Scalable Positioning Method for MAV Localisation using Two onboard UWB Tags

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Scalable Positioning Method for MAV Localisation usingTwo onboard UWB Tags

by

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Preface

Within this document, the report of my masters thesis can be found. This masters thesis concludes my studies at the faculty of aerospace engineering at the TU Delft that started back in 2015. During this thesis I researched a new localisation method for micro aerial vehicles. During this time I had the opportunity to develop new skills and work on things that I had no prior knowledge of and no experience with. This included developing code in a new programming language, running code in real time and working with micro electronics. This time, like the rest of my studies at aerospace engineering, have been an enjoyable and enlightening experience.

During the course of my thesis I was lucky to have excellent supervision that enabled me to have such an instructive experience. Even during times of limitations and restrictions my supervisors always provided the support and facilities needed for my project. I therefore wish to thank Guido de Croon for his advise and support. Furthermore, do I owe many thanks to my daily supervisor Sven Pfeiffer for his valuable advice, assistance and feedback on many occasions.

I also had the pleasure of having people around me who made the period during my studies a lot more enjoyable. Especially during the time of the pandemic, I have realised that good company is very important. I want to thank my friends, with whom I spent much time over the years. I have really appreciated their company and I am certain that I will continue to do so in the future. Additionally, I want to thank my family for their support and interest in my work.

Finally, I wish the reader an enjoyable time while reading this document. Furthermore, am I grateful for the curiosity of the reader for this work.

Bas van Beurden
Delft, November 2021

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Nomenclature

AOA	angle-of-arrival
COTS	commercially available off the shelf
CSI	channel state information
EKF	extended Kalman filter
GPS	Global Positioning System
IMU	inertial measurement unit
MAV	micro aerial vehicle
PDOA	phase-difference of arrival
SLAM	simultaneous localisation and mapping
TDOA	time-difference of arrival
TOA	time-of-arrival
tof	time-of-flight
TWR	two-way ranging
RMSE	root-mean-squared error
RSS	received signal strength
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UWB	ultra-wideband
WLAN	Wireless Local Area Network

1

Introduction

An unmanned aerial vehicle (UAV) is an aircraft that does not carry a human pilot or passengers onboard. UAVs exist in many shapes, sizes and configurations. Smaller variations of UAVs, such as micro aerial vehicles (MAVs) have the advantage of a low weight and low power consumption and high manoeuvrability. Because of these traits, many types of UAVs are becoming very popular for applications such as inspection, reconnaissance or communication relay.[1] Often these applications attain a high degree of automation for navigation of the UAV.

When striving for highly automated control of UAVs, it is important that an accurate position estimate of the position of the UAV is available. Therefore, often for indoor applications of unmanned aerial systems (UAS), dedicated infrastructure is utilised to accommodate localisation of UAVs. These indoor positioning systems use sensors at known locations to laterate and angulate signals and determine a position estimate of the UAV continuously and in real-time.

Many types of indoor positioning systems exist. Different positioning systems can vary greatly in terms of accuracy, technology, cost, availability and scalability.[1] In more recent years, Ultra-wideband (UWB) technology has gained a reputation of one of the most accurate and promising methods of indoor localisation.[2, 3] In UWB localisation radio frequency signals are sent from a transmitter to a receiver. Some properties of this signal can be used to determine a relative position between the transmitter and receiver. Many types of algorithms exist that exploit different properties of the signal propagation in order to make an estimate of the position of a UAV.

In order to make indoor positioning systems appealing for commercial use, good accuracy performance and scalability are needed. However, positioning systems that can attain high accuracy often use reciprocal communication between the receiver and transmitter, therefore limiting the number of simultaneous users of the system.[4] The challenge is to create a positioning system that can attain high accuracy without the need for reciprocal communication. For this reason, in this research a novel localisation method is implemented using commercially available off the shelf components. The localisation method was implemented by connecting two UWB sensors to a MAV and generating measurements only by receiving signals sent by the reference sensors of the system. Therefore, this localisation method can achieve both good accuracy performance, as well as a high level of system scalability.

In this final report, the works of a masters thesis are presented. The first part consists of a scientific article that describes the results of the research. The second part of this document contains a literature review that was performed in preparation of the research. Here, background information about the field of indoor positioning is provided for the reader. Both parts of this document have been written as a standalone document and can therefore be interpreted as such.

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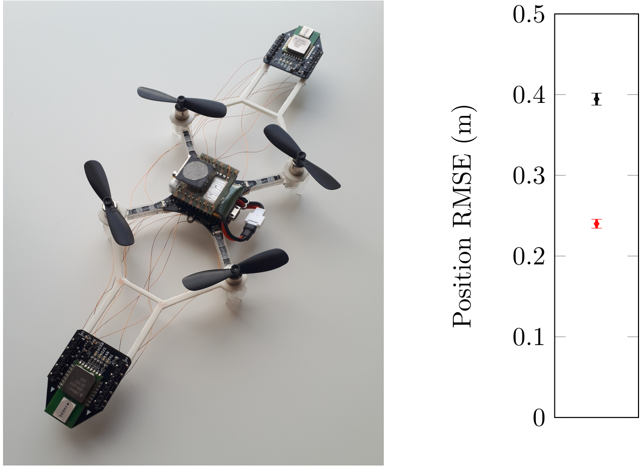
Thesis Paper

In this chapter, the resulting report of the masters thesis is provided in the format of a scientific article. This article can therefore be read as a standalone document describing the research that has been conducted.

Scalable Positioning Method for MAV Localisation using Two onboard UWB Tags

B. van Beurden, S. U. Pfeiffer, G. C. H. E. de Croon

***Abstract*—Ultra-wideband (UWB) ranging is a very suitable method for indoor localisation of unmanned aerial vehicles (UAVs). Current solutions of UWB ranging however either focus on achieving a high accuracy or focus on scalability. In this research a positioning algorithm for UAVs is presented that combines high accuracy performance with a high level of system scalability. The localisation method uses commercially available off the shelf components and is implemented by connecting two UWB sensors to a micro aerial vehicle, as shown in Figure 1. From both sensors, time-difference of arrival (TDOA) measurements were collected during flights and additionally, a tag-TDOA between the two UWB sensors was measured which estimates the angle-of-arrival of the incoming signals. It was found that state estimation using TDOA measurements from both UWB sensors has a reduced positioning error compared to the algorithm using TDOA measurements from one UWB sensor (see Figure 1), without significantly affecting yaw estimation accuracy. Furthermore, the tag-TDOA measurement did not improve the estimation accuracy at the implemented baseline of 0.22 metres as the measurement error was too large compared to the baseline.**



(a) (b)

Figure 1: Overview of the final configuration of the MAV with the connected UWB sensors and the achievable positioning accuracy (in black the position error of a conventional TDOA algorithm is shown, in red the position error achieved using the implemented configuration is indicated)

I Introduction

The field of indoor positioning concerns itself with providing position estimates of objects in indoor environments. Such estimates can be used for tracking or navigation purposes. Ultra-wideband (UWB) positioning technology is mentioned as one of the most accurate and promising technologies in the field of indoor positioning.[1, 2] UWB signals are radio frequency signals which use a high bandwidth signal for communication.[3] Due to this large bandwidth, UWB systems can achieve a high time resolution for ranging and exhibit limited distortion effects as caused by multipath and shadowing effects.[3] As a result, UWB technology is very suitable for indoor localisation of drones.

Much research performed on indoor positioning of unmanned aerial vehicles (UAVs) using UWB signals is performed with a focus on achieving a high accuracy, which can attain centimetre order of magnitude such as in [4, 5, 6]. These applications make use of two-way ranging (TWR), which uses reciprocal communication between the different components of the localisation system. While this implementation is able to achieve a high accuracy, it limits the number of users of the system and can experience high latency.[7] Several other implementations exist that can achieve a high accuracy, often using a method resembling time-of-arrival estimation. Such applications often face high complexity and cost of the solution and do not attain high scalability.[8]

In recent years, the application of small sized unmanned aerial vehicles (UAV) or micro aerial vehicles (MAV) for indoor purposes has gained popularity. In order to expand the applications for which unmanned aerial systems (UAS) can prove to be useful in the future, scalable positioning systems are needed both in terms of operational area and the number of simultaneous users. For this reason, positioning systems that are used by UAS shall also be implemented such that scalability can be facilitated in a cost-effective manner.

In this research therefore, we present an UWB localisation method which combines a high accuracy performance with a high level of system scalability. The presented localisation method uses commercially available off the shelf (COTS) components and retains a low level of complexity in order to create a low-cost positioning system. The positioning method is implemented by connecting two UWB sensors to a MAV. Using measurements from these UWB sensors, three versions of passive localisation algorithms were created and evaluated by comparison to a conventional time-difference of arrival (TDOA) algorithm. As by using two UWB sensors, a measurement is generated that depends on the heading of the MAV, the performance of the positioning algorithms is compared based on yaw estimation accuracy as well as position estimation accuracy.

II Related Works

In recent years, research in indoor UWB localisation has implemented methods that account for the above mentioned trait of scalability.[9, 10] In these publications UWB positioning systems for indoor applications are presented that use passive localisation algorithms by implementing a TDOA algorithm. Using these methods, these studies were able to achieve decimetre level accuracy, while removing any limitation on the number of users. Therefore, these works have established that scalable solutions can also achieve good accuracy performance.

In [11] a positioning system for pedestrians is presented that uses multiple sensors located on the body. This study shows that using multiple sensors on an object that shall be localised can drastically reduce the position estimation error and can also provide information which can be used for heading estimation. Furthermore, it was demonstrated that fusing multiple measurements into a state estimator can improve the overall quality of the position estimate while experiencing the same measurement accuracy from the sensors.

A heading estimation method for a ground based robot that makes use of four UWB positioning sensors is presented in [12]. Here, the heading of the robot is determined by computing the position of each UWB sensor and determining their relative angles in the global coordinate frame. Furthermore, was the two-dimensional position computed by averaging the positions of the different sensors on the robot. Using this method, a positioning accuracy reached centimetre order of magnitude while the heading estimation error attained a value of roughly one degree.

In a vast quantity of research regarding indoor UAV localisation, sensor fusion is performed in order to increase the accuracy performance of the estimation, such as in [13, 14, 15]. Fusing different measurements to create a hybrid localisation method can improve the state estimate to an accuracy greater than what can be achieved using the individual measurements.[16]

For this reason, this paper presents a passive localisation method which implements sensor fusion of two UWB sensors connected to a MAV. From both sensors TDOA measurements will be collected. Additionally, to generate information about the heading of the MAV, a separate TDOA measurement is generated by measuring the difference in signal receptions between the two sensors on the MAV. This paper analyses the performance of several algorithms using different measurement filtering methods for the implemented localisation method.

III Methodology

In this section information is provided on the the implementation of the presented localisation method. First, a theoretical analysis is provided on the integration of the localisation method. Subsequently, this section elaborates on the implementation of the chosen localisation method on the MAV and the different algorithms that will be evaluated. Finally, the wireless synchronisation method that was designed to implement the tag-time-difference of arrival algorithm is explained. In the remainder of the paper, the UWB sensor to be localised will be referred to as a tag. Furthermore, the term anchor will be used to indicate the reference points with known location used to trilaterate and triangulate signals in order to perform localisation on the tag.

