Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Computer Science

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Radio-Tracking of Sheep

Evaluating Performance in High-Density Foliage

Master's thesis in Informatics
Supervisor: Svein-Olaf Hvasshovd
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Abstract

About two million sheep are released into the Norwegian wilderness every summer to graze. Locating and gathering the sheep in the autumn is time-consuming, relying on farmers manually searching large geographical areas of rough terrain.

Master's students at NTNU have previously developed a custom sheep localization system using an autonomous UAV and lightweight radio tags attached to the sheep's ear. The UAV uses a custom Bluetooth Low Energy Round Trip Time (RTT) ranging method and multilateration to calculate the position of the sheep. This thesis aims to evaluate how well the system performs in areas of high-density foliage, as sheep often seek cover in foliage. Field tests evaluating the custom RTT-ranging method's accuracy and range have been performed, in addition to several large-scale system tests in a forest. A literature study on the best radio technology for foliage penetration has also been conducted.

Our tests have demonstrated that the system can estimate distances in high-density foliage up to 100 meters with an average error across all distances of around 7 meters. The system can also locate sheep in thick forests with an average localization error of 20.7 meters. The literature suggests that changing from BLE to LoRa could increase performance in foliage. Still, this is not suggested, as the potential upside does not justify the work needed to develop a new system using LoRa.

Sammendrag

Rundt to millioner sauer slippes ut i den norske villmarken hver sommer for å beite, og å lokalisere og samle sauene om høsten er en tidkrevende oppgave som er avhengig av at bøndene manuelt søker store geografiske områder med ulendt terreng.

Masterstudenter ved NTNU har tidligere utviklet et sauelokaliseringssystem ved hjelp av en autonom UAV og radiosendere festet til sauenes øre. Dronen bruker Bluetooth Low Energy og Round Trip Time (RTT) til å regne ut avstanden mellom seg selv og sauene, og så multilaterasjon for å beregne posisjonen til sauene. Målet med denne oppgaven er å evaluere hvor godt systemet fungerer i områder med tett skog, da sauer ofte søker ly i slike områder. Vi har utført felttester for å evaluere RTT-metodens nøyaktighet og rekkevidde, i tillegg til flere storskala tester av systemet i skog. Et litteraturstudie som undersøker hvilken radioteknologi som er best for forplantning i skog er også blitt gjennomført.

Testene har vist at systemet klarer å estimere avstander i skog opp til 100 meter med en gjennomsnittlig feil over alle avstander på rundt 7 meter. Systemet klarer også å lokalisere sau i tett skog med en gjennomsnittlig lokaliseringsfeil på 20.7 meter. Litteraturen tilsier at en endring fra BLE til LoRa kan øke ytelsen i skog, men dette anbefales ikke dette da det potensielle fortrinnet ikke rettferdiggjør mengden arbeid som trengs for å utvikle et nytt system som bruker LoRa.

Preface

This Master's thesis is a collaboration between two master's students at the Norwegian University of Science and Technology. Oscar Bergan and Marcus Schrøder are both studying for a Master of Science in Informatics with a specialization in software engineering. The main motivation for choosing this topic for our master's thesis was the possibility of working with hardware and testing our work in a real-world environment. Radio technologies and UAVs is not a typical topic for Informatics student, but the prospect of learning new technologies and challenging ourselves made us interested in working on this project. Both of us had very limited experience with UAVs and radio wave propagation, and the work has therefore been challenging. We did, however, have experience with using Bluetooth Low Energy and Nordic Semiconductors nRF Development Kits from our Bachelor's thesis, which has been very valuable during the work on this thesis.

We have had a lot of problems with getting the UAV to work properly, and it has been destroyed and repaired several times. Our limited hardware experience has led to much time being spent on troubleshooting, repairs, and finding new solutions for getting the UAV to work as intended. We have worked closely together during both the preparatory project and the writing of this thesis, and our cooperation has been invaluable when working with new concepts and technologies.

Acknowledgements

We want to start by thanking our supervisor Svein-Olaf Hvasshovd for valuable discussions, guidance, and support throughout the work on the preparatory project and the Master's thesis. His knowledge of sheep farming and gathering has been invaluable in our work on this thesis, and his input has made a challenging research topic much more manageable for us.

We thank Toni Vucic and Christian Axell for providing us with the UAV and other necessary equipment used during their work on this topic. We would not have been able to perform our research without their initial help with operating the UAV and radio modules.

We also want to thank Grzegorz Swiderski and Nordic Semiconductor for providing us with nRF52833 Development Kits and the source code for the implementation of the distance estimations method used in our testing.

Furthermore, we want to thank NTNU Hackerspace for helping us repair the UAV after every crash. Our limited hardware knowledge made it challenging to fix the UAV ourselves, but no challenge was too cumbersome for the people at Hackerspace.

Finally, we want to thank everyone who helped proofread this thesis.

Contents

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Acronyms

AoA Angle of Arrival.

BLE Bluetooth Low Energy.

CNN Convolutional Neural Network.

CSS Chirp Spread Spectrum.

dBm Decibel-Milliwatts.

DevKit Development Kit.

EM Electro Magnetic.

FLIR Front Looking Infrared.

GCS Ground Control System.

GHz Gigahertz.

GPS Global Positioning System.

ISM Industrial, Scientific, and Medical.

kpbs Kilobit Per Second.

LoS Line of Sight.

MCPB Minimal Custom Protocol-Based.

NB-IoT Narrowband IoT.

NTNU Norwegian University of Science and Technology.

PDR Packet Delivery Ratio.

PoC Proof of Concept.

RF Radio-Frequency.

RFID Radio Frequency Identification.

RSSI Received Signal Strength Indicator.

RTT Round Trip Time.

SNR Signal to Noise Ratio.

SoC System on a Chip.

TDoA Time Difference of Arrival.

ToA Time of Arrival.

UAV Unmanned Aerial Vehicle.

UHF Ultra High Frequency.

UWB Ultra-Wideband.

VHF Very High Frequency.

Chapter 1

Introduction

Using rangelands for grazing is an old and ubiquitous sheep farming tradition in Norway. About two million sheep are released into the Norwegian wilderness every summer to graze and roam freely in forests, fields, and mountainous terrain [1].

Once the grazing period ends, the farmers must locate and gather their sheep for the winter. This is a time-consuming and cumbersome process, often lasting several weeks. Farmers can usually locate and gather most of their herd during the first weeks by searching the main grazing areas, but some sheep may break away from the rest of the herd during the grazing period. Locating these smaller groups of sheep is the most challenging, and the farmer is often forced to manually search large geographical areas of rough terrain. The success of these searches is based mainly on the farmer getting lucky, and despite their efforts, some sheep are never found. Sheep not gathered before the winter poses a significant economic and ethical issue for farmers and Norway's traditional sheep farming practices.

Most farmers today use GPS collars to track their animals, but the high cost of this equipment relative to the economic value of the sheep does not make it affordable for farmers to equip each sheep with tracking equipment. Lambs will typically not be able to wear GPS collars, as they will outgrow their collar during the grazing period. Sheep equipped with these collars must also be located within range of radio towers or satellites for the farmer to see their location. Farmers, therefore, only provide some of their sheep with tracking equipment, hoping they can locate at least one sheep in a break-away group.

As a proposed alternative to GPS-tracking of the sheep, previous Master's students at the Norwegian University of Science and Technology (NTNU) have developed, through several iterations, an automated sheep-localization system as the basis of their Master's theses. As sheep and lambs are already equipped with an ear tag, this system aims to integrate the tracking hardware into each animal's ear tag, making it usable for all animals. In addition, the system uses inexpensive Bluetooth Low Energy (BLE) transceivers, making it affordable for farmers to equip each sheep with tracking equipment, making the sheep-gathering process much more manageable.

1.1 Problem Statement

The feasibility of using BLE transceivers for the localization of sheep was first explored by Nyholm [2] in 2020. The thesis evaluates several different ranging and localization methods and estimates the expected battery life of the transceivers integrated into the sheep's ear tags.

Nerland [3], Steinsvik [4], and Swiderski [5] continued the work on the system in 2021. A Proof of Concept (PoC) consisting of a Unmanned Aerial Vehicle (UAV), BLE transceivers, and a Ground Control System (GCS) was developed, and initial tests of the system were conducted. This PoC allows users to mark a geographical area they want to search in the GCS, and the system then automatically generates a flight path for the UAV. The UAV follows its predetermined path, collecting data from the ear tag of each sheep. The system can estimate the sheep's location by collecting data from the same sheep from a minimum of three different locations. The collected sheep-location data is then processed, and each sheep's position is displayed to the user on a map in the GCS. **Figure 1.1** illustrates how the system operates. A more in-depth explanation of this system is presented in **Chapter 3**.

