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A system for indoor positioning using ultra-wideband technology

Master's thesis in Embedded Electronic System Design

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Abstract

The global positioning system is used in a wide array of applications. The ability to get an accurate location of a person or object has led to a number of so-called location-based services, mainly in logistics but also in more consumer applications such as localized weather information etc. This works well where a clear view of the sky will enable the GPS system to pinpoint your location with sufficient accuracy. However, in an indoor environment the signals will be badly disrupted by the material between the user and the satellites, making it significantly harder to use the system to determine your location. Here, a localized system based on a different technology is needed to allow all of the incredibly useful applications based on the user position to continue functioning as intended.

In this thesis multiple possible techniques for usage in indoor positioning are presented and what their main advantages and disadvantages are. A technology was then chosen to be implemented and evaluated, which was ultra-wideband technique because of its accuracy and robustness. This technique uses radio frequencies with large bandwidth to send a high amount of energy in a short pulse, making it robust to obstacles as well as enabling the time of the received signal to be accurately calculated.

The end product is a working indoor positioning system using ultra-wideband technology with a high accuracy in line of sight, and graceful degradation in non-line of sight and mixed conditions. The latency is low enough to be able to use as a real-time location system, providing that the problems with the information transfer to the server over Ethernet are fixed. The system has the possibility of tracking multiple tags, and has an accuracy of 15 to 30 centimeters depending on the conditions. This coupled with the range of upwards of 20 meters means that the system is viable for a wealth of applications, and ultra-wideband is a strong contender for the large amount of systems targeted at indoor positioning applications.

Keywords: Indoor Positioning, Ultra-WideBand (UWB), Time of flight (ToF), Thesis, Two-way ranging (TWR), Decawave DWM1000, Real-Time Localization System (RTLS).

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Sebastian Dädeby, Gothenburg, June 2017
Joakim Hesselgren, Gothenburg, June 2017

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Nomenclature

Anchor	Fixed reference point, page 20
AoA	Angle of Arrival, page 11
BLE	Bluetooth low energy, page 14
DR	Dead-reckoning, page 16
ECC	Electronic Communications Committee, page 7
GUI	Graphical user interface, page 24
IC	Integrated Circuit, page 20
IMU	Inertial measurement unit, page 16
LoS	Line of Sight, page 7
NLoS	Non-line of sight, page 2
RFID	Radio frequency identification, page 13
RSS	Received Signal Strength, page 11
RSSI	RSS Indication, page 11
RTLS	Real Time Location Services, page 20
SPI	Serial Peripheral Interface, page 20
Tag	Searched object, page 20
TDoA	Time Difference of Arrival, page 9
ToA	Time of Arrival, page 9
ToF	Time of Flight, page 10
TWR	Two Way Ranging, page 25
UWB	Ultra-wideband, page 14
VLC	Visual light communication, page 16
WLAN	Wireless local area network, page 13

In navigation, dead reckoning is the process of calculating one's current position by using a previously determined position, or fix, and advancing that position based upon known or estimated speeds over elapsed time and course.

Radio-frequency identification (RFID) uses electromagnetic fields to automatically identify and track tags attached to objects.

1

Introduction

The introduction of the global positioning system has led to a wealth of new applications [1, 2]. The ability to get an accurate location of a person or object down to a few meters has not only had an effect on the way we navigate but led to a number of so-called location-based services, mainly in logistics but also in more consumer applications e.g. localized weather information, location-based gaming, fitness tracking etc. This works well in outdoor conditions, where a clear view of the sky will enable the GPS system to communicate the information necessary to pinpoint your location with sufficient accuracy. However, in an indoor environment the signals containing this information will be badly disrupted by the amount of material between the user and the satellites orbiting the earth, making it significantly harder to use the system to determine your location [3]. Here, a localized system based on a different technology is needed to allow all of the incredibly useful applications based on the user position to continue functioning as intended.

1.1 Background

Indoor positioning systems have not seen a widespread deployment yet, despite the availability of many promising technologies such as light-based communication, computer vision, ultra-wideband radio, WLAN, Bluetooth, dead-reckoning and RFID-based solutions among others [4, 5]. It is also likely that there will not be a one-technology-fits-all solution, meaning that several technologies will likely coexist, each with their own purpose. With the availability of indoor positioning systems increasing [3], it is expected that new indoor location services will become available in the fields of navigation and tracking, marketing, entertainment, information retrieval, safety and security. For many of these applications, accuracy and response times are key requirements, and achieving the desired levels of performance can be challenging in an indoor environment because of the presence of refractive surfaces, interfering technologies etc. The problems with these environments need to be further studied in order to allow the same development of position-based applications as has already happened for outdoor environments

1.2 Aim

The objective of this thesis is to investigate a number of different technologies for indoor positioning in a supermarket/shopping mall setting and implement the best technique for a acquiring a high accuracy and low latency while maintaining a good power efficiency in a demonstrator setup. The goal of the demonstrator is to emulate the tracking of individual customers with reasonable accuracy such that the customer flow can be analyzed. It should also be possible to alert the customer when he or she enters a predefined area, for example to alert for nearby promotions. The system should be able to be integrated in existing shopping baskets and trolleys, meaning that power efficiency is an important requirement.

1.3 Performance factors and definitions

When comparing different indoor positioning systems, several problems can be seen regarding the performance of said systems [4–8]:

Accuracy is an important aspect when considering indoor positioning systems, and is critical to ensure that the data received is useful for the desired application. Accuracy can be seen as how far away the measured position of the object which is tracked, called the tracking target from here onward, is to the real point measured in meters. For the considered system to provide valid data, inaccuracies need to be kept below 2-3 meters and ideally as low as possible.

Latency is important when considering a moving target, since a high latency will result in a high inaccuracy. Latency can be seen as the time in seconds from the system acquires data until it is finished processing it.

Power consumption is needed to be kept low to make the system small, portable and flexible by enabling it to be powered by battery.

Scalability is the amount of targets the system possibly can track, and how easy it is to scale the system to different requirements in terms of size. This needs to be good in most indoor positioning applications since there is usually a large area that needs to be covered and a lot of targets to keep track of. This will be an important factor for this project since the objective is to make a system, which can be put up in public places and which needs to be able to track multiple targets.

Robustness of the system affects how reliable the accuracy will be in demanding environments. Having low maximum errors and small disturbances are important factors, and being able to handle non-line of sight (NLoS) is needed for applications where the environment contains obstacles such as shelves, moving objects etc.

The **complexity** refers to how difficult and time consuming it is to install a system in a new environment or to calibrate it if needed. This is an important factor to enable a system to be commercially viable.

Cost per object being tracked needs to be kept low to enable tracking of multiple objects, and also to allow for tracking objects in harsh conditions where the hardware may suffer from a reduced life time.

Portability describes how easy the hardware that is used as a target is to move around. This is needed to be kept good since the goal is to be able to implement the tracking target in something like a basket or a trolley which introduces limitations on size, weight and power consumption.

Security and integrity is an important factor since the system keeps track of movements of humans which could be seen as violating their integrity. By putting tracking target hardware on things rather than tracking persons or their phones would make it less of an integrity violence. If the system is keeping track of phones it will also be able to keep the id of the device making it possible to track individual people rather than a random person. Since the system keeps track of and saves the movement of persons it might be a security risk, making the security needed to be high.

Of significant importance when considering what system type and implementation that is the best for an application is the weighing of latency and accuracy. On a moving target, the latency itself will introduce an error in accuracy for real-time applications, since the target will have moved from the time that the data was collected to the time when the result is available for viewing. The effective inaccuracy in real-time can be calculated by the following equation:

$$A = B + t \cdot v \tag{1.1}$$

where A is the effective inaccuracy, B is the inaccuracy of the measured point, t is the latency and v is the velocity of the target. This means that the accuracy of the technique does not matter if it has a high latency and vice versa, making a good combination of the two needed.

1.4 Method

Initially a review of the current available literature will be performed to assess the strengths and weaknesses of the different types of technologies available, and a choice will be made as to which technology is the most suitable to solve the problem at hand. When the main technology has been decided, some more extensive research will be performed regarding previous works, expected outcomes and system design options. At the same time a review of existing hardware manufacturers to use as a base for the system will be performed. The most suitable hardware will be chosen based on the requirements described above, and from there a prototype system will be developed to assess the base performance of the chosen technology. From there, optimization will be performed to enhance the performance of the system for the problem at hand. When the system is finished an evaluation of the technique along with the implementation is to be carried out and conclusions will be drawn from here regarding the performance of the implemented system as well as the viability of the technology itself.

1.5 Limitations

To ensure that the thesis project is possible to complete within the given time, some limitations to the scope have been decided. The algorithms for determining the position will be taken from existing literature, meaning that no work will be done to develop new methods for position estimation. The system will be evaluated in a demo environment, and will not be extended to real commercial applications. This also means that the accompanying system and software including the user interface will be developed with this in mind, and therefore no additional work will be done to make the system user-friendly. After the initial technology research, only one type of system will be chosen for implementation. The thesis will be limited to performance evaluations using only the chosen technology.

1.6 Ethics and security

As always when a project or product is centered around the collecting of data related to personal activity, in this case the estimation of the position of an object possibly connected to a person's movement, special thought has to be given to the ethical dilemma of collecting such data. Either there has to be some kind of consent required from the person in question before the acquisition of data can begin, or care has to be taken to ensure that the data in question is completely anonymous. This can be accomplished in several ways to ensure that the integrity of the tracking target is not violated, and methods for this should be integrated in the core design of a system of this kind. A way of accomplishing this is by distancing the tracking hardware from the individual carrying it by for example implementing it in a shopping trolley, and thereby ensuring that no personal data is collected together with the position.

In addition to the ethical dilemmas of the tracking of individuals, security must also be considered every time potentially sensitive information is collected by a system. Since this thesis only aims to deliver a demo environment, no security measures will be implemented. However, in the event of a commercial system of this type is set up, protection needs to be implemented in order to ensure that no malicious accesses to the system is possible. If the system is to be connected to the Internet, it needs to be secured like every other connected device to prevent the possibility of hijacking for use in malicious activities in addition to preventing the data to be compromised.

1.7 Report outline

The report has started by introducing the reader to the problem at hand, describing why this problem is relevant and what questions hope to be answered at the end of the thesis. Then the theory regarding indoor positioning will be presented, including different methods for estimating the position of an object, what sources of errors may be present and how the effect of these errors might be mitigated. The following chapter will also briefly describe the different technologies available for indoor positioning systems, and finish off with a brief summary of the strengths and weaknesses of each technology. Next the work done will be described, focusing on challenges met and what decisions have been taken to overcome these challenges, and the chosen design will be motivated with a basis in the theory from the previous part. After this, the results from tests conducted during the work will be presented, aiming to answer the question posed in the introduction. Then the implications of these results on the goal of the project will be discussed together with some suggestions on further work to be done within the area, and lastly conclusions will be drawn from the discussion and the results.

2

Theory

This chapter will go deeper into the theory behind indoor positioning to give an understanding about what needs to be considered when designing such a system. First the different factors that introduce difficulties when operating in indoor environments will be described, together with what limitations they introduce. Next the way of estimating the target's position is detailed, together with the different methods for determining the distance to the target from the reference points needed for the position estimation.

2.1 Spectral interference

Any wireless system that operates through the use of any kind of electromagnetic waves for information transmission needs to adhere to certain rules regarding what frequencies can be used to avoid different devices from interfering with each others transmissions. In Europe, these frequency bands are controlled by the Electronic Communications Committee (ECC) which limits what bands can be used for what cases [9] with the purpose of avoiding equipment working within these bands to critically interfere with each other. This causes the unlicensed bands to become generally crowded, and so performance degradations from spectral interference is a common issue in most wireless transmission systems [10–12], especially when operating indoors since the density of such systems will be generally higher than outdoors. This may pose a major problem for any kind of location estimations, since they are generally sensitive to any deviations from the ideal case to be able to provide accurate results, and care must be taken to avoid affecting other systems present in the area.

2.2 Line of Sight (LoS)

One of the most significant problems regarding position estimation indoors is that, unlike outdoors where a clear view of the sky for satelite communication can be mostly guaranteed, the space between the source and the target often is obstructed by objects such as people, walls etc [13]. This gives rise to the need to define two different situations when performing these types of distance estimations, namely Line of Sight (LoS) when the way between a source and the target is free, and Non-Line of Sight (NLoS) when the path is obstructed by some obstacle. The LoS case is very well defined both with respects to signal strength changes and propagation times for electromagnetic waves, and therefore all systems for position estimation perform well under these conditions assuming that no spectral interference is present. However the NLoS case is much more complex to handle since it introduces unknowns that are highly dependant on the individual environment and the technology used [14]. Electromagnetic waves can penetrate some objects depending on the frequency of the wave and the material of the obstruction, however they will be heavily attenuated and the propagation time will be longer than for air. In some cases the signal in the direct path will be blocked completely, causing the target to either be reached by only reflections whose characteristics will depend on the reflecting surface, or not at all. These problems are problematic to handle [15], and a systems ability to do so without a heavy loss in performance is critical to be useful in indoor environments [16].

NLoS can be described by Fig. 2.1 where it can be seen a tracking system trying to make contact with an object but there is an object between them blocking signal. Depending on technology this will affect the system in different ways. Some would not get any contact at all while some would be able to pierce the object but with obscured result, and the last case would be that a reflected signal would reach the object also obscuring the result.