A Theoretical Background

In [17] an extended Kalman filter (EKF) is presented that utilises UWB data together with inertial measurement unit (IMU) data in order to perform state estimation of the position and attitude of the UAV. The measurement equation included in the EKF to represent the conventional TDOA measurements collected on the MAV are given in Equation 1. Here, z represents the measurement value, $\boldsymbol{x}$ represents the position state of the MAV in the EKF. Furthermore, are the coordinates of the reference anchors given by $\boldsymbol{p}_{uwb}$.

$$z_{TDOA} = \|\, \boldsymbol{x} - \boldsymbol{p}_{uwb,i} \,\| - \|\, \boldsymbol{x} - \boldsymbol{p}_{uwb,j} \,\| \tag{1}$$

When using multiple tags on a UAV and collecting a TDOA measurement between these, the measurement equation for this tag-TDOA can be described as in Equation 2. Here, $\boldsymbol{x}_t$ is the position of a tag on the MAV. The rotation matrix used for transformation from the body-fixed frame to global reference frame as implemented in the EKF is denoted as $\boldsymbol{R}_{ref}$. Furthermore, are superscripts G and B used to indicate that the coordinates are expressed in either the body-fixed frame or the global reference frame.

$$\begin{aligned} z_{TTDOA} = {} & \|\, \boldsymbol{x}^G + \boldsymbol{R}_{ref}\ \boldsymbol{x}^B_{t,1} - \boldsymbol{p}^G_{uwb,i} \,\| - \\ & \|\, \boldsymbol{x}^G + \boldsymbol{R}_{ref}\ \boldsymbol{x}^B_{t,2} - \boldsymbol{p}^G_{uwb,i} \,\| \end{aligned} \tag{2}$$

As can be seen, using conventional TDOA measurements a relative measure of the position of the tag is generated. In this measurement, no information about the orientation of the UAV is included. In case of state estimation of a UAV, the attitude is therefore mainly observable through the measurements from the inertial measurement unit (IMU). The IMU however suffers from considerable biases and noise.[18, 19] When computing a TDOA between two tags on a UAV, a measurement is created that is dependent on the orientation of the UAV. Using this approach, a method for estimating the angle-of-arrival (AOA) of the incoming signal is fabricated. Therefore, the attitude of the UAV is made observable through these ranging measurements which should not suffer from bias.

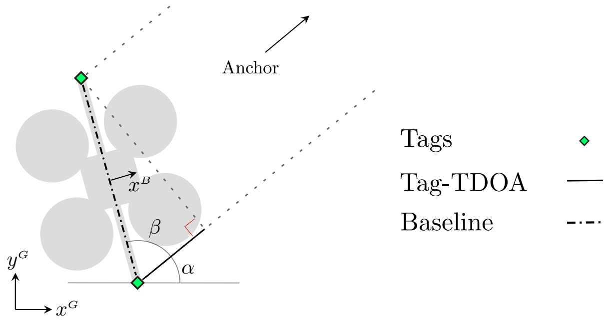


Figure 2: Visualisation of the tag-time-difference of arrival

In Figure 2 a schematic overview of the TDOA between the tags is displayed for level flight condition. Here, α denotes the heading direction of the UAV relative to the reference anchor and β represents the relative direction of the anchor as seen from the UAV. As described in Equation 3, these angles can be related to the yaw (ψ) of the UAV, which is the angle between the x-axes of the body frame and of the global reference frame. The tag-TDOA represents the difference in the reception times of a signal from a single anchor in the two different tags. As can be seen does this depend on the direction of the anchor relative to the attitude of the MAV and the baseline i.e. the distance between the tags.

$$\psi = \alpha + \beta - 90° \tag{3}$$

$$d_{TTDOA} = b \cdot \cos(\beta) \tag{4}$$

When assuming small angles for the pitch and roll of the UAV and sufficient distance between the anchor and UAV, the distance difference between the tags relates to the relative direction of the anchor as described in Equation 4. Here, b denotes the baseline and β is the angle between the baseline and the incoming UWB signal, as displayed in Figure 2. Using this equation it can be determined how different ranging resolutions translate to the angular resolution of the AOA estimate. When considering that a measurement of the tag-TDOA consists of the true distance d_{TTDOA} and a measurement error e, the estimated relative direction of the anchor can be described as in Equation 5.

$$\hat{\beta} = \arccos\left(\frac{d_{TTDOA}}{b} + \frac{e}{b}\right) \tag{5}$$

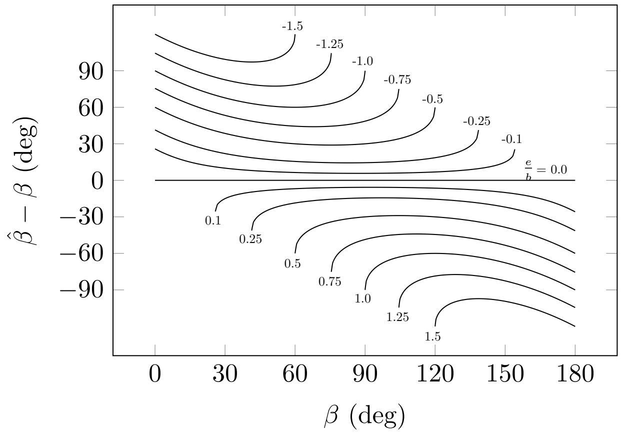


Figure 3: Propagation of the ranging error into the attitude estimation for different relative directions of the anchor (β) and different magnitudes of the ranging error relative to the baseline $\left(\frac{e}{b}\right)$

Using Equation 4 and Equation 5 a relation can be found between the orientation of the UAV and the angular resolution. In Figure 3 this relation is plotted for different magnitudes of the error added to the ranging measurements. Each line represents a different value of the error added to the measurement relative to the baseline $\left(\frac{e}{b}\right)$. As can be seen, for greater magnitudes of the error, no estimate exists for part of the attitudes, which is caused by the trigonometric inversion in Equation 5.

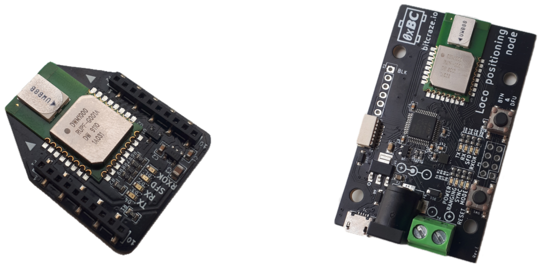
Regarding the accuracy of the AOA estimation it can be seen that measurements with an error which is equal or greater than half the length of the baseline do not provide any relevant information about the heading of the UAV. For the case of an error of half the baseline the angular resolution does not reach below 30 degrees. Furthermore, it can be observed that when the baseline becomes more aligned with the line of sight from the anchor, the accuracy of the AOA estimate rapidly deteriorates. This should also be accounted for in the implementation of the localisation method by ensuring that the UAV is surrounded by anchors in multiple directions.

B Hardware Implementation

The chosen localisation method shall be tested in a practical setup. This means that an implementation shall be found which can generate the desired UWB measurements. Furthermore, does this measurement scheme need to be implemented using a suitable UAV and sensors and additionally sound communication between all components shall be ensured.

The UAV that was selected to perform the experiments is the Crazyflie 2.1 from Bitcraze. Reasons for choosing this quadcopter are that the software and hardware design is completely open source and elaborate development support is provided. Furthermore does the Crazyflie have an expansion interface, with several buses such as I2C, UART and GPIO and several commercially available expansion decks that can be connected to the drone. The Crazyflie weighs only 27 grams and is therefore considered a micro aerial vehicle.

The Locodeck is available to complement the Crazyflie and allows onboard localisation using UWB signals, using either a TWR or TDOA method.[20] In addition, Loco positioning nodes are similarly available from Bitcraze, which can serve as anchors for the UWB positioning system.[21] Both the Locodeck as well as the Loco Positioning node make use of the Decawave DWM1000 module for the UWB communication.[22] This module is widely used in indoor positioning systems and provides a precision of approximately 0.1 metres for indoor ranging.[22] A Locodeck, together with a Loco positioning node is displayed in Figure 4.



(a) Locodeck (b) Loco positioning node

Figure 4: Crazyflie positioning components

The localisation method is integrated on the Crazyflie by connecting two Locodecks to the MAV. In order to maintain some distance between the different decks, a set of holders for the tags have been designed which can hold two sets of pins similar to the expansion interface of the Crazyflie at a baseline of 0.22 metres. The pins on the tag holders are connected to the expansion interface via soldered wires. Moreover, one of the two Locodecks uses an alternative pinout in order to communicate with the Crazyflie independently from the other Locodeck. Using this configuration, measurements can be generated that include information about the heading and position of the MAV.

In order to log data during flights with the Crazyflie, an SD card connector is attached to the expansion interface. The connector allows for communication between the MAV and a micro SD card. To support the use of two Locodecks and the SD card connector, some small adjustments were made to the Crazyflie firmware. The final configuration of the MAV with the connected decks is displayed in Figure 1a. Using this setup, several different algorithm structures can be leveraged by applying different filtering methods on the collected measurements. The following scenarios will be evaluated by inclusion of specific measurements to the EKF.

- *Single-tag TDOA*: regular time-difference of arrival scheme using a single tag, as widely employed in localisation applications. This algorithms serves as a benchmark performance for TDOA algorithms to which the other algorithms can be compared.
- *Two-tag TDOA*: regular time-difference of arrival scheme using the measurements from both connected tags.
- *Tag-TDOA*: using only the ranging measurements with the time-difference of arrival between the two tags. This method therefore can be classified as an AOA-method.
- *Two-tag Hybrid*: using both the regular time-difference of arrival measurements from both tags and the time-difference of arrival between the tags. Therefore, does this algorithm combine TDOA and AOA localisation.

C Wireless Synchronisation

One difficulty that arises when measuring the tag-TDOA is that the internal clocks of both tags suffer ever so slightly from clock drift. Due to this clock drift, the clocks of both tags do not coincide exactly and cannot be directly compared. This slight difference needs to be corrected for in order to achieve an acceptable level of accuracy for the tag-TDOA measurements. In order to correct for these inaccuracies, a wireless synchronisation algorithm was employed that uses communication between the two tags on the MAV in order to determine the clock offset and the difference in ratio at the moment of synchronisation.

In order to determine the mentioned clock ratio and clock offset a communication scheme similar to the double-sided TWR method presented in [23] is used. An overview of the communication between the two tags carried out for wireless synchronisation is illustrated in Figure 5. Here, a reciprocal communication scheme is incorporated by sending three packets between the two tags: a poll, answer and final packet.

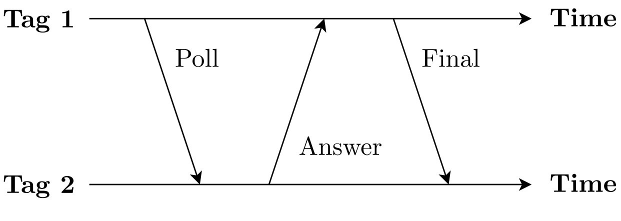


Figure 5: Communications overview of the wireless synchronisation algorithm

By means of these three communication signals, a time-of-flight (tof) between the tags can be computed which is only influenced by clock drift of between the devices.[23] This time-of-flight between the tags is compared with the actual difference between the reception timestamp (t_{rx}) of the final packet in tag 2 and the transmission timestamp (t_{tx}) of this packet in tag 1. By this comparison, the clock offset (t_{offset}) at the moment of reception of the final signal is computed, as shown in Equation 6.

$$t_{offset} = t_{rx,final} - t_{tx,final} - tof \tag{6}$$

The clock ratio (r_{clk}) is then determined using the poll and final packets sent by tag 1. The time difference of transmission of both packets in tag 1 can be compared to the time difference in reception in tag 2 to get the ratio between the two clocks, as displayed in Equation 7. This process is continuously repeated roughly every 30 milliseconds in order to revise the estimated clock ratio and offset. When a signal is received in tag 2 at time t_{tag2}, the time in tag 1 will then be approximated by adding the offset and correcting the time past since the latest synchronisation by the clock ratio, as shown in Equation 8. Here, $t_{rx,final}$ denotes the time of reception of the latest synchronisation packet in the clock of tag 2.

$$r_{clk} = \frac{t_{tx,final} - t_{tx,poll}}{t_{rx,final} - t_{rx,poll}} \tag{7}$$

$$t_{tag1} \approx t_{rx,final} + r_{clk}\left(t_{tag2} - t_{rx,final}\right) - t_{offset} \tag{8}$$

IV Experimental Evaluation

In this section the evaluation of the implemented localisation system is presented. First an overview is given of the experimental setup which was employed to collect the necessary data for assessing the positioning algorithm. Furthermore, the results of the experiments are presented along with a discussion of the results at the end of this section.

A Experimental Setup

In order to test the performance of the positioning system implemented on the MAV, several test flights were performed. All measurements taken by the Crazyflie, consisting of IMU and ranging data were logged during flight. Along with the onboard measurements, data from the present OptiTrack system was also logged in order to act as ground truth measurement of the position and attitude of the MAV. The OptiTrack system is a motion capture system which has a millimetre order of accuracy.[24]

The data collected during approximately thirty flights is used to make an offline simulation of the onboard state estimation of the MAV. This simulation is performed by means of an EKF as described in section III, which is also used onboard the Crazyflie to perform real time state estimation of the position and attitude. Several different trajectories were followed by the MAV, including a square, circle, hourglass figure and a vertical square along with variations in yaw. Several different scenarios were created in order to test the relationship between the number of anchors used and different methods of filtering the UWB data.

