Virtual alignment of real-world objects

A survey of indoor positioning research focused on trilateration utilizing Ultra-wideband technology

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Abstract

High accuracy localization of objects is a crucial function for many modern applications, such as virtual and augmented reality, robotics, and self-driving cars, among others. This requires determining precise location of objects indoors, which is a challenging task. In recent years, Ultra-Wideband technology has seen increasing interest as a potential solution to this problem by the research community. This is mainly due to its innate capabilities of high update frequency and low power consumption which makes it a suitable technology for precise distance measurement and location determination. This study has aimed to answer what the state-of-the-art in the field of trilateration in Ultra-Wideband based indoor positioning systems utilizing other complementary technologies is. This was done by conducting a document survey using a Grounded theory approach for the analysis. To ensure validity and reliability of the study, the sample was collected through searching IEEE Xplore using different sets of keywords, and the potential samples was then checked using a data quality form. The analysis consisted of identifying categories and concepts in the sample. The analysis found that the Ultra-wideband based systems can achieve high positioning accuracy, but limitations such as non-line-of-sight disturbance must still be overcome for the technology to consistently achieve centimetre accuracy. These limitations are being mitigated using filtering, machine learning, and multi-sensory fusion. With these complementary technologies researchers can eliminate some of the limitations. The field does however seem to be in an exploratory stage where best practices for overcoming the current limitations are yet established.

Keywords: Ultra-wideband, Indoor positioning system, Document survey, NLoS, Multi-sensor, Trilateration, Localization

Synopsis

Background	With the proliferation of technological concepts such as Extended reality and Internet of Things the need for accurate positioning data for objects is increasing. As of writing this GPS, WiFi and Bluetooth are common technologies used for positioning, these solutions suffer from inaccuracy and low update frequency which results in incorrect data. Ultra-wideband (UWB) is a radio technology that has innate characteristics which might have the possibility to provide a sufficient solution.
Problem	The positioning of real-world objects in virtual coordinate systems is essential to ensure correct measurements. Current solutions do not meet these criteria which is caused by insufficient position accuracy and update frequencies. UWB-sensors are being considered as a possible solution to this problem due to its high innate accuracy, update frequency and power efficiency. Since IoT currently is a hot topic as well as UWB being extensively researched as a solution for said alignment issues, a lot of different solutions regarding alignment are presented at a rapid rate. Recognizing the landscape of today's solutions enables a greater understanding of future work to further the advancement of indoor positioning systems.
Research Question	What is the state-of-the-art in the field of trilateration in Ultra-Wideband based indoor positioning systems utilizing other complementary technologies?
Method	This study takes the form of a document survey with a Grounded Theory analysis approach. A document survey aims to produce results that can be used to map out the current state of a research field. By utilizing a Grounded Theory approach in the analysis process, we intend to draw conclusions regarding the state of the art of indoor positioning systems and propose potential methods and techniques for the research field.

Result	The results are presented in the form of categories generated from the analysis. First, current limitations are covered, where the biggest limitation identified is NLoS-propagation. This is followed by a section on the different areas of use for indoor positioning systems, then a section on the complementary technologies used to improve indoor positioning systems. Lastly, a section detailing the different proposed localization systems, UWB-characteristics and the most commonly used ranging techniques.
Discussion	Researchers are increasingly exploring the use of machine learning algorithms, such as neural networks and support vector machines, to improve accuracy. Other complementary technologies, such as additional sensors and multiple UWB technologies, have also been utilized to enhance the performance of IPS. Filtering techniques, including variations of Kalman filters, have been commonly used to reduce disturbances, such as Non-line-of-sight, and improve accuracy. The field is still in an early stage with significant limitations, such as cost, complexity, and scalability. Conclusively, the answer to the research question is to utilize Machine Learning methods to identify NLoS-signals, to then supplement the estimation with additional sensor data such as an IMU and lastly process the signal with a EKF to reduce potential noise and disturbance.

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List of Abbreviations

Abbreviation	**Definition**
BLE	Bluetooth-Low-Energy
BAST	Best Anchor Selection for Trilateration
CNN	Convolutional Neural Networks
EKF	Extended Kalman-Filter
GPS	Global Positioning System
GT	Grounded Theory
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
IPS	Indoor Positioning System
IoT	Internet of Things
KF	Kalman-Filter
LiDAR	Light Detection and Ranging
LoS	Line of Sight
ML	Machine Learning
NLoS	Non-line-of-sight
PICO	Problem-Intervention-Comparison-Outcome
RF	Radio Frequency
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SLAM	Simultaneous Localization and Mapping
SVM	Support Vector Machine
TEAM	Trilateration for Exploration and Mapping
TDoA	Time Difference of Arrival
ToA	Time of Arrival
TWR	Two-Way-Ranging
UKF	Unscented Kalman-Filter
UWB	Ultra-Wideband

1 Introduction

This introductory chapter presents the background, problem, and research goal of this thesis.

1.1 Background

With the proliferation of 5G the vision of the Internet of Things (IoT) is being realized (Shafique, 2020). The IoT is a part of the Internet's future where heterogeneous, intelligent things will communicate with each other and utilize information with or without human agency (Li et al., 2015). These ubiquitously connected things can, through sensor data determine the conditions of their surroundings, based not only on their own device.

With billions of devices connected (Ericsson, 2016) the scope of IoT has been extended with new aspects emerging, two of those being intelligent sensing and low energy wireless communications (Li et al., 2015). This development has further bridged the gap between the physical and virtual world, but to shorten this gap accurate positioning and spatial orientation is crucial (Ling et al., 2018). In many cases the devices that are the target for positioning are smartphones which have sensors that at time of writing produce suboptimal results when it comes to accuracy and update frequencies (Nguyen et al., 2020). Different smart phones sensors also produce varying results (Kuhlmann et al., 2021).

So far, different methods have been developed to track and locate such devices. GPS being the most common of these (JongBae et al., 2008), but since it is lacking in accuracy, especially in indoors scenarios (Alarifi et al., 2016), it cannot be deemed suitable for indoor positioning purposes. To highlight this, Benford et al. (2006) presents a study where GPS as well as Wi-Fi technology was used for localization in a mixed reality environment and the findings showed that uncertainty in sensing and wireless communication strongly influences participants' experiences, further discouraging the usage of GPS for precise indoor localization. Wi-Fi and Bluetooth could also be considered alternatives (Nguyen et al., 2020), but as they utilize the RSS (Received Signal Strength) method to determine location they have been proven inefficient since it struggles to provide high accuracy because of signal sensitivity to multipath interference (Alarifi et al., 2016). Location Fingerprinting is a method that tries to address this problem, but it instead brings with it other complications since it requires high maintenance in case of any environmental changes (Nguyen et al., 2020).

Ultra-Wideband (UWB) has interesting aspects and properties that tie well with the treatment of the difficulties within localization of IoT-devices (Ling et al., 2018; Minoli & Occhiogrosso, 2018). UWB signals have a very large bandwidth which corresponds to high time resolution and is therefore accurate on time-based ranging. Furthermore, UWB signals cover a large portion of the frequency spectrum which enables penetrable capabilities. Consequently, applications that require high positioning accuracy benefit from UWB signals. However, two challenges exist with time-based ranging, timing error in clock drift and power consumption. Timing errors can be mitigated through two-way ranging protocols, and power consumption can be reduced through the usage of low-rate samples (Soganci et al., 2011). One of the most prominent methodologies that can be used to exploit the properties of the UWB signals for positioning is Trilateration, a method of determining the location of a device by measuring the distance from that device to three or more reference points (Silva et al., 2014).

In general, UWB has seen a resurgence in recent years. Apple and Samsung have started incorporating UWB into their cellular devices due to its many benefits and researchers have also taken notice of UWB's power in different applications. Extended reality-based applications for education (Zhang & Tang, 2022; Zhang & Zi, 2020), construction (Wu et al., 2022; Li et al., 2020), social media (Kanter, 2021) and general localization optimization (Gee et al., 2011) regarding alignment via UWB are some examples of recent advancements. UWB seems to apply well for precise indoor localization, but complementary technologies to further enhance UWB's aspects and properties are many. Sensors, techniques, methods, algorithms et cetera are used frequently in conjunction with UWB. Which complementary technologies that serve the overall greatest benefit to UWB's accuracy is not to our knowledge figured out.