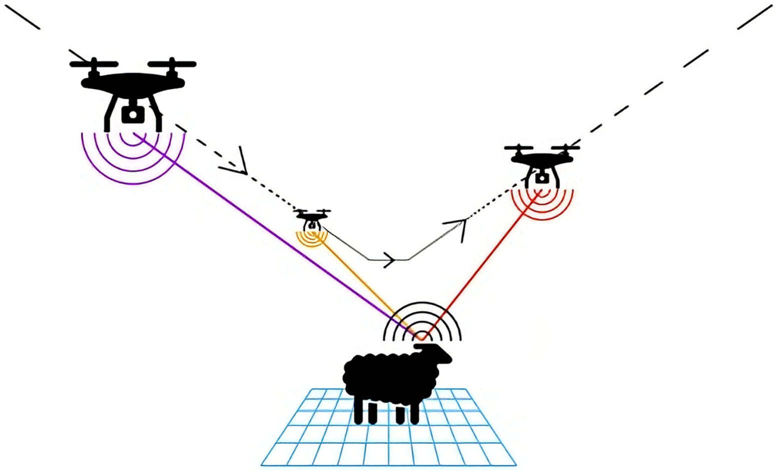


Figure 1.1: Illustration of the UAV flying a predetermined route and encountering the same sheep on three different locations [5].

In 2022, Vucic and Axell continued working on the system in [6]. The PoC was developed further, and the first real-world tests were conducted. Vucic and Axell performed performance tests using real sheep equipped with trackers in their ear tags. A literature study of the potential performance of other radio technologies was also conducted, as well as tests of different antennas and their optimal orientation on the UAV. The thesis concludes that the system can locate stationary sheep in a farm environment with an average error of 15 meters. The system can also detect signals from sheep in thick forests 226 meters away.

This thesis aims to evaluate the third and latest iteration of the system, developed in [6], focusing on its performance and accuracy in high-density foliage. The most valuable use case for sheep-localization systems is to determine the position of sheep that have strayed away from the main grazing areas into forests, and the large number of resources needed to search areas of rough terrain manually can be avoided if the position of sheep in these areas can be determined accurately and consistently. Previous theses on this system have shown its feasibility in open fields and farm environments, but its performance in foliage has yet to be thoroughly examined. This thesis will evaluate the system's performance through field trials in high-density foliage. In addition, a literature study of alternative radio technologies and their expected localization performance in foliage will also be performed.

1.2 Research Questions

1.2.1 RQ1: Is Bluetooth Low Energy the Best Radio Technology for Localization of Sheep in High-Density Foliage?

This research question will be answered by performing a literature study on radio wave propagation in high-density foliage, followed by a review of alternative radio technologies and their expected performance in this terrain type. The radio technologies in question must also be feasible for use in a system consisting of radio transceivers and a UAV.

1.2.2 RQ2: How Well Does the UAV and BLE-based Localization System Perform in High-Density Foliage?

The system's performance is measured by its average error when estimating the position of sheep and the size of the uncertainty area of each estimated position.

This research question will be answered through field trials of the system. Performance tests like those conducted in [6] will be executed, and the results will be used to conclude how well the system performs.

1.2.3 RQ3: How Can the Existing System Be Modified to Increase Its Performance in High-Density Foliage?

The experiences gained throughout the work on this thesis will be used to suggest how the system could be altered to increase its performance in foliage without decreasing its performance in Line of Sight environments. This includes recommended changes to both hardware and software.

1.3 Thesis Outline

This thesis is structured in the following way:

Chapter 2 - Background starts with an overview of the state of the art within commercial sheep-tracking, together with an explanation of why there is a need to improve sheep-tracking technologies. The various methods available for ranging and localizing radio signals are then presented. Lastly, a description of radio-wave propagation in areas of high-density foliage is given, followed by a review of how well different radio technologies perform in vegetation.

Chapter 3 - System Architecture explains the existing localization system, including the UAV, the ground control station, and the radio transceivers. The system's different ranging and localization methods are also introduced.

Chapter 4 - Evaluation of the System presents the tests and evaluations of the existing localization system performed during the work on this thesis.

Chapter 5 - Discussion of Research Questions uses the results from the tests and literature review to discuss the three research questions.

Chapter 6 - Conclusion summarizes the work, conclusions, and findings of the thesis.

Chapter 2

Background

This chapter introduces the technologies, solutions, research, and methods used to determine objects' positions using radios. The state-of-the-art commercial solution for livestock tracking is presented with a comparison of these, followed by an overview of previous research on sheep localization methods. Furthermore, fundamental principles and practices for estimating distances and positions using radios and different UAV search patterns are introduced. Finally, an explanation of how radio waves propagate in a forest environment is presented, followed by an overview and comparison of alternative radio technologies for sheep localization.

2.1 State of the Art

This section presents the existing commercially available solutions for sheep localization. The technologies used for the current solutions are primarily based on Narrowband IoT (NB-IoT), Global Positioning System (GPS), and satellite technology. These are bulky GPS collars placed around the neck of the sheep as one would with the traditional sheep bells. GPS is used by every solution to find the exact position of the sheep. After that, they use the cellular network (2G, LTE, or NB-IoT) or satellite technology to transmit the position data to the user. This section will present further details about the different solutions available for commercial use.

2.1.1 Telespor

Telespor's *Radiobjella* is a GPS collar that only weighs 103 grams [7]. The collar comes with rechargeable batteries with a life of up to 15 years (24-hour transmission interval). *Radiobjella* uses GPS to obtain the collar's exact position and transmits the data to the user via LTE-M and NB-IOT. The collar is the same size as a regular sheep bell and will not be uncomfortable for the animal.

In addition to gathering location data, the collar is equipped with a motion sensor. For example, *Radiobjella* uses the sensor to alert the user if the animal has not moved for 3 hours, of suspicion of the animal being injured or dead.

Radiobjella is one of the cheapest commercially available GPS collars and costs 989 NOK per unit. The operating costs for a twelve-month subscription, including access to the mobile platform and covering the mobile data traffic, are 169 NOK.

2.1.2 Smartbjella

Smartbjella is also a collar that uses GPS for localization and transmits the data to the user using the NB-IoT network. The collar only weighs 140 grams and has integrated batteries that are not replaceable or rechargeable. The battery lifetime of the collar is up to 20 years (transmitting data once every 24 hours). The collar has a guaranteed lifetime of 5 years.

The collar is the cheapest commercially available and has a unit cost of 849 NOK. In addition to the unit costs, the collar has an operating price of 149 NOK which covers the mobile data traffic and software.

After some years of operating, Smartbjella increased its customer base to 1200, with 30 000 active collars. The company went bankrupt in the spring of 2022 due to Covid-lockdown in China that prevented the company from obtaining the necessary parts for production in Trondheim.

2.1.3 Findmy

Findmy is also a GPS collar. However, it uses satellite technology to transmit the data to the user. The GPS collar utilizes low-orbit satellites for communication between the collars and the user. As a result, the collar has coverage throughout Norway as long as the collar has a clear view of the sky. This means the collar will have coverage if the animal is not indoors, under a roof, or under rock shelves. The collars weigh 200 grams, have replaceable batteries, and have a battery life of 1 year (2-3 half-year seasons depending on transmission intervals).

In addition to localization with GPS, the farmer can use Bluetooth to locate the sheep in the terrain during inspection or collection of the sheep. The system can also alert the farmer if the animals are registered as stressful. It also has an internal Geofence that the farmer can set up and adjust. Finally, the farmer will be alerted whenever the animal leaves or enters the Geofence-created area.

Findmy has over 40 000 active collars throughout Norway. *Findmy*'s collar is by far the most expensive one available on the market and has a unit cost of 2190 NOK and an operating cost of 249 NOK covering the data transmissions.

2.1.4 NoFence

Nofence is the only commercially available GPS collar in our selection that does not primarily focus on the localization of the sheep. Instead of locating the animal, *Nofence* focuses on keeping the animals within a digital boundary while grazing. The farmer sets this boundary through *Nofence*'s mobile app. In addition to the digital boundary, the user can check the animal's location in real-time using their app. The collars use GPS for localization and LTE Cat-M1 and 2G for communication between the mobile app and the collars.

The collars weigh 505 grams and are also solar-driven with rechargeable batteries, making the battery time vary, but it lasts approximately one year. After twelve years in the business, *Nofence* has the largest market share with 3200 customers and a total of 48 000 GPS collars.