Scenarios with different numbers of anchors were created by disregarding the data of a selection of anchors from the data where ranging measurements of eight anchors were logged. This step was performed to mimic the effects of using less infrastructure for the uwb localisation system. This process was performed for each of the algorithms presented in section III. For each scenario, a state estimation was performed using an EKF and both the estimated position and attitude were compared to the ground truth data.

B Results

In the following, an evaluation of the simulation using the offline EKF is given. The different localisation algorithms as mentioned in section III were compared based on the resulting estimation error, expressed in root-mean-squared error (RMSE) of position and RMSE of yaw of the MAV. Figure 6 shows the convergence of the different TDOA algorithms implemented for a different number of UWB anchors used. The threshold adopted to determine convergence is a position RMSE of 1.0 metre for a given flight. The percentage shown on the vertical axis represents the share of flights that were simulated with an estimation error below one metre for the given condition.

The most notable observation that can be made is that the condition of the tag-TDOA without any conventional TDOA data has a convergence of zero percent in all cases. This means that this algorithm is not able to estimate the position of the MAV with a RMSE smaller than one metre in any of the reconstructed flights. As the state estimation was not performed successfully for this condition, the data for the tag-TDOA algorithm is not taken into consideration for the remainder of this section where the position and yaw error are quantitatively compared. This applies also to the condition using only three anchors for all algorithms.

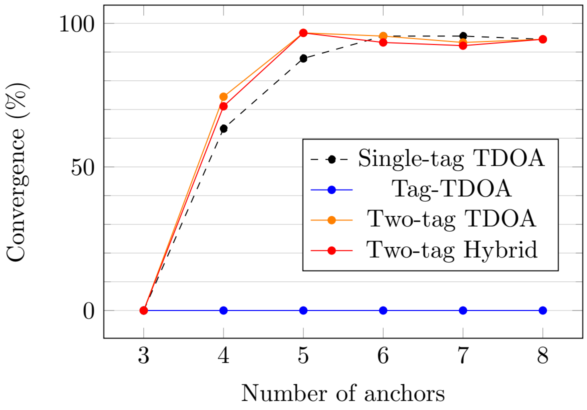


Figure 6: EKF convergence under different conditions (position RMSE < 1.0 m)

When looking at the algorithms in Figure 6 that do include some form of conventional TDOA data, the convergence or performance of the estimation seems to increase with the addition of more anchors. It can also be seen that the convergence of the methods using two tags is higher compared to the other methods for smaller numbers of anchors, that is four or five anchors.

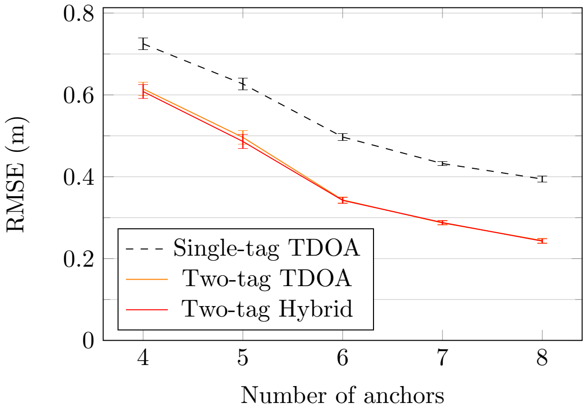


Figure 7: Position estimation error of the different algorithms

Figure 7 shows the performance of the estimation of the position of the MAV for the different conditions. The average RMSE of all flights is displayed for each algorithm and for different number of anchors. The bars are used to indicate the standard error of the of the position RMSE. As can be seen does the positional estimation error decrease with increasing number of anchors included in the UWB measurements.

What is furthermore striking is the improvement of the estimation of the methods using measurements from both tags compared to the single-tag TDOA. In case of a small number of anchors the average position RMSE is roughly 0.1 metres higher for the single-tag TDOA. In case of larger number of anchors used, this disadvantage for the single-tag method increases to up to 0.15 metres. In all cases, the difference in performance is significantly larger than the standard error of the measurements. Furthermore, it can be observed that the increase in accuracy can compensate for using fewer anchors. Accordingly, the position accuracy in case of five anchors and using two tags compares to the performance when using eight anchors with only a single tag on the MAV.

In Figure 8 the performance of the yaw estimation is depicted. Here, for the different scenarios, the average RMSE of the yaw estimation compared to the ground truth data is presented along with the standard error of the yaw RMSE. Remarkably, the different algorithms do not differ significantly in accuracy of the yaw performance as can be seen from the overlapping bars representing the standard error. Another observation that can be made from the figure is that there is no clear effect on the heading accuracy when including more anchors in the measurements. This indicates that the ranging measurements do not provide information about the attitude of the MAV as accurately as the IMU data.

Based on the presented results, the following conclusions can be drawn. First of all it is evident that the position accuracy improves with increasing number of anchors. For this reason, the convergence similarly improves when increasing the number of reference anchors.

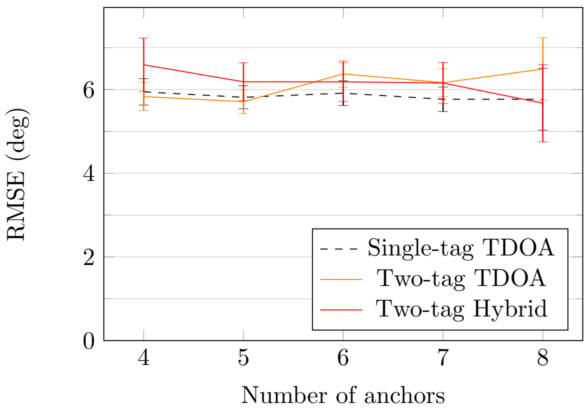


Figure 8: Yaw estimation error of the different algorithms

Furthermore, it can also be observed that utilising an additional tag on the MAV improves the accuracy of the position estimate. Concerning the attitude estimate, no significant differences in performance between the different scenarios can be recognised. Finally, it can be seen that the tag-TDOA measurements with the implemented baseline of 0.22 metres does not significantly improve on the accuracy of the position estimation.

C Discussion

In this part of the report, the previously presented results will be discussed. This entails an evaluation of the experimental setup, as well as providing a theoretical explanation of the results.

The quality of the estimation depends largely on the accuracy of the measurements that are provided to the EKF. In the EKF it is assumed that the incoming measurements are affected by zero mean Gaussian noise. In order to check the validity of this assumption for the current application it is important to check the distribution of the noise of the ranging measurements. This can be done by comparing the TDOA measurements with the position of the MAV as reported by the ground truth measurement.

Figure 9 shows the error distribution of the regular TDOA measurements in a histogram. The figure shows the estimation error on the x-axis and on the y-axis the probability density of occurrence for each bin such that the area under the histogram integrates to a value of one. As can be seen does the error distribution resemble a zero-mean Gaussian distribution. In Figure 10 the error distribution of the tag-TDOA is displayed. The measurements show similarities with the Gaussian distribution, however does seem slightly more heavy-tailed.

When however looking at the individual anchors in case of the tag-TDOA and individual anchor pairs in case of the conventional TDOA it can be seen that the measurement errors become more skewed as shown in Figure 11. This can be seen as a violation of the assumption of zero-mean Gaussian distribution of the noise to some degree. Therefore it is possible that the shape of the distribution induces inaccuracies in the state estimation.

Moreover, looking at the distribution of the tag-TDOA in Figure 10, it can be noticed that the majority of the ranging errors supersedes the baseline of 0.22 metres between the two tags on the MAV. The tag-TDOA measurement represents the distance difference between the two tags on the MAV. Therefore, if the measurement error shows inaccuracies close to or greater than the baseline, no information can be derived from the tag-TDOA value, as already indicated by the results shown in Figure 3. However, only roughly more than 40 percent of the measurement errors of the tag-TDOA is smaller than the baseline of 0.22 metres. This could be an additional justification for the adverse effect of the tag-TDOA on the state estimation for the current application.

In [25] a phase-difference of arrival (PDOA) method is presented using similar hardware from Decawave. Here, it is shown that using this method, heading estimation can be performed with much greater accuracy compared to a TDOA method. PDOA methods however would require antenna and circuitry design, which is highly complex and therefore out of the scope of this research. Furthermore, is the resulting accuracy very sensitive to imperfections in the hardware design. However, when correctly implemented, a PDOA method could provide a way to increase the AOA estimation accuracy and therefore potentially improve on the presented localisation method.

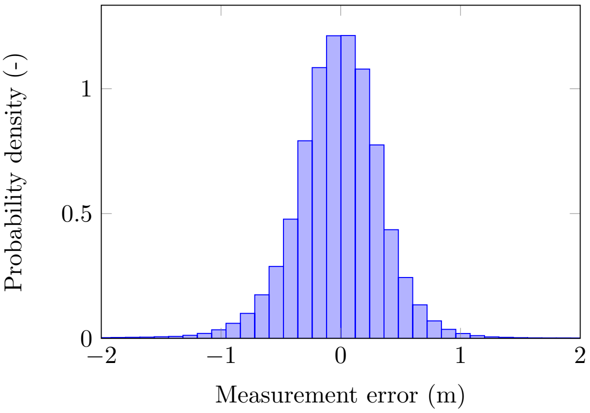


Figure 9: Histogram of the TDOA measurement error

A further potential source of inaccuracies in the simulation of the state estimation may be the comparison between different number of anchors. The manner in which this is implemented is by using the data from a flight where all anchors were used and disregarding a selection of the anchors. In reality however, using less anchors could leave more time for communication for the remaining anchors and therefore a greater level of accuracy could potentially be reached. In order to test the effect of reducing the number of anchors in use, several flights were performed with only four operational anchors.

Figure 12 illustrates the position error distribution for each algorithm for both the case of using four anchors during the flight and the case of using eight anchors during the flight and disregarding four. It should however be noted that the data with eight operational anchors does contain more flights. Additionally, in Figure 13 the yaw estimation error distribution for the identical conditions are displayed.

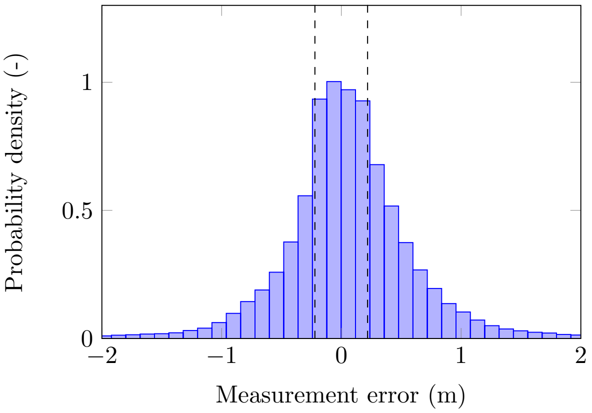


Figure 10: Histogram of the tag-TDOA measurement error (the dashed lines indicate the baseline length)

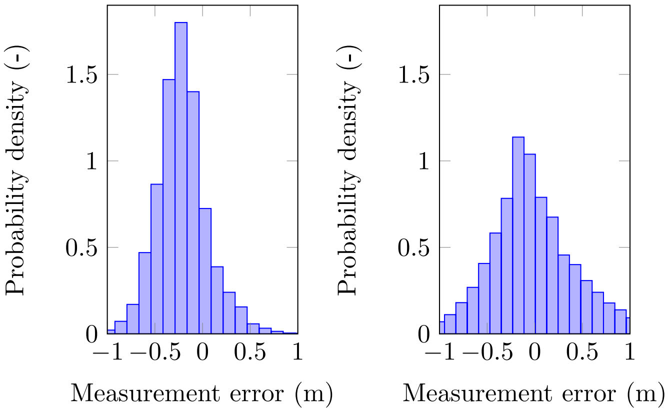


Figure 11: Histogram of the TDOA measurement error of an individual anchor combination (left) and tag-TDOA measurement error of an individual anchor (right)

In both figures it can be observed that small differences in performance occur between the different scenarios. It can however be identified that these distinctions are not large enough to explain the variation in performance between the use of different numbers of anchors as seen in Figure 7, where the difference in position accuracy between using four anchors and eight anchors is roughly 0.4 metres. Therefore, the method chosen to evaluate the performance of different numbers of anchors can be justified and shown to include the effects of containing additional anchors, rather than the effects on the total communication time.