1.2 Problem

The positioning of real-world objects in virtual coordinate systems is essential to ensure correct measurements. Current solutions do not meet these criteria which is caused by insufficient position accuracy and update frequencies. UWB-sensors are being considered as a possible solution to this problem due to its high innate accuracy, update frequency and power efficiency. Since IoT currently is a hot topic as well as UWB being extensively researched as a solution for said alignment issues, a lot of different solutions regarding alignment are presented at a rapid rate. Recognizing the landscape of today's solutions enables a greater understanding of future work to further the advancement of indoor positioning systems.

1.3 Research Question

What is the state-of-the-art in the field of trilateration in Ultra-Wideband based indoor positioning systems utilizing complementary technologies?

1.4 Scope

By conducting a document survey of the research field this thesis provides knowledge about the state of the indoor positioning systems research field focusing on Ultra-wideband solutions using trilateration. Additionally, new methods and techniques can be proposed as the landscape is studied, such as machine learning algorithms and multisensory fusion, respectively.

1.5 Delimitations

This study focuses on Ultra-wideband based indoor positioning systems. Therefore, no other applications of Ultra-wideband have been considered.

2 Extended Background

This chapter presents a more detailed overview of Ultra-wideband technology, Indoor positioning systems, ranging techniques, and what complementary technologies entail.

2.1 Ultra-wideband

Ultra-wideband (UWB) is a technology based on radio frequency (RF) that is broadly defined as a RF signal occupying a portion of the frequency spectrum that is greater than 20% of the centre carrier frequency or has a bandwidth greater than 500 MHz (Federal Register, 2002). This means that UWB carries information in a large part of the spectrum (Svalastog, 2007). Thus, it allows for high transmission of data, which allows UWB transmitters to consume a small amount of energy. Additionally, UWB's low energy density does not interfere with existing radio systems because of its low power spectral density (Oppermann et al., 2004). UWB uses a pulse-based system which permits high accuracy in Time of Arrival (ToA) while under the influence of multipath interference. These low frequency pulses enable signals to effectively pass-through occluded objects and walls (Alarifi et al., 2016). In addition, the UWB signal is difficult to intercept and detect due to being noise-like (Oppermann et al., 2004). Furthermore, UWB does not suffer from multipath fading and can therefore almost guarantee reliable communication (Win & Scholtz, 1998). Another quality of UWB-technology is the small size of the sensor and that it does not require any fixed infrastructure which makes deployment quite simple (Rahayu et al., 2008).

The pulse-based system in UWB produces short pulses through its transmitter. These short pulses can propagate without the need for additional up-conversion and amplification, known as carrier-frequency. This is due to UWB already having a very wideband signal, unlike a conventional radio system. The absence of a carrier-frequency translates to UWB not needing an additional radio frequency mixing stage, which normally adds to complexity and cost (Oppermann et al., 2004).

The large bandwidth and noise-like characteristic of the transmitted signal achieves high multipath resolution, which bolsters the UWB signal from severe multipath propagation and jamming/interference. This offers low probability of interception and detection, which are attractive properties for secure applications (Oppermann et al., 2004).

Li et al. (2007) demonstrates that UWB can potentially be a promising candidate for wireless personal area network due to its low-power-transmission and high-data-rate. While UWB is not universally used like Wi-Fi and Bluetooth, it does indeed have some real-world applications. For example, NXP has collaborated with Samsung to utilize UWB in Samsung's Galaxy Note20 Ultra (NXP, 2020). NXP's UWB technology provides relative-location in crowded and multipath environments, making it useful for a variety of security applications such as Near-field communication-based payments, mobile ticketing, and spatial-aware applications (NXP, 2020). One of Samsung's biggest competitors, Apple, also supports UWB in their mobile models for localization (Apple, 2022).

Additionally, BMW has also utilized UWB technology in their new BMW iX and the optional BMW Digital Key Plus (Bmw, 2021). This allows for the car to automatically unlock, turn on its lights, or launch preconfigured personalized settings when the UWB-equipped device, such as a digital key installed on a phone, is nearby. This also prevents relay attacks and only allows the car to start when the key is physically within the vehicle (Bmw, 2021).

Evidently, a multitude of applications can benefit from UWB. Although localization in an indoor environment seem to be the most common application for UWB, Porcino and Hirt (2003) identifies several practical usage scenarios such as wireless ethernet interface link, intelligent wireless area network and outdoor peer-to-peer network to potentially benefit from UWB.

2.1.1 Indoor positioning system

Indoor positioning system (IPS) is the umbrella term for technologies that are used to locate objects in tight, cramped or otherwise small locations. IPS is normally used when GPS and other satellite-based technologies fail to maintain acceptable accuracy levels (Chelly & Samama, 2009), i.e., indoor environments. The most common approaches for localization systems are triangulation and trilateration, which both are based on geometry. Time of Arrival, Time Difference of Arrival and Received Signal Strength are used within trilateration, and Angle of Arrival is used within triangulation. These are the typical positional algorithms used to determine positional information about transmitters and GPS receivers (Alarifi et al., 2016). Worth noting is that a combination of these algorithms is common practice to complement each other. These algorithms are then called hybrid-based algorithms, and naturally have a higher complexity, but tend to have higher accuracy (ibid).

2.2 Ranging

Ranging is the technique to measure the distance between two nodes. Precise travel time measurements are paramount for accurate estimations of objects' whereabouts (Alarifi et al., 2016). There are a multitude of different methods to calculate the distance, e.g., one-way- and two-way ranging as well as RSS ranging. The main difference is if the calculation takes place at the sender or receiver, and whether some prerequisite needs to be in place, such as time-synchronization.

To obtain high quality localization it is necessary to verify the performance of the range measurements. Since ranging accuracy can be volatile (Dardari et al., 2009) it is important to understand the ingoing method and its implications. Fortunately, there exist complementary technologies to achieve a less volatile state. For instance, probabilistic and statistical algorithms, e.g., Kalman-filter and particle filter, can be used to estimate the range of error to ensure precise measurements. To put it lightly, the choice of ranging technique leads down a rabbit-hole of important decisions that all together account for the accuracy of the localization.

2.2.1 Time of Arrival

Time of Arrival (ToA) is the term that explains the time it takes for a radio signal from a transmitter to be reached by a remote receiver. The distance is measured by the signal propagation time between the transmitter and receiver. If the received signal is to be taken as evidence, then the estimated range $d = c \cdot t_{arrival} - t_{sent}$ with $c = 3 \cdot 10^8$ being the speed of light. This equates to a circle with a radius of d with the center location being the transmitter. By the usage of multiple transmitters, the position of the receiver is found at the intersection of circles in two-dimensions or spheres in three-dimensions (O'Keefe, 2017). Position ambiguity is removed through trilateration since the intersection of three circles should correspond to a single point, whereas ambiguity is present with fewer references.

Since the medium in which the signal is travelling through is very rarely in free space (due to noise, reflection, multipath or signal scattering), it can lead to erroneous values. Therefore, a single point is not the solution, but a region that is an estimate in which the best guess likely resides in (Brena et al., 2017). See Fig. 1.

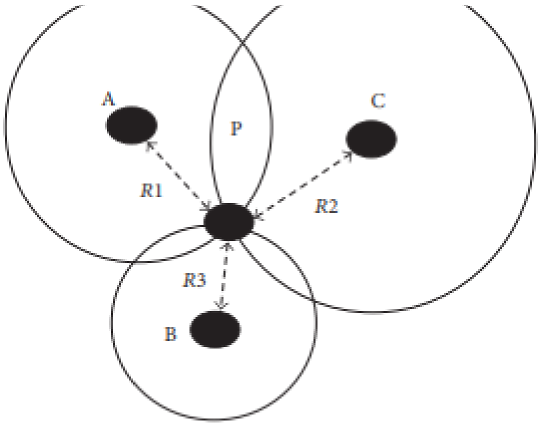

Figure 1. ToA illustration. Transmitters A, B and C are transmitting signals to Receiver P. Estimated location of P is within the estimated Area of P (Brena et al., 2017)

Evidently, ToA requires time-synchronization to ensure precision at the arrival time. Poor accuracy in this regard translates directly to an imprecise location.