The collars have a unit cost of 1950 NOK and a varying operating cost depending on the length of the grazing season. One collar costs 640 NOK for a year for a fixed operating cost.

2.1.5 Comparison of Existing Solutions

Most GPS collars commercially available have a high cost per unit, making the first year where the farmer has to purchase the collars very expensive. The operation costs, in general, are low. A collar that lasts over many years could provide value to the farmer.

In many municipalities and counties in Norway, it is possible to get subsidies for purchasing electronic tracking equipment, which makes the unit costs lower.

	Unit cost	Operating cost	Technology	Battery life
Telespor	989kr	169kr	GPS & NB-IoT	$>$ 15 years
Smartbjella	849kr	149kr	GPS & NB-IoT	$>$ 20 years
FindMy	2 190kr	239kr	GPS, BLE & satellite	1 year
Nofence	1 950kr	640kr	LTE, 2G, BLE & GPS.	1 year
Our system	100kr	0	BLE, GPS	$\approx$ 67 weeks

Table 2.1: Table with an overview of the commercially available solutions compared

Table 2.1 gives an overview of the different commercially available solutions for tracking grazing animals. The table compares the various solutions with a focus on the cost per collar, the costs of operating the collar, which technology the solution uses, and the battery life of the collar. As seen in the table, the initial cost for the farmer will be high due to the high unit cost. It is also considerable differences in costs between the different brands, such as Telespor's product costs half of what FindMy costs.

100 Sheep	**Telespor**	**Smartbjella**	**FindMy**	**Nofence**
Unit costs	98 900kr	84 900kr	219 000 kr	195 000 kr
Yearly operating cost	16 900 kr	14 900 kr	23 900 kr	64 000 kr
Total yearly costs	115 800 kr	99 800 kr	242 900 kr	259 000 kr
300 Sheep	**Telespor**	**Smartbjella**	**FindMy**	**Nofence**
Unit costs	296 700 kr	254 700 kr	657 000 kr	585 000 kr
Yearly operating costs	50 700 kr	44 700 kr	71 700 kr	192 000 kr
Total yearly costs	347 400 kr	299 400 kr	728 700 kr	777 000 kr
Cost per sheep first year	1 158 kr	998 kr	2 429 kr	2 590 kr

Table 2.2: table with an overview of the solutions and the costs for 100 and 300 sheep.

Table 2.2 shows the farmer's initial and yearly operating costs with the existing solutions. This exposes how expensive it is for the farmer to equip each sheep with a collar. Even though sheep are herd animals, some can stray from the rest. The manufacturers, therefore, recommend that at least 25% of the herd be equipped with a GPS collar, and the best is that 100% of the herd be equipped with the collars.

With the solutions shown in **Table 2.2**, it is expensive for the farmer to equip a large portion of their herd with collars. As stated in [8], a farmer in Norway has 69 sheep on average. It is important to specify that this also includes the farmers that do not have any sheep. The most expensive solution would cost the farmer 259 000 NOK in unit and operational costs for only 100 sheep. Equipping each sheep with tracking equipment is not affordable for farmers, considering the economic value of each sheep. The total number of units sold for the mentioned brands is under 100 000 units. As mentioned earlier, there are approximately 2 million grazing sheep in Norway. This constitutes to only 5% of the total number of grazing sheep in Norway being equipped with tracking equipment. The adaptation rate of the GPS collars has been low, which could be due to the high prices and unreliability.

As stated in [3], the estimated production cost for the radio tag prototype for our system is approximately 100 NOK. However, our system requires a UAV to operate. The UAV for our system does not have a fixed price, but it is estimated that the parts needed to build the UAV could cost nearly 2000 NOK. Compared to existing solutions, our system is substantially cheaper, and the initial cost for the farmer would not be that high.

2.2 Previous Research on Sheep Localization

Localization of animals has become a popular research topic worldwide in the last few years, and several different approaches and solutions have been developed and tested. This section introduces some of the previous research on the localization of animals, their systems, and how they have performed. The proposed solutions are mainly based on either radio-localization using UAVs or object detection on video footage from UAVs.

In 2018, Rognlien and Tran [9] started researching and developing a system that uses a UAV equipped with a Front Looking Infrared (FLIR) camera to gather footage of sheep in the grazing areas. The footage was used to compare the performance of classic image processing against multiple machine-learning algorithms. Classic image processing performed best, with a recall of around 83%. Muribø [10] continued researching this in 2019 and switched to using regular cameras instead of infrared. He used YOLOv3, a one-stage object detector, to detect sheep in the collected footage. The method ended up having a recall of around 99%. Still, the lack of variability in the training footage made it difficult to give a conclusion on the system's real-world performance. The research on this topic continued in 2020 by both Imingen and Woodcock [11] and Kaarud *et al.* [12] where they combined the use of infrared and regular camera footage to create a complete system, also using YOLOv3. In 2021, Sørensen Bøckman [13] also researched this topic, using a Convolutional Neural Network (CNN) called EfficientNet. The research mainly focused on designing the system so that the drone could power and run the identification algorithms by itself. An accuracy of around 95% across the algorithm's networks was reported.

Several papers outside of the ones concerning this thesis' system have been written on radio-localization. In 2018, Dressel and Kochenderfer [14] used a UAV equipped with an antenna to locate different Sub-Gigahertz transmitters. Hui [15] created a system using UAVs, RSSI-ranging, and multilateration to locate transmitters with an accuracy of around 19 meters. Roberts *et al.* [16] designed a UAV system to estimate the position of Radio Frequency Identification (RFID) tags. No ranging methods were used, but the UAV noted its position using a GPS on every reading from a tag, and the mean position of the UAV was used to estimate the tag's position. They concluded that this system would only be viable for locating animals in enclosures, as it depends on operating a specific flight pattern.

2.3 Ranging Methods

Some localization methods depend on distance estimations between known anchor points and the objects in question. Various Radio-Frequency (RF) ranging techniques can be used to estimate the distance between an anchor point and an object. The following section gives an overview of relevant ranging methods feasible for the localization of sheep.

2.3.1 Received Signal Strength Indicator

Received Signal Strength Indicator (RSSI) is a measurement of the strength of a signal as it propagates in space and is received by other units. RSSI is measured in Decibel-Milliwatts (dBm) and can be used to calculate the distance to the transmitter of a signal. Path-loss models and measurements can be used to create a propagation model that gives a mapping between dBm-values and their corresponding distance, enabling receiving units to convert RSSI into an estimation of the distance to the transmitter of the signal.

RSSI-based ranging is often cost-effective, as most RF units have inbuilt RSSI capabilities. However, the method's accuracy is affected by changes in the environment it is used in, multipath propagation, and inference [17]. Experiments conducted by Jianyong *et al.* [18] show that RSSI-ranging methods are accurate for indoor localization. However, its feasibility in locating grazing sheep is not great, as the large distances and constant changes in the sheep's environment will make it challenging to perform range estimations accurately.

2.3.2 Time of Arrival

Ranging using Time of Arrival (ToA) is done by knowing the exact time a signal was sent, the exact time the signal was received, and the propagation speed of the signal [19]. Radio signals travel at the speed of light, and the time difference between the signal being sent and received can be used to calculate the distance between the sender and receiver. Accurate ToA ranging requires precise timing information with synchronized clocks at the sender and receiver, a costly and challenging problem to combat [20].

2.3.3 Round Trip Time

Ranging using Round Trip Time (RTT) utilizes the principle of ToA without the need for precise timing information and clocks. RTT ranging is done by transmitting a signal to another node, having the other node process the signal, and return with a response signal to the transmitter. The distance between the sender and receiver can then be calculated by timing the whole interaction between the nodes, as the propagation speed of the signal is known. This removes the need for synchronized clocks, and the transmitting node can do all timings [20].

The time a unit needs to receive, process, and return a signal varies and can be measured through experiments. The time between a signal being received and a new signal being returned will also have minor differences between measurements due to the jitter in the hardware [2]. This can be combated using the average of several measurements taken in quick succession.

2.4 Localization Methods

A localization method is necessary to estimate the position of an object. Various localization methods can be used by Radio-Frequency (RF)-devices, and this section gives an overview of the most used techniques.

2.4.1 Triangulation

Triangulation uses several known positions together with the Angle of Arrival (AoA) of a signal to determine the location of its transmitter. By knowing the AoA of the signal, triangles can be constructed to estimate the position of its transmitter. Triangulation does not depend on knowing the distance between the object and known points, removing the uncertainties introduced using the ranging methods presented in **Section 2.3**. AoA does require directional racks of antennas, which may make it challenging to incorporate on a constantly moving unit like a UAV [21]. **Figure 2.1** illustrates the principle of triangulation.