V Conclusion

This paper presents a passive positioning method where two UWB tags were employed to generate supplementary

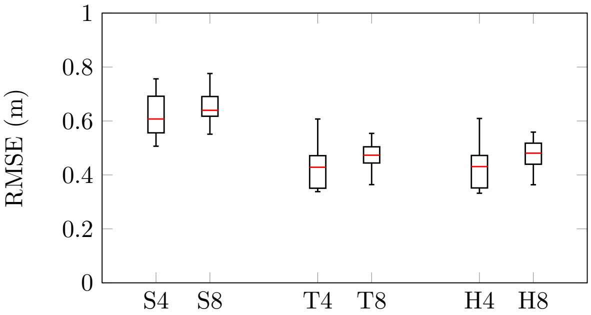


Figure 12: Position estimation error for different algorithms (*S = Single-tag TDOA, T = Two-tag TDOA, H = Two-tag Hybrid*) in case of four operational anchors (*4*) and eight operational anchors and disregarding four (*8*)

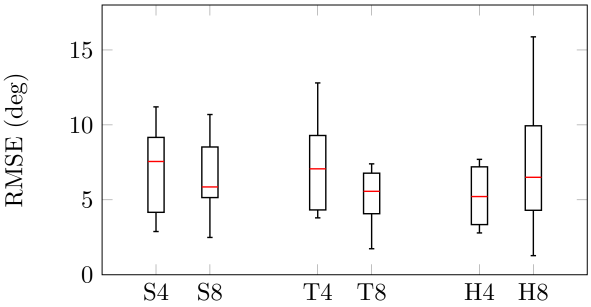


Figure 13: Yaw estimation error for different algorithms (*S = Single-tag TDOA, T = Two-tag TDOA, H = Two-tag Hybrid*) in case of four operational anchors (*4*) and eight operational anchors and disregarding four (*8*)

TDOA measurements. Measurements were collected by flying several trajectories with a MAV and used in order to make a post hoc state estimation using several localisation algorithms. It was found that the algorithms that use conventional TDOA measurements from both tags on the MAV reduced the position estimation error as a result of an increased number of incoming ranging measurements.

For attitude estimation it was found that no significant impact on the yaw estimation accuracy was achieved by the implementation of the alternative algorithms. Additionally, it was found that at the applied baseline of 0.22 metres, the tag-TDOA did not enhance the performance of the state estimation.

As a potential improvement of the AOA estimation method, it is worth mentioning that the heading estimation accuracy could be improved significantly. This might be done either by increasing the baseline or using a more complex method such as PDOA. Additionally, increasing the heading estimation accuracy could also further improve the performance of the two-tag hybrid algorithm as the results of this study have commonly shown that increasing the amount of measurements improves the estimation accuracy.

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3

Literature Review

In this chapter, literature review that was conducted prior to the performed research is presented. This report has been written and graded for the course AE4020. Small adjustments to the original report have been made in order to improve the coherence of the report in the arrangement of the current document.

3.1. Introduction

In recent years, the application of small sized unmanned aerial vehicles (UAV) for indoor purposes has increased significantly. Due to the fundamental workings of UAVs, application of these allow for removing part of the human involvement in operations which can prove to be advantageous in many scenarios.[5] Because UAVs are able to move in three dimensions, more agility and coverage area can be achieved compared to more conventional means such as human inspection and ground-based robots. As a result of the above-mentioned characteristics and recent advancements in technology of UAVs and autonomous systems, many new purposes are discovered for application of UAVs. Recent utilisations found for systems implementing UAVs in indoor environments are very diverse and range from camera inspection of crops to creating data relays for cost-effective data collection and many more.[6, 7] The MAVLab as part of the Delft University of Technology has undertaken a research project in cooperation with Royal Brinkman, a company that specialises in agricultural equipment. For this project, an unmanned aerial system (UAS) will be developed that is able to monitor crop conditions in a cost-effective way. The UAVs used in this system shall be able to fly in the complex environment of a greenhouse without any human intervention. In the scope of this project, this study focuses on creating a more efficient way to perform the indoor localisation of the UAVs that will be used.

Due to the research effort spent on developing indoor localisation systems and the constantly decreasing costs of microelectronics, the possibility to perform indoor positioning becomes more available for an increasing amount of operations. A sophisticated estimate of the position of a UAV, or any asset for that matter, can be useful for tracking or can provide valuable information for navigation purposes. The field of indoor positioning has emerged to provide for this urgency. A distinction is made between the field of indoor versus outdoor positioning as either purpose requires different technology to be applied for their needs and constraints. For instance, the outdoor positioning field is dominated by satellite navigation systems such as the well known Global Positioning System (GPS). The service of GPS is very effective in the field of outdoor positioning as it has globally achieved a very high level of availability and is able to provide a position estimate with an accuracy of a few metres.[8] For indoor purposes however, GPS is very much less a suitable option. GPS signals will become easily distorted when there is no line-of-sight connection between the transmitter and receiver of the signals.[9] Furthermore do indoor positioning systems generally aim to achieve lower uncertainty than several metres because of the proportion of the operational area.

The current state of the art concerning indoor positioning systems can be classified in six categories based on the medium used for determining positions. These are (1) infrared, (2) ultra-sound, (3) radio frequency, (4) magnetic, (5) vision based and (6) audible sound based positioning systems respectively.[10] In each of these categories, many examples can be found and each implementation presents its own trade-off between the various performance measures by which indoor positioning systems can be evaluated. Performance measures that can be utilised for indoor positioning systems are accuracy, availability, coverage, scalability, cost and privacy.[1] Many different situations where indoor positioning systems can be applied demand specific emphasis on various performance aspects of the positioning system. For this research for example, where crops in greenhouses shall be monitored, availability, coverage and cost are likely to be more important than excellent performance in accuracy or privacy. The best type of positioning system to choose in case of indoor positioning systems is therefore dependent on the specific application.

In recent years, ultra wide band (UWB) technology has gained increasing amount of attention in the field of indoor positioning. UWB positioning technology is mentioned as one of the most accurate and promising technologies in the field.[2, 3] UWB signals are radio frequency signals which use a high bandwidth signal for communication.[11] Due to the higher bandwidth of this technology, UWB positioning has some advantages compared to other indoor positioning systems. The main benefits of UWB systems are a high time resolution for ranging and limited distortion effects of signals experienced as caused by multipath and shadowing effects.[11] Current implementations of UWB positioning technology mainly concern asset tracking applications, such as the Ubisense system.[12] Furthermore, much research performed on indoor positioning of UAVs using UWB signals is performed with a focus on achieving a high accuracy, which can attain centimetre order of magnitude such as in [13, 14, 15].

Often however, these efforts to perfect the accuracy of the positioning systems disregard other important aspects of commercial viability of a positioning system such as scalability in number of users of the system and latency.[4] The origin of these issues is that these studies, as well as the asset tracking applications either centrally perform the position determination, or use two-way ranging (TWR), this introduces limitations on the number of position determinations that can be performed in a given time frame.[4] Comparing to the outdoor positioning technology of GPS, its power very much lies in the fact that the satellite network of GPS only transmits signals with whereabouts of the satellites. These can consecutively be processed by the receiver to find a position estimate. This structure imposes virtually no limit on the amount of position estimates that can be made simultaneously.[8] In case of creating a UAS for greenhouses, scalability is very important as the system shall be applied in greenhouses ranging from smaller sizes to many acres of area. This varying area may also require a varying number of UAVs needed for inspection. It would be very undesirable if a limit would be imposed on the number of UAVs that can be localised by the system or even if availability of a position estimate would deteriorate when increasing the number of UAVs to be localised.

Only in recent years, research in indoor UWB localisation has implemented methods that account for the above-mentioned traits of scalability in number of users and latency, such as in [16, 17]. In these publications UWB positioning systems for indoor applications are presented that use receiver-end localisation algorithms to present a location estimate. This step represents an important advancement towards a practical application of indoor positioning systems, such as for localisation of UAVs. The current development of UWB indoor positioning systems can be generally divided into two categories. On one hand, there has been a trend of trying to perfect the accuracy performance by using the most sophisticated localisation algorithms. On the other hand, efforts have been made that contribute to practical implementation of UWB positioning system, e.g. by removing the dependency on clock synchronisation of the tag. The field of indoor positioning could benefit greatly from efforts to combine both philosophies. This would entail implementing a more complex localisation algorithm on a system that allows for good scalability. A hybrid localisation algorithm combines multiple positioning methods in order to make a position determination. This approach has the ability to increase efficiency of the system by reducing the required infrastructure and therefore is an excellent positioning technique for current research.

This research therefore aims to improve the state of the art of indoor positioning technology by answering the question stated below. This research question is however very extensive and can therefore be divided in the sub-questions stated thereafter in order to specify the general steps that will be performed in this research.

> *How can the performance of UWB positioning for indoor localisation of small-sized UAVs be improved by developing a receiver-end hybrid localisation algorithm?*

- *What are the potential shortcomings of existing indoor positioning systems and why are these shortcomings a problem for indoor localisation of UAVs?*
- *How can a localisation algorithm be constructed such that shortcomings of current indoor positioning systems are overcome?*
- *What hardware requirements are posed on the implementation of such localisation algorithm to localise UAVs?*
- *How can the performance of the constructed localisation algorithm be evaluated?*
- *How does the constructed algorithm compare to the performance of existing indoor positioning systems?*

The choice for constructing a receiver-end hybrid localisation algorithm is based on two motivations. First, it is believed that a receiver-end localisation algorithm helps to satisfy the demand for practical implementation of UAS, such as scalability in terms of number of users and latency. Secondly, it is believed that a hybrid localisation algorithm allows for a system structure that is efficient and also relatively low cost. Any further motivation for the current subdivision and formulation of the research questions should become more apparent the in remainder of this report. In this report an overview of the current state of the art of indoor UWB positioning systems is provided. Furthermore, the motivations for this research and the proposed approach are summarised in section 3.4, where the methodology of this research is explained.

The report is structured as follows. In section 3.2 an overview of the different algorithms currently used for indoor positioning systems will be presented. Hereafter, section 3.3 elaborates on the different possible implementations of indoor positioning algorithms. Subsequently, section 3.4 summarises the motivations and goals for this research and additionally presents a methodology that will be adopted in order to perform the proposed research in a well-structured manner. Finally, a conclusion of the report is presented in section 3.5.

3.2. Positioning Algorithms

UWB signals can be used effectively for indoor positioning purposes. The term UWB or ultra wide band relates to the frequency characteristics of the signal transmitted through the air to the receiver. The information that can be extracted from these signals and the method used to transform the acquired information into a position estimate depends on the positioning algorithm that is implemented. Many variations exist regarding the employed algorithm used to determine a position estimate. The existing positioning algorithms can be classified in the following categories based on what properties of the signal propagation are used for localisation: (1) time of arrival (TOA), (2) angle of arrival (AOA), (3) time-difference of arrival (TDOA) and (4) received signal strength (RSS).[1] In this chapter these types of indoor positioning algorithms will be reviewed and evaluated. Furthermore, some additional methods to enhance existing localisation algorithms are discussed. In the context of indoor positioning, the object which shall be localised is usually referred to as a tag and a reference point with known location is often referred to as a node. These nodes are generally strategically placed at fixed locations in the environment in which a position estimate shall be provided.

3.2.1. Time of Arrival Algorithms

Time of arrival (TOA) algorithms measure the distance between an object for which a position estimate shall be generated and a set of reference points. In TOA algorithms, the distance of the tag to each of the nodes is computed by extracting the propagation time of each of the signals. This time is found by the difference between time of signal transmission and reception. If the location of a node is known and a distance from the node is known, the possible locations of the tag can be represented by a circle centred around the node. In a two-dimensional plane, a position estimate can therefore be established when time of arrival information from three nodes is available, as shown in Figure 3.1. In three-dimensional space, a position estimate can be obtained when provided with information from an additional node, hence a total of four nodes would be required.

For TOA algorithms, the distance between the tag and the nodes are computed based on the travel time of each of the signals. In order to accurately determine this travel time, it is essential that the internal clocks of all devices, that is of all nodes and the tag, are synchronised with each other with a high accuracy.[18] If successfully performed, this method can yield very good accuracy performance. As mentioned before, UWB localisation can reach up to centimetre accuracy.[13, 14, 15] Most of these efforts of reaching very high accuracy in UWB positioning make use of TOA based algorithms.[14, 15] Some methods exist that omit clock synchronisation requirements by using two-way ranging algorithms. These algorithms make use of round-trip times of signal propagation between two devices to compute the travel time of the signal and therefore do not require clock synchronisation when the reply delay of the other device is known. These and other different applications of TOA ranging will be further explained in section 3.3.