2.2.2 Time Difference of Arrival

Time Difference of Arrival (TDoA) is very much akin to ToA because TDoA also requires precise time-synchronization. The difference lies within TDoA only considering the different arrival times of signals reached to two distinct receivers. Hence, the time-synchronization is no longer required at the transmitter, but only between and within the receivers. This removes the burden of estimating the absolute time between transmitter and receiver, though similar issues occur for TDoA that it does for ToA, i.e., cochannel interference, blockage and multipath (Guo, 2004). The time difference can be defined as hyperbolic curves to map the constant distance difference between two receivers. Much like ToA, two receivers can tell the coordinates, but three are needed to remove position ambiguity (Munoz, 2009). See Fig 2.

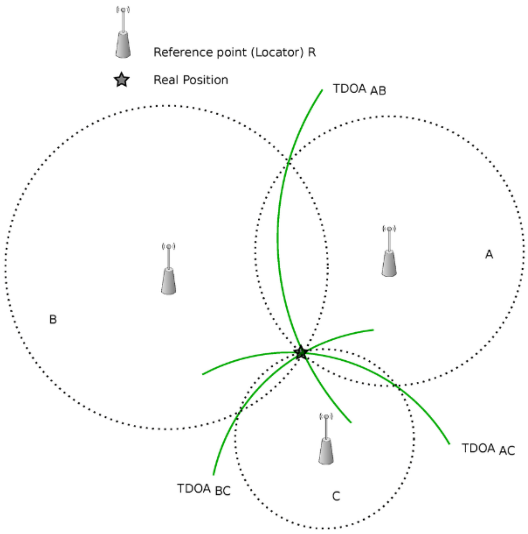

Figure 2. TDoA illustration. Hyperbolic curves created through arrival time measurement between Receivers A, B and C. Position of the Transmitter is marked with a star (Alarifi et al., 2016)

2.2.3 Received Signal Strength

Received Signal Strength (RSS) is a technique for measuring the distance between nodes based on the strength of the received signal and it is currently one of the most common techniques for indoor positioning (Wu, 2022). If the relationship between the transmitted and received signal strength is known the RSS measurement can be used to determine the distance from one node to the other based on the attenuation of radio waves according to the inverse-square law (Sadowski et al., 2018). RSS is one of the cheaper and easier positioning techniques to implement, but because of its susceptibility to interference it cannot be considered accurate enough without filtering to be used for localization (ibid.).

2.2.4 Non-line-of-sight

In dense environments there is high risk of multipath propagation which is when a signal reaches its destination by more than one path. Non-line-of-sight (NLoS) propagation occurs when a signal path with line-of-sight (LoS) is obstructed. This results in a longer path that causes inconsistent time delays which means positioning estimates are not accurate (Alarifi et al., 2016). Considering the efficiency of time-based position algorithms in combination with UWB's ultra-fine time resolution (Rahayu et al., 2008), the mitigation of NLoS propagation is an important factor.

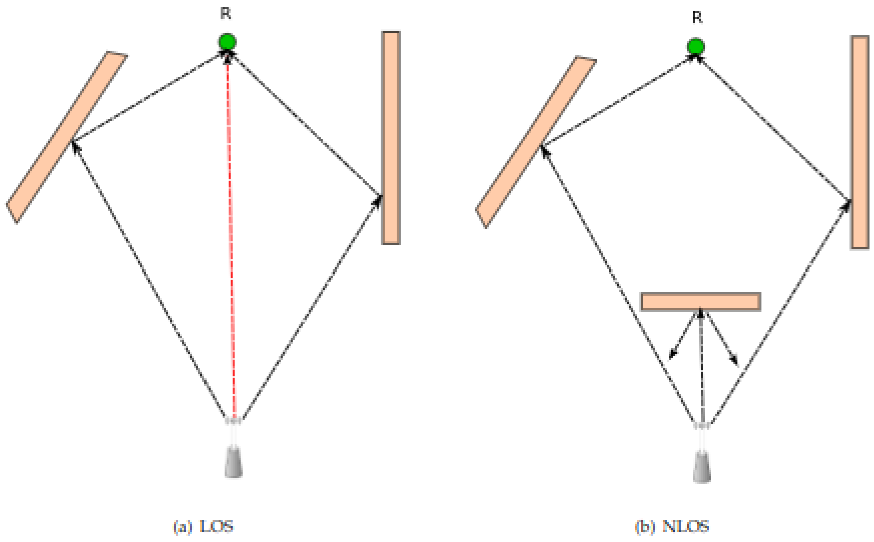

Figure 3. (a) Line-of-sight (LoS) vs. (b) non-line-of-sight (NLoS). (Alarifi et al., 2016).

According to Nikookar et al. (2008) NLoS propagation is the most critical error in radio-based positioning system. Since NLoS propagation results in a larger distance measured, they can be countered by not considering paths that exceed a certain threshold (ibid.). This is one way of negating NLoS propagation and according to Khodjaev et al. (2009) would be classified as a NLoS identification technique in which the goals are to identify NLoS signals and discard them. The alternative is what Khodjaev et al. (2009) calls NLoS error mitigation techniques in which the focus lies on selecting LoS signals by post processing, for example by using a particle filter.

2.3 Complementary technologies

So far mentioned the use of complementary technologies has been mentioned. This refers to technologies that are not necessarily needed for UWB based positioning but can be used to optimize or improve the performance greatly of such a system. These technologies range from accelerometers, gyroscopes, GPS to different signal processing and machine learning algorithms. The technologies that are present in the results of the study are detailed below.

2.3.1 Filtering

Filtering is a technique used to extract useful information from a mix of conflicting signals. These signals can be in the form of sound, light, or any other type of waveform. They can be natural or fabricated and can be in the form of analog or digital signals. The goal of filtering is to pick out the useful information from a mix of signals and discard the unwanted information (Schilling & Harris, 2017).

Filtering can be used in a wide range of applications, such as noise reduction, image processing, and audio processing (Schilling & Harris, 2017). In noise reduction, for example, the filter is used to remove unwanted background noise from an audio signal, leaving only the useful information, like speech.

As range estimations are made based on radio signals, the same methods of filtering can be applied to these to reduce the effects of disturbances in estimations.

2.3.2 Inertial Measurement Unit

An IMU, or Inertial Measurement Unit, is a device that is composed of three accelerometers and three gyroscopes. These sensors are used to detect linear and angular motion respectively (Yang, 2022). The device uses these sensors to calculate six quantities, including linear acceleration and angular rate, to transform the platform coordinate system, navigation coordinate system and inertial coordinate system. It provides information such as acceleration, speed, yaw, roll, pitch angle and other information (Yang, 2022). IMUs are commonly used in navigations systems, such as GPS and inertial navigation system (Yang, 2022). However, IMU has relatively short-term, high-frequency motion measurement accuracy due to the existence of systematic errors which increases over time. Therefore, IMU is usually combined with external information such as GPS or UWB to improve long-term accuracy (Yang, 2022; Wang & Li, 2017).

2.3.3 Machine Learning

Machine Learning is the idea of building machines or methods that improve their performance by executing tasks on training data (Brown, 2021). This way they can make more accurate decisions without being explicitly programmed to do so. Machine learning methods have varying applications and is applied in many different fields (ibid.). Machine learning can be applied to IPSs to determine if a signal originates from NLoS-propagation, as suggested by Khodjaev et al. (2009).

3 Methodology

In the following chapter details about the thought process behind the chosen research strategy and methods are presented. Ethical considerations and the research project’s validity and reliability are also discussed. Lastly the application of the methods is detailed.

3.1 Survey

The research strategy chosen for this thesis is to conduct a document survey. A survey is a research strategy which aims to scrutinize the state of a specific research field and draw conclusions based on the survey's findings (Denscombe, 2010). Surveys are deemed to be suitable for topics that are narrow in scope and are well-defined (Johannesson & Perjons, 2014), this makes it a good fit for this research project as there is a clear focus on UWB based IPSs which is an expanding field with plenty of information. Surveys are sometimes considered to lack depth (Denscombe, 2010), but for the purpose of being comprehensive they produce desired results. A key aspect to conducting a survey is that of sampling, which is the strategy of how sources should be collected (Denscombe, 2010). The sampling for this research project has been done through what Bryman (2016) calls theoretical sampling, which is when an analysed sample is used to decide on what data to collect next. A theoretical approach to sampling was deemed the most suitable, due to this project’s interest in the use of complementary technologies in combination with UWB based indoor positioning systems. As this aspect of the research field is not too well-defined.