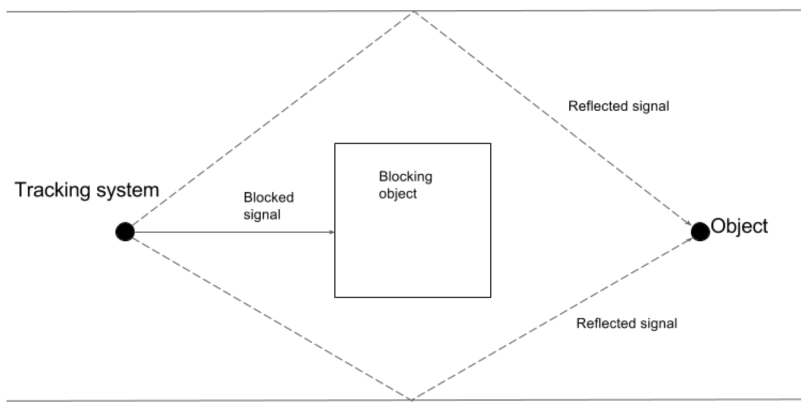

Figure 2.1: Communication between system and target with an object blocking the sight between them.

2.3 Multipath fading

Another problem caused by complex indoor environments is a phenomenon called multipath fading. This is caused when the reflections of the signal from different surfaces interferes with itself [17], often with a difference in phase causing the original signal to possibly lose signal strength or else become distorted [18]. Additionally it can become difficult to determine which the original signal is from the reflected components, possibly causing the time of flight or signal strength of the signal to become inaccurate since the reflected path is longer than the shortest one [19]. Effects like these are hard to predict in severe indoor environments, and may cause inaccuracies for all of the types of position estimate methods described in section 2.4. Advanced algorithms can be used to correct for some multipath fading effects [20], which can be beneficial depending on the technology and the complexity of the environment.

In section 2.2 a description to Fig. 2.1 was given which describes this problem as well. The multipath fading in that case would be the reflected signals interfering with each other destructively, which could cause the signals to fade before reaching the receiver.

2.4 Distance estimation

In this section different types of distance measuring methods for multiple systems are described. The distances that are given out of these methods are then used in trilateration between three or more reference points for being able to find the coordinate of the tracked system related to the reference points positions [21].

2.4.1 Time of Arrival (ToA)

Time of Arrival (ToA) is the simplest of the time-based distance estimation methods. It uses one-way communications for the estimations, meaning that units are either dedicated transmitters or receivers which can greatly lower their individual complexity. A ranging operation consists of only one transmission, where the transmitter sends a timestamp of the current time to the receiver. The data is then compared to the time at the receiving instant, and since the speed of light is a known constant the distance between the transmitter and receiver can be determined [21, 22]. However, the accuracy of the result from ToA is highly dependant on the accuracy of the clock in the transmitters and receivers, which therefore needs to be synchronized and have a very low drift [22–24]. Since a clock error of 1 ns results in an error of roughly 30 centimeters, ToA systems are difficult to implement in practice.

2.4.2 Time Difference of Arrival (TDoA)

Time Difference of Arrival (TDoA) is very similar to ToA, but instead of calculating the time for each message to pass from the transmitting point to the receiver, is uses the difference in arrival time from several known points to calculate the relative distances to each [21–23]. TDoA requires a strict synchronization between the reference points to ensure that the measuring signal is sent at the exact same time but, unlike with ToA, the receiver doesn't need to share this synchronization since the relative difference in arrival time is measured instead of the absolute [24, 25]. This simplifies the system somewhat since the reference points usually are fixed in space, and therefore can be connected through a wire thereby eliminating the need for more complex wireless clock synchronization algorithms. If the master point responsible for the synchronization would break however, the entire system would quickly degrade making reliability an issue.

2.4.3 Time of Flight (ToF)

Time of Flight (ToF) is a further extension of TDoA to remove the need for synchronization between points in the system altogether [21]. This is achieved by sending the measuring signal from a reference point to the target, which then responds after a known delay as illustrated in Fig. 2.2. This allows the reference point to calculate the total time of flight, and by using the following equation:

$$Distance = C \cdot \frac{(t_{Rx} - t_{Tx}) - t_{reply}}{2} \tag{2.1}$$

where C is the speed of light at $299792458 m/s$, t_{Tx} and t_{Rx} is the transmission time of the first message and the reception time of the second message respectively, and the difference between these two becomes the total round-trip time. The distance can be calculated without any influence of clock offsets between the involved nodes [26]. Using this method, the clock error can be reduced to the drift that happens between t_{Tx} and t_{Rx}, which will depend on the drift rate of the oscillator used as a time reference and the set length of t_{reply}.

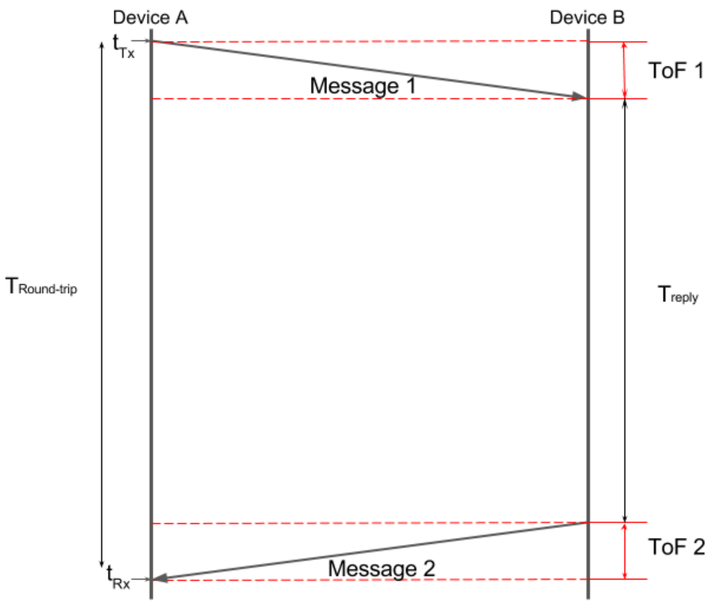

Figure 2.2: Message structure for ToF measurement.

For system with a highly accurate oscillator and a short t_{reply} this error will often be negligible, however in systems where one or both of these requirements cannot be met, double-sided ToF can be used to nullify a large part of the error induced by the reference clock offset [27]. This message structure is shown in Fig. 2.3 which essentially gives two separate ToF measurements, which then are averaged to give the ToF and consequently the distance according to eq. 2.1.

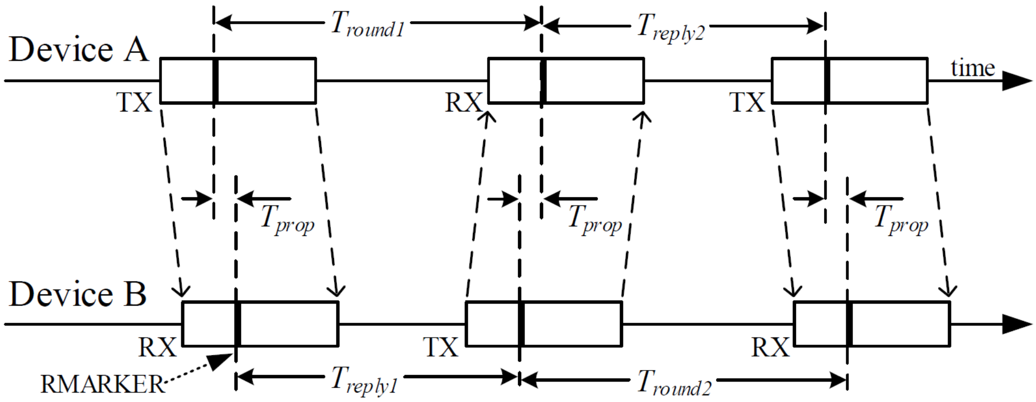

Figure 2.3: Double-sided ToF message structure [28].

2.4.4 Angle of Arrival (AoA)

Angle of Arrival (AoA) uses the angles of two incoming signals to the receiver to determine its position relative to the two fixed reference points [21, 24]. This allows a position estimation to be performed using one less fixed point compared to using one of the time-based methods significantly reducing system hardware needed, and additionally suffers from fewer error sources. However determining the angle of an incoming signal with the required precision is significantly more complex than time-stamping, and this together with the fact that reflected signals will severely impact the accuracy in NLoS situations this method is much less used than the time based counterparts [24, 29].

2.4.5 Received Signal Strength (RSS)

Received Signal Strength (RSS) uses reference points or searched objects as transmitters and the other side as receivers. This makes it possible to get the signal strength in decibel in the receivers which was transmitted from the transmitters [30–32]. To ensure that the RSS can be easily read and utilized by a system, many transceivers using various RF-techiques for communication are enabled to produce something called Received Signal Strength Indication (RSSI) which is a normalized value which uses a reference value at a distance of one meter from the transmitter as a baseline. RSS is easy to use since relies on simple measurements of the signal strength, but a problem is if the reference points and searched object is NLoS of each other since the signal can get absorbed by many different types of materials. RSS is usually used in low cost applications with a lower demand in accuracy since the results are notoriously inconsistent [24, 33].

2.5 Trilateration

Trilateration is done by the usage of three or more distances to an object to determine the relative position of the said object, which is illustrated in Fig. 2.4 [34]. A simplification of trilateration algorithm is to put one reference point at origin, one along the x-axis and the last one does not need any specific position. These three reference points can be seen in the figure where A0 reference point is at (0,0,0), A1 at (x_1,0,0) and A2 at (x_2,y_2,0). The x, y and z position of the object is then possible to calculate with the following equations:

$$x = \frac{r_0^2 - r_1^2 + x_1^2}{2x_1} \tag{2.2}$$

where r_0 is the distance between reference point one and the object. r_1 is the distance between reference point two and the object.

$$y = \frac{r_0^2 - r_2^2 + x_2^2 + y_2^2}{2y_2} - \frac{x_2}{y_2}x \tag{2.3}$$

where r_2 is the distance between reference point three and the object.

$$z = \pm\sqrt{r_0^2 - x^2 - y^2} \tag{2.4}$$

In a trilateration problem there is needed to have N+1 reference points to find a N-dimensional position which can be seen here where with three reference points only an exact x and y position is calculated while the object has two possible heights making an additional reference point needed for being able to get the correct plane.

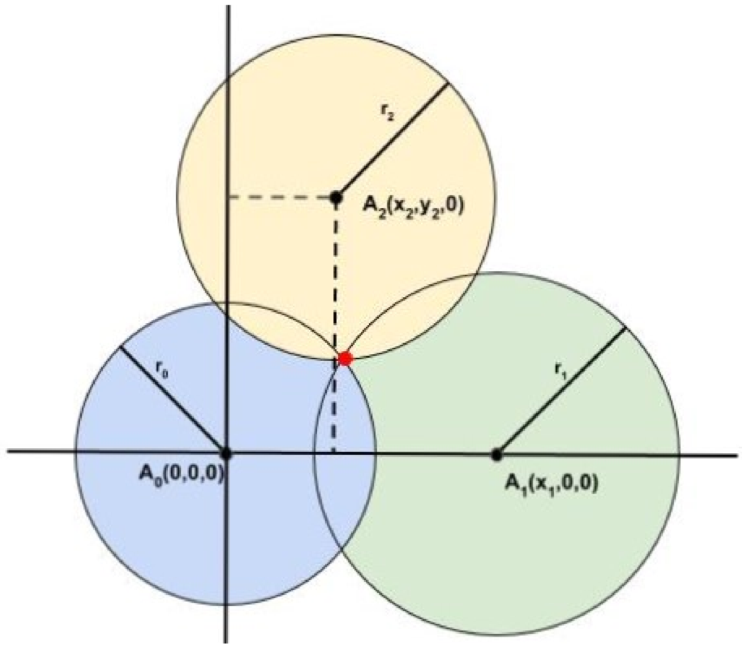

Figure 2.4: Trilateration with three anchors.

3

Techniques for indoor positioning

There are multiple methods for solving the problem of indoor positioning, each with its own strengths and drawbacks. Many of them require the tracking target to be equipped with some kind of hardware which communicates with the rest of the system to relay the information used to determine the targets position. This section will give an overview of related works with these methods and technologies, and a summary will be provided at the end to emphasize their key characteristics.

In section 2.4 different methods for measuring distances between two transceivers were given. In this chapter these are used to group techniques as either RSS based, time based or miscellaneous which characterises systems based on their primary method of distance estimation.

3.1 Received signal strength based

In this section the techniques rely mainly on RSS as their measuring method are described. As described in section 2.4 these are generally cheaper, however are often lacking in either accuracy or range, and have trouble handling mixed conditions.

3.1.1 Radio frequency identification

Radio frequency identification (RFID) can be used for indoor positioning by trilateration using the RSSI to determine the distance between the target and fixed reference points [6, 35]. As with many of the other techniques that utilize RSSI, it suffers from inaccuracies caused by environmental influences such as objects and people between the transmitter and receiver. This coupled with the low range of RFID readers and the fact that multiple tracking target severly limits the performance is a major drawback for this technology [36]. However, RFID has been around for a long time, meaning that the technology is mature, and the price of passive RFID tags is very low meaning that they can be used liberally to track items such as tools etc.

3.1.2 Wireless local area network

Wireless local area networks (WLAN) also called Wi-Fi can be used for a multitude of different applications, and indoor positioning is one of them [37]. It opens up the possibility to individuals in motion through there phones, which means that no additional hardware is needed at the tracking target [38]. Wi-Fi is a RF-based communication, and therefore the RSSI can be used in the same way as with RFID to get the distance to a user from an access point [39]. It can also be implemented on top of existing Wi-Fi infrastructure, meaning that the installation cost can be very low in the ideal case. The problem with this kind of indoor positioning system is that the accuracy is very limited, and therefore needs extra algorithms or hardware to compensate to ensure that the result is good enough to use [40]. Its use cases are better than many others since services can easily be built around it through apps.

3.1.3 Bluetooth

Bluetooth can be used in similar ways to Wi-Fi to estimate the position of the target by measuring the RSSI, and consequently suffers from many of the same drawbacks regarding accuracy although it's better than what is achievable with Wi-Fi, with the addition of significantly lower range [41]. The advantages are also somewhat similar to Wi-Fi in that it allows tracking of phones when applicable, eliminating the need for additional hardware on the tracking target, although a system of reference points needs to be installed [33,42]. The addition of bluetooth low energy (BLE) also allows for the building of designated hardware that is small and energy efficient.