TOA implementations as described above are usually referred to as one-way ranging algorithms and require accurate synchronisation of the clocks of the nodes and tags. Applications of these TOA algorithms are mainly allocated to experimental setups and proof of concepts. For these applications, accurate clock synchronisation of all devices can be achieved relatively conveniently as the total time of measurement is relatively short, allowing the effect of the clock drift to be minimal. In practical applications however, it is desirable to be able to perform measurements for a long period of time without the need to synchronise the clocks of all devices. Reason for this is that dealing with clock drifts is difficult and costly.[1] Hence, TOA based algorithms that rely on clock synchronisation, such as one-way ranging, do not appear often in commercial indoor positioning systems.

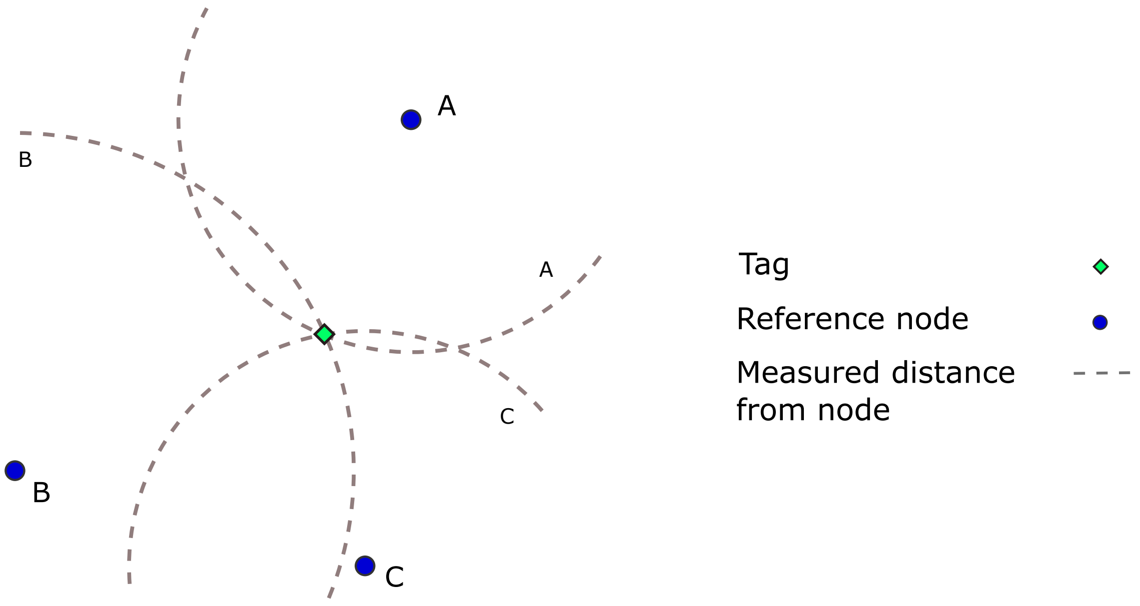

Figure 3.1: Visualisation of time of arrival algorithms.

3.2.2. Angle of Arrival Algorithms

The angle of arrival (AOA) algorithms, often also referred to as direction of arrival (DOA), are algorithms that determine the location of the tag by determining the angle of the tag relative to the given node. The determination of the angle relative to the node is usually performed by measuring the transmitted signal in multiple points, such as an antenna array.[19, 20, 21] By comparing the received signals either in terms of phase or time of arrival, the angle relative to a node or multiple nodes can be determined.[20] If the angle of the tag relative to the node is known, the possible locations of the tags can be represented by a line originating from the node, following the measured angle relative to the node. In two-dimensional space, a position estimate can then be provided when given information from at least two nodes, such as in Figure 3.2. In case of a three-dimensional position estimate, at least three nodes are required.

A remark should be made on the number of required nodes however. In case of a two-dimensional space, the implementation of a system with two nodes can give very poor accuracy performance in some specific situations. This is the case especially when the tag is close to the imaginary line connecting two nodes. If the tag is located anywhere on this line, the measured angle relative to the node will be the same (namely the angle pointing towards the other node). Hence, if the tag is located on this line, the positioning algorithm cannot distinguish between any position on this line. For this reason, it is therefore preferred to use at least three nodes in case of two-dimensional position estimates and at least four nodes in case of three-dimensional determinations. Furthermore, does AOA positioning have a high complexity, both in terms of required equipment as well as in terms of implementation.[22] The high complexity of the implementation originates from the multipath effects, which can affect the direction and therefore incoming angle of (part of) the signal.[22] Additionally, the performance of the position determination is influenced by many other factors, such as the antenna array geometry and the distance between transmitter and receiver.[23, 24]

Because of some of these difficulties, AOA algorithms are not very often used as sole means of providing a position estimate. More often AOA based algorithms are used in combination with other methods to complement on the characteristics of other localisation methods.[22] Most applications of AOA algorithms are based on the well-established MUSIC algorithm, which can provide asymptotically unbiased estimates of the direction of arrival of an incoming signal.[25] The MUSIC algorithm presents a general approach to model the incoming raw signal as the sum of point source emissions and noise. Most popular use of localisation systems using this technology include centrally tracking locations of tags, such as in [26, 27, 28]. Another application of an asset tracking system using AOA positioning technology is the Ubisense system, that is used for real-time tracking of assets in indoor environments.[12] Ubisense however uses a hybrid algorithm of AOA technology combined with TDOA algorithms. Applications of hybrid algorithms are described more elaborately below in section 3.3. The main advantage of AOA algorithms in case of centrally tracking assets is that it poses very low requirements on the hardware of the tags. These requirements can be as limited as exclusively the transmission of signals, such as in [26, 28]. Most applications of AOA algorithms therefore use similar system structures.

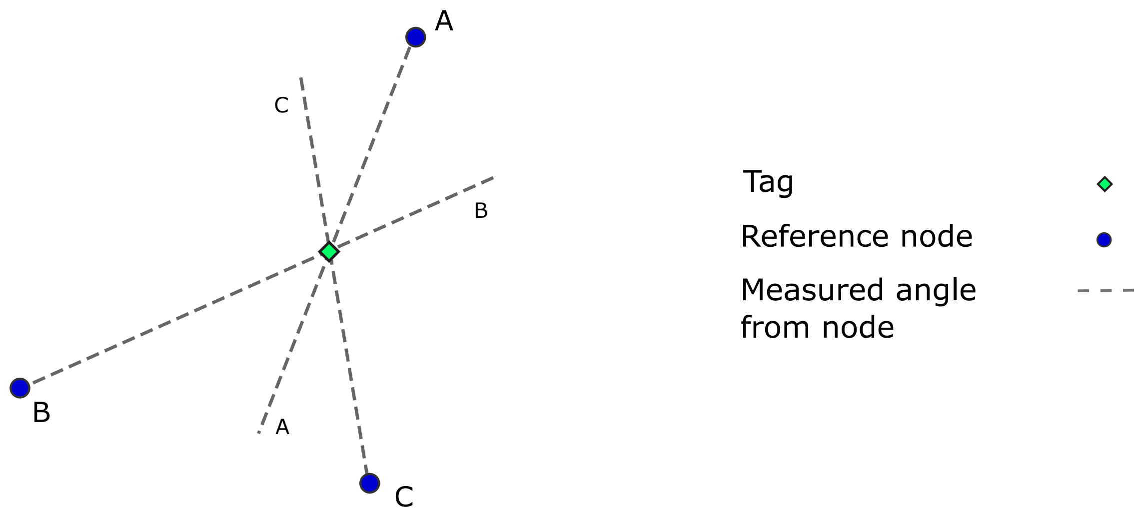

Figure 3.2: Visualisation of angle of arrival algorithms.

3.2.3. Time-Difference of Arrival Algorithms

The time-difference of arrival (TDOA) algorithms, similar to TOA algorithms, use the propagation times of the signals to determine a position estimate. Instead of computing the absolute travel time of the signal from transmitter to receiver, these algorithms compare the relative difference between propagation times of signals from or to different points. This means that the algorithm makes a pairwise comparison between the propagation times to two different nodes based on the difference in signal travel times. This method can be applied both with the signal sent by the tag and multiple nodes as receivers, as well as multiple transmitting nodes with the tag as receiver. In both cases the potential location of the tag can be described by a parabola between the two nodes used in the pairwise comparison. For generating a two-dimensional position estimate therefore, at least three nodes are required, as depicted in Figure 3.3. In case of a three-dimensional estimate a minimum of four nodes is required.

As TDOA algorithms compute relative time differences, clock synchronisation is only required between the reference nodes, not between nodes and the tag.[29, 30] Hence, whereas TOA usually is able to provide better accuracy performance, the TDOA positioning algorithms are simpler to implement compared to TOA methods. Furthermore, does TDOA show more reliable accuracy performance compared to techniques such as AOA or RSS. For these reasons, TDOA makes a very suitable candidate for practical implementation of indoor positioning systems.[30, 31]

Current implementations of TDOA algorithms for indoor localisation mainly concern recent studies where the emphasis is placed on scalability rather than accuracy. This transition has been made in order to satisfy demands of commercial use of indoor positioning systems. An example of such a system is presented in [17]. Here a receiver-side TDOA algorithm is used to locate a UAV using UWB signals. An accuracy could be reached of roughly decimetre level, while following a reference trajectory with the UAV. A similar application of a TDOA localisation is the Snaplock algorithm, which uses a receiver-end TDOA localisation algorithm to locate tags in two dimensions with similar decimetre level accuracy.[16] Scalability and multi-user implementations for indoor localisation have only recently become a concern. Therefore, the use of TDOA algorithms also only recently became popular. For future implementations however, TDOA algorithms appear to be very promising, due to the absence of clock synchronisation requirements for the tag.

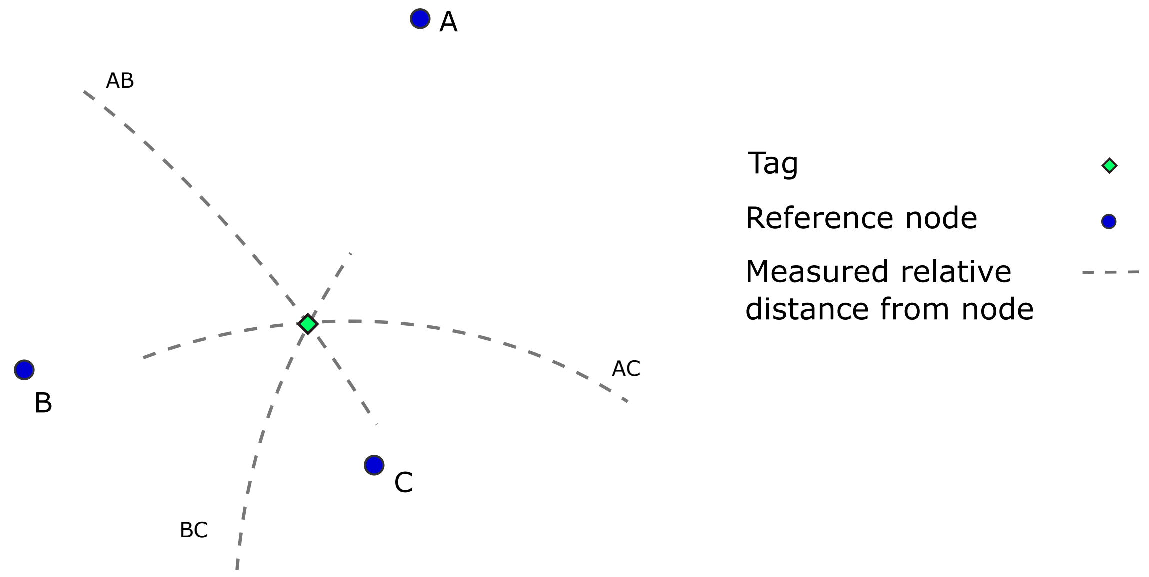

Figure 3.3: Visualisation of time-difference of arrival algorithms.