3.1.1 Alternative research strategy – Case Study

Case study is a research strategy that revolves around in-depth investigation of a phenomena. Usually, a mixture of a multitude of different methods to collect and analyze data are used within a case study to ensure a deep understanding of the different dynamics of any phenomena. As this study tries to explore the current literature to find satisfactory conclusion to the research question, a case study could work. Through rigorous and deep analysis of present data and current solutions, it could help in finding some state-of-the-art conclusions. A case study is also argued (Denscombe, 2014) to be suitable for a small-scale research project. It is also arguably a great match with this study’s means of analyzing collected data, Grounded Theory, as they are both being of inductive nature. Despite this, case study inherits flaws that results it as a less-optimal research strategy than document survey. For instance, a common criticism is the credibility of generalizations from the results (ibid.). Investigating any phenomena needs careful deliberation regarding its application to similar cases. This study's research question demands some sort of general answer that can be applied to the whole of its area which case study has difficulty providing.

3.2 Data collection method

The data for this study has been collected by reviewing documents. Documents can take many forms such as books, articles, social media posts and audio-visual content (Denscombe, 2014). For this study, the type of documents has been limited to research papers as they provide the latest findings in the IPS research field. The documents have been collected through searches in scholarly literature databases using relevant keywords and selected by following a data extraction form. The selection takes exploratory sampling as a base, which Johanesson and Perjons (2014, s.43) explains as "*a means for gathering information in order to explore a new area*". Exploratory sample fits Grounded Theory due to both being exploratory. This is used in combination with theoretical sampling as these fit each other well. One factor that makes documents an attractive choice as a data source is the general accessibility of them (Denscombe, 2014). In the case of this study the relevant research papers are made available through universities and other scientific institutions. Another advantageous factor of documents is that data can be collected quickly compared to other methods such as interviews or questionnaires. This makes documents as this study's primary source of data fitting since time restraints limits its scope. Johanesson and Perjons (2014) make a noteworthy remark that researchers need to consider the author's intention of every document as this might affect that document's credibility. To make sure that biased documents do not affect the review, different measures have been added to the data extraction form to exclude these.

3.3 Alternative data collection methods

3.3.1 Interview

This study could have benefitted from interviews as a data collection method. Expert insight could have given us valuable, in-depth detailed data. While this is an attractive method, it has some disadvantages that cannot be overlooked. It would have required a lot of different experts for sufficient groundwork to be established. Additionally, there was some time limitation for this study, as a result it did not bode well to go down the path of long and extensive interviews that could potentially have required follow-ups. In general, interviews are great for attaining expert information, but at the cost of a lot of time (Denscombe, 2014) which this research project does not have.

3.3.2 Questionnaire

A more resourceful data collection method could have been questionnaires. As this research tries to explore the landscape it would seem natural to form the questionnaire with a qualitative approach with open-ended questions. Questionnaires are inexpensive and relatively easy to arrange (Denscombe, 2014) which would benefit this study. However, the problem of expert insight lies within the response rate. Much like interviews, it would be troublesome finding, contacting, and getting a response from said experts. Furthermore, questionnaires are seemingly unfair to the scope of the question since the pre-coded questions could impose some sort of structure that does not reflect the truth. While open-ended questions intend to counteract this, the discussion and exploratory aspect would likely be damaged by this method. Hence questionnaire is not the chosen data collection method.

3.4 Data analysis method

This study used Grounded Theory to extract useful information from the collected documents. Grounded Theory is an iterative process of collecting and analysing data through theoretical sampling and open-, axial- and selective coding (Johannessons & Perjons, 2014). The process is terminated when theoretical saturation is achieved, meaning when additional analysis no longer contributes anything useful to the coding (Denscombe, 2014). In essence, Grounded Theory is an inductive research strategy that develops theories through the usage of empirical data, in contrast to other research strategies that often begin with a hypothesis and then develop methods to answer it (Johannessons & Perjons, 2014). However, Grounded Theory has a framework to analyse the accumulated data through a qualitative approach that suits this exploratory research study. Further, Grounded Theory enables researchers to find theories that may lay preliminary foundations for future research (Bryman 2016). This goes hand in hand with the research question. In addition, Grounded Theory does not require a substantial amount of data and is therefore well suited for small-scale research projects, such as this one. This study follows Bryman (2016) steps of theoretical sampling, a non-random selection of samples, in qualitative analysis. These steps are:

1. General research question
2. Sample theoretically

3. Collect data
4. Analyse data (concepts, categories)
5. Theoretical saturation
6. Generate hypotheses

As step 6 is finished, it is possible to cycle back to step 2 for another round of analysis. This should be iterated till the research question is adequately answered. The general idea of Grounded Theory can be seen in the figure below.

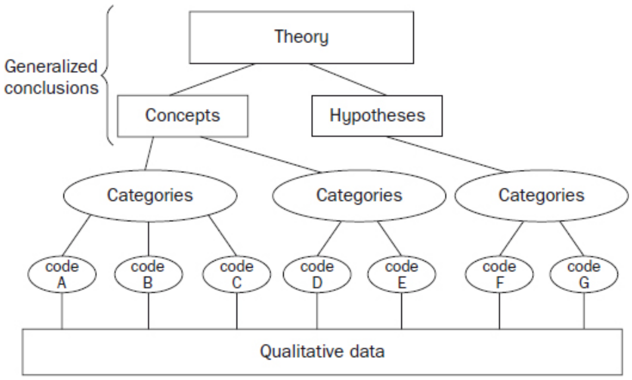

Figure 4. Grounded Theory illustrated. Qualitative data transformed into code, then into categories, then into concepts/hypotheses and finally a theory (Denscombe, 2014)

3.4.1 Coding

When the sampling of data is over in Grounded Theory, it is time to analyse the sample data via the generation of codes. The generation can be divided into three separate phases, open-, axial- and selective coding. The first thing Grounded Theory suggests is to organize the sample text. Excerpts that define, or highlight, concepts that seem interesting regarding the research question are brought up in the open coding phase. When all sample data is sufficiently looked over and corresponding codes have been generated, the next phase beings. Axial coding is the process of trying to tie these concepts together under some form of category. Usually, categories can be seen as a more abstract and high-level form than the underlying concepts. The ties between the codes can be contexts, consequences, patterns of interaction and causes (Bryman, 2016). Finally, when all codes have been generated and put under some category, selective coding takes place. The objective of selective coding is to identify a core category in which all categories, or most categories, can be connected to. Categories that cannot be identified with the core category are prone to be a reference for future work. As mentioned in earlier sections, Grounded Theory is an iterative process. Categories that cannot be put into some core category will need further refinement which means that new data sampling must be made, but through different criteria that would arise from the unsaturated categories. A category is saturated if no new or relevant data can be obtained, if the category is well developed and the relationship between the categories are well established and validated (Bryman, 2016).

While coding, especially in the open and axial phase, it is common to take memos. These are notes that the researchers use to remind themselves what certain terms mean in their specific context. They are especially useful for reflection and to spark ideas (Bryman, 2016). Memos contain even more value through iteration since the researchers can compare memos and ideas with previous knowledge.

3.5 Validity and Reliability

As mentioned in the beginning of this chapter, securing validity and reliability is paramount to ensure rigorous scientific results. Validity is according to Denscombe (2014, p.301): “The idea of validity hinges around the extent to which research data and the methods for obtaining the data are deemed accurate, honest and on target.”. Obtaining validity in a document survey requires thoughtful and careful reflection regarding the choice of literature as well as interpretation. In this study, relevance as well as quality of the sources have been evaluated through the data quality form. However, validity hinges on the deliberations made by the researchers. Therefore, all evaluations have been recorded for the reader to follow. Meaning, how to find sources, how to decide upon which to include and exclude as well as the justification for the assessed quality of the data is all adequately explained in the coming chapter Application of method. It is via this transparent and rigorous consideration that validity is achieved.