3.2 Time based

In this section the techniques that has the possibility to use the time based methods are described. As described in section 2.4 these techniques are often more accurate than RSS based ones, however they come with an addition in both cost and complexity due to the nature of determining a distance based on the speed of a signal

3.2.1 Ultra-wideband

Ultra-wideband (UWB) uses broad frequency bands to allow transmission using high-energy pulses while limiting the interference with other RF equipment operating within the same frequencies [4]. UWB-based systems usually rely on time-based methods discussed in section 2.4 to determine the target position, and while AoA or RSS are possible to use, they prove both more difficult and less reliable than time-based approaches. UWB has a good accuracy assuming that you have high enough precision when measuring the travel time, and supports NLoS conditions since the wide frequency band is robust to the destructive interference caused by reflected signals [22, 24], and the high energy content of the signal can penetrate many softer materials. Since varying degrees of obstruction is common in normal indoor environments, this makes UWB an excellent choice for systems designed for the general case rather than specialized systems where LoS can be guaranteed. The long range of the high-energy signal means that it has excellent scalability, and the complexity can be kept relatively low since the high innate accuracy of the technology reduces the need for complex processing of the obtained results. This accuracy comes mainly from the fact that since the signal energy is dispersed over a broad frequency range, the time frame can be compact without exceeding the energy density limits which in turn compresses the edge used for determining the receive time, allowing for very accurate time-stamping of incoming messages. The main drawback of UWB is that the technology itself is not as mature as many of the others, which makes the specific hardware more expensive and limits the amount of support available [4]. This is bound to change over time as more suppliers release their own products, but at the moment this is the greatest concern regarding a system based on this technology.

3.2.2 Ultrasonic sound

Ultrasonic sound uses a transmitter that sends out high-frequency sounds waves outside of the hearing spectrum of humans [43], which is then picked up by a receiver allowing it to calculate the distance between them using a time-based approach. The result from multiple transmitters can then be used to locate the target [6]. The main advantage of ultrasonic sound is the lower speed of the measuring signal compared to RF-technologies, which means that the effect of inaccuracies of the system clocks at the different measuring points has a smaller effect on the overall accuracy. This removes the need for tight clock-synchronization or multiple messages that other techniques using time-based approaches needs. This together with the fact that the technology has been used for a long time in systems such a sonar gives it a high accuracy, however ultrasonic sound requires LoS to the target and suffers from low range, which makes it hard to utilize in most indoor environments.

3.3 Miscellaneous

In this section the methods that does not fit in under the previous categories are described. These all use unique methods to determine the location of an object, each with its own advantages and disadvantages.

3.3.1 Image-based

Image-based indoor positioning uses a camera to identify either persons or specific objects and then maps the position found for this object to a coordinate in the horizontal plane. This technique is easy to set up and could use existing cameras, and does not require the target to carry any kind of tracking device. Some form of image processing is needed to find the target in the frame and determine its location, with more complex environments requiring more sophisticated processing algorithms [44]. There is also a significant trade-off in cost versus range, as a camera with a larger field of view needs to have a greater pixel density to allow for an accurate detection of tracking targets. The largest downside of this type of system is the requirement of a clear LoS to the target, often requiring multiple cameras to be installed to cover one area which can rapidly increase the price and complexity beyond that of the other system types. Another concern is the potentially unethical behaviour in recording and tracking individual people where this is the application, making it undesirable for public applications.

3.3.2 Visual light communication

Visual light communication (VLC) uses different types of light emitters and detectors determine the targets position within the enclosed area [45]. Indoor positioning systems based on VLC can be partitioned into two different types. The first type uses a grid of rather basic photodiodes to receive light from the tracking target, and based on which detectors can see the emitted light the position can be computed. This allows for a system consisting of cheap hardware, but does not allow the target to know its position without extra communication, and does not support more complex setups involving a large amount of targets etc. The second type uses a camera as a detector on the target together with stationary emitters which each send a unique ID by blinking a binary sequence, allowing the target to compute its position based on the angle to each individual emitter [46]. This method is very exact and allows an almost unlimited amount of targets, however the cameras are rather expensive and heavy image processing to detect the emitters and decode the information relayed from them. A large problem with any form of VLC is that it demands LoS, making it unsuitable for dynamic environments.

3.3.3 Dead-reckoning

Dead-reckoning (DR) uses the last known positioning of the target combined with data about its movement to estimate the new position after a short delay. It uses an accelerometer to get the speed of the moving object [47] and a gyroscope gives the angular velocity to determine the direction of the movement. These units together are called an Inertial measurement unit (IMU) , with the possibility of adding a magnetometer to correct for the gyroscopes drift [48, 49]. Additionally to get the altitude it is possible to use a barometer for preasure measurements if a position in three dimensions is needed. DR systems are prone to error propagation since every new position is based on the previous one, which introduces the need of frequent calibration to ensure that the position estimate is reliable [50]. This makes the DR system impractical by itself, but it is often used to improve on the accuracy of other technologies.

3.4 Hybrid systems

Since most of these methods have drawbacks they could be combined with each other to get better. A combination of this is WLAN together with BLE [51]. This combination manages to get better accuracy while still maintaining a better range in comparison to them individually. It still has a bad accuracy compared to other methods but its use case are better than others.

Another combination would be to combine UWB and DR which would give an increased accuracy but requires more hardware, as well as more processing of the data to estimate the position[50]. The combination between UWB and WLAN opens up for the possibility to utilise the advantages of WLAN and UWB, while canceling most of their respective weaknesses [52]. This makes it possible to build apps and communicate over WLAN while still maintaining the high precision of UWB. However, this approach would require more power since two different transceivers will be running, and would also increase the cost of the system due to the extra hardware needed.

3.5 Summary

In table 3.1 the techniques described in this chapter are summarized according to how accurate they are, how well they are possible to scale, i.e how easy it is to cover a large area and have multiple objects followed. Complexity is compared by looking at how easy they are to set up in a new environment and how much it takes to develop a system. The robustness of the system is seen as how reliable the accuracy is to replicate, i.e how good is it at withstanding NLoS, multipath fading, moving objects etc. A yes in the personal identification means that the system needs to do an identification of the object to be able to locate it, while possible is depending on how the system in implemented. As an example, using image-based techniques for tracking individuals requires identification of unique features, which often means facial recognition that can be potentially troublesome from an integrity point-of-view. On the other hand there are technologies like RFID, where the tag is completely anonymous unless explicitly paired with a specific individual.

Table 3.1: Summary of the performance of the discussed technologies

	Accuracy	Scalability/ Complexity	Robustness	Personal identification
Miscellaneous				
Image-based [6]	10cm	Moderate/High	Low	Possible
DR [53, 54]	>2m	High/Low	Low	No
VLC [45, 46]	10-15cm	Low/Low	Moderate	Possible
Time-based				
UWB [6]	15cm	Moderate/Moderate	Moderate	No
Ultrasonic [21, 55]	10-15cm	Low/Moderate	Moderate	No
Received signal strength				
RFID [21]	2m	Low/Moderate	Moderate	Possible
WLAN [6, 21]	2m	High/Low	Moderate	Yes
Bluetooth [6]	2m	Moderate/Low	Moderate	Possible
Hybrid systems				
WLAN/BLE [56]	2m	High/Moderate	High	Yes
UWB/DR [50]	15cm	Moderate/High	High	No
UWB/WLAN [6, 52]	15cm	High/High	High	Possible

4

Implementing the indoor positioning system

In this chapter the practical part of the project will be described, including important design decisions with motivations as to why they are made with regards to the goal of the project. First the choice of technology will be described and motivated, followed by a overview of the implemented system and the included parts. After this the method for distance estimation will be explained together with a brief overview of the software architecture.

4.1 Technology

In chapter 1 the goal of the system was discussed where a high accuracy, low latency, good power efficiency, good scalability and a low integrity breach was desired. By usage of table 3.1 in chapter 3 some technologies could easily be discarded right away. WLAN, RFID and Bluetooth are good for low-complexity systems, but are lacking in accuracy and therefore not suitable for this project. Dead-Reckoning and Image based systems are accurate, however their robustness is not as good as other technologies and require a lot of complex techniques for them to be usable in a commercial environment. VLC and ultrasonic are the most accurate technologies, however they scale very poorly which limits their usefulness for larger systems and lack robustness for different environments.

This leaves us with UWB, a fairly new technology that still has not been fully explored and tested, but has shown promising results for these kinds of problems due to the long range and robust nature of the system. The possibility of sending actual data with the messages used for measuring is an added bonus which can be exploited in a potential further version of the system, and the hardware needed can be made very low-power which further increases the scalability of the technology. This technology also offers possible extensions to further increase the accuracy, for example combining the measurements with data from DR using sensor fusion or adding a WLAN architecture on top to be used for time synchronization and information transfer. The main disadvantage of this technology is the relatively high cost of the hardware compared to more established technologies such as Bluetooth. Because UWB is such a new technology, only one supplier exists that sells this hardware which means that the price is high. However this will likely change in the future as new suppliers release their own products, driving the prices lower which cancels out the biggest drawback of UWB.

4.1.1 Ultra-wideband transceiver (DWM1000)

The main functionality of the system is made up by a transceiver made by Decawave, called DWM1000. It is built up from their integrated circuit (IC) DW1000 along with some surrounding components such as a crystal oscillator, an antenna and some power management circuitry. The IC is designed specifically for real time location services (RTLS) in mind, and contains functionality for sending and receiving messages using the UWB technology together with an advanced edge detection algorithm that can determine the time of incoming messages with high precision. The transceivers support a wireless information transfer rate of up to 8.6 mbps, and contain functionality to individually change several parameters such as preamble length to tune the transceivers for the intended area of use. The transceivers can operate in six different frequency bands spaced from 3.5 to 6.5 GHz with different frequency bandwidths. Communication with the transceiver IC is done over a serial peripheral interface (SPI) from the host processor with a maximum speed of 20 MHz which enables fast acquisition of the ranging data which is critical for RTLS systems.

4.2 System overview

In the introduction it was stated that the problem in hand is to find the position of an object. With UWB as technology for this it is needed to use trilateration to find the position of this object making it a two-dimensional problem. In section 2.5 it was stated that it is needed to have N+1 points to be able to find N-dimensional position. This makes the design needing to have three reference points to find the position of the object. From now on these reference points are called anchors and the objects are called tags .

A distance is calculated between the anchors and the tag which then needs to be transferred to a server for processing into a position. This is done over Ethernet between the anchors and the server. The design of the system can be seen in Fig. 4.1 where three anchors are communicating to a tag over UWB and the anchors are communicating to the server over Ethernet. Fig. 4.2 illustrates how the system works to localize a tag using all three anchors. As can be seen the tag initiates all exchanges, which is a decision that was made to ensure that its power consumption is kept as long as possible by enabling it to stay in idle when not actively performing a ranging exchange. The other way to do this would be to have a dominant anchor initiate the exchange, this however would mean that any tag in the area would need to be constantly looking for messages, which in turn draws more power since the receiver will need to be active for extended periods of time. When a poll has been sent out the tag waits for responses from all anchors with a fixed time delay between each one. If a response is not received from all anchors, the tag will then abandon the exchange and return to the idle state, from where it can send out a new poll message after a fixed delay. If all three replies are found, the tag then embeds the time stamps of these into the final message, and sends this to the anchors. Each anchor then uses the times for its own messages, and calculates the distance to the tag which is then sent over Ethernet to the central localization server which trilaterates the position of the tag using all three distances received. More details on how the message structure is designed and how the different time stamps are used can be found in section 4.3.