3.2.4. Received Signal strength Algorithms

Received signal strength (RSS) algorithms use the strength of the incoming signal to determine the distance to a node. An estimate of the distance between transmitter and receiver is based on the incoming signal power, which can be modelled as a function of travel distance. Similar to the TOA algorithms, the possible locations of the tag can be represented by a circle centred around the node.

The location estimate of the tag is then represented by the point of intersection of these circles. For two-dimensions, this means that three nodes are required for a position determination, with an additional node necessary for an estimate in three dimensions.

The RSS algorithms are generally the simplest and therefore the most widely implemented approaches for general indoor positioning purposes.[29] A consequence of the simplicity of the algorithm is that the accuracy performance is of low quality compared to other methods. This is because RSS ranging is very sensitive to path loss due to shadowing and multipath effects, which often cannot be accurately determined.[1, 32] Because the accuracy performance for this positioning is very weak, it is not well suited for indoor positioning of UAVs.[1] Furthermore, does the received signal strength not exploit one of the main benefits of UWB positioning systems: high time resolution. It can therefore be concluded that an RSS algorithm is not suited for indoor localisation using UWB signals.

Because of previously mentioned reasoning, implementations of RSS methods for indoor positioning limit themselves to applications with lower requirements for accuracy. Usually these implementations of indoor positioning systems do not use UWB signals, but focus on wireless networks.[32, 33, 34] In these implementations, the existing Wireless Local Area Network (WLAN) is used to make an estimation of the location of a connected device, such as a smartphone or tablet. RSS can be considered a method that can be used best for low-cost applications of indoor positioning with lower requirements on performance.

A noteworthy implementation of RSS algorithms that has gained attention in recent years however, is the channel state information (CSI) method. Where RSS algorithms try to find the overall signal strength, CSI aims to create an overview of the received strength of the signal across the frequency spectrum.[35] This then allows for implementing an algorithm that can distinguish between multipath effects and propagation effects of the signal.[35] As different multipath effects only influence specific parts of the spectrum, CSI can be used to distinguish between the different multipath effects within the environment.[18] CSI algorithms shall therefore be able to provide more stable and more accurate results compared to regular RSS implementations.[36, 37] Similar to the RSS method however, CSI is often applied in combination with existing wireless networks such as in [38, 39, 40, 41]. This is done as the cost of the required equipment is relatively low in case of a CSI analysis using wireless networks.[35, 36] The applications of the CSI algorithms mentioned here are mostly used in combination with fingerprinting. With the fingerprinting technique, a map is created with the signal properties that will be received at each location. The fingerprinting technique will be explained in more detail in the next subsection.

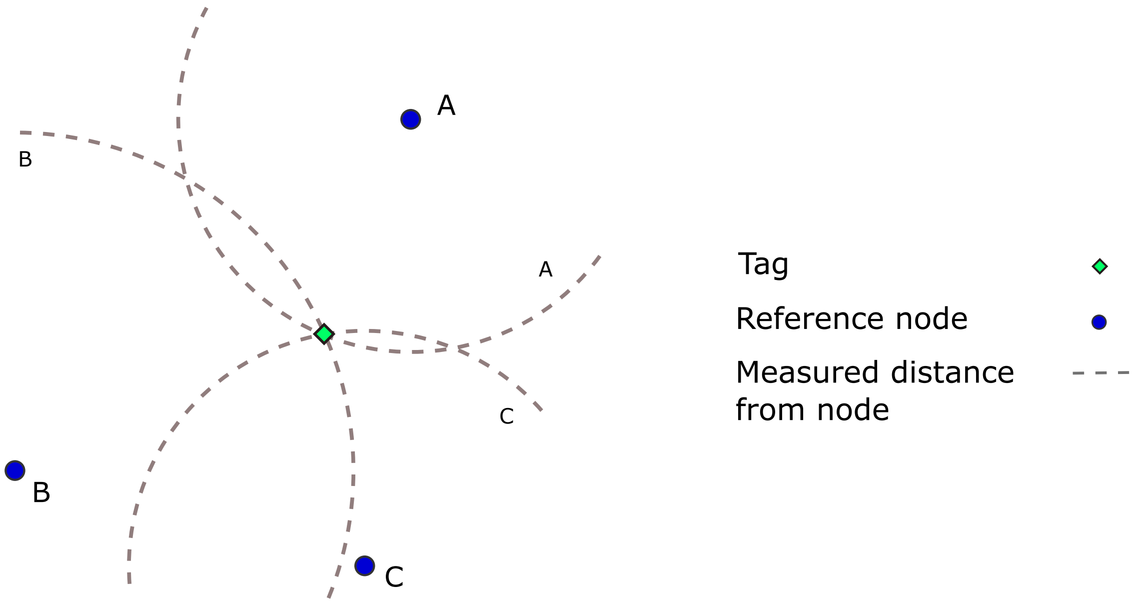

Figure 3.4: Visualisation of received signal strength algorithms.

3.2.5. Algorithm Enhancements

Previously presented in this report are the main types of algorithms that can be used in order to provide a position estimate. Some additional techniques exist however, that augment the existing positioning algorithms in order to obtain better performance. In the remainder of this chapter, two of those techniques will be discussed, respectively fingerprinting and hybrid localisation algorithms.

Fingerprinting algorithms as mentioned before are algorithms that compare the received signal to a map of measured signals at many locations. The data set containing the measured signals is generated by performing measurements in the environment where the localisation shall be made. The fingerprinting method does not provide a method of lateration or trilateration on its own, therefore the fingerprinting method needs to be combined with an existing positioning algorithm to create a map of signals. When a measurement is made, the received signal is compared to the data points measured earlier. The final determination of the location is made using either a deterministic approach, probabilistic approach or pattern recognition.[42, 43] Deterministic approaches to find a solution include nearest neighbours algorithms, whereas probabilistic approaches use e.g. Naive Bayes Classifiers or aim to compute a probability for possible locations given the measured signal. Finally, the pattern recognition approaches are implemented mainly using machine learning techniques such as support vector machines and neural networks.[42]

Similar to RSS algorithms, the main advantage of this method is that it is cheap to implement. Whereas fingerprinting is slightly more complex than RSS, these algorithms are generally able to provide slightly better results as they can better account for multipath effects. The main drawback of this method however, is the fact that it is expensive to construct the map that stores all the data of the received signals.[42, 44] This results in the choice of creating a system, which is either frequently updated and expensive or only seldom updated and therefore sensitive to fluctuations of the environment over time. In office settings, these fluctuations could for example be represented by people or furniture moving around the room. Another drawback of this method is that large errors in the position estimate can originate when fingerprints in the data show correlations.[42] Especially when using many measurement points, the chance of having correlated fingerprints can increase. Therefore, making this a less suitable option for larger scale applications.

Besides the fingerprinting technique, localisation algorithms can be enhanced by fusing multiple algorithms to create a hybrid positioning method. Each particular method of determining a position in indoor environments has its own characteristics. This includes advantages and disadvantages as well as best situations of application. As different techniques have different strengths and drawbacks, multiple techniques can be combined to complement each other and improve on the performance of the localisation. When properly fusing different methods of positioning, the performance of the positioning system can be improved and potentially show better results than either individual part of the system.[45, 46, 47] As well as potential for better performance, hybrid algorithms generally show higher levels of complexity and cost.[1]

Hybrid localisation systems can be created by combining different positioning algorithms as explained above, such as combining a TOA algorithm with an AOA algorithm in order to decrease the required number of nodes. Furthermore, hybrid localisation systems can also be created by combining different technologies, such as sending UWB signals in combination with measuring signals from the existing wireless network. In the following chapter some applications of different hybrid localisation algorithms are discussed.

3.3. Implementations of Localisation Algorithms

As for this research a hybrid UWB indoor positioning algorithm will be constructed, it is relevant to investigate the present implementations of existing UWB algorithms. This chapter therefore elaborates on these implementations and provides some examples of applications where these algorithms have been used. First, the two-way ranging approach is presented. This is a very popular implementation of a TOA algorithm where communication from both the nodes and the tag is required. This structure is adopted in order to remove the clock synchronisation requirement for the tag. The example of two-way ranging nicely demonstrates that conventional localisation algorithms can be adjusted in order to change certain characteristics of the system. Furthermore, in this chapter receiver-end positioning systems will be discussed. Here another way of implementation is shown where the dependence on the clock synchronisation of the tag is removed. The receiver-side algorithms furthermore are able to achieve very good scalability performance due to their structure. Finally, the hybrid implementation of indoor positioning systems is discussed in order to display the current state of the art of indoor localisation algorithms. Hybrid algorithms often combine traits of single algorithms and therefore have the ability to improve on the performance of conventional algorithms. The overview in this chapter serves as a measure of the performance of current indoor positioning systems and can later be used to compare to the results found by evaluating the to be constructed localisation system.

3.3.1. Two-Way Ranging

In two-way ranging (TWR) algorithms, the distance with respect to a reference node is determined by timing a signal that is transmitted at one device, received at another device and consequently transmitted back to the original device.[48] Using this method, a round trip between both devices is made by the signal. The first device measures the total time between transmission of the first signal and reception of the second signal. The total round-trip time consists of the two components of the transmission time, plus the reply delay time taken by the second device. If this delay is known, the one-way distance of the signal propagation can be derived without a requirement for clock synchronisation. As the delay time is often much larger compared to the signal travel time, the TWR accuracy is often lower than conventional TOA localisation algorithms.[49] Reason for this is that the reply delay is often very hard to control and determine with the required accuracy of a few nanoseconds. The general approach adopted to reduce this inaccuracy to a minimum is to fix the time delays to a predetermined constant value.

Several variations of two-way ranging algorithms exist. [50] presented an extension to the conventional TWR by adding a reciprocal double-sided signal. This second signal contains information about the reply time in order to determine the signal propagation time more precise. [50] further explains that in the algorithm compensation factors are introduced at the individual nodes in order to account for the different values for the clock drift present in the different devices. This method is able to reduce the errors originating from clock drift by increasing the amount of information that is transmitted through the signals. One additional disadvantage of this method is however that the signals sent in this ranging method need to be encrypted with a message. Therefore, the hardware required for this system has higher requirements compared to standard TWR solutions. Some efforts have later been made in order to make a more efficient extended TWR algorithm, where the exchange is reduced to only three messages sent in roughly half the time as the previously mentioned extended TWR, such as shown in [51].

[52] presents the result of a passive extended two-way ranging algorithm using UWB signals. Here, a combination of TOA and TWR is implemented to find a position estimate of the tag. The algorithm uses a regular extended TWR scheme between a node and a tag. Additionally, this localisation technology uses an extra node that only receives signals sent as result from the extended TWR scheme. Using the information from the second node another equation can be added to the positioning algorithm without any additional signals sent. The main advantage of this positioning method is that it reduces the number of signals that are required to provide a localisation and therefore presents a very efficient and precise method for indoor localisation. The main drawback of this technique is however that the positioning determination must be carried out centrally, as information of multiple nodes is required.

The accuracy performance that can be reached with TWR method is elaborately analysed in [48]. Here, multiple implementations of TWR methods are presented and evaluated in terms of accuracy for multiple scenarios. These scenarios range from ideal line-of-sight conditions without clock drift to realistic scenarios with all practical difficulties of TWR present. It was shown that during these experiments, the ranging could be performed with inaccuracies of a few centimetres, depending on the utilised delay times of the devices. As furthermore can be seen from the results of this paper, the different versions of the TWR methods implemented show similar performance in terms of ranging accuracy for ideal circumstances. For increasingly complex environments however, it was found that more elaborate TWR methods, such as extended or double sided TWR, show better performance in terms of both root-mean-squared error (RMSE) as well as standard deviation of the estimation.

To conclude, TWR is a ranging method that is used in order to implement TOA ranging methods without the need for clock synchronisation between the tag and the reference nodes. The approach of sending reciprocal signals does however pose limitations on the capacity of the localisation system. Reason for this is that both the node and tag must actively transmit signals, meaning that only one tag can be localised concurrently. For this reason, research efforts in the field of TWR are focused on both increasing accuracy as well as increasing the (time) efficiency of the positioning algorithm. Often these two goals are conflicting as mostly, the complexity of the algorithms has to increase in order to improve the accuracy performance of the system. TWR is currently widely implemented in many indoor positioning applications. Due to the limited concurrent ranging capacity, these applications usually involve either smaller scale applications, such as previously mentioned implementations, or applications with lower requirements on latency, such as asset tracking in [53].