Denscombe (2014) explains reliability as the degree to which research instruments results in the same measurements on two different occasions. Meaning that minimal ambiguity is present in the results, and bias from the researchers are accounted for. Obviously, the collected data is constant, and no ambiguity should arise. On the other hand, the choice of data as well as interpretation need to be deliberately explained. This study achieves high reliability through many stages of transparency. Firstly, the scope of the review has been described and justified. Secondly, an explicit description of the process has been recorded through Grounded Theory analysis. Lastly, relevant sources are adequately referred to so that any researcher can follow the procedure.

3.6 Ethical issues

When conducting any kind of research, some sort of ethical overview needs to be considered. As researchers, we are obligated to not jeopardize anyone or anything in any way, shape, or form. Denscombe (2014) and Johannesson and Perjons (2014) map four general ethical principles that should be considered when conducting research.

Two out of the four principles concern the ethical issues regarding participants involved in the research. These two principles are not covered since the data gathering does not include any active participants in this study.

One of the principles posits that researchers should be open and honest with their work and findings. This is highly relevant to this study. All references are credited that have been used in this study. This research is solely to be used for its research purpose. No third-party investor or otherwise biased party is involved in this study. The purpose of the study is also honest in its approach and intention. Potential benefits as a result of this research are clearly and honestly shared. Any form of deception is promptly refrained upon.

The last principle is to comply with the law. This study is conducted in Sweden and has therefore follow their laws.

3.7 Application of Method

This chapter thoroughly explain how the document survey and Grounded Theory analysis was conducted.

3.7.1 Data collection: Scoping the search

A prerequisite for a document survey is enough previous research within the topic area. One first step is to ensure a narrow enough scope for an adequate research question. Kitchenham (2007) explains how to formulate a reasonable research question through a model called PICO. This model ensures that the research questions take account of Population, Intervention, Comparison and Outcome. What this means is that you identify a *population* or in more general terms a *problem*. In the case of this study the problem area would be Ultra-Wideband indoor positioning systems. You then assert the intervention or the so-called main treatment. In this case the use of complementary technologies. The third step is concerned with any alternative interventions, this has not been applied due to the lack of one. The last step is to formulate the outcome and establish the relationship between the problem with the *intervention* (Nishikawa-Pacher, 2022). The application of the PICO model can be seen in Table 1.

Problem	Ultra-Wideband indoor positioning systems
Intervention	Ultra-Wideband based Indoor Positioning Systems utilizing complementary technologies
Comparison	N/A
Outcome	Complementary technologies effect on Ultra-Wideband based Indoor Positioning Systems

Table 1. Application of PICO-model.

3.7.2 Sampling data

After the research question is established, some sort of sampling must be considered. As stated earlier, this study utilizes theoretical sampling, which means that sampling have be done iteratively. When performing the search process, initial keywords were chosen that capture the essence of the topic. These keywords were used when searching for research literature. The searches have been made through IEEE Xplore which is a database that stores documents such as journal articles and conference proceedings regarding computer science and electrical engineering. The reason for choosing IEEE Xplore is because its highly regarded as a reliable source for peer-reviewed sources in the aforementioned fields. The content of IEEE Xplore has been made accessible through Stockholm University. When collecting the sample for each search, the Boolean operator AND were used in-between each keyword. Since this study is using a Grounded Theory approach keywords have been refined during the search process. The search process took different directions based on previous iterations of the analysis. The keywords and in which searches they were used are shown in Table 2. The complete sample can be found in Appendix A.

Keyword	**Used**
UWB	Search 1 - 3
Indoor positioning system	Search 1
Trilateration	Search 1-2
Localization	Search 3
Indoor	Search 2

Kalman Filter	Search 2
Machine Learning	Search 3

Table 2. Search keywords – numbering indicating at which stage they were added.

3.7.3 Data quality

Henceforth, some evaluation regarding quality must be established to collect relevant data. This has been done by using a data quality form to evaluate the quality of the gathered sources. As such a data quality form has been developed. This includes explicit criteria used to check that every source meets the set-out requirements. Criteria such as the age of the literature, peer-review status and source of funding and type of study were considered. Sources that did not fulfil the criteria were disregarded. The data quality form contains the following requirements:

Criteria	**Condition**
Age of source	Lowest threshold: 2019
Is the source reliable and valid?	Is the method clearly presented and reproducible?
Is the source biased?	Is there any external funding? Does the source clearly acknowledge stakeholders? Has the paper been peer-reviewed?
Is the source focused on UWB-based indoor positioning systems?	
Will the source benefit the progress of this study?	Does it present a new perspective? Does it provide new concepts previously not identified?

Table 3. Data quality form.

The decision to set the lowest threshold for data sampling at 2019 was based on the principle that utilizing more recent data can provide a more accurate representation of the current state-of-the-art. However, due to a lack of sufficient relevant studies prior to 2019, the threshold was ultimately set at that year to ensure a sufficient amount of data for analysis.

3.7.4 Grounded theory analysis

As Grounded Theory is an iterative process the sampling and analysis step has been completed multiple times. The process of theoretical sampling has been followed. Meaning, at this stage the sample data is being read and analysed, generating codes through open coding. These codes represent some discrete phenomena, known as concepts. One such example could be the occurrence of multipath propagation and how the problem is tackled. When all sources of the sample had been coded, the findings were merged into one document, where similarities and differences in the concepts were identified. The next phase was to ensure that consistent types of concepts were being generated, therefore notes were taken of where that concept was identified and the reasoning behind that coding. This way sources that share concepts can be easily cross-referenced.

Categories were then identified which tie these codes together. This is known as axial coding, where a reoccurring feature with a higher level of abstraction can be used to group together concepts. To further the previous example, this category could perhaps encapsulate disturbances in UWB.

When all code had been identified under some category, the next iteration began, and new keywords was chosen through the codes generated. Each iteration has been presented with its new keywords and generated codes. When theoretical saturation was reached, a map was created using the free software Diagrams.net as an assisting tool to visualise the relations between different concepts and categories while conducting the analysis. The map is presented in chapter four. When the map had been finalised, conclusions and discussions were produced. The whole process has been documented and presented in chapters four and five.

4 Results

This chapter presents the findings of the analysis. First off, the map visualising the categories and concepts is presented. Some concepts had overlap between categories. These concepts were placed in the most fitting category, then a connection was drawn between its relating concepts which might be a part of another category. Every overarching category and their concepts have been given its own colour in the map for visual clarity. The overarching categories have also been outlined with a solid black line. These six categories are presented as subheadings in this chapter. There are other categories in the analysis, but these have been considered sub-categories to one of the overarching categories and are therefore presented inside that subheading. Each one of these has a dotted outline around them. The red lines indicate where categories connect.