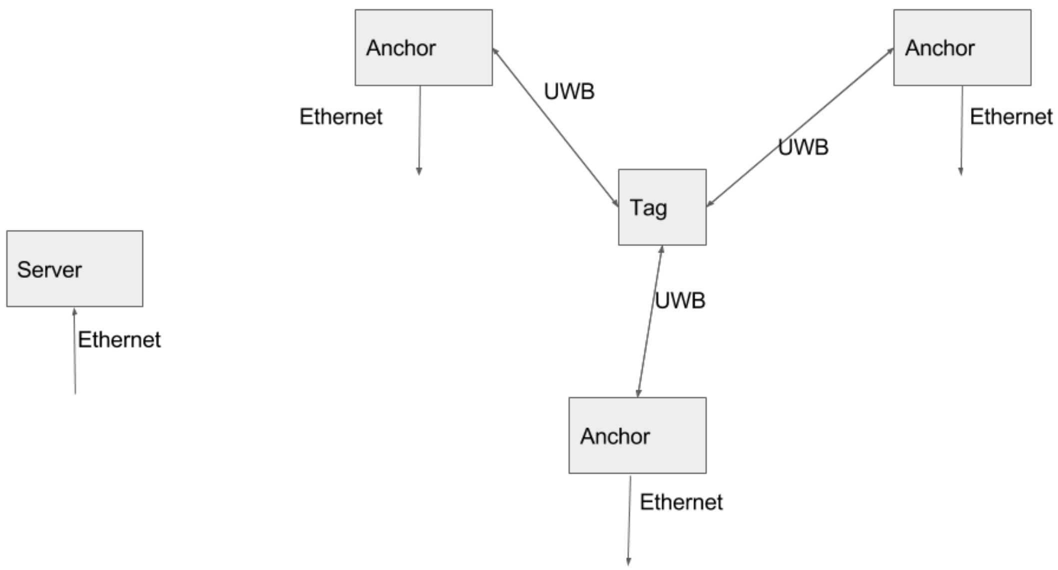

Figure 4.1: Overview of design solution

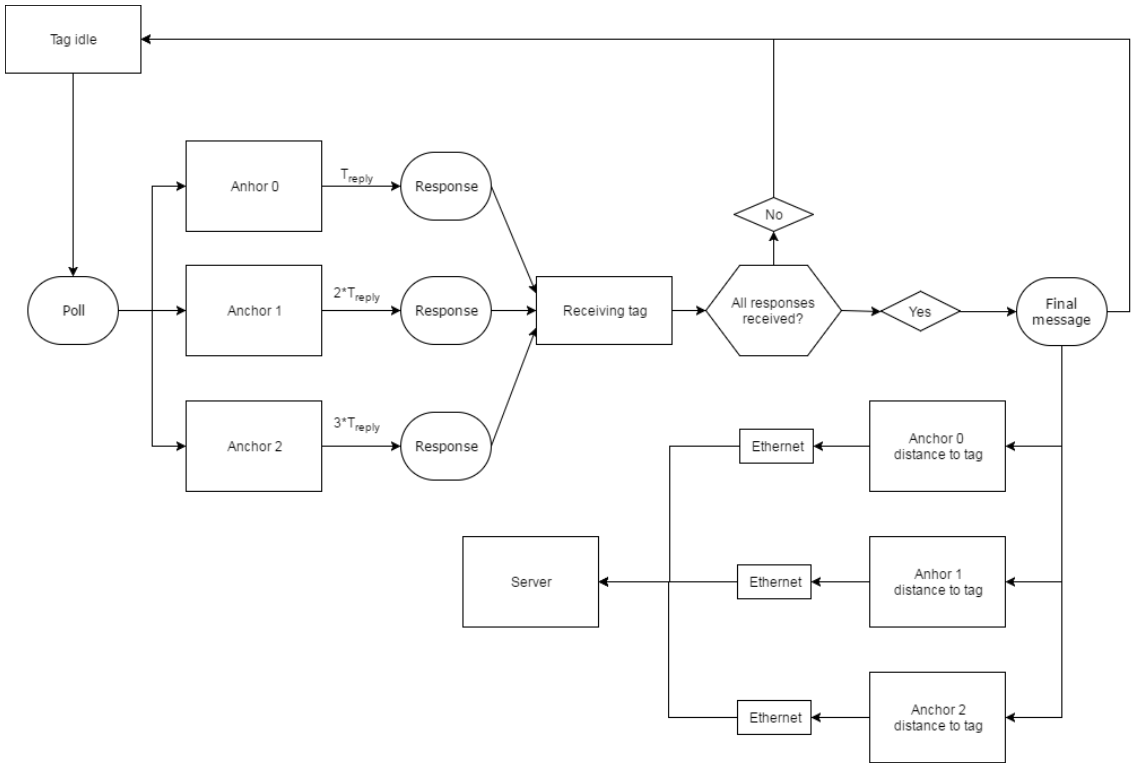

Figure 4.2: A flowchart describing the positioning of one tag

4.2.1 Anchor design

The anchor is implemented on the QRx made by QRTECH, a scalable automotive platform made for rapid prototyping running a version of AUTOSAR made by ARCCORE, that can be seen in Fig. 4.3. AUTOSAR is a operating system standard for the automotive industry, and this was chosen to enable an easy implementation from the start of the project with the added functionality that an operating system brings to time-critical tasks. The OS also includes functionality for communication over SPI and Ethernet, which helped the project in the early stages. The on-board processor expansion board is built around the microprocessor MPC5744P from NXP which has more than enough computational power to handle the use case for this project.

As described in section 4.2 the anchor acts as a responder to communication initiated by the tag to gather the distance between them, which was described more in detail in section 2.4.3. The anchor then relays the calculated distance over Ethernet to the localization server which then performs the necessary operations to calculate the position and display it in various ways.

Figure 4.3: Picture of the QRx made by QRTECH which is used as anchor.

4.2.2 Tag design

The portable part of the system, called the tag, is an important part of the system since it is the part that needs to be carried by the target in order to determine its location. This introduces significant restrictions to the design in order to keep the system practical in a real scenario. Firstly the tag must be able to be moved around freely, which means that the power supply needs to be portable too, without relying on long power cords. This means that a battery powered tag is the only alternative, and this in turn means that the power consumption of the tag is important to allow a small battery to power it for longer periods of time without having to be changed or charged. This was the primary criteria when choosing the few components needed for the tag. The DWM1000 from Decawave was used here too, which stands for a major part of both the footprint and the energy consumption. A small micro-controller is needed to control the transceiver, and for this purpose the Atmel ATMEGA328 was chosen mainly because of its low energy consumption and small footprint. Some peripherals were also added such as dip switches to enable the switching of some settings on-the-fly, a reset button and three LEDs for simple debugging purposes. The whole design is powered by two AAA 1500 mAh batteries attached to the bottom of the PCB. The design was made in the Altium software, a picture of the finished PCB can be seen in Fig. 4.4. As can be seen here the design is compact meaning that it can easily be integrated in items to be tracked, for example shopping trolleys, and with enough power to last for roughly 100 hours of continuous use. With additional power-management techniques implemented such as a sleep mode when the object is not in motion, this time could feasibly be stretched to several weeks of use in a normal setting.

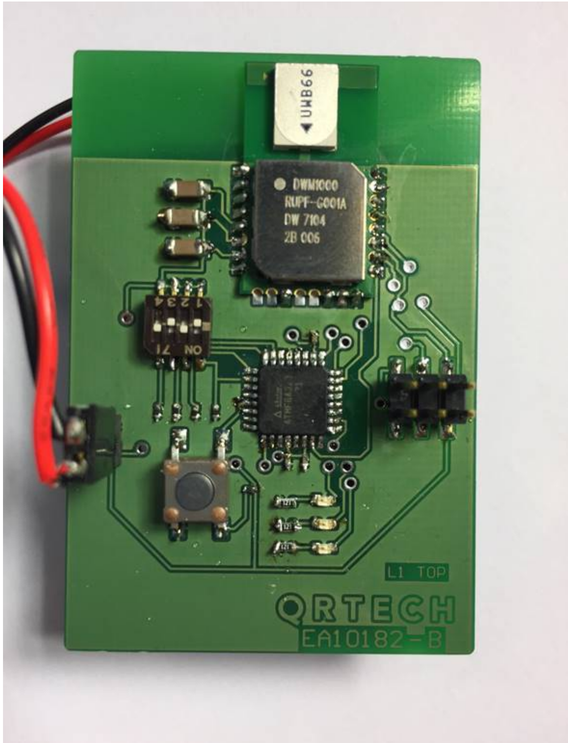

Figure 4.4: Picture of the custom made PCB used as a tag.

4.2.3 Localization server design

For processing the distances and usage of the position a server is constructed which is designed to be a Windows PC. This sever communicates over Ethernet by creating a socket to each anchor when initialized. On the socket the anchors send their distance to the server which process it. The initialization is done from a graphical user interface (GUI) shown in Fig. 4.5. In the GUI it is possible to configure the positions of the anchors and configure how many tags is supposed to be shown. When initialized the GUI will paint up a grid where each box is 10x10 centimeters large. The large boxes represents the anchors positions while the tags current positions are those that are medium sized and the small boxes are the tags old positions which can be hard to see because of the clustering in this picture.

Socket programming is a way of connecting two nodes on a network to communicate with each other. One socket(node) listens on a particular port at an IP, while other socket reaches out to the other to form a connection. Server forms the listener socket while client reaches out to the server.

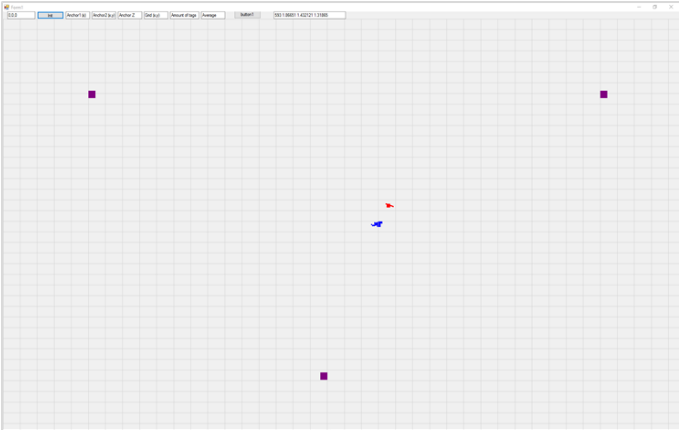

Figure 4.5: GUI for demonstration setup and debug purpose

The processing of the distances are done by the usage of trilateration which gives out the position relative to the anchors, which was described more in section 2.5. In the GUI it is allowed to send in a height of the anchors which was assumed to be 0 in section 2.5. This is possible since it is assumed that the height of the anchors are set at the same height and always above the tags which makes the new equation for z to become:

$$z = z_0 - \sqrt{r_0^2 - x^2 - y^2} \tag{4.1}$$

where z_0 is the height of anchor at origin. As told before $z_0 = z_1 = z_2$.

The reason for using this implementation way for localization server is because it is dynamic, high processing power and opens up for more possibilities.

4.3 Ranging communication

In section 2.4 five different distance measurement methods were introduced. For this project the ToF method was chosen for its excellent accuracy, no need for synchronization and the possibility for two-way communication between the tag and anchor. The downside of this is the increase in messages compared to the other methods for distance measuring which in turn increases the power consumption as well as the time to complete one ranging, however this is less off an issue than the importance of high accuracy. In this section the method of getting the distance using the DWM1000 is described, and how the message structure is implemented to support both multiple tags and anchors.

4.3.1 Two way ranging (TWR)

As described earlier Two way ranging (TWR) opens up for communication both ways between the anchors and tags. This makes it possible to send data between them which opens up a lot of possibilities for indoor positioning systems. In this case it is used for being able to identify tags, which type of message it is and to tag each ranging exchange with an index to aid in data pairing in the case of data not arriving at the server side at the same time. It can also be used to identify when a ranging result is lost, and thereby compensating for it by either using the distance from the previous exchange or discarding the results from the other anchors.

When running a TWR message structure, the largest error source becomes the random drift of the clock frequency between sending the first and receiving the second one. This causes the difference in time used to calculate the distance to contain possible errors, which impacts the overall accuracy of the measurement. To reduce this error one may use higher precision crystal oscillators as a clock reference, however this can increase the cost of the system significantly. What can be done instead is to add a third message to each ranging exchange, called a poll message. This message structure is called a double-sided TWR, and offsets a large portion of the drift error by taking the average of two ToF meassurings. Assuming that the clock drift error is uniformly distributed, this will remove most of that error thus increasing the accuracy by a large amount at the cost of an increase in the number of message per ranging exchange. An illustration of this message structure is shown in Fig. 2.3, and to be able to calculate ToF by this method the following equation is used:

$$T_{prop} = \frac{T_{round1} \cdot T_{round2} - T_{reply1} \cdot T_{reply2}}{T_{round1} \cdot T_{round2} + T_{reply1} \cdot T_{reply2}} \tag{4.2}$$

where T_{prop} is ToF and the others are the times represented in TWR between message Poll-Response and Response-Final. Another advantage of this message structure is that it allows the tag to initiate the ranging exchange, allowing it to stay in a low-power mode until it decides to send a poll message. This saves power, and simplifies adding more tags to the system.

4.3.2 Multiple anchors

The method described in section 4.3.1 is designed for communication between one anchor and one tag. However to be able to find the position of a tag it is necessary to have the distance to three anchors as described in section 4.2. To allow distance measuring to three anchors in the most efficient way possible the message structure needs to be modified, the result can be seen in Fig. 4.6. As before the tag sends out a poll message which is then received by all three anchors. The anchors then respond to this message with different pre-defined delay which is long enough to not make the anchors interfere between each other, and gives the tag enough time to receive each one separately. Finally the tag sends out the final response, which contains all the time measurements collected by the tag, to all the anchors which can then extract the times for their individual exchanges with the tag. This makes it possible to calculate the distance between each anchor and the tag with the minimal amount of messages, while keeping the advantages of double-sided TWR described earlier. The ToF in this case is the T_{prop} for each anchor.

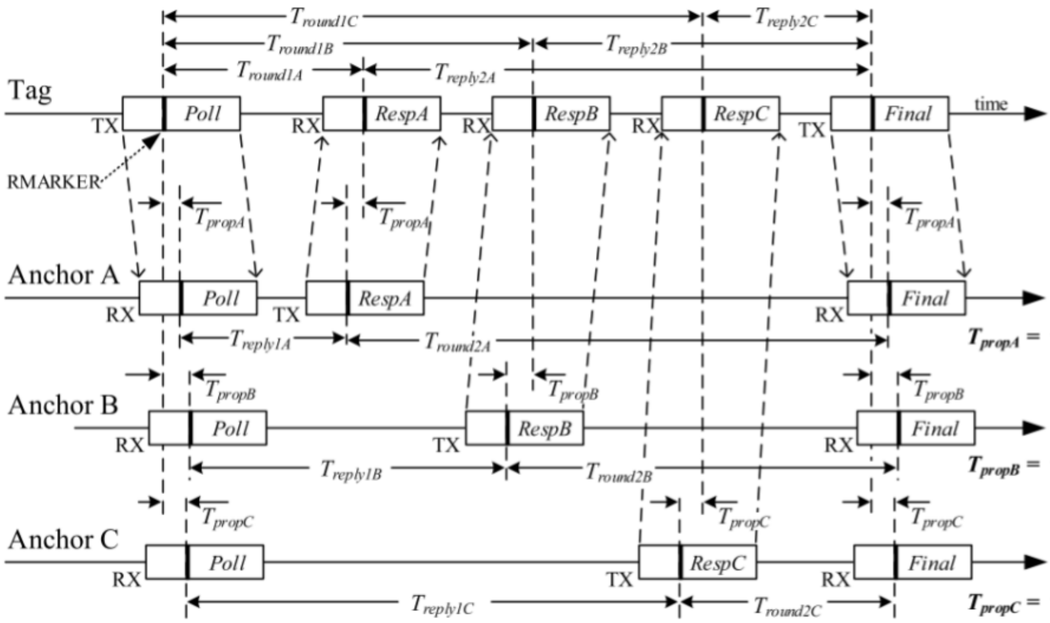

Figure 4.6: Two way ranging with three anchors and one tag with a poll message [28].