3.3.2. Receiver-End Solutions

Receiver-end positioning systems are systems that do not require any direct communication between the nodes and the tags. Here, the reference nodes are used to transmit a signal with data that allows any receiving tag to determine the time and location of transmission of the signal. The tag can then use this information to make an independent estimation of its location. Receiver-end solutions for indoor localisation have gained increasing amount of attention only in recent years and are developed with the aim of increasing the scalability performance of the system. Similar to the earlier mentioned GPS, the structure of the positioning system will consist of the series of nodes transmitting the signals and the tag(s) receiving these signals and computing a position estimate of its own. This structure imposes no limits on the capacity of the system in terms of users. Furthermore, does an increasing number of users have no effect on the latency of the system, which otherwise could possibly introduce an additional source of error.

The research of [16] presents a novel localisation algorithm that is executed on the receiver side. The implemented algorithm is a TDOA algorithm using UWB signals that is initialised by one reference node. This node sends a reference signal to the surrounding nodes. These nodes will then send a signal used by the tags for localisation. Each node applies its unique time delay, such that the signals from the each of the different nodes can be recognised. On reception of the signal, the tag computes its own TDOA position. The time taken to determine the position of the tag is several hundreds of microseconds long. Depending on the selected time delays, an update rate can be reached of approximately one to two-and-a-half kHz.

This positioning system was tested by localising several tags placed at known locations in a number of test environments. These test environments were representative of practical workplaces and contained many scattering and reflective objects that could cause multipath effects. The accuracy performance was measured by performing many measurements at each tag, which was fixed at its location. It was found that the algorithm was able to achieve an accuracy performance of roughly 18 centimetres as median error. Furthermore, the 90% quantile error was found to be roughly 33 centimetres. This experiment was however conducted in a two-dimensional setup as all reference nodes and tags were placed in a single horizontal plane. This work does however prove that scalable receiver-end solutions for indoor positioning can be implemented with reasonable accuracy performance.

Similar work can be found in the efforts of [17]. Here, it was reasoned that existing solutions for indoor navigation provided poor performance in terms of multi-user scalability and show large inefficiencies in terms of channel utilisation per position determination. This study therefore presents a receiver-side TDOA positioning algorithm implemented on consumer grade UAVs. This TDOA algorithm uses wireless clock synchronisation in order to overcome multi-user limitations found in previous indoor positioning systems, such as two-way ranging. The wireless synchronisation is performed by sending reference signals from one reference node to all other nodes in the system using the existing UWB infrastructure. The utilised algorithm is presented in [54] along with a detailed evaluation by means of a complex experimental setup. Here it was already proven that the created algorithm showed an accuracy performance comparable to existing solutions with limited scalability.

In the research of [17], the mentioned algorithm was implemented in order to localise UAVs using UWB signals in an indoor environment. The system performance was then assessed by conducting a set of experiments. First, several experiments were conducted in order to assess the accuracy performance of the implemented algorithm. It was found that when performing a trajectory, the UAV was localised with a 90% quantile error of roughly 12 centimetres. Here, the positioning error was determined by comparison with a reference positioning system. This reference system consisted of a motion capture system which has a sub-millimetre resolution and was simultaneously implemented during this experiment.

Another experiment was performed in order to prove the multi-user scalability of the system. Three UAVs were tasked to follow a reference trajectory with different starting locations. During this examination, it was found that the synchronous localisation of these UAVs could be performed such that the predetermined trajectory could be repeatedly executed in a stable manner. All measurements of the UWB localisation performed during these experiments were compared to the reference localisation system. Despite the very high accuracy of the reference localisation system, perfect tracking of the trajectory using this position information was not achieved during this experiment. Reason for this are amongst others the limitations of the control system. This nicely demonstrates that tracking performance is influenced by more factors aside from accuracy of the position determination. The UWB TDOA algorithm showed slightly worse, but comparable, tracking accuracy. Therefore, this study proves the feasibility of implementing position control of UAVs using a scalable UWB TDOA algorithm.

As final example of how receiver-end localisation can be applied to improve on certain characteristics of existing types of positioning algorithms, the works of [55] are summarised. Here, an UWB positioning system with a receiver-end TDOA algorithm is presented that employs a scheme of concurrent transmission of signals. Similar to the works in [16], a time delay is applied between transmission of two succeeding UWB signals. In order to ensure correct order of reception of the signals, the applied time delay is sufficiently large as to exceed the travel time between the furthest separated reference nodes. In this research, the introduced algorithm is implemented and tested in a representative environment. Here it was shown that the implementation of this algorithm leads to an accuracy performance comparable to other TDOA implementations that do not use a receiver-side implementation.

More interestingly however, this research proposes a method for achieving scalability in terms of area and number of reference nodes. This approach suggests dividing the area into cells in which a number of nodes, preferably four, are able to cover the entire area. In order to keep a similar update rate, the signals sent can be given a different configuration in each of the cells in order to prevent interference between localisation system in different cells. This could possibly be achieved using signal modulation or preamble signals as can be done with the DecaWave DW1000 module using complex channels.[56] Alternatively, addition of a number of cells can also be achieved by scheduling the localisation in the different cells. In this case the interference of different localisation systems is prevented at the cost of lower update rates, proportional to the number of cells. The addition of cells will in any case require extra coordination in order to allow any tag to dynamically alternate between signals originating from different cells.

The previously mentioned works have presented developments of performing localisation by using receiver-end algorithms. These receiver-end algorithms shall provide better scalability performance compared to conventional positioning systems, such as centralised position determination and TWR. Due to the structure of receiver-end solutions, no limit is imposed on the number of simultaneous users nor is any reduced performance in terms of latency experienced when increasing the number of users. This development is a very important step for creating a positioning system for large scale commercial use.

3.3.3. Hybrid Algorithms

Different methods of providing a position estimate as presented above can be combined in order to create a new localisation system. [47] presented a multitude of ways to perform data fusion of TOA and TDOA data of wireless networks. Here it is shown that fusing the two localisation methods can lead to better accuracy results in terms of bias and standard deviation of the position determination. This displays that combining multiple technologies can be done in such a way that some of the effects of the drawbacks of either technology involved can be reduced. Similar results have later been found in [57]. In this study, an AOA-TDOA hybrid localisation method using UWB technology is introduced. During this research it was reasoned that time-based positioning methods can be effectively combined with angle-based positioning as both categories have very different characteristics. An extended Kalman filter was subsequently used to mitigate the errors originating from non line-of-sight ranging. This hybrid localisation method accomplished reducing the RMSE to lower than half a metre. Once again, this research proved the possibility to improve the performance of the localisation by combining different positioning algorithms.

In the earlier mentioned Ubisense system a hybrid positioning solution is presented for an asset tracking task, as discussed in [12]. This system centrally performs tracking of certain assets, such that the hardware required for the tag is reduced to a minimum. The Ubisense algorithm utilises a hybrid AOA and TDOA algorithm to provide a position estimate of the tags. In the process of determining a position, the tag transmits a single UWB signal. This signal is subsequently received by at least three reference nodes at a fixed location. The information of when the signal is received at the nodes is then used to determine a position in one of the nodes, called the master node.[58]

This system is already in use commercially and provides high accuracy performance. Usually this system is used in offices or workplaces with multiple areas. If necessary, the operating environment of the system will be divided into multiple cells, each containing several reference nodes, usually four to seven.[58] Each cell then has one node that functions as its master node. For asset tracking, this system is able to provide a good accuracy performance. The position accuracy that can be reached in an open environment is 15 centimetres in 95 percent of the measurements.[58] The drawback of this system however, is the limited capacity in the number of users caused by the centrally executed position determination. As further explained in [58], in case of the Ubisense system the capacity of the system is managed by assigning specific time slots to the different tags. Each individual tag here has a maximum update rate of approximately 10 times per second.

Aside from the possibility to combine different algorithms in order to increase the overall accuracy performance of the system, hybrid localisation algorithms can also be created by implementing another technology in combination with UWB signals. In [59] a unique solution is proposed for indoor tracking of UAVs. This research implemented visual based odometry based on optical flow and combined this technology with UWB localisation. The reason for implementing visual based positioning is that in case of very challenging environments, the availability of an accurate UWB signal cannot always be guaranteed. Therefore, this implementation is very suited for indoor positioning systems that are limited in either cost or coverage area.

This hybrid positioning system is implemented by evaluating the quality of both measurements. The final position determination is made by computing a weighted average of both methods. As the visual odometry is made without any global reference or orientation, the measurements need to be translated and rotated in order to be comparable to the UWB measurement. In order to determine the weighting of the translations, the system needs to be calibrated in an initialisation phase before regular use. Here the correct translational and rotational parameters are determined. The evaluation of this positioning method was performed by localising a UAV flying around in a small, controlled environment. The aim of this experiment was to identify the inaccuracies of the system along each axis. The hybrid UWB-visual odometry system was able to produce a 90% quantile error of roughly 14 centimetres in the horizontal direction. This is a significant improvement over the exclusive UWB localisation, which provided an accuracy of roughly 20 centimetres for the same condition. Secondly, the UAV was tasked to follow a reference trajectory around the environment when given a collection of way points. Here it was further shown that the UAV had no difficulty with accurately following the given reference trajectory.

A similar hybrid implementation was found in the works of [60]. Here, the possibility was researched of combining ubiquitous wireless networks with the accurate UWB localisation technology. The research aimed to improve the accuracy of existing position determination systems based on wireless networks by addition of a small number of UWB beacons. An experiment was performed in which a number of configurations of indoor positioning systems were evaluated. Each configuration consisted of a positioning system with four nodes. The different configurations each have a different number of nodes operating on the existing wireless network and a number of nodes operating on UWB signals. In this experimental setup, four configurations were tested, including only Wi-Fi nodes, one UWB node and three Wi-Fi nodes, two UWB nodes and two Wi-Fi nodes and four UWB nodes. In case of increasing number of UWB nodes it was observed that a better accuracy performance was achieved. The results of this experiment therefore produced strong evidence that the addition of any number of UWB nodes can significantly reduce the average localisation error.

The configuration consisting of one UWB node was able to reduce the average error from roughly 70 centimetres to roughly 50 centimetres when comparing to the configuration consisting of only wireless network nodes. The inclusion of an additional UWB node in the next configuration improved the performance of the localisation even further with to average error of approximately 20 centimetres.

In this study it was shown that replacing Wi-Fi signal transmitters with UWB leads to better accuracy performance. What is more, this study provides evidence that the addition of a small number of UWB nodes already significantly reduces the estimation error of a positioning system based on existing Wi-Fi infrastructure.

In the previous examples it is shown that hybrid positioning algorithms can be created in order to profit from the advantages of the involved algorithms with limited effect of the drawbacks. Hybrid positioning algorithms can be created either by combining multiple localisation algorithms, such as TOA, AOA and TDOA, or by combining multiple technologies, such as UWB signals and wireless networks, or possibly even both. Implementation of such systems can lead to increased performance in terms of accuracy compared to any individual technology involved. Furthermore, does the implementation of hybrid algorithms also provide a possibility to increase the overall efficiency of the system e.g. by reducing the number of required nodes such as in [59]. Using this approach, the cost of implementation of an indoor positioning system can be severely reduced.

3.4. Proposed Research

In this chapter, the aim and methodology of the proposed research will be explained. The methodology is formulated in order to assist with performing a well-structured research. First, the research goals of the project will be elaborated upon. This includes the motivation for performing the research, as well as the motivation for several choices made regarding the configuration of the algorithm that was chosen for investigation. Furthermore, the adopted approach of this research will be briefly explained and an overview of the proposed experimental setups of the research will be presented.

3.4.1. Research Goals

In this research project an accurate, scalable and efficient indoor navigation solution will be designed for an application of crop monitoring in greenhouses using UAVs. The goal is to improve on the current state of the art of indoor positioning by creating an indoor positioning system that has good performance in terms of accuracy, scalability and minimal requirements in terms of necessary infrastructure. In this report, an overview is given of the currently available methods for indoor positioning. In subsection 3.3.2, receiver-end applications of positioning systems are discussed. Several works were found where such system structure was adopted. Receiver-end positioning systems allow for tags to independently compute an estimate of their location. Similar to the widely used GPS, receiver-end solutions for indoor navigation do not impose any limits on the number of position estimates that can be made simultaneously. What is more, the latency performance of the localisation algorithm will not decrease with increasing number of synchronous users. For this reason, a similar receiver-end structure will be embraced in this research.