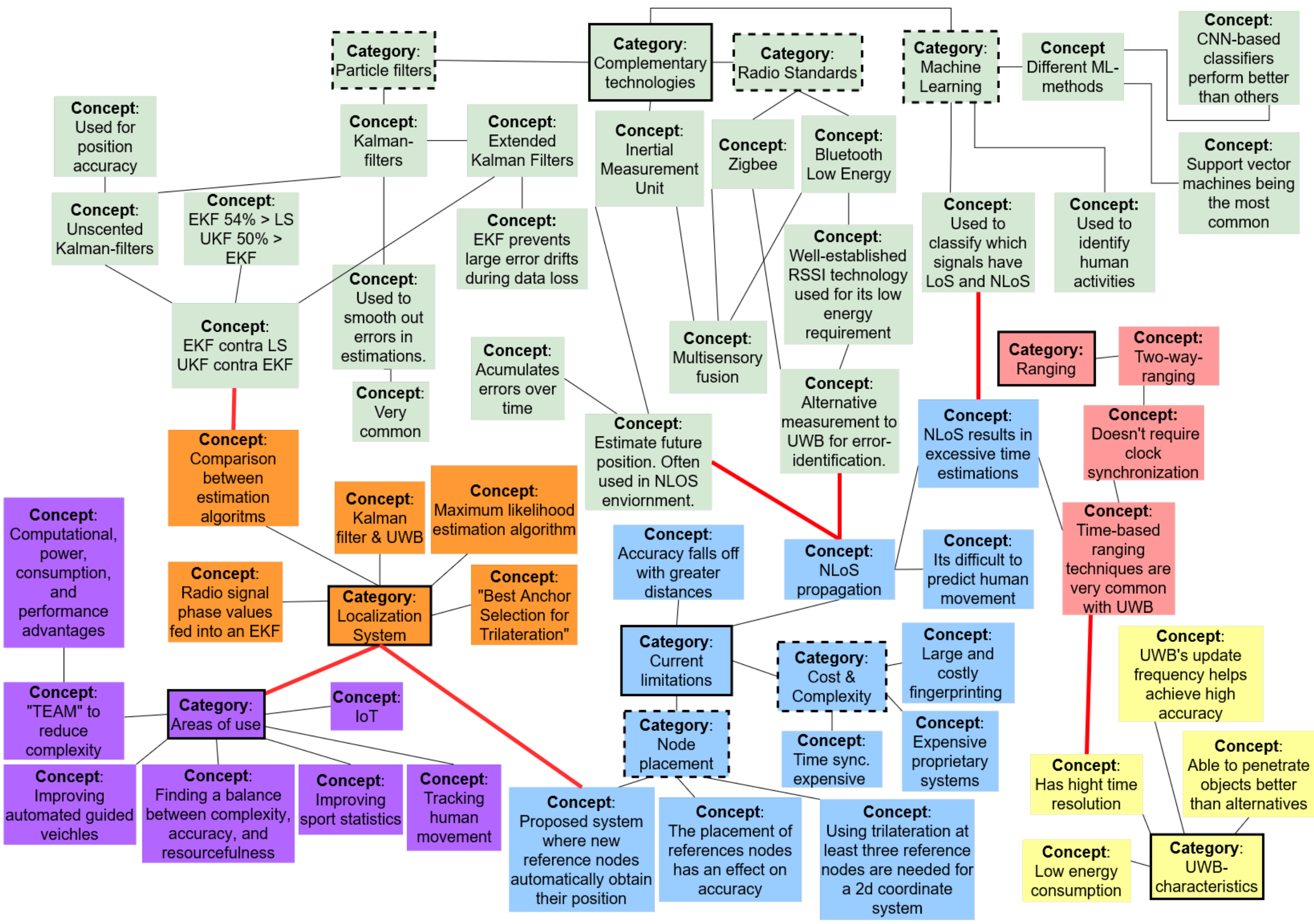

Figure 5. Map presenting the categories and concept of the analysis.

4.1 Current limitations

The conducted analysis has identified a few limitations in the field of UWB-based indoor positioning systems. These are presented under the coming subheadings.

4.1.1 NLoS

The most prominent of the current limitations is the effect of NLoS signals on ranging estimates. As covered in chapter two, NLoS-signals results in over estimations of the distance between reference node and target. Consequently, the position estimates do not achieve the centimetre accuracy that UWB has the potential to. Almost every source of the sample tries to mitigate the effects of NLoS-propagation in one way or another. The different methods to counter NLoS-signals identified in the sample are more thoroughly presented under the subheading *Complementary technologies*. Another identified problem is how estimate errors become greater with longer distances. According to Che et al. (2020) this problem gets worse with NLoS-propagation. This means that the mitigation of NLoS is of even greater importance. Tian et al. (2019) studied NLoS-propagation caused by the obstruction of human bodies. If a person carries a UWB-tag which is to be located, the person's body may cause disturbances to the signal. The problem is that the disturbance is not constant as humans move about which causes the conditions to constantly change (Tian et al., 2019). Therefore, an area crowded with humans is a bigger problem, than a more static indoor environment.

4.1.2 Cost & Complexity

The analysis also found that the cost and complexity of solutions were a key concern to researchers. The analysis found that researchers deemed some proven methods to be either too complex or too costly. One example is Chen et al. (2020) which argue that fingerprinting – even though it is very effective for positioning – requires too many resources. Fingerprinting is the method of collecting measurements from different positions and then storing them in a database, when an item is supposed to be localized in the area the current measurements are compared to the ones stored in the database to conclude which position is the most likely. The lack of use of fingerprinting in the sample points to that the research field is more interested in more dynamic solutions that do not require pre-measured positions. The concepts found in the samples does however suggest that reference node placement is something that must be measured and considered before the deployment of a positioning system (Maneerat et al., 2020).

4.1.3 Node Placement

Most of the analysed sample, apply the more common method of setting up reference nodes in fixed positions. This often included at least three reference nodes, as this is required to be able to use trilateration in a two-dimensional coordinate system. There does however seem to exist an interest in more dynamic solutions which allow for more ad-hoc systems. Phoojaroenchanachai et al. (2021) developed a system that enables new reference nodes to be added to a system without measuring its true position. Instead, a new reference node would find its own position in relation to the reference frame defined by the first reference node. This allows for a system where expansion does not require re-configuration of the system which would mean that maintenance of such a system would be more manageable (ibid). Their system did however require a more extensive initial calibration of the reference nodes to ensure high accuracy.

An even more advanced and specific system is presented by Clark et al. (2021). Their proposed UWB based positioning system functions in absence of any infrastructure. They call their solution Trilateration for Exploration and Mapping (TEAM). It is intended for lunar exploration in which a network of mobile robot map their surroundings with LiDAR. It works by using the robots as reference nodes when an area is about to be mapped. This means that at times the robots become static to act as a reference node while another is mapping its own surroundings (ibid.). Their system was more resource efficient than the more common *Simultaneous localization and mapping* (SLAM) solutions. This however meant that the system did underperform in overall task efficiency as the robots had to be temporarily static.

Moreover, it would normally be needed to install multiple anchors without occlusion in a complex environment, but Penggang et al. (2022) proposes a localization method that utilize fewer anchors in such an environment.

4.1.4 Time Synchronization

Time synchronization between nodes was a common occurrence in the sample, which seems to be a consequence of the use of ranging techniques such as ToA or TDoA as these techniques work well with UWBs high time resolution. Time synchronization does however require a lot of resources which makes systems more costly. A solution to this is by using Two-Way-Ranging (TWR) which does not need clock synchronization, unlike One-Way-Ranging which does (Le Minh et al., 2021). The drawback to using TWR is that it requires more messages to be sent between clients in the system, which decrease its scalability potential. Most of the sources in the sample rely on variants of Two-Way-Ranging and the systems developed would be considered small scale. This may indicate that the solution to Time Synchronization has not yet been found.

4.1.5 Expensive proprietary solutions

None of the sources in the sample studied any established UWB-based indoor positioning systems. Every study either developed their own systems to experiment with or ran simulations. This might have to do with a lack of established UWB-systems that are available for scrutiny. Bottigliero et al. (2021) calls established systems very expensive and based on proprietary hardware.

4.2 Area of use

UWB usage in IPS environments has many different use cases. In many cases, it revolves around UWB's ability to improve certain aspects within a system. One prominent example of this is the need for accurate localization of different objects. Tracking for automated guided vehicles and of human movements were two areas of use that were found to be currently important. The tracking of human movements was applied to help athletes track their statistics of movement in training and competition. In addition, IoT was a recurring theme that seemed to be the overarching theme with many of the papers, or at least relevant to IoT. However, the data showed that accuracy was not the only area of focus for IPS but also optimization. Noticeably, finding a balance between complexity, accuracy and resourcefulness seems to be heavily studied upon now. A lot of the studies argue for low-cost solutions that enhance some aspects of the system. For instance, Bottigliero et al. (2021) reduces cost and complexity of UWB targets in complex environments and Chen et al. (2020) achieves reasonable cost and complexity for a multi-source positioning system. In many of the studies there seems however to be a focus on performance with cost and complexity being a secondary objective.

4.3 Complementary technologies

A wide variety of options exist to enhance any IPS. As mentioned in Area of use, accuracy is the main objective, but complexity and cost are also frequently mentioned. The most common categories of tools to achieve the objectives are filters, radio standards and machine learning.

4.3.1 Filters

The absolutely dominating noise-reduction tool currently is the Kalman-filter (KF). In most of the samples, a variation of the KF was used along with UWB. A recurring problem within IPS is NLoS which filters are used to handle in some way. While KF seems to be the most popular filter at moment, there were some mentions of particle filters as well (Tian et al., 2019; Courtay et al., 2019). Both KF and particle filters have the same objective of reducing NLoS errors, though the consensus seems to be that KF or some variant of it is more efficient.