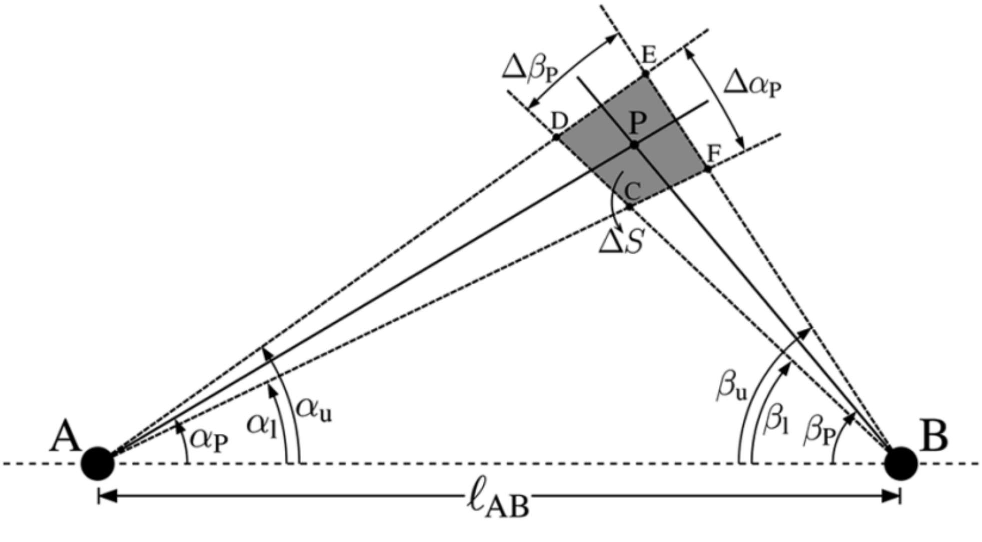


Figure 2.1: Illustration of triangulation [21]. The object is estimated to be located in the □$CDEF$ area.

2.4.2 Multilateration

Multilateration is a localization technique that combines known anchor points in space, distance estimations, and geometric shapes to determine the position of an object. The object's position can be estimated by estimating the distance between at least three known anchor points and the object. A circle is constructed around each anchor point in space, using the point's location as the center and the distance to the object as the circle's radius. The object is then estimated to be located at the intersection of the constructed circles. Uncertainty in the distance estimations may lead to no exact point of intersection by the circles. This is further explained in **Section 3.4**.

Figure 2.2 illustrates the principle of multilateration.

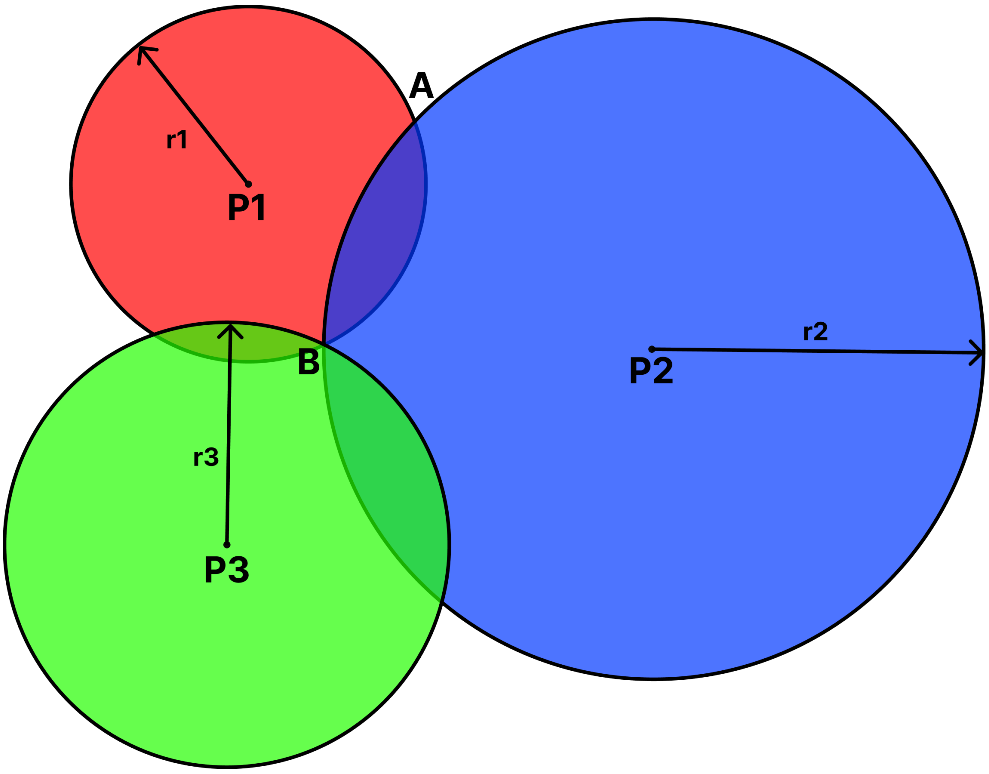


Figure 2.2: Illustration of two-dimensional multilateration [22]. The object is estimated to be located at point B.

2.4.3 Time Difference of Arrival

Time Difference of Arrival (TDoA) is a localization method that uses several measuring units with known positions and the multilateration method in combination with the principle of Time of Arrival (ToA) to locate an object. The distance between at least three measuring units and an object is calculated by measuring the time between the object transmitting a signal and the signal being received at the measuring units. Multilateration is then used to estimate the position of the object. An accurate estimation of the object's location requires that the measuring units are synchronized [23]. TDoA does not require synchronization between measuring units and the object but introduces other challenges, as several measuring units need to be synchronized to achieve precise estimations. The nature of the system evaluated in this thesis makes it challenging to use TDoA, as this would require using several UAVs simultaneously.

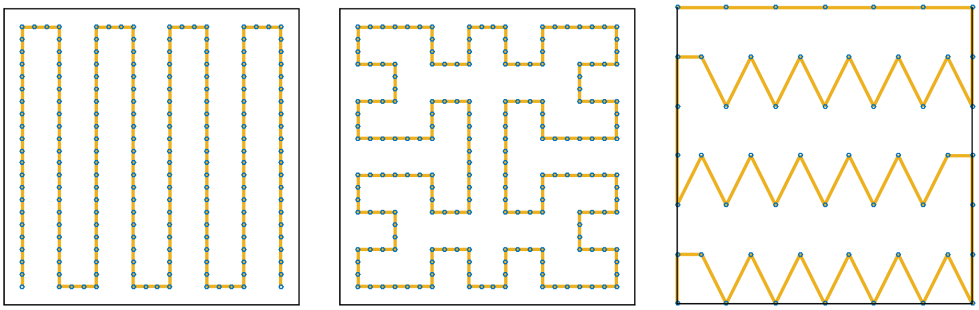
2.4.4 Monte Carlo Localization

Monte Carlo localization is a method that uses the density of samples in a set of samples to estimate the location of an object using probability [24]. Several estimations of the distance between known positions and the object are sampled and weighted to fit the state space of the object. The method analyses the density of samples, and the samples' approximation of the normal distribution of the set is then used to calculate the most probable location of the object. The estimation is not a single location but rather an area consisting of locations within the standard deviation of the normal distribution of the sample set.

2.5 UAV Search Patterns

The pattern a UAV uses to search a geographical area will affect localization performance. The previously presented localization methods rely on fixed anchor points and distance estimates to perform position estimations. When using a UAV for localization, the UAV acts as a single mobile anchor that removes the need for several fixed anchors [25]. The flight pattern of the UAV will therefore decide where these known points can be located, and the distribution of these known points affects the system's performance. Multilateration and the Monte Carlo method rely on distance estimations from known points spread around be object to ensure an intersecting point, and the search pattern of the UAV needs to ensure that this is possible.

Another important aspect when using UAVs is the maximum flight time. A search pattern that needs a short flight path allows the UAV to cover a larger area during its flight time but may lead to an insufficient amount of distance estimations for performing localization. Therefore, the shortest possible search pattern that ensures that localization can be performed successfully in a given situation is optimal. **Figure 2.3** illustrates a selection of different search patterns.



(a) SCAN. (b) HILBERT. (c) LMAT.

Figure 2.3: Illustration of different flight patterns. Figure taken from [25].