4.3.3 Multiple tags

For being able to track multiple tags an extra couple of bytes were added to the message body to enable the anchors to identify which tag started the poll. When a ranging has been initiated by a tag, no other tag will be able to initiate their own exchange until the previous has been completed, which is facilitated by the anchors ignoring messages from other tags when in the middle of an exchange with another one.

By adding more tags the performance of the system will degrade, and the possible frequency will be limited depending on how many tags are used. This maximum frequency depends on the time needed for a complete ranging exchange, which in turn depends on several factors such as the message length, the speed of transmission and the time needed for the hardware to perform the necessary operations between messages. Therefore the system may be designed differently for different applications depending on the specific needs and the resources available. For this project the focus has been to evaluate the system for several concurrent tags, however further optimizations such as active scheduling of poll message time slots could be employed to increase the amount possible.

4.4 Error sources of the RTLS system

In general, UWB is a highly accurate technology for RTLS systems due to the robust nature of the signal and the amount of energy that can be transferred over a short amount of time, as described above. This means that the largest error sources will not originate from innate flaws of the technology used, which is the case in systems relying on for example RSSI, but from limitations in the hardware used to measure the times used in the distance calculations. Here the main three sources of error will be presented, together with what has been done to minimize their impact.

4.4.1 Antenna delay

The first and possibly largest error source is the delay which results from the time it takes for the signal to propagate through the antenna when receiving and transmitting. Since this is a function of antenna characteristics such as size and material, as well as the length and quality of the transmission line between the IC and the antenna, this time will vary between implementations. The DWM1000 contains parameters that allow this to be compensate for, and these values need to be calibrated to get the optimal performance out of the system. This was done by placing an anchor and a tag 8.1 meters apart and measuring a large enough set of samples to determine the mean distance measured. The delay was then tweaked to adjust the value closer to the known distance, and this process was iterated until the results were satisfactory. Since the delay parameters have a finite resolution some small offset was still present after this calibration process, but this was then compensated for in software.

4.4.2 Received signal strength bias

Another source of errors comes from the time stamping in the DWM1000, which has a bias depending on the RSS. This is detailed in Decawave's application note "Sources of error in DW1000 TWR schemes" [57], where the bias is shown to vary from around -11 to 8 centimeters which is significant for the accuracy of this system. However this can be corrected by using an approximate equation from taking samples for multiple distances within a controlled environment and from that designing an equation to correct this offset.

This equation would use the measured distance D to roughly estimate how much bias was introduced by the signal strength, and proceeds to correct the final result based on this. For systems with very high requirements for accuracy over larger distances, this simplified version of correction will not be enough and a more complicated method based on a large number of measurements should be used instead. In this case however the simplified method works well enough, and results in this error source having a minimal effect on the overall accuracy. The correction values are determined when analyzing the results of the distance tests.

4.4.3 Clock frequency drift

The third significant source of error using this particular technology is the frequency drift of the reference oscillator used for the system clock in the DWM1000. Clock frequency drift is defined as a error in the actual frequency over time compared to the ideal, and is calculated in ppm. For example, a 1 MHz oscillator with a relative drift of 1 ppm a will have a frequency error of $\Delta f = \pm 1$ Hz every second. A drift in frequency from the calculated one results in an error Δt being introduced to the time stamp for the transmit or reception of a message, since the system time is defined as a set number of clock pulses by the internal oscillator, which uses the external crystal oscillator as a reference. Naturally this error can be reduced by choosing a reference oscillator with a smaller frequency drift, but since the more accurate oscillator also come with a higher cost this is not always a viable solution. However the magnitude of this error will correlate with the difference in time between the timestamps being used for the calculations, and this time is dominated by the defined t_{reply}. However the chosen message structure of double-sided TWR has the distinct advantage of using the average of two messages, which reduces this error to correlate with $\Delta t_{reply} = t_{replyA} - t_{replyB}$ [57]. In practice this means that as long as the difference in t_{reply} is kept small, the error introduced by the frequency drift will subsequently be minimised.

4.5 Implementation summary

In summary a UWB RTLS with three anchors and multiple tags has been designed for indoor tracking over moderately large distances with high accuracy. In addition to this a localization application has been created to process the data and visualize it in real-time on a PC. The main functionality is provided by the UWB transceiver DWM1000 from Decawave and is used for both the anchor and tag part of the design described above. The anchor is as described in section 4.2.1 designed around the platform QRx by QRTECH, running a version of AUTOSAR from ARCCORE. The anchor serves as a reference point for being able to find the tag, and computes its own distance to the tag and sends this information to the localization server over Ethernet.

For the tag the power efficiency and portability are more important than computational power, so a custom PCB was designed for this purpose as described in section 4.2.2. The result is a small, battery powered device which can be attached to the target that needs to be tracked with ease, and requires little maintenance to stay operational for long periods of time.

The localization server is used to gather the distances between the tags and anchors from each of the anchors and use this data to trilaterate the position of the tags. This server includes a graphical interface to show the position of the tags in real-time relative to the anchors, described more in detail in section 4.2.3.

In the end the communication between tags and anchors is described and how this is designed to get the maximum accuracy possible in the least amount of time. This includes the message structure TWR along with a description of how three anchors are to be able to communicate with one tag, and how multiple tags are handled by the current system. The last part of the chapter then presents some of the error sources present in the system together with the measures that have been taken to minimise the impact of these errors on the final accuracy.

5

Results

In this chapter the the performance of the system will be tested, and the results from these tests are presented. These results will then be discussed in the following chapter. First the accuracy of the UWB technology is tested by performing four simple distance measurement tests at different distances to establish a best-case accuracy. After that the full RTLS system is tested under several different conditions and ranges. The power consumption of the tag is then presented as a function of updatign frequency. The results are gathered from testing just one of the tags and not comparing the performance between tag to tag since this is something that should be negligible or fixed in the hardware. There is also no offset correction in the results except for an antenna delay calibration.

5.1 Distance measurement

The following tests uses one anchor and one tag to measure the accuracy of a fixed distance. Four different tests are carried out with the tag placed at 5, 10, 15 and 20 meters away from the anchor, and 5 000 ranging exchanges are performed. The purpose of the tests is to verify the best-case accuracy of the DWM1000, and to detect any possible error sources that could be corrected for by examining how the measurements vary over time.

5.1.1 5 meter distance test

In Fig. 5.1 the result of 5 000 samples with a sample rate of 7.1 samples per second is shown in a histogram and as a function of time at a distance of 5 meters. Here it can be seen that the normal distribution is at around 4.91 meters which is confirmed with the average distance for this test, which was 4.91 meters, with a standard deviation of 2.02 centimeters. In table 5.1 a summary of the data is presented together with the results from the three other tests.

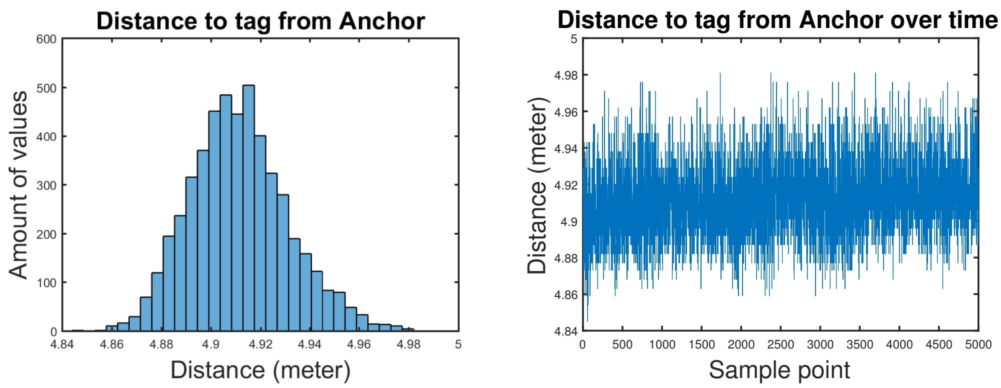

Figure 5.1: Results from the 5 meter test, presented in a histogram and as a function of time.

5.1.2 10 meter distance test

In Fig. 5.2 the result of 5 000 samples with a sample rate of 7.1 samples per second is shown in a histogram and as a function of time at a distance of 10 meters. Here it can be seen that the normal distribution is at around 9.94 which is confirmed with the average distance for this test, which was 9.94 meters, with a standard deviation of 2.27 centimeters. In table 5.1 a summary of the data is presented together with the results from the three other tests.

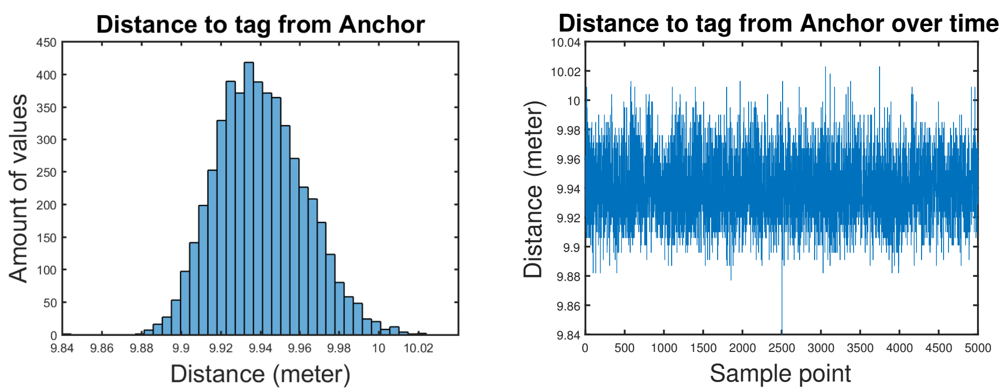

Figure 5.2: Results from the 10 meter test, presented in a histogram and as a function of time.

5.1.3 15 meter distance test

In Fig. 5.3 the result of 5 000 samples with a sample rate of 7.1 samples per second is shown in a histogram and as a function of time at a distance of 15 meters. Here it can be seen that the normal distribution is at close to 14.94 meters which is confirmed with the average distance for this test, which was 14.94 meters, with a standard deviation of 2.51 centimeters. In table 5.1 a summary of the data is presented together with the results from the three other tests.

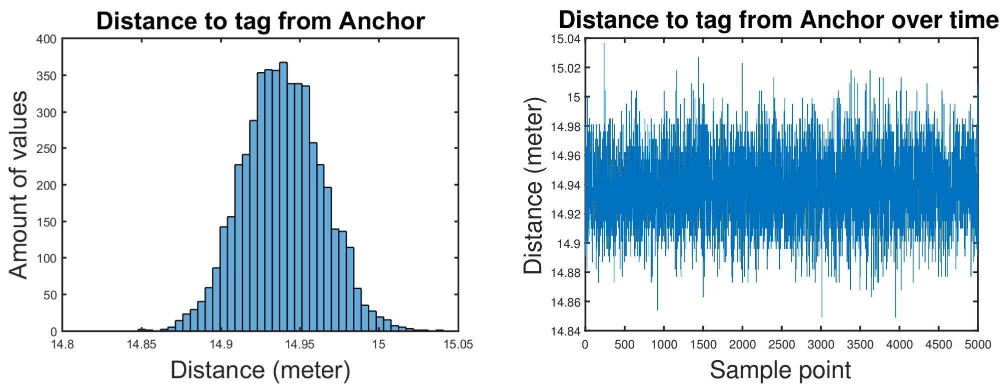

Figure 5.3: Results from the 15 meter test, presented in a histogram and as a function of time.

5.1.4 20 meter distance test

In Fig. 5.4 the result of 5 000 samples with a sample rate of 7.1 samples per second is shown in a histogram and as a function of time at a distance of 20 meters. Here it can be seen that this test has multiple normal distributions which are located at around 19.76, 19.92 and 20.12 meters. The average value of this test is 19.88 meters with a standard deviation of 15.35 centimeters. In table 5.1 a summary of the data is presented together with the results from the three other tests.

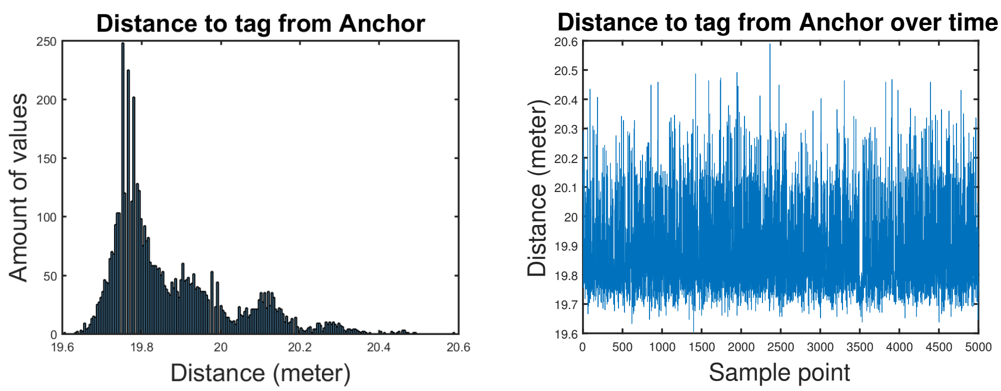

Figure 5.4: Results from the 20 meter test, presented in a histogram and as a function of time.

5.1.5 Distance measurement summary

In table 5.1 the average, maximum, minimum and the standard deviation is given for all four of the distance measurement tests.