EKF and UKF have been extensively discussed throughout the samples. In general, EKF and UKF are useful for measurement of nonlinear character (RSS, propagation time), something KF falls short on. Moreover, EKF and UKF are shown to both improve the positioning accuracy remarkably compared to other algorithms (Feng et al., 2020). EKF is mainly used to prevent large error drifts during data loss, while UKF is mainly used for position accuracy.

Throughout the analysis it has been made clear that filters always occur when inertial measurement unit (IMU) is present. This is mainly because the accuracy estimations of UWB and IMU combined benefit a lot from filters. For example, Yue et al. (2022) proposes a method that uses an EKF to process IMU data, which is then fused with UWB data to suppress the influence of NLoS interferences. Similar tools to improve position accuracy were used by Penggang et al. (2022), Feng et al. (2020) and Lee at al. (2021). Feng et al. (2020) did find that, in terms of position accuracy, UKF was 50% better than their proposed EKF algorithm which in turn was 54% better than their proposed least squares algorithm (trilateration/multi-lateration). Kolakowski (2022) did also find that UKF outperformed EKF, but this time in a Bluetooth-Low-Energy (RSS measurements) UWB based localization system. Furthermore, a periodic EKF proposed by Mendoza and O'Keefe (2021) outperformed trilateration and EKF with constant velocity.

To summarise, KF does find a lot of usage in IPS but is currently getting compared to EKF and UKF. EKF seems to be the main contender to KF, with UKF being mentioned and finding some significant advantages over EKF.

4.3.2 Radio standards

The analysis found that ZigBee and Bluetooth-Low-Energy (BLE) have been experimented with in UWB focused IPS. ZigBee and BLE are both radio technologies based on RSS. Chen et al. (2020) utilizes ZigBee to strengthen UWB, arguing that they can supplement each other in a productive manner, whereas Kolakowski (2022) used UWB to support a BLE-based localization system. While their work is significantly different from each other, it can be assumed that both ZigBee and BLE can be used in conjunction with UWB. However, whether ZigBee and BLE are useful in any environment other than their respective experimental environment is yet to be determined. Whenever ZigBee and Bluetooth are mentioned in the overall samples, it is repeated that they generate poor results in position accuracy for IPS standards. Despite this, Kolakowski (2022) raises a couple of interesting points with BLE. Its main advantage over other common radio technologies is its low energy requirements which in turn reduces maintenance costs. In addition, almost all smartphones are equipped with Bluetooth radio module, which creates a massive network of points of interest. The cost of the system device can also be low due to its commercial presence.

4.3.3 Machine learning

During the analysis of the first sample, an interest in machine learning and how it could potentially improve UWB-based positioning systems was noted. As a result, a new search was conducted with the focus on machine learning in UWB-based positioning systems. The analysis found that machine learning was mainly used to classify NLoS-signals and then to mitigate them to improve accuracy. Other use cases did however occur, like the system Cheng et al. (2020) developed which localizes and recognizes human activity with the help of machine learning. They concluded that UWB was effective when using machine learning to simultaneously recognize and localize human activities (ibid.).

Many different machine learning methods were present in the sample such as support vector machines (SVM) and convolutional neural networks (CNN) with SVM being the more common. Stahlke et al. (2020) applied different CNN architectures to identify NLoS-signals and found that their model could outperform the more common SVM alternative with over 10%.

As stated in under the Kalman Filter sub-section of this chapter, Yue et al. (2022) used a back propagation neural network to process IMU- data which was then fused with UWB-estimations. When NLoS-propagation was high, the processed IMU-data could be used to make more accurate estimations then the ones generated from only UWB-data (ibid.).

To summarise, machine learning seems to have an important role in future developments of UWB-based systems, not only to improve accuracy but in other supportive functions. This part of the field does however still seem to be in an exploratory phase where best practices has yet been established.

4.4 Localization system

Through the iterations of sampling, different novel systems have been proposed to tackle the many unanswered questions of IPS. Bottligliero et al. (2021) focused on a low-cost TDoA estimation with the niche of not requiring time synchronization among the sensors. In their paper, trilateration is of most importance to obtain high accuracy. In similar way, Chen et al. (2020) used trilateration to realize high precision but fused it with maximum likelihood estimation algorithm as an improvement to the trilateration algorithm. Clark et al. (2021) applied their own novel low-complexity algorithm, Trilateration for Exploration and Mapping (TEAM), to mobile robots. A direct comparison to particle filter for Simultaneous Localization and Mapping (SLAM) was made and was found to achieve satisfactory results in both map accuracy and maximum localization error. Common for these papers are that they use preplanned anchors for trilateration. Courtay et al. (2019) experimented with a Best Anchor Selection for Trilateration (BAST) algorithm that determines which three anchors to be the best for trilateration on mobile targets, tennis players in their case, which showed to generate results that outperformed positioning algorithms such as Multi-lateration, Trilateration, Gauss-Newton, and Weighted Centroid Localization.

For added accuracy, combining a filter to reduce disturbances is a common approach for many of these systems. Feng et al. (2020), as mentioned in the Filter section, showed that an implementation of EKF or UKF in IPSs generated much more accurate results than algorithms that did not. Pham et al. (2022) showed that Kalman filters in conjunction with UWB had higher positional accuracy than if they were standalone components. Indeed, Alasiry et al. (2019) used a Moving Average Filter which they considered to be the simplest digital filter and would still generate results with centimeter accuracy in real-time simulations. Many different variations of filters can be used, and many are being tested and refined, but they are regardless improving the positional accuracy of the overall system if applied correctly.

4.5 UWB-characteristics

It is repeatedly mentioned in the sample that satellite solutions, i.e., GPS is lacklustre in indoor environments and should be used with care and deliberation when doing so. UWB on the other hand is utilized for its many useful aspects and properties. It is used for its high time resolution and is therefore also used with ranging algorithms such as ToA and TDoA, as explained in the Time Synchronization section. However, ToA algorithms still suffer from challenges such as multipath-propagation, NLoS and time synchronization. Chen et al. (2020)

utilized an entropy-based approach for the ToA estimation to counter-act these challenges with results satisfying a minimum error-rate threshold. UWB also saw usage for its low power draw and is considered relatively cost-effective. UWB was also considered for its penetration capabilities of certain obstacles (Yue et al., 2022).

Satellite solutions for indoor localization is considered poor. The update frequency provided by the short and high-bandwidth pulses is seemingly enough to obtain high accuracy and low latency in LoS environments (Feng et al., 2020), there are some challenges in how to read the ingoing data from the high frequency in NLoS (Yue et al., 2022). Ranging techniques with or without time synchronization was mentioned, but not in the context of update frequency.

4.6 Ranging

The results show that some variation of a two-ranging method was most used within the sample. As mentioned in earlier sections, it was due to not needing time-synchronization as ToA does. Bottigliero et al. (2021) proposes an architecture that uses a reference tag in a known position to overcome the issue of time-synchronization whilst using one-way ranging ToA. Most use cases used some variation of two-way ranging, for example Alasiry et al. (2019) used an asymmetric double sided-two-way ranging method on their DWM1000, Clark et al. (2021) used two-way ranging due it being applicable with UWB and Pham et al. (2022) also took advantage of two-way ranging in UWB due to deeming it the most appropriate IoT wireless technology for accuracy. Ranging seems to be a bit sporadic, and a significant amount of effort is used to optimize these methods. However, two-way ranging seems to be the common approach since it does not require clock synchronisation between units.

5 Discussion

The research question for this study is: “What is the state-of-the-art in the field of trilateration in Ultra-Wideband based indoor positioning systems utilizing complementary technologies?” The discussion aims to explain the results of the document survey and put them in context in order to present the conclusion.