The Scan pattern results in a relatively short flight path, making the UAV cover a larger geographical area each flight. The main drawback of Scan is the large amount of co-linear anchor points resulting from the straight vertical lines, which can reduce accuracy and cause positional ambiguity. The Hilbert pattern tries to combat the amount of co-linear anchor points by increasing the number of changes to the flight direction. The Hilbert pattern requires a much longer flight path than Scan, significantly reducing the area the UAV can cover in a single flight [25]. The LMAT pattern, developed by Jiang *et al.* [26], tries to combat the co-linearity of anchor points by using a pattern consisting of many equilateral triangles. Each object in the search area falls into a single triangle, and the anchor points at the vertices of the given triangle are used for multilateration. LMAT is accurate, but many turns in the flight path may be challenging for some types of UAVs [25].

2.6 Radio Wave Propagation in Forest Environments

This thesis focuses on using radio waves for locating objects in high-density foliage. It is necessary to have a good understanding of the theory and factors impacting radio wave propagation in forest environments. Forests are random and unpredictable environments with many discrete scatters like bushes, leaves, and tree trunks. Radio waves propagating in the forest naturally experience multiple scattering, diffraction, and radiation absorption effects. Combined vegetation-induced propagation mechanisms can result in severe fades of the radio signal [27]. This section will present the most important principles and factors of radio wave propagation in forests.

2.6.1 Types of Forest Environments

An overview of the characteristics and variations of forests is required to understand how radio waves propagate in them. Forest environments consist of randomly distributed trees, bushes, and leaves, making it challenging to make assumptions and statements about radio wave propagation in the environment as a whole. To combat this issue, Li *et al.* [28] uses the layering model presented in **Figure 2.4** as a way to classify discrete and homogeneous mediums in forests. These layers have different properties and will affect radio waves differently. Defining a clear border between these layers is challenging as vegetation varies in size and foliage density, but a general separation border between the layers can be made. The air layer includes everything over the crown of the trees, the canopy layer includes the area of the crowns, the trunk layer includes everything below the crowns, and the ground layer includes the forest's ground.

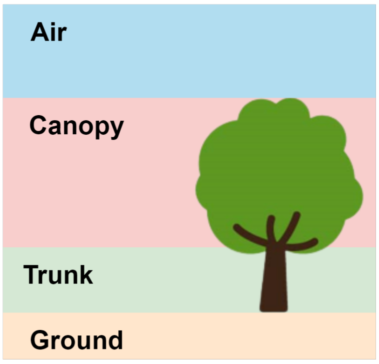
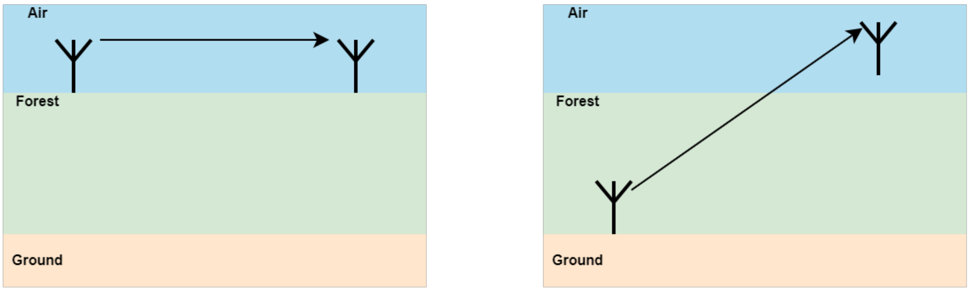


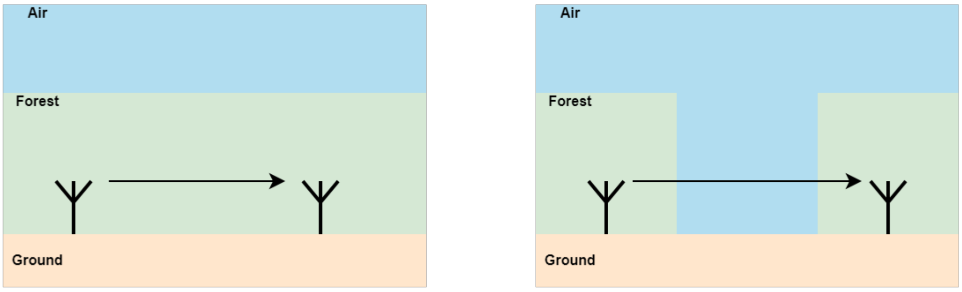
Figure 2.4: The different layers in a forest environment [28]. The figure of the tree was taken from [29], with permission.

2.6.2 Communication Configurations

The configuration and location of the transmitter and receiver in a forest environment will greatly affect how the radio waves propagate. The four layers previously presented all introduce different propagation influencing factors, and it is necessary to understand the type of configuration a radio communication is performed in. Ng [30] presents the four main configurations, as illustrated in **Figure 2.5**. The radio waves in these different configurations will propagate in all four forest layers, but each layer's effect on the radio waves will vary greatly from configuration to configuration.



(a) Air to Air **(b)** Forest to Air



(c) Forest to Forest **(d)** Forest to Forest via Air

Figure 2.5: Four different configurations for communication in a forest environment [30].

2.6.3 Propagation Mechanics

Radio waves in forests can propagate as direct waves, reflected waves, or lateral waves. These classifications of waves propagate through their mediums differently, and a combination of them is often present. The combination of these mechanics greatly influences the range, quality, and feasibility of a radio wave in forest environments. Understanding their properties is essential when evaluating a localization system used in high-density foliage. This section explains the three propagation mechanics and their effect on the transmitted signal. An illustration of the three different propagation mechanics is presented in **Figure 2.6**

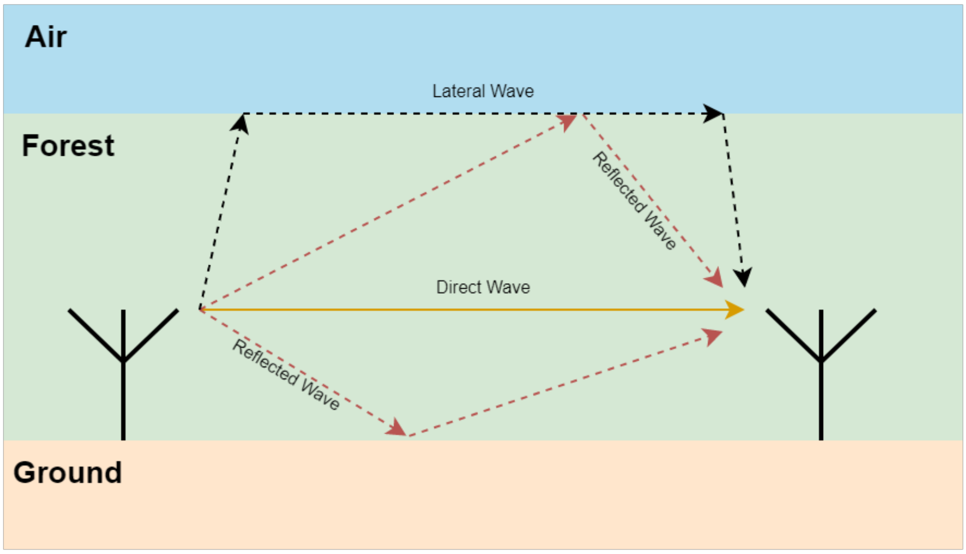


Figure 2.6: Simplified illustration of the different propagation mechanics in foliage [30].

Direct Waves

When a radio wave travels from the transmitter to the receiver in a straight line, it is called a direct wave [31]. This is possible when there exists a Line of Sight (LoS) between the transmitter and receiver of the wave, meaning no obstructions that can completely block the wave exists between the transmitter and receiver. The best-case scenario for forest propagation is when no objects exist between transmitter and receiver, but the nature of forests results in this rarely happening. Small transmission distances may facilitate this, but the probability of no obstructions decreases drastically as the transmission distance increases. The typical propagation medium for direct waves combines the air, canopy, and trunk forest layer. Although Electro Magnetic (EM) waves of lower frequency can propagate fairly well through objects like tree trunks and bushes, radio waves will experience shadow fading when propagating through obstructions [32]. Shadow fading can significantly affect localization performance negatively if RSSI ranging is used. Shadow fading attenuates the radio signal, and since RSSI ranging uses this metric to estimate the distance between transmitter and receiver, the distance will appear longer. This will affect the localization methods, resulting in inaccurate position estimations. Shadow fading does not have a direct negative impact on RTT ranging, as the method does not use the signal strength metric. The effective range of RTT ranging may, however, be reduced as shadow fading reduces the distance the radio waves can propagate without experiencing packet loss for the receiver.