Table 5.1: Results from distance measurement tests

	5 meters	10 meters	15 meters	20 meters
Average value	4.91	9.94	14.94	19.88
Maximum value	4.98	10.02	15.04	20.59
Minimum value	4.85	9.84	14.85	19.61
Standard deviation (cm)	2.02	2.27	2.51	15.35

5.2 Position measurement

For gathering enough data of the performance of the system multiple different tests were performed. Firstly a small scaled but very controlled test is used to determine the accuracy at a very controlled environment. The second environment was a large scale that had both a LoS part and a NLoS part for evaluation. This environment was less controlled but a more practical setup than the small scale one. During this environment a slow and fast movement speed was tested along with having the tag in a pocket and having multiple tags in the system was tested.

5.2.1 Small scale

For measuring the accuracy of a moving object a miniature train-set was set up which had an average speed of 26 centimeters/second around the track. The track was just a simple loop with some straights in it for being able to have controlled test results. This loop was 180x72 centimeters large, making a 464 centimeters long railway shown in Fig. 5.5 which took about 18 seconds per lap recorded. During the test 10 laps were recorded along with a pause in the beginning. All of the measuring points are shown in Fig 5.6 along with the position of the anchors and the railway. The dotted grid shown in this figure is 10x10 centimeters large.

Figure 5.5: Test environment used during the test, an electronic miniature railway with length of 464 centimeters with tag attached on train shown in the circle.

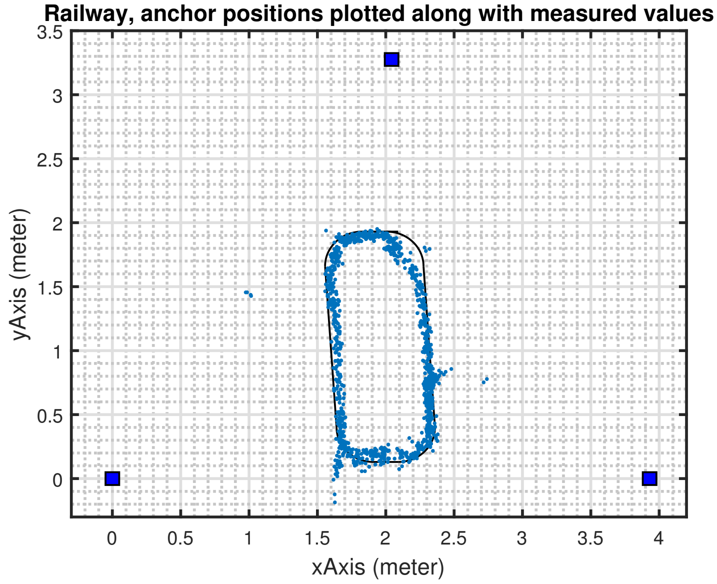

Figure 5.6: The sampling points during the small scale position test plotted along with the railway and the anchors.

The data shown in the previous figure is compared to the closest point of the railway which makes it possible to get the error of the position measurements which is shown in Fig. 5.7 where a histogram of the distance to the railway is presented along with a distance over time graph is shown. The average, maximum and standard deviation is given for the distance to track error in table 5.2.

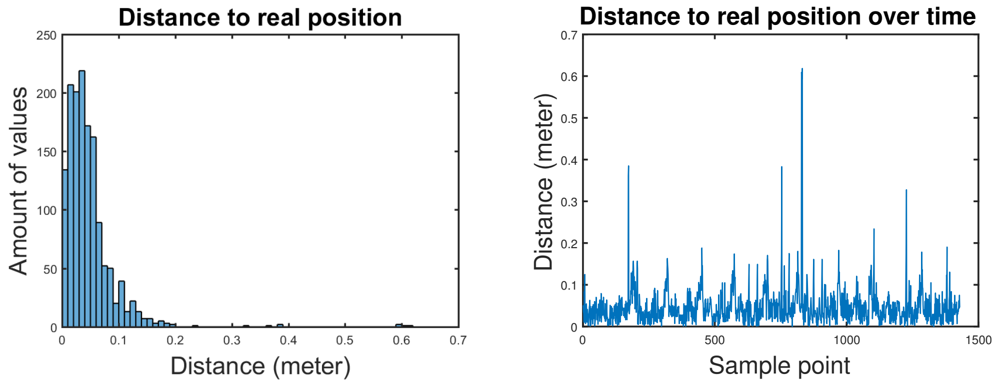

Figure 5.7: Results from the small scale position test, presented as a histogram and as a function of time.

Table 5.2: Results from small scale position measurement test, all shown in centimeters

	Distance
Average error	4.72
Maximum error	61.84
Standard deviation	4.76

5.2.2 Large scale (slow)

In Fig. 5.8 a map over the course walked is shown as a line along with the three anchors are shown at coordinate (0,0), (12,0) and (12,13). There is also a concrete pillar shown as a large red circle. The measured data that is shown in small dots are from five different tests for showing recurrence. The start point of the walk was at (11,12) walking down to (11,2.4) and then turn to (1.44,2.4). Now there was a 4 meter walk up to (1.44,6.4) and at this point the tag was moved into a room to (1.44,9.8).At this endpoint a turn around was made back to (1.44,4.8) where a turn to the left was made to the coordinate (3.84,4.8) and then walking to the stop point at (3.84,9.8). The walking distance was 38.8 with speed different by a small amount between test to test but was around 40 centimeters/second.

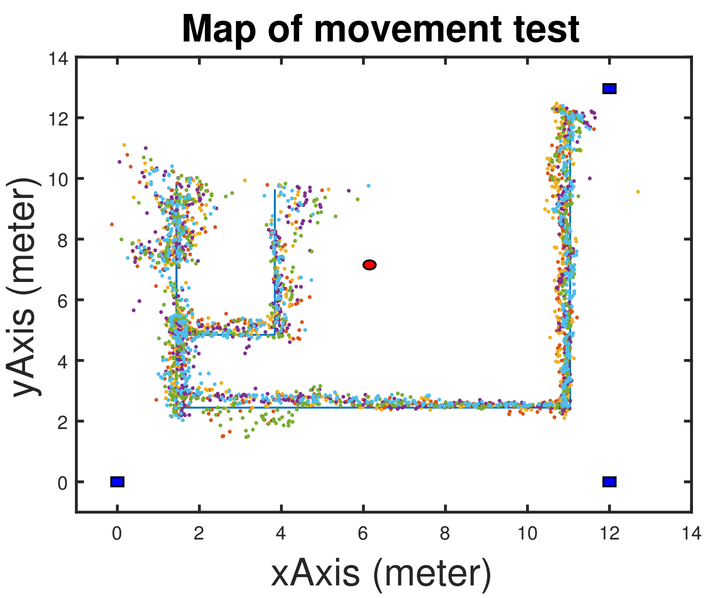

Figure 5.8: The sampling points during the large scale (slow) position test plotted along with the course, concrete pillar and the anchors.

The measured points are compared to to the course that was walked and the result of the distance to this line is shown in Fig. 5.9 as a histogram, where the left one is for the first half of the course and the right one is the second half of the course, i.e just before walking into the room where NLoS starts to affect the result. The histogram for the complete course is shown in Fig. 5.10.

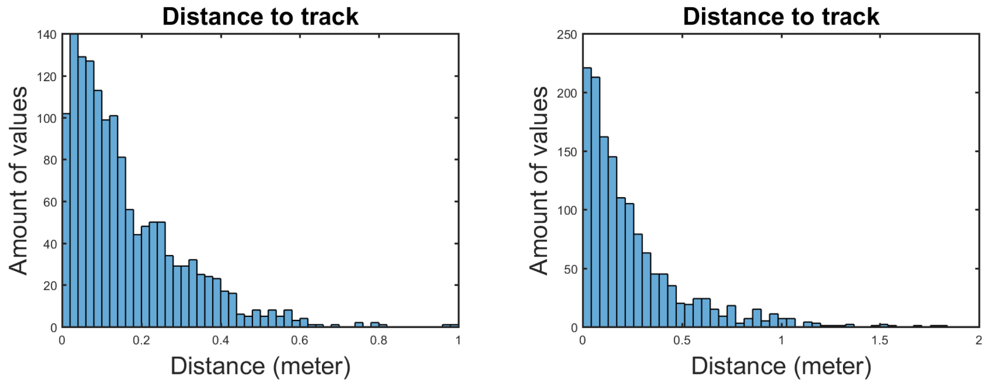

Figure 5.9: Histogram of distance deviation from the course during large scale (slow) position test for first half (left) of the course and second half (right).

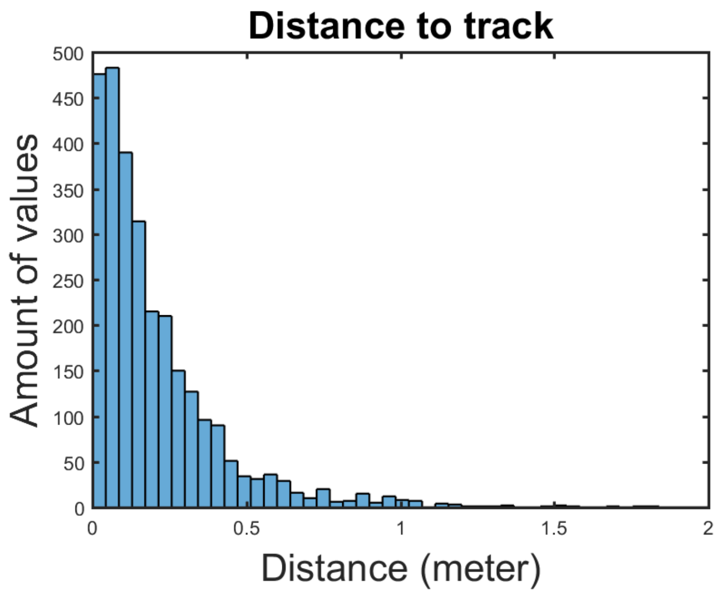

Figure 5.10: Histogram of distance deviation from the course during large scale (slow) position test for the full test.

In Fig. 5.11 the distance to the course over time for all five of the tests are shown. The data of this is shown in table 5.3 where the average, maximum and standard deviation distance error is given.

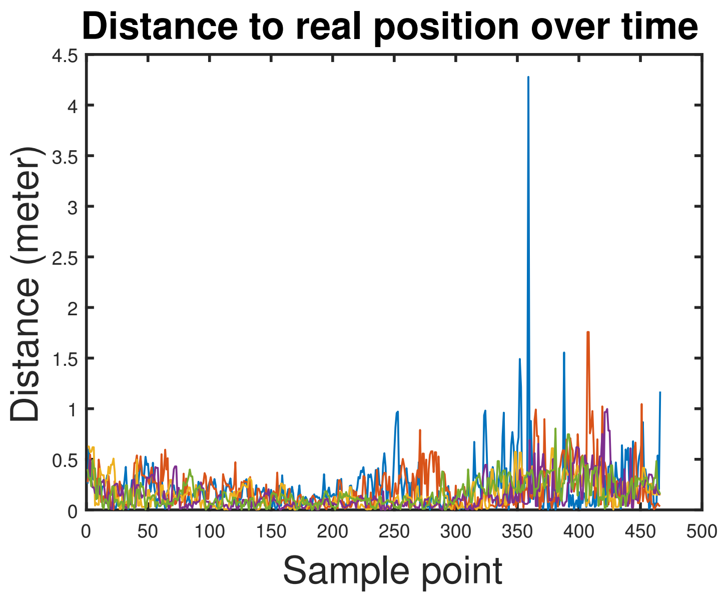

Figure 5.11: Results from the large scale (slow) position test, presented as a function of time.

Table 5.3: Results from large scale (slow) position measurement tests, all shown in centimeters

	First half	Second half	Total
Average error	16.18	25.40	20.79
Maximum error	100	428	428
Standard deviation	13.97	29.94	23.81

5.2.3 Large scale (fast)

This large scale test used a much faster walking speed of around 1.3 meter/second and the map along with the data points collected is shown in Fig. 5.12. The average, maximum and standard deviation distance error to the course is shown in table 5.4.

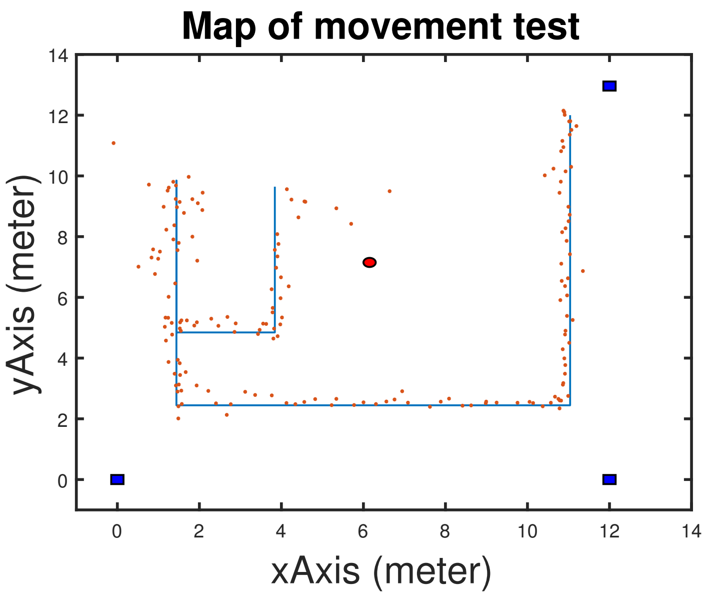

Figure 5.12: The sampling points during the large scale (fast) position test plotted along with the course, concrete pillar and the anchors.

5.2.4 Large scale (pocket)

During this test a walking speed of about 58 centimeters/second was used and at this time the tag was placed in the front pocket of pants and the map of the data points collected are shown in Fig. 5.13. The average, maximum and standard deviation distance error to the course is shown in table 5.4.

