), 2014 IEEE 15th International Workshop on, IEEE, 2014, pp. 110–114.

[47] M. M. Hyder and K. Mahata, “Zadoff-chu sequence design for random access initial uplink synchronization,” arXiv preprint arXiv:1604.01476, 2016.

[48] Z. Wang, L. Zhang, F. Lin, D. Huang, and Y. Huang, “Aidloc: An accurate acoustic indoor localization system,”

[49] J. Zhang, V. Grabe, B. Hamner, D. Duggins, and S. Singh, “Compact, real-time localization without reliance on infrastructure,” The first place 3D entry, 2016.

[50] E. G¨”unes and G. Ibarra, “Intranav–low-cost indoor localization & navigation system,”

[51] H. Liu, H. Darabi, P. Banerjee, and J. Liu, “Survey of wireless indoor positioning techniques and systems,” IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews), vol. 37, no. 6, pp. 1067–1080, 2007.

[52] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, “The cricket location-support system,” in Proceedings of the 6th annual international conference on Mobile computing and networking, ACM, 2000, pp. 32–43.

[53] D. Wobschall and Y. Ma, “Synchronization of wireless sensor networks using a modified ieee 1588 protocol,” in Precision Clock Synchronization for Measurement Control and Communication (ISPCS), 2010 International IEEE Symposium on, IEEE, 2010, pp. 67– 70.

[54] X.-Y. Lin, T.-W. Ho, C.-C. Fang, Z.-S. Yen, B.-J. Yang, and F. Lai, “A mobile indoor positioning system based on ibeacon technology,” in Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE, IEEE, 2015, pp. 4970–4973.

[55] Y. Zhou, “An efficient least-squares trilateration algorithm for mobile robot localization,” in Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on, IEEE, 2009, pp. 3474–3479.

[56] T.-K. Lee and K. Yang, “On the correlation properties of generalized chirp-like sequences and their application,” in Signal Design and Its Applications in Communications, The Sixth International Workshop on, IEEE, 2013, pp. 88–91.

[57] N. Suehiro and M. Hatori, “Modulatable orthogonal sequences and their application to ssma systems,” IEEE Transactions on Information Theory, vol. 34, no. 1, pp. 93–100, 1988.

[58] F. Thomas and L. Ros, “Revisiting trilateration for robot localization,” IEEE Transactions on robotics, vol. 21, no. 1, pp. 93–101, 2005.

[59] A. Srinivasan and J. Wu, “A survey on secure localization in wireless sensor networks,” Encyclopedia of Wireless and Mobile communications, p. 126, 2007.

[60] R. Kapoor, S. Ramasamy, A. Gardi, C. Bieber, L. Silverberg, and R. Sabatini, “A novel 3d multilateration sensor using distributed ultrasonic beacons for indoor navigation,” Sensors, vol. 16, no. 10, p. 1637, 2016.

[61] F. Miao, D. Yang, J. Wen, and X. Lian, “Moving sound source localization based on triangulation method,” Journal of Sound and Vibration, vol. 385, pp. 93–103, 2016.

[62] Z. Yang and Y. Liu, “Quality of trilateration: Confidence-based iterative localization,” IEEE Transactions on Parallel and Distributed Systems, vol. 21, no. 5, pp. 631–640, 2010.

[63] V. Filonenko, C. Cullen, and J. D. Carswell, “Asynchronous ultrasonic trilateration for indoor positioning of mobile phones,” in International Symposium on Web and Wireless Geographical Information Systems, Springer, 2012, pp. 33–46.

[64] O. Tekdas and V. Isler, “Sensor placement for triangulation-based localization,” IEEE transactions on Automation Science and Engineering, vol. 7, no. 3, pp. 681–685, 2010.