Reflected Waves

When a radio wave encounters a change in medium, some or all of it may propagate into the new medium, and the remainder is reflected. The part that enters the new medium is called the transmitted wave, and the other is called the reflected wave [33]. This will occur in forest environments when the radio wave hits objects like the ground, trees, or bushes. The radio wave will reflect off the new medium at the same angle as the incident angle. The reflection will typically be repeated as the wave is reflected off the ground and the tree crown as it propagates. Although reflections enable radio waves to propagate from a transmitter to a receiver without a clear LoS between them existing, the reflection may negatively impact the signal carried by the wave. The change in medium causes part of the wave to continue propagating in the new medium without being reflected. This, combined with irregularities in the surface of the encountered medium, results in refraction loss [34]. In real transmission paths, radio waves are often reflected by various surfaces, and these multiple reflections lead to the signal arriving at the receiver via several paths [33]. This gives rise to multipath propagation, with is further explained in **Section 2.6.4**. Reflected waves will also result in inaccurate distance estimation when using the RTT method. The distance the wave needs to travel between a transmitter and receiver increases when no direct path is possible, which leads to the receiver experiencing an increase in the distance to the transmitter. However, this can be combated if a propagation model for forest environments that considers this is used for distance estimations.

Lateral Waves

The lateral wave travels horizontally from the transmitter and propagates along the air-canopy interface [35]. Direct and reflected waves suffer more attenuation than lateral waves, as they must propagate through tree trunks, leaves, and branches [27]. The lateral wave appears dominant at the treetops over a considerable forest depth when using Very High Frequency (VHF) and Ultra High Frequency (UHF) radios. Therefore, for VHF and UHF near-ground radio waves propagating through a considerable foliage depth, the main contribution to the received signal strength is the lateral waves, not the direct or reflected waves [27]. The impact of the lateral wave on the received signal strength is, therefore, more significant when communicating in a forest-to-forest configuration compared to the forest-to-air configuration mainly used in this thesis.

2.6.4 Multipath Propagation

As previously explained, multipath propagation happens when waves propagate from the transmitter to the receiver using several paths. A forest is a random medium with many obstructions, leading to the radio waves being a combination of direct, reflected, and later waves. These different types of propagation mechanics lead to waves rarely using a single path when transmitted, and multipathing is therefore expected. Multipath propagation can negatively affect the transmitted signal, including fading, distortion, and data loss [36]. There will be differences in the time of arrival of the waves when a signal propagates using several paths, as the length of the paths differs. Reflection and obstructions can also cause a shift in the wave phase, and inference will affect the received signal. This can mean that the waves either add together if they are in phase or cancel each other out if they are out of phase. Propagating through different paths can also lead to waves transmitted at different times being received simultaneously. When the two waves are received together, distortion can arise if they have similar signal strength levels [36]. The effect of multipath propagation can be combated using directional antennas, as the waves are focused in a single beam toward the receiver, reducing the strength of reflective waves toward the receiver [36].

Multipath propagation has a negative effect on both RTT and RSSI ranging. The inference and attenuation caused by a signal propagating through different paths and mediums will decrease the received signal strength. The distance between the transmitter and receiver is calculated directly from the RSSI values of a signal, causing the transmitter to appear further away, resulting in inaccurate distance estimations. The RTT ranging methods suffers from multipath propagation as data loss, fading, and distortions can result in packet loss, inaccurate ranging calculations, and reduced range. RTT ranging relies on aggregating multiple successful readings from each transmitter, and multipath propagation can lead to the UAV being unable to perform enough readings as it flies past the transmitter. Multipath propagation can also lead to inaccurate calculations due to the longer propagation paths of the signal.

2.6.5 Effect of Frequency in Forest Environments

The wavelength of a radio wave decreases as its frequency increases, and this factor dramatically impacts how radio waves propagate in forest environments. Generally speaking, the object penetration of a radio wave will be the best when its wavelength matches the size of the obstructions in the environment. Attenuation from the crown layer is lowered when using frequencies of 30MHz to 1.2GHz, as the wavelength somewhat matches the size of twigs, branches, and leaves [37].

2.7 Performance of Different Radio Technologies for Foliage Penetration

This section presents the most commonly used radio technologies and compares their performance in the localization of objects in areas of high-density foliage. Our system uses BLE for the transmission of data. Although BLE is the only technology field-tested in foliage in this thesis, a literature review of the other alternative technologies is provided. The setup and configuration of the communication affect how different technologies perform, and forest-to-air communication is used as the baseline of this evaluation. This means that the radio waves mainly need to penetrate the canopy layer. Although some technologies may be superior for pure foliage penetration, other metrics such as range and accuracy must also be considered when evaluating. A technology that increases foliage penetration while decreasing the overall performance and feasibility of the system will not be recommended for further exploration. One Sub-Gigahertz technology (LoRa), one 2.4GHz technology (BLE), and one Ultra-Wideband (UWB) technology will be evaluated.

2.7.1 LoRa

LoRa (Long Range) is a wireless modulation technique that is derived from Chirp Spread Spectrum (CSS) [38]. LoRa can operate in a large spectrum of frequencies, and different continents are assigned specific frequency bands for LoRa usage. 868MHz is the standard in Europe and will therefore be the frequency used for this review [39]. LoRa offers ultra-low power consumption, and tests performed in [40] shows a Line of Sight (LoS) range of around 20 kilometers. The sub-GHz frequency allows for good object penetration, and LoRa signals can easily penetrate buildings. Field experiments conducted by Ferreira *et al.* [41] tested the performance of LoRa in a forest environment, looking at metrics like RSSI, Packet Delivery Ratio (PDR), and Signal to Noise Ratio (SNR). The research concluded that LoRa has a maximum effective range in forests of around 250 meters, despite its 20-kilometer LoS range. LoRa can be configured using different spread factors, where the chirping can be altered to increase or decrease the bit rate and range of the signals. SF12 provides the highest range and lowest bit rate and should perform best in forests. The tests indicate a PDR between 0.4 (worst case) and 0.8 (best case) using SF12 at a distance of only 150 meters in high-density foliage. The low PDR will make it challenging for a moving object like a UAV to perform enough RTT reading from a node during a fly-by to confidently estimate a distance, making the system unable to locate objects.

When considering the result from Ferreira *et al.* [41], the communication setup used during testing is an important aspect. A forest-to-forest configuration was used, meaning the transmitter and receiver were located in the forest. This configuration is highly exposed to multipathing effects, as the direct path is full of obstructions. The use of LoRa for the system evaluated in this thesis would be in a forest-to-air configuration, where the signals would need to penetrate a substantially smaller foliage distance. Signals in a forest-to-air configuration only need to penetrate the canopy layer before propagating unobstructed in the air, whereas forest-to-forest requires object penetration throughout the path. No forest-to-air testing of LoRa was found when writing this thesis, and no conclusion can be made about its performance in this configuration. Still, a better performance than concluded in [41] is expected.

2.7.2 Bluetooth Low Energy

Bluetooth Low Energy operates in the 2.4GHz Industrial, Scientific, and Medical (ISM) band and is designed for highly efficient data transmission with low energy usage [42]. Bluetooth is known as a short-range technology, but the introduction of BLE Long Range for Bluetooth 5 has made BLE a viable option for longer-range applications. Nerland [3] conducted tests on BLE and found the LoS range to be around 1200 meters, which matches the official range estimations. Although BLE Long Range increased the LoS range of BLE, the higher frequency of BLE compared to LoRa results in it having trouble propagating through forests. Experiments performed in [43] show that BLE can transmit data over a distance of 95 meters in a forest. A connection was also established at 110 meters, with a PDR of around 0.33. Mathew *et al.* [44] also performed range tests of BLE in forests and reported a practical range in high-density foliage of approximately 20 meters. As with LoRa, both tests were performed in a forest-to-forest configuration. Therefore, the practical range of BLE in foliage using a forest-to-air configuration is expected to be higher than concluded in [43] and [44].