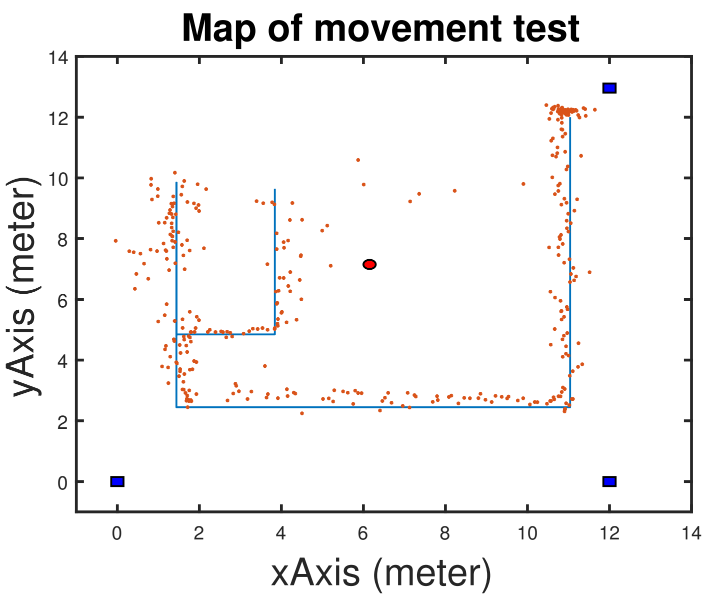

Figure 5.13: The sampling points during the large scale (pocket) position test plotted along with the course, concrete pillar and the anchors.

Table 5.4: Results from large scale (fast/pocket) position measurement tests, all shown in centimeters

	Fast	Pocket
Average error	26.05	30.37
Maximum error	282	354
Standard deviation	33.96	37.37

5.2.5 Multiple tags in the system

During this tests two tags were used which were held in different hands a small distance from the course and then following it. The map of the data points collected are shown in Fig. 5.14. This to prove that it is possible to have multiple tags in the system and still have a working position. This test was done with a walking speed of around 46 centimeters/second.

What about time delay?

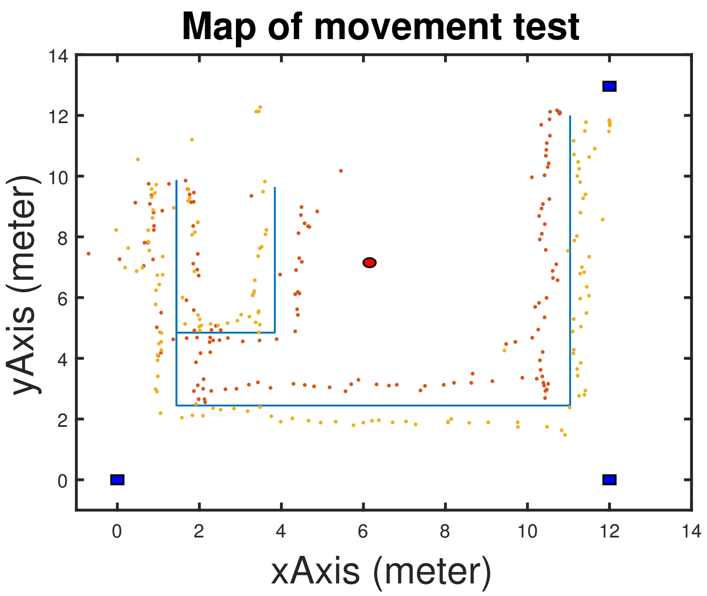

Figure 5.14: The sampling points during the large scale (multiple tags) position test plotted along with the course, concrete pillar and the anchors.

5.3 Power consumption of tag

The maximum current drained by the tag is 50.8 mA when sending a message, and the idle current is 17.6 mA. The average current drained during 60 seconds of continuous transmissions at 1 Hz updating frequency is 22.4 mA making it possible for two 1500 mAh batteries to provide power for 134 hours of work at most. In practice this number will be slightly lower since the voltage supplied by the batteries will drop below the nominal operating voltage of the DWM1000. The difference between idle current and average gives how much the transmissions affect the result per Hz, which is 4.8 mA/Hz. This could be summarized by the following equation:

$$I_{avg} = I_{idle} + f \cdot 4.8 \tag{5.1}$$

where I_{avg} is the average current drained and I_{idle} is the current drained when no transmissions are being done. f is the updating frequency set and 4.8 mA/Hz is how much 1 Hz affect the average current. This gives that a 10 Hz updating frequency would have about 46 hours of battery while the maximum amount of time would be at 170 hours with the tag in a permanent idle state.

5.4 Summary of results

Three different test environments were used, distance measurements of 5, 10, 15 and 20 meters distance for evaluation of the technology. Second test was a well controlled small scale positioning test and lastly a large scale uncontrolled test was carried out where first half was LoS and second was NLoS.

The technology has a standard deviation of less than 2.5 centimeters for all cases except for the 20 meter test but there are some offsets which is below 10 centimeters. As for the system it is possible to track multiple tags at the same time and during the well controlled small scale test the average positioning error was below 5 centimeters while for the larger scale test it was at 16 centimeters during the LoS path and 25 centimeters during the NLoS part.

During the large scale test a high movement speed was tested which had a low influence of the end result as with having the tag in a pocket had a small influence as well.

Lastly a power consumption test was done where the consumption during idle time and transmission was measured for being able to get the maximum measuring time as a function of updating frequency. For an updating frequency of 1 Hz the tag could be active for a total of 134 hours.

6

Discussion

In this chapter the method of the project is discussed along with a discussion of how the implementation was carried out. A discussion of the tests is given along with an evaluation of the results given. After this a discussion of some trade-offs that has to be taken into account when implementing a system is discussed and lastly some ideas of how the system could be improved are given.

6.1 Discussion on project method

In section 1.4 an outline of how the project was to be carried out is presented. The first part of the project consisted of performing an initial review of different technologies, where it was found out that UWB would be a suitable technology to implement. However, since this was a literature review it is not certain that this technique is as good as it looked. The project method could be improved by comparing basic systems using the two most promising technologies, and then choosing the best one for our own implementation. The same can be said about when choosing which manufacturer to purchase the hardware from. The only real UWB transceivers available are the ones that we have used, however if another technology had been chosen there would have existed several different manufacturers to choose from. Then it would have made sense to perform the initial performance evaluation on several of these manufacturers hardware, and then choose the best one for the full implementation. These two improvements to the project method would have ensured that the end system was implemented in the best way possible with a higher certainty compared to choosing technology and hardware manufacturer based solely on a literature review.

6.2 Test limitations

In the testing of the accuracy of the system three different testing environments were used, one for distance measurements, one for small scale position test and one for large scale position measurements as described in chapter 5. In this section the reliability of these environments are discussed, and how their limitations affect the reliability of the results.

A source of error present in all three tests comes from the voltage level of the tag. With two 1.5V batteries as a supply the voltage is on the low side from the start. From measurements the voltage of a new battery was between 1.5V and 1.6V, and this may cause the output signal power to vary slightly, especially when the batteries start to drain and the voltage drops. Since the DWM1000 introduces a bias depending on the received signal strength, this may affect the results. An effort was made to minimize this by changing the batteries when the voltage started to drop, but there may still be some error introduced by this.

A limitation set during all the tests are that it is just one of the tags that is evaluated rather than testing the drift between hardware to hardware. Since the results are as good the tag used is most likely fully functional.

The DWM1000 circuit has multiple configurations for example changing the transmit power, transfer speed among others. During this project it was not evaluated to test different configurations and only using the initial ones given by Decawave. This makes the evaluation of the system not completely tested. The testing of different configuration settings would be a good test for further information of the performance of this method.

6.2.1 Distance environment

The environment set up for this test was a full LoS test which was designed to show the capabilities of the hardware in optimal condition. The measurement of the real distance was using a 5 meter measuring tape which naturally will introduce some measuring errors. Steps were taken to minimize these errors, however we estimate that they could be as large as 5 centimeters. Since this is as large as the standard deviation of the tests, these errors are significant. This means that the tests are mostly useful for determining the random part of the error related to the clock drift.

6.2.2 Small scale position environment

For this test the tag was fixed to a miniature train on a track to get as controlled of a test environment as possible. This allowed for the tag to be moved along precisely the same track for multiple tries, giving a good way to evaluate the stability of the system without getting any changes between runs. The speed of the train varied slightly around the track since the voltage of the railway varied slightly, which caused some sections of the track to get fewer measuring points than others, however this difference is small enough not to affect the test. The measurements between the anchors and the position of the track were done using a 3 meters measuring tap making this distance have an error affecting the end result, which shows from the small offset that the measured values have in Fig. 5.6 .

6.2.3 Large scale position environment

During the large scale position tests the square patterned floor was used to measure all the distances. These squares were measured to be 48x48 centimeters with high accuracy, however the space between two squares varied slightly which adds a small error to these measurements. All in all we estimated this error to be smaller than would be possible from using the tape measure, which is why this method was used. These squares also provided straight lines to follow when walking the course to ensure that the person walking avoided weaving between the reference points. The largest error source for this test comes from the person walking the track who held the tag in his hand. This means that the actual position of the tag may drift a bit around the measured track. This error is hard to estimate but could be up to 5 centimeters away from the course in either direction.

6.3 Distance measurement

In table 5.1 the data for the distance measurements tests were presented. It could here be seen that the standard deviation was promising, and indicates that the system should be able to have an error well below the goal of set up in introduction. In table 3.1 the UWB design was stated to be able to achieve an error below 15 centimeters, and this point seems to be validated from the results gained here. As discussed in section 4.4 there are multiple sources of error in the measurement data, which means that the inaccuracies seen here can be explained. First the antenna delay was calibrated for a distance of 8.1 meters, however this proved hard to do with high enough accuracy to fully center the values around the true value. This however can be corrected for in software, and from studying the 10m test results this calibration offset seems to be close to 7 centimeters. The next error present is the range offset bias which depends on the received signal strength. When applying a correction of the calibration error by increasing all values by 7 centimeters, the error from the real value is reduced even further, and the remaining offset is a combination of the signal strength bias and measuring errors made when setting up the tests. The uniform distribution of values around the center point is likely due to clock drift, which is a random error described in section 4.4.

For the long 20 meter test, the results are significantly worse than for the other three, and part the reason for this can be seen in the histogram in Fig. 5.4. Here a large peak is present at 19.8m, which could be very close to the actual value when taking into account measuring errors from us and both the calibration and received signal strength bias. However, the data also shows that the system sometimes has trouble communicating at that range. The smaller peaks at larger distances suggests that sometimes the receiver misses the initial signal, and instead receives and time stamps a reflection from one of the walls around. Most likely, for systems operating at these ranges the transmitting signal strength should be increased, and a better antenna could be used to avoid these problems.

In summary these tests show the accuracy possible by the UWB technology, and provided us with an upper bound on which distances are possible before our system risks becoming innaccurate.

6.4 Position measurement

In this section the results from the actual position estimation tests will be discussed, including how they relate to the goal set up in the beginning of the project how these results compare to what we expected.

6.4.1 Small scale

In table 5.2 the data from the small scale measurement test was presented, and comparing it to the goals set up in in section 1.3 these results are very promising. The standard deviation of the result is a mere 4.7633 centimeters which is significantly better than expected, without any filtering done which likely could improve the result even further. Since the test was ran for ten laps around the track, we consider these results to be reliable enough to be presented as real. This however is a small scale test which means that most systems will not be able attain such precision, simply because they want to operate over a larger area. In addition the position of the track was precisely known, minimizing the error caused by the test environment.

These results alone are not that significant when compared to other types of positioning technologies, since there are several that can match the accuracy over such a small area. However they do further prove the capabilities of UWB, and provide an upper bound for what our system is capable of. This test could be extended to test the real-time capabilities of a positioning system by knowing the speed of the train and setting up a couple of checkpoints to synchronize in time using some kind of sensor, however we felt that this was outside of the scope of the problem definition and therefore did not justify the time needed to set up.

6.4.2 Large scale

In table 5.3 the data from the slow large scale tests were given. This gave that the standard deviation distance error was 13.9711 centimeters for the half of the course that was LoS while it was 29.9439 centimeters for the half that was a combination of LoS and NLoS. This test environment is much closer to a real setting, and these results are therefore both significant and very promising. An accuracy of about 30 centimeters in mixed conditions is good enough for most applications for indoor positioning, and this shows that it is indeed feasible to use UWB for this purpose. The real result is slightly obscured because of the human error in this test, but it still shows an accuracy far better than our initial expectations. Since the result from the distance tests were so good, we can assume that the positioning could be even better in a more controlled test environment.

During the theory, NLoS was discussed as a large problem for a lot of technologies, which can be crucial in real environments where a clear line of sight cannot be guaranteed. UWB was said to be more robust against NLoS than many other techniques, so we designed our test to incorporate a NLoS part to study how it affects the results. This could be seen in the map figures for the large scale tests where the accuracy started to vary when going into the room at coordinate (1.44,6).

The mean error distance from the actual route increased, and there were significantly more large deviations. I could also be seen that at around (3,2.44) where a solid concrete pillar blocked one of the anchors, causing the signals from that anchors to be reflected before reaching the tag, thus increasing the distance measured. The points at the end of the course also varied a lot which is probably because of the concrete pillar, and because the anchor at (0,0) is being blocked by a wall. From these results it can be said that UWB does handle NLoS quite well up to a certain thickness of the material blocking, and even then the reflections will still likely reach the receiver. However the accuracy suffers, and more extreme values are seen making it important to perform some sort of processing on the data to minimize the effect these have on the final position.