In subsection 3.3.3 hybrid implementations of positioning systems are discussed. Here, it was shown that different localisation algorithms can be combined in order to create a positioning system that benefits from the advantages of both individual systems with limited negative effects. In essence, hybrid algorithms can be introduced in order create a more efficient system i.e. increasing performance and/or reducing required infrastructure. For this reason, the choice for a hybrid positioning system is made. The included algorithms are chosen based on the characteristics as presented in section 3.2. First of all, for practical implementation, it is important that the dependency of clock synchronisation of the tag is omitted as coping with this issue is both complex and expensive. Furthermore, it is important that the utilised algorithm will exploit the benefits of UWB technology, such as a high time resolution and limited distortion effects. Based on these above-mentioned traits, a combined AOA-TDOA hybrid is presumed to be the best combination for this application.

To summarise, in order to adhere to demands of accuracy, scalability and infrastructure cost, an AOA-TDOA hybrid receiver-end UWB localisation algorithm will be constructed during this research. In order to most efficiently use the infrastructure of reference nodes, the to be researched hybrid algorithm will be physically implemented by placing two UWB receivers on each UAV that needs to be localised. The thought behind this method of implementation is that a hybrid method, which could increase the overall performance of localisation compared to single algorithms, can be implemented without any additional infrastructure required. Only one additional UWB receiver is required for each UAV that shall be localised compared to a regular TDOA implementation.

In Table 3.1 below, a relevant collection of current applications of UWB indoor positioning systems presented in this report can be found. For each system, some important characteristics are indicated to show the relevance of the solution. In order to assess the different implementations, the performance measures of accuracy, availability, coverage, scalability, cost and privacy as presented in [1] are again adopted. In order to translate these measures to the current application of localisation of UAVs in greenhouses, some practical characteristics are chosen to represent these measures. These characteristics are specified in the second column in Table 3.1. The performance measure of coverage is omitted in this case as this is dependent on the signal properties, which do not differ as all solutions utilise UWB signals.

At the right-hand side of the table, the relevant and current applications are shown along with an evaluation of their performance. All applications are evaluated and for measures in which favourable characteristics are observed for a certain solution a plus sign is used to indicate good performance. The included positioning systems are: (A) two-way ranging implementations [50, 51, 52, 53], (B) the SnapLock algorithm as presented in [16], (C) the scalable and precise TDOA-based UWB localisation algorithm as presented in [17], (D) the Ubisense system [12, 58] and (E) the simultaneous localisation and mapping (SLAM) augmented UWB localisation system [59]. Finally, the proposed localisation algorithm (PA) that will be researched is added, along with the anticipated characteristics that will follow from the adopted system structure. As can be seen, the algorithm proposed for this research will provide a unique combination of properties and therefore prove to be relevant in the field of indoor positioning.

Measure	**Clarification**	**A**	**B**	**C**	**D**	**E**	**PA**
Accuracy	Relative accuracy performance	++			+	+	+
Availability	Possibility of simultaneous localisation of many tags		+	+			+
Scalability	Effect of increasing users on latency		+	+			+
Cost	Infrastructure requirements (number and type of nodes, clock synchronisation, etc.)	+			+	+	+
Privacy	Independence of the tag		+	+		+	+

Table 3.1: Overview of the characteristics of current indoor positioning applications and the proposed algorithm.

In order to achieve the goal of this research, the research questions as presented in section 3.1 will be answered. It is expected that answering these questions will achieve the goal of improving on the current state of art of indoor positioning systems. The stated research questions concern the design, implementation and evaluation of the proposed algorithm. This research will evaluate the novel algorithm based on performance measures and adopt an analytical approach rather than a descriptive approach. Furthermore, as an experiment will be performed where the novel algorithm will be implemented and evaluated, an applied research approach will be adopted. The results of the evaluation will be expressed in a quantitative manner, such that the performance can be compared to the currently existing solutions.

3.4.2. Methodology

The goal of this research is to construct a novel positioning algorithm and evaluate its performance and therefore its relevance to practical use of indoor positioning systems. In order to most efficiently construct and evaluate this algorithm, the project shall be divided into different steps, for which some experiments are required. These experiments can include making observations of the performance in a controlled real-world environment, but also include the testing of the performance in a simulation on a computer. This section will elaborate on the different steps and experimental setups that are expected to be included in this research along with some technical details of the execution of the experiments.

When looking at the research question and in particular the sub-questions formulated above in section 3.1, some different steps in the process of the research can be identified. These steps include the review of current localisation methods, creation of the algorithm, the implementation of the algorithm, the evaluation of the algorithm and finally making a comparison between the constructed algorithm and current positioning systems available. For three steps of this research project, it can be concluded that to some extent some experimental analysis is required in order to test a hypothesis.

During the second step of the research, the algorithm is constructed as a prototype. At the end of this step it should be verified that this algorithm works as intended. In order to efficiently test this hypothesis, some simulations will be performed on a computer. It will most probably take many cycles of trial and error before compliance with the requirements for indoor localisation is reached. Therefore, it is crucial that these tests can be performed without making any time consuming adjustments to the model. For this reason, the testing of this prototype algorithm will be performed using an interpreted programming language such as Python or MATLAB. Much preferably, these tests of the preliminary algorithm will be performed using the same programming language in which the prototype algorithm will be constructed. Tests that will be performed to check correct performance of the positioning algorithm include unit tests to verify correct implementation of basic principles, as well as integration tests to validate the working of the complete model.

Besides the correct working of the algorithm, it is important that during the design of the algorithm specific requirements for implementation are identified. Most importantly, any requirements for the UAV that will be localised shall be identified. This includes prerequisites in terms of size and minimum payload. Any of these requirements can heavily influence the choice for the UAV that can be used during this research. As this choice needs to be made during the next step of this research, it is essential that any requirements for the UAV are identified as soon as possible.

Once the preliminary localisation algorithm is constructed and tested, the next step in the project is to implement the model in a practical setup. In order to achieve this, the constructed model needs to be converted from the preliminary algorithm created in the previous step to an algorithm in a programming language compatible with hardware modules used to perform the UWB communication. As this concerns real-time performance, the programming language chosen here shall be a compiled language such as C or C++, as this provides much better latency while executing code. Similar to the previous step, again correctness of the model needs to be tested in order to verify that the transition to the new programming language has been made without any mistakes. Furthermore, integration tests should be performed in order to validate that the positioning algorithm works when applied in combination with the available hardware. This validation could be executed by performing some localisations of a tag in a real environment.

Finally, after the implementation of the positioning systems is validated, the overall performance of the algorithm can be tested. For this experiment the positioning algorithm shall be used to localise one or more UAVs in a physical and representative environment. A set of performance measures shall be found which can express the performance of the algorithm. The results of the experiment shall then be measured and expressed in these pertinent measures such that observations can be made about relevance of the scientific research.

The results of this research will be verified and validated in order to ensure sound quality of the results. Verification will be implemented by performing unit tests on the code of the algorithm as well as integration tests that ensure correct working of the entire algorithm. These integration tests could for example be implemented by computing results for a simple representation of a practical scenario. The Validation of the results will be achieved by testing the uncertainties of the measurements in a practical environment. The results following from these measurements should agree with the findings from the measurements performed during the experiments that will be conducted to evaluate the performance of the positioning algorithm. The uncertainties of the position estimation could possibly be experimentally determined by generating a position determination for an accurately known path (such as stationary) and comparing the measurements.

3.4.3. Hardware Requirements

In this section the hardware that will be used to implement and evaluate the algorithm will be discussed. It is useful to determine this in an early stage of the project as it will affect how the algorithm needs to be constructed and also may pose any requirements on the design of the entire positioning systems.

In order perform this research as efficiently as possible, some important characteristics of the necessary hardware are defined and some suitable options for the necessary are highlighted that can be used during this research.

In order to perform UWB ranging, it is important that a system is used that is both accurate and can be easily implemented. The DecaWave DWM1000 module can be used for performing UWB ranging. This module is widely applied in the field of UWB localisation and allows for multiple localisation schemes, such as TOA, TWR and TDOA. The reason that this module is popular is that it is relatively cheap and also very much simplifies the design integration. The module consists of an integrated system including an antenna, power management and clock control. The DWM1000 module can be connected to a printed circuit board on the UAV. If this is performed for two receivers, these can be connected to a processing unit in order to make calculations for a position determination.

Aside from the localisation system itself, a UAV needs to be selected in order to perform localisations on during the experiments. It is important that this UAV has some flexibility in terms of software that can be adjusted and hardware that can be connected. This can for example be useful in case the control system requires position information for a tracking task or when the localisation system requires state information of the drone. For this reason it will be useful that some adjustments can be made to the control system of the drone. One UAV that is therefore very interesting is the Crazyflie from bitcraze. This is a very light weight micro aerial vehicle that operates on software that is completely open source. For this reason, software adjustments can be made more easily and support for development of the software is therefore more easily accessible.

The crazyflie is however very small sized as it fits in the palm of a hand. The choice for UAV therefore also depends on the hardware requirements that follow from construction and implementation of the algorithm. If a larger sized UAV is required, one similar to the parrot bebop can for example be used. This drone is roughly 30 centimetres by 30 centimetres. The parrot bebop comes with a built-in camera and is also used in research projects with similar purpose of performing UWB localisation, such as in [17] and [59]. It can therefore also be concluded that this UAV would be suitable for use in this project. As mentioned before, it is very important that any requirements for the UAV, such as size and payload, shall be determined as early in the project as possible. If all these requirements are identified during construction of the preliminary algorithm, the hardware implementation of the algorithm can be performed with full knowledge of the choice of UAV. This will ensure that the transition from software implementation to hardware implementation of the localisation algorithm can be performed as efficiently as possible.

3.5. Conclusion

This report describes a proposal for a research that aims to improve the state of the art of indoor positioning using UWB technology. Current solutions for indoor positioning using UWB technology are generally focused either on achieving very high accuracy performance or good characteristics for practical implementation, e.g. by implementing scalable solutions. Indoor localisation technology could benefit greatly from an effort where both these philosophies will be combined. Therefore, this study will focus on creating a hybrid receiver-end algorithm. It is believed that implementing this type of algorithm will ensure good characteristics for both accuracy performance as well as practical implementation. This research will be performed in the scope of an ongoing collaboration between the TU Delft and Royal Brinkman. For this project, a UAS shall be developed that is able to autonomously fly around in a greenhouse and monitor corps in a cost-effective way.

Several localisation algorithms exist for generating a position estimate from the generated signals. The time of arrival algorithms generally perform best in terms of accuracy. Time of arrival ranging does however require clock synchronisation of all nodes together with the tag. Time-difference of arrival algorithms remove the need for clock synchronisation of the tag, often at the cost of slightly worse accuracy results. Furthermore, Angle of arrival algorithms also do not require any clock synchronisation of the tag. As the position estimate is generated by triangulation of the directions with respect to the reference nodes, accuracy of AOA methods decreases strongly with increasing distance from the node. Often these algorithms therefore do not achieve high accuracy, however these systems are often able to significantly increase performance when used in combination with other algorithms due to its different characteristics. Some more algorithms and algorithm enhancements exist, such as received signal strength and fingerprinting. These methods do however not exploit the benefits of UWB signalling.

Hybrid implementations of localisation algorithms can be implemented by fusing two positioning algorithms or even two different technologies. When fusing multiple methods of positioning, the final solution can profit from the strengths of the involved systems with limited effects of the weaknesses. Implementations of such systems can therefore significantly increase the overall performance of the positioning system compared to the individual localisation methods. What is more, hybrid implementations of localisation systems have the potential to increase the overall efficiency of the entire localisation system, e.g. by reducing the number of nodes required to make a localisation in a certain area. This could help reduce the implementation cost of an indoor positioning system.

The research question that will be answered during the proposed research is *how can the performance of UWB positioning for indoor localisation of small-sized UAVs be improved by developing a receiver-end hybrid localisation algorithm?* This question will be answered by designing, implementing and evaluating a receiver-end AOA-TDOA hybrid UWB localisation algorithm. Because of the above-mentioned characteristics, it is expected that this hybrid implementation will best satisfy the demands of practical implementation of localisation of UAVs. The evaluation of the localisation algorithm will be performed by conducting an experiment in a representative real-world environment and quantitatively expressing the results. After this evaluation is conducted, the performance of the novel algorithm will be compared to the current state of the art of indoor positioning systems in order to determine the relevance of the implemented solution.

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