2.7.3 Ultra-Wideband

Ultra-Wideband (UWB) is a short-range radio protocol that can capture accurate spatial and directional data [45]. UWB can operate on a broad spectrum of Gigahertz frequencies and is used to calculate the distance between two transmitters through the Time-of-Flight method. UWB has a reported LoS range of approximately 200 meters and can effectively measure distance with an accuracy of 10 centimeters in indoor environments [46]. However, the high frequency of UWB makes it less feasible for outdoor localization, especially in forests and foliage. Anderson *et al.* [47] have tested how UWB propagates in different forest environments. The transmitter and receiver were separated by a distance ranging from 4 to 50 meters, and all tests were performed in a forest-to-forest configuration. Using UWB in the frequency range of 3 GHz to 4.2 GHz, a path loss exponent of 6.4 and a standard deviation from the used log-distance shadow model of 14 dB were recorded. The effects of multipathing could be combated using a rake receiver with at least 12 fingers, but this would require an unrealistically complex receiver. No direct tests evaluating ranging accuracy or effective range were conducted. However, the results indicate that UWB is not feasible for communications in forests at distances beyond 50 meters.

Chapter 3

System Architecture

This chapter presents the sheep localization system evaluated in this thesis. The system has three main components; a UAV, BLE modules, and a custom-made Ground Control Station. Its first iteration was developed by Swiderski [5], Steinsvik [4], and Nerland [3] in 2021. The current version of the system was developed by Vucic and Axell [6] in 2022. A good understanding of the system's components, architecture, and functionalities is necessary to ensure a correct and thorough evaluation. An overview of possible performance-affecting factors will also be useful for recommending performance-enhancing changes to the system. The implemented radio technology, search pattern, ranging method, and localization methods will first be presented, followed by a presentation of the three different components of the system.

3.1 Radio Technology

The system uses Bluetooth Low Energy (BLE) for communications between devices. BLE operates in the 2.4 Gigahertz (GHz) Industrial, Scientific, and Medical (ISM) band and is designed for highly efficient data transmission with low energy usage. The research by Vucic and Axell [6], Steinsvik [4], Nerland [3], Swiderski [5], and Nyholm [2] has proved that BLE performs well for localizing sheep in open environments.

3.2 Search Pattern

The system uses a search pattern implemented by Steinsvik [4] that is a variation of the SCAN-pattern presented in **Section 2.5**. The search pattern is adapted to any geometric shape and designed to ensure the UAV detects each sheep from at least two sweep lines.

Ambiguity in the sheep's position can occur if all distance measurements between the sheep and the UAV are made while the UAV is on a single sweep line [4]. This can lead to two different intersection points existing at once, creating a false positive sheep position. The concept of two different intersection points existing at once is illustrated in **Figure 3.1**. This problem is easily avoided using a search pattern where the sweep lines are close enough to ensure the UAV discovers each sheep from at least two sweep lines. This is considered by the system when generating the UAV's flight paths.

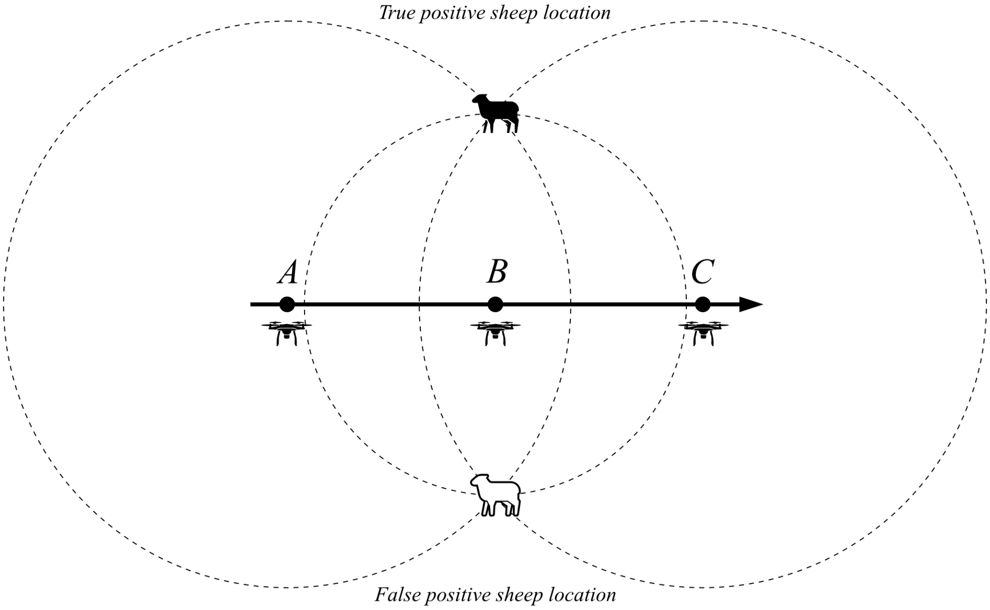


Figure 3.1: Geometric dilution of precision when distance is measured from a single sweep line. Taken from [4], with permission.

3.3 Ranging Method

Round Trip Time (RTT)-ranging is the ranging method used by the system. Although the BLE radio modules used by the system could also be programmed to support RSSI-ranging, it was concluded by Nyholm [2] in 2020 that RTT outperforms RSSI in regards to the accuracy of distance estimations. The currently implemented RTT-ranging method was developed by Swiderski [5] in 2021.

The BLE module attached to the UAV acts as a central device, and the BLE modules attached to the sheep act as peripheral devices. The central device actively scans while the UAV flies its route, constantly listening for advertisement packets from peripheral devices. Once the central receives an advertisement from a peripheral device, it sends the targeted peripheral device an RTT ping packet. The peripheral then responds to the ping, sending data back to the central device. This RTT-ping loop is performed until a predefined number of iterations is finished. The central device then aggregates the RTT measurements and calculates the distance to the peripheral. The distance estimation is saved in the central device's RAM, together with its own GPS position at the time of the readings. This process is performed for each peripheral device encountered during a flight, and each distance estimation is connected to a unique ID of the given peripheral. The collection of GPS positions of the UAV and distance estimations to the peripheral devices makes it possible to later use the implemented localization methods to calculate the position of each peripheral device. **Figure 3.2** gives an overview of the implemented RTT-ranging method.

In 2021, Swiderski [5] proposed two possible implementations of this method. The first implementation is called the Bluetooth Low Energy Stack-Based Method, which runs on top of the BLE stack and can be used by any BLE-enabled device. The second method is called the Minimal Custom Protocol-Based Method, which uses a custom protocol that runs on the BLE hardware and is only functional for the BLE module it was designed for. It was also concluded by Swiderski [5] that the Minimal Custom Protocol-Based Method had the highest ranging precision and the lowest power consumption of the two and is the method currently used by the system.

The Minimal Custom Protocol-Based Method does not run on the BLE stack but shares most of its attributes. It uses the same 2.4GHz frequency as BLE, has the same bandwidth of 1MHz, uses the same GFSK modulation technique as BLE, and has a similar packet format. In addition, the protocol uses BLE-encoded PHY with S=8 and a transmission speed of 125 Kilobit Per Second (kpbs) to ensure maximum transmission range [5].

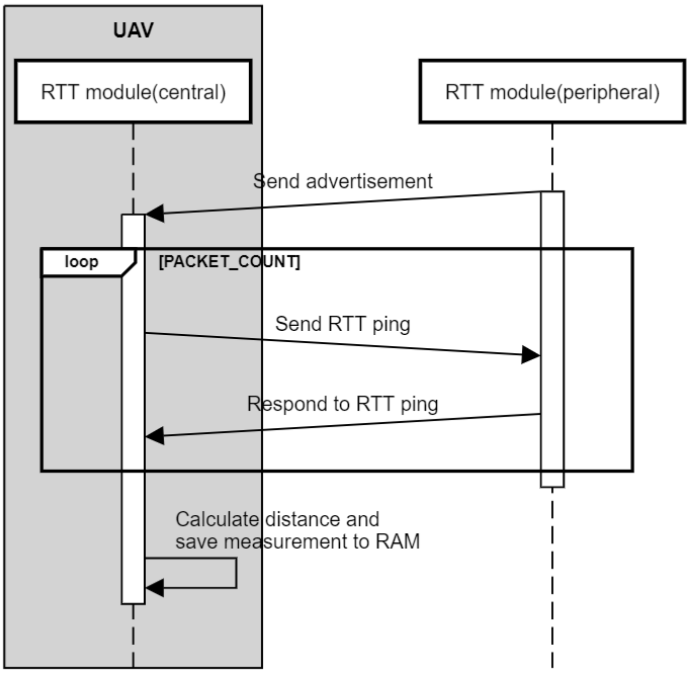


Figure 3.2: Overview of ranging using RTT. Taken from [3], with permission.

3.4 Localization Methods

The system has implemented two localization methods: multilateration and a variation of the Monte Carlo method called Particle Filter. Both of these methods use the same ranging and GPS data from the UAV to perform position estimations but differ in how the estimation is performed. This section explains how these methods work and deal with uncertainty caused by inaccurate distance estimation data. Both methods were developed and implemented by Steinsvik [4] in 2021.