The large scale test used a higher moving speed in one of the tests to see if this would affect the end result. The standard deviation from this test did increase by 10 centimeters in comparison to the five slow tests, however this may be caused by the fact that the fast test gets fewer sample points meaning that a few large error could have a significant impact on the final result. This error could also be seen getting even larger during the test when the tag was carried in a pocket. By removing the last 10 samples for both the fast and pocket test however, the standard deviation would go down by 10 centimeters and 15 centimeters respectively, causing the error to be similar to the slow test. This indicates that there were likely some human error involved when the test was started and stopped, with the end result that the speed of the carrier or covering the tag with something thin does not impact the accuracy in a significant way. The pocket test is especially important to note, since this means that the tag could likely be covered by some kind of casing without losing accuracy, which would be necessary for a commercial system.

For proof of concept a multiple tags test was added just to show that this is possible. That this worked could easily be seen in Fig. 5.14 where the two tags were moved on each side of the course, with roughly the same distance to the center. The human error is much larger here due to the difficulty of holding two objects at the same distance from each other, but the important thing to note from this test is that multiple tags can be used concurrently, and the accuracy does not suffer noticeably from it.

6.5 Performance trade-offs

The possible scope of indoor positioning is a broad subject, and there are as many solutions as there are variations in the problem to be solved. A system therefore needs to be developed with the particular problem in mind, and the performance trade-offs needs to be analyzed to provide the best result for the intended application. For this project a general system with a good all-around performance has been developed with the aim of evaluating the feasibility of building such a system for commercial applications. Focus has been on improving all areas of the performance metrics to a level where it can be useful in most settings, however there exists a lot of room for improvement for a specific case. Fig. 6.1 attempts to visualize four of these important factors for a systems overall performance. The shaded area represents the scope of this project, representing a balanced all-around system. The area covered can be seen as a prediction of the system complexity, which highlights the fact that to improve the system in one aspect either the complexity will grow or another area will suffer instead.

For example, if power efficiency is not an issue because all of the system parts will have access to large power sources, the implementation can disregard this factor and instead focus on the precision by doing more frequent updates and using more powerful hardware capable of filtering the results. On the other hand, if the important part is to have a lightweight system that can be installed on small tracking targets, and run for a long time without needing maintenance the update frequency can be lowered and the tags can be put into sleep mode for long periods of time. This will result in a ranging frequency, which in turn yields a longer latency between position estimates and thereby also a lower ability to process the data to increase the accuracy. All in all, to get the best performance for the intended use case the system needs to be properly designed with this in mind to get the most out of the technology.

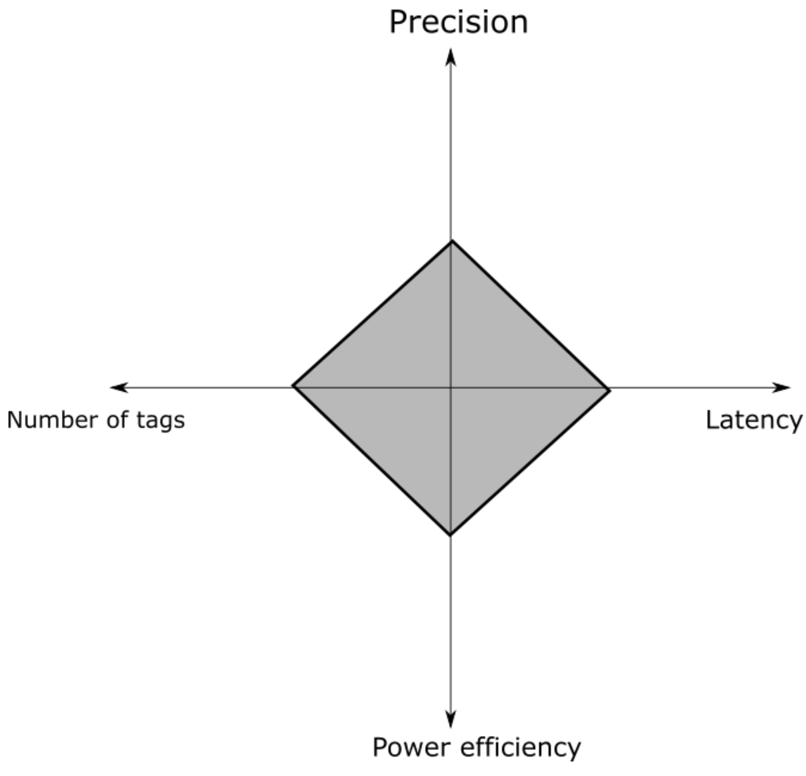

Figure 6.1: A visualization of the system performance, with the shaded area representing the current implementation and the size of this area representing system complexity.

6.6 System performance

In the introduction there were some performance factors introduced. The end product manages to get a **accuracy** well below 2-3 meters including the **latency** inaccuracy except for some times which is discussed more in next section. The latency is during testing set to about 20 ms in the distance gathering which could be lowered more. There is also a small latency for the Ethernet communication which is no more than 10 ms. In an average moving persons speed at 1.5 meter/second this would mean 4.5 centimeters inaccuracy of the position from latency. As told before there is some sporadic Ethernet latency which is discussed more in next section.

As told in section 4 the communication to the server is used with Ethernet. The transferring of data uses the Nagle algorithm which doesn't let small packages of data to be transferred continuously. This makes it sometimes gather up the data and sends it in one large package. There is a possibility to remove this algorithm but this makes the anchors Ethernet connection stop working after a while. The Nagle algorithm makes the system not completely work as a RTLS system since the algorithm will sometimes add a delay giving it a larger latency above one second.

The tags **power consumption** is quite small making the battery manage to survive for about 134 hours of continuous transmissions at 1 Hz updating frequency, which makes it possible to implement in many applications. This could be increased further by usage of the sleep functions in both the UWB component and microprocessor. The power consumption depends on the updating frequency making this a good tool to reduce the consumption if not needed.

The **scalability** of the system is not great as it lowers the updating frequency linearly with the amount of tags in the system. There are ways around this which are discussed more in section 7.1.1. The **robustness** of the system is great as the spectral interference is minimum and it handles NLoS situations well as could be seen from the large scale tests.

For the **complexity** of the system it is quite high since the antenna delay could be needed to be calibrated which takes some time. The current system takes some time to install since need to measure the distances between the anchors. There is a possibility to have at start-up to measure a couple of values between the anchors and then use these distances to find the position of the anchors through trigonometry.

The **cost** per object being tracked is higher than many other technologies. The main reason for this is that UWB is a fairly new technology, and at the moment there only exists one manufacturer who provides UWB hardware to the public. This makes the related hardware more expensive than many other technologies, and this is unlikely to change unless another manufacturer develops a competing product. However, is should be noted that the range of UWB is higher than most other technologies, which means that the cost per area covered is comparable. The **portability** of the tag hardware is very good since it is a 4x6 centimeters large, battery powered chip. This means that it could be integrated in almost any type of device, and since there are a lot of excess space on the chip for debug purposes it could be made even smaller if needed.

The system only tracks the local ID number of the different tags, which are separate from any device they would be connected to. This makes the **integrity** issues non-existent as long as the specific implementation does not take active steps to allow identification of individuals based on the tag IDs. The **security** that is needed for the system is minimum since no personal identification saved by the system, and the anchors does not need to be connected to the internet. If an internet connection to the system is desired, some sort of internal security needs to be added, however this is not an issue until an implementation needs that specific functionality.

7

Conclusion and future work

In this chapter some suggestions for future development of the system described in chapter 4 are provided, together with some predictions on how these improvements would affect the performance of said system. After that a conclusion of the thesis is given, both with regards to the results and the experiences gained in the area of indoor positioning using UWB.

7.1 Future development

In this section we will provide some suggestions on how to further develop and improve the system described in Chapter 4. These suggestions will tie in to the performance trade-offs discussed in section 6.5, and will use this as a basis to justify why they are improvements worth doing.

7.1.1 Improvement of multiple tags

There are two main problems with using multiple tags, both of which can be improved by system design. The main problem for this project was that the time for the anchors to localize one tag was quite long, which puts an upper limit on how many can be localized at once at a given update frequency. The primary solution to this problem is to increase the speed to the SPI link between the host processor and the DWM100 together with moving to the high-speed mode for the transmission to decrease the time needed for one ranging. This alone would significantly increase the number of possible tags at a the price of a slightly more complex host processor, and lower range from the faster transmission speed.

If still more tags are needed the next step to improve would be to add scheduling for when the tags can transmit. This project utilizes no scheduling, and a tag that does not get a response from a poll simply waits for a short period of time before trying again. By giving each tag a specific time slot to transmit in, the amount of collisions between messages would be drastically reduced, which in turn would increase the number of tags possible for the same hardware. This however comes with a rather significant cost in system complexity, and some transmission time needs to be devoted to transmitting the scheduling to the tags from the central control unit.

If a higher update frequency is still needed there is a possibility to use multiple sets of three anchors operating on different channels and spreading the tags among these channels. This would make it possible to scale the amount of tags without disturbing the updating frequency, and without causing channel congestion. The complexity of this solution depends on whether or not the tags needs to be dynamically moved between channels, but it will demand more hardware and still has a limit on the amount of tags if a high update frequency is wanted.

A possibility for some implementations where the tag spends a lot of time in a stationary position is to lower the update frequency when it is not moving. This can be done either by software detecting that a tag has been still for a while, or by adding an accelerometer to it. This would allow a system to track a large number of tags if the majority are stationary, since these will have a low impact on the overall busy time of the system. If the position of such a stationary tag needs to be very precise it is possible to let a tag do its ranging multiple times in a row to get an accurate value, and then stop while other tags do the same. This would give a high accurate position but with a low frequency interval, and could be ideal for cases where the tags move infrequently but needs high precision.

7.1.2 Large areas

In chapter 4 the designed system described uses three anchors to determine the position of a tag in the area between them. This implementation is limited to the maximum practical range of the UWB transceivers which depends a lot on the environment, and drops sharply when certain objects are in the way. The system will therefore only be suited to covering a medium-sized area, with no significant obstructions such as concrete walls or metal barriers in the way. To enable coverage of larger and more complex regions, the system could be extended to include more than three anchors which could be spaced evenly throughout the area to be monitored. However to avoid each positioning operation being unnecessarily long by having the tag wait for an answer from all anchors, a hand-over would be needed to ensure that only the three closest anchors are communicating with each tag. This would have the side-effect of increasing the capacity for the amount of tags the system could handle, providing that the tags are distributed evenly throughout the area and are scheduled to avoid spectrum congestion. These changes could be made on top of the current system, with most of the needed work being related to how the server decides which anchors should communicate with each tag, and how this control information should be relayed through the system.

7.1.3 Wireless system

The current system requires physical connections for both power and Ethernet to each anchor, which severely limits the freedom of where they can be deployed in the target area. One approach to solve this problem is to make the anchors use power over Ethernet, and thereby removing the need for a power outlet nearby. This would be useful for smaller systems in areas with a limited amount of power outlets, but for larger systems with multiple anchors the Ethernet connections will likely be a much larger nuisance. In this case the solution could be to add a WiFi connection to each of the anchor. This would greatly improve the flexibility of placing the anchors, especially since most location already have an existing WiFi system that they could connect to. To remove the power connection completely would be to make it battery powered, which was proven to work with the tag, but since the anchors generally consume more power it would require significantly larger batteries. This would be possible since they are designed to be fixed to a certain point, but would increase the cost by a decent amount.

7.1.4 Filtering

As can be seen in section 5 the inaccuracies of the system are mostly uniformly distributed around the actual value, after correcting for the signal strength bias. This makes it possible to get a large improvement from a simple averaging algorithm, depending on the number of samples available and the impact on latency that this would cost. This could be further expanded by rejecting values that based on the target's speed have moved too far from the previous position, again with consideration to the impact on latency discussed in section 6.5.

A more advanced filtering algorithm such as a Kalman filter is also a possible implementation since this would take in account the current position, the variance of the specific system and the speed of the target to find a possible future position and then compare this to the measured position [45]. This has been shown in similar systems to provide a large gain in accuracy, with the drawback of an increase in complexity as well as a larger load on the localization server to calculate each position.

7.2 Conclusion

The end product is a working indoor positioning system using UWB technology with a high accuracy in LoS, and graceful degradation in NLoS and mixed conditions. The latency is low enough to be able to use as a RTLS system, providing that the problems with the information transfer to the server over Ethernet are fixed. The system has the possibility of tracking multiple tags, provided that the update frequency is lowered depending on the number of tags. The effective range is somewhere between 15 and 20 meters, and the accuracy is between 15 to 30 centimeters depending on the conditions as shown in section 5. However, as can be seen from the distance tests, the technology still has more to offer and in section 7.1 a few suggestions were made on what could be done to increase the performance further.

In this thesis we have added to the increasing knowledge in the area of indoor positioning systems by showing that UWB is a viable technology for applications where accuracy and robustness are important criteria, and where the conditions are not ideal with regards to LoS etc. With an accuracy of between 15 and 30 centimeters in a mixed environment, and the range of up to 20 meters in realistic conditions, the technology should have many possible applications for commercial use. The main drawback of the system is the same as is shared among almost all indoor positioning systems, which is the significant cost associated with covering an area due to the limited range in indoor environments. This however is an intrinsic limitation of indoor positioning systems in general due to the various difficulties associated with the indoor environment, and there does not seem to exist a solution for this problem at the time of the project. However, the system developed here still does significantly better than most other technologies in this area. The implementation can be adapted to the current use case, to provide a performance and flexibility hard to achieve with other types of systems. In addition the concerns about the ethics of potentially tracking individuals outlined in section 1.6 are not a problem, since this system relies fully on hardware which is in no way connected to an individual, compared to for example a system built around using users phones for tracking.

In section 6.5 it was also concluded that although UWB is a very versatile technology specific decisions must be made regarding the implementation for each case. This also means that the technology can be used for highly specific scenarios, where for example a very high accuracy is needed. These special cases need to be studied further, however this thesis has shown that it is both possible and feasible to do with UWB as a base technology.

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