Trilateration is a widely used technique in UWB-based IPS. Complementary technologies, such as machine learning algorithms, additional sensors, algorithms for handling disturbances, such as NLoS, and multiple UWB technologies, are often utilized to improve the accuracy and reliability of these systems. In recent years, researchers have commonly utilized filtering techniques such as Kalman filters to improve accuracy of trilateration estimates (see section *Localization system*, pages 26). It is however becoming increasingly more common to implement machine learning methods such as neural networks or SVM to improve accuracy, both with and without Kalman filters. The incorporation of multiple UWB technologies and the integration of additional sensors, such as IMU and different radio standards, have also helped to enhance the performance of IPS. The findings that IMU works well in combination with UWB is especially positive as most modern smartphones contain IMUs which might indicate that the implementation of accurate smartphone localization will be more straightforward (see section *Complementary technologies*, pages 24).

As stated in Chapter 4.1.5, every source either conducted experiments or simulations on systems developed by the researchers themselves. There were no instances of case studies of larger scale systems or established systems for that matter. This might have to do with the fact that there are few established UWB-systems available. The few that are available, such as Samsung and Apple, do not offer developer APIs for their respective UWB-systems, which makes them difficult for researchers to study. As shown by the variation of solutions in the sample, the field is still working on determining the most effective solution for achieving high accuracy using complementary technologies. This could suggest that deployment of larger scale systems is still in its infancy and when the technology is more commonplace it would be easier to conduct such research.

It appears that there has been a lack of discussion regarding machine learning methods in achieving localization (See section *Machine learning*, page 25). Other methods such as NLoS signal mitigation techniques and node placement strategies have been more commonly addressed in the literature. This may indicate that the field is still in an early stage and has a long way to go before machine learning is widely utilized in UWB IPS. It is also possible that the resources and complexity required for implementing machine learning in these systems may be a barrier to its widespread adoption. However, it appears that researchers are experimenting with a range of different approaches to improve these limitations. This includes the use of novel algorithms, such as TEAM algorithm, as well as the fusion of different techniques, such as the combination of trilateration and maximum likelihood estimation (see section *Localization system*, pages 26).

One significant concern for the researchers is the challenges NLoS brings. In 2008, NLoS seemed to be one of the biggest hurdles to pass for UWB applications (Nikookar et al., 2008). It seems that NLoS is still a common problem. Che et al. (2020) discuss the increased error in estimates with longer distances, which is exacerbated by NLoS propagation. Tian et al. (2019) studied NLoS propagation caused by the obstruction of human bodies. These issues highlight the importance of effectively addressing NLoS disturbances. Several methods have been utilized to address these disturbances, such as filtering by Yue et al. (2022), machine learning by Stahlke et al. (2020), multi-sensory fusion by Chen et al. (2020) and path thresholds mentioned by Khodjaev et al. (2009). The efficacy of these methods is adequate for their proprietary system but does not prove to be generalizable. Furthermore, while there are several methods to mitigate the effects of NLoS signals, it is not clear which method is the most effective. Perhaps a combination of pre-processing techniques, such as the one Khodjaev et al. (2009) proposed, and post-processing techniques, such as filtering, would generate sufficient results.

Overall, the use of complementary technologies in UWB-based indoor positioning systems have shown promising results in improving the accuracy and reliability of these systems.

5.1 Conclusion

The answer to the research question “What is the state-of-the-art in the field of trilateration in Ultra-Wideband based indoor positioning systems utilizing complementary technologies?” is that based on the analysis, a UWB based indoor positioning systems that utilizes Machine Learning methods to identify NLoS-signals, to then supplement the estimation with additional sensor data such as an IMU and lastly process the signal with a EKF to reduce potential noise and disturbance. The variation of solutions presented in chapter four does however suggest that the UWB-based IPS field is moving in multiple directions and exploring different alternatives that could provide high accuracy. The analysis has identified several limitations in UWB IPS. The effects of NLoS signals on ranging estimates and the increased errors with longer distances are significant challenges that researchers are attempting to mitigate through various methods, such as sensor fusion with IMU. This is especially important for IPS since indoor environments are generally obstructed. The cost and complexity of solutions are also concerns for researchers, as some proven methods are deemed too costly or complex (Chen et al., 2020). While there is interest in more dynamic solutions, node placement is still an important factor to consider when deploying a positioning system. Additionally, time synchronisation between nodes, which is necessary for certain ranging techniques, also requires significant resources and can increase the cost of a system. Filters and machine learning techniques, as well as alternative ranging methods such as TWR, may potentially be useful in addressing some of these limitations and improving the accuracy and efficiency of UWB-based IPS. Furthermore, update frequency is innately sufficient in UWB, and no techniques or methods were found to explicitly improve this aspect.

5.2 Limitations

There are many research documents available on UWB-based IPS. Due to time constraints, only a few selected keywords were used in the Grounded Theory process and the iterative process was only carried out thrice. This led to a rather small sample size, reaching 25 sources. If more time had been available for this document survey, more concepts and categories would likely have been discovered and other conclusions may have been drawn.

This research project could have also benefited from a meta-analysis, with which the different solutions in the sample could have been compared. This would have produced results which could point to which UWB based IPS system is the most accurate and efficient. This would however have required expertise and resources not available for this project.

In addition, the sample size of sources used in this survey may be considered small, which could potentially limit the generalisability of the findings. The method of sampling did also affect the generalisability, as theoretical sampling does not follow a rigorous method, but instead promotes an exploratory approach. This means no measures are put in place to ensure generalisability. Despite this limitation, the application of method in this study is meant to be clear and concise, allowing for reproducibility. The results of this study should however be interpreted with caution and further research with larger sample sizes is needed to increase the reproducibility of the findings. Determining the credibility of the study is done by examining if the data collected corresponds with the sample. This is possible for the reader to determine as the sample is readily available in Appendix A.

Another aspect that is worth mentioning is the validity of the study. If more resources were available, it would have been beneficial to triangulate the data using multiple methods of data collection, such as document surveys and interviews, to increase the validity of the results. However, validity should be adequate through the transparency of the application of method.

5.3 Ethical and social considerations

This study relies on published, peer-reviewed research documents from IEEE Xplore as its data source. The selected data sampling is included in Appendix A for transparency. The study has the potential to contribute to the development of the field of UWB IPS and as a result, potential consequences may arise.

Some ethical and social considerations that may arise include the potential for UWB IPS to be used for tracking and surveillance of individuals, as well as the potential for these systems to disproportionately benefit or disadvantage certain groups of people based on their access to and ability to use the technology. There may also be concerns about the privacy implications of collecting and storing data on individuals' locations and movements. Researchers could consider implementing privacy-preserving techniques, such as anonymous tracking or data aggregation, to protect the privacy of users. The use of UWB-based systems may have social implications, such as changes to how people interact in public spaces. Additionally, there may be ethical considerations around the cost and complexity of these systems, as well as the potential for them to perpetuate existing inequalities if they are not made accessible to all members of a community. A high accuracy UWB IPS could on the other hand, have life changing effects in certain applications. One such example would be the possibility to track if an elderly person has fallen to the ground, which could enable faster emergency care.

5.4 Future work

The categories presented are to be some form of guideline for some potential areas for future work. Neural networks and SVM are some machine learning algorithms that are improving the accuracy of UWB IPS. Experimenting with different machine learning algorithms under different conditions could prove fruitful for future research on the effectiveness and efficiency of precise indoor localization on trilateration usage in UWB.

Furthermore, a continued development of algorithms and techniques for handling NLoS in UWB IPS. Perhaps through improvement in accuracy of already existing methods, or exploration of alternative approaches, i.e., additional sensors such as LiDAR. It may also be interesting to compare the update frequency of different ranging techniques in UWB IPS, in terms of factors such as data rate, accuracy, cost and complexity.

Another potential area for future work is the exploration of more dynamic positioning systems that do not rely on fixed reference nodes, such as those proposed by Phoojaroenchanachai et al. (2021) and Clark et al. (2021). Trade-offs in accuracy, complexity and scalability would all be interesting aspects to evaluate. Studying established systems or deploying and testing new systems in real-world environments would provide a more realistic and comprehensive evaluation of the currently used technologies. Indeed, some form of case study of a large scale UWB-based IPS is to our knowledge lacking.

Another interesting aspect to study is that of user privacy in IPSs and what engineers can do to ensure that the users' privacy is protected. Researchers could study what data is needed to be output from the sensors and what data that can be kept within the sensors.

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Appendix A – Sample

Sample 1
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Sample 2

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Sample 3

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