3.4.1 Particle Filter

The Particle Filter method is a variation of the Monte Carlo method presented in **Section 2.4**. The method uses distance estimations and GPS data to create discrete particles that represent the possible positions of a sheep, and statistical inference is then used to estimate the correct position [4]. An overview of this concept is illustrated in **Figure 3.3**.

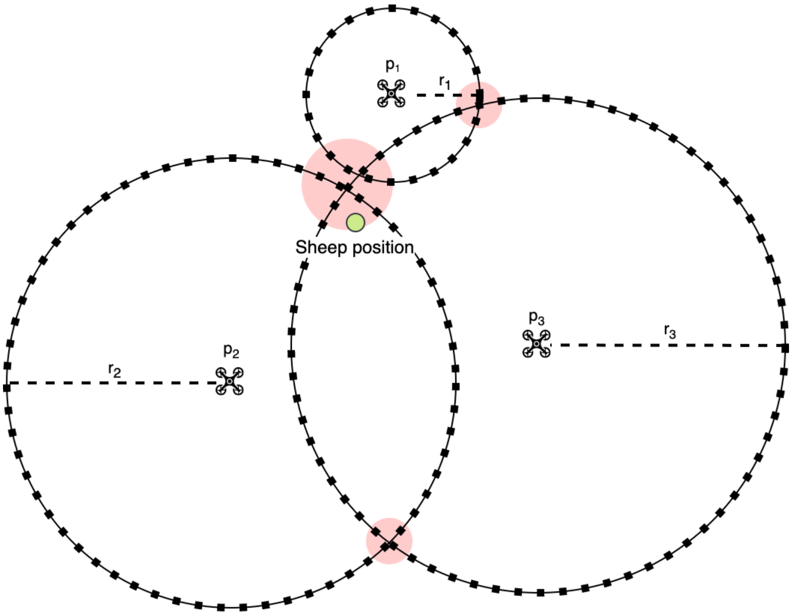


Figure 3.3: Overview of localization using Particle Filter. Taken from [4], with permission.

The method creates a fixed amount of particles around the circle created by each distance estimation, and the intersection between these circles will create clusters of particles. The method looks at particle clusters in longitude and latitude separately, where the density of the particles along the axis is higher around the sheep's actual position [4]. **Figure 3.4** illustrates the density of particles along a single axis.

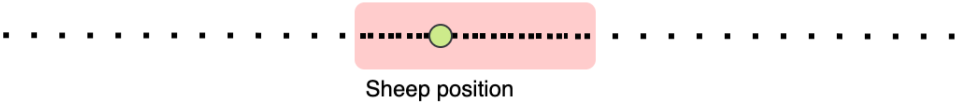


Figure 3.4: Single-axis coordinate series of longitude or latitude. Taken from [4], with permission.

These series of single-axis coordinates are then placed in a normal distribution, which can be used to calculate the probability of each particle being correct. The particle with the highest probability of being correct can be interpolated, together with the standard deviation of the series [4]. **Figure 3.5** illustrates this principle. The method then estimates that the sheep is most likely located within the area created by the standard deviation of the mean particle of the longitudinal and latitudinal coordinate series.

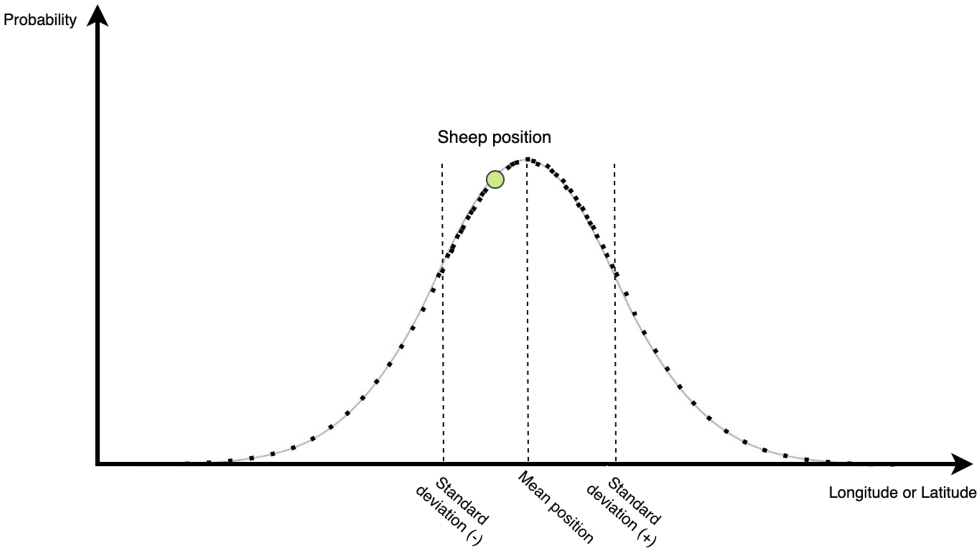


Figure 3.5: Single-axis coordinate series in a normal distribution. Taken from [4], with permission.

3.4.2 Multilateration

The implemented multilateration method is conceptually the same as presented in **Section 2.4** but is slightly modified to account for noise and uncertainties in the GPS and ranging data. The method tries to find a single point of intersection to determine the sheep's position, but this is often impossible using real-world data. Errors in the distance estimation may result in no single intersection point existing, disabling the use of standard multilateration.

This is solved by incrementing the error distance of the ranging data, making the method return an area instead of a single point. The method will iteratively increase the error distances until it finds an area in which all circles intersect [4]. The area of the intersection is then calculated, as illustrated in **Figure 3.6**.

After an area of intersection is found, the method returns the mean point of the area as the sheep's position. The uncertainty error of this position being the sheep's actual position, is calculated to be the distance from the mean point to the border of the intersection area [4]. This is illustrated in **Figure 3.7**

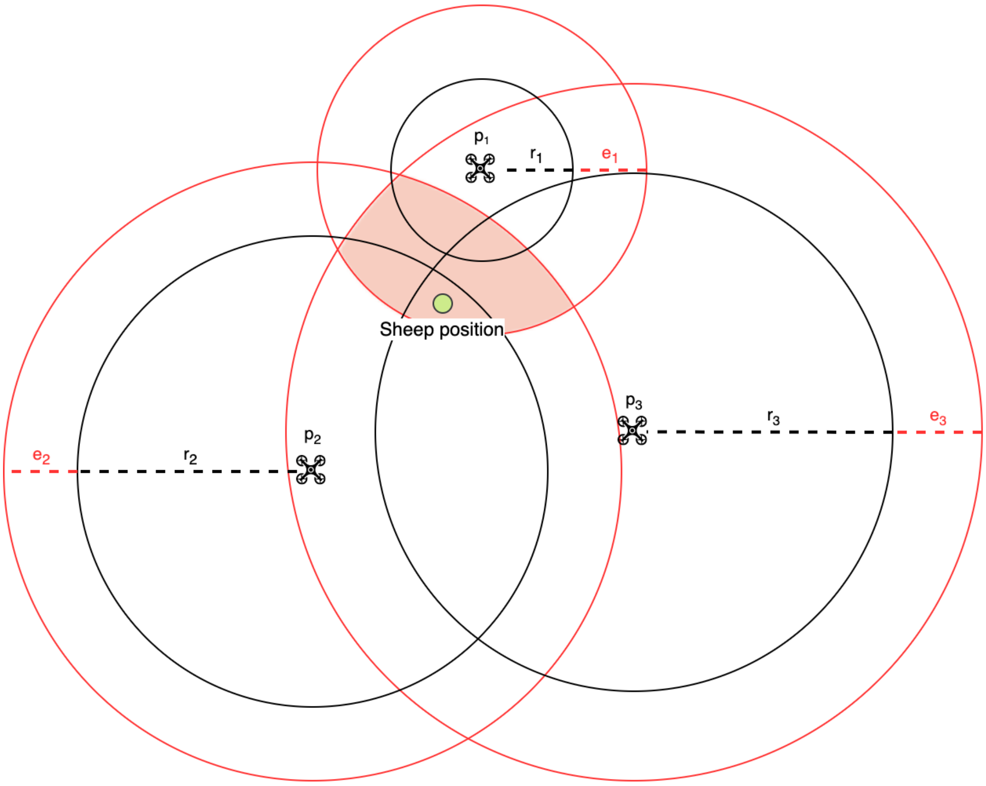


Figure 3.6: Illustration of the implemented multilateration method. Taken from [4], with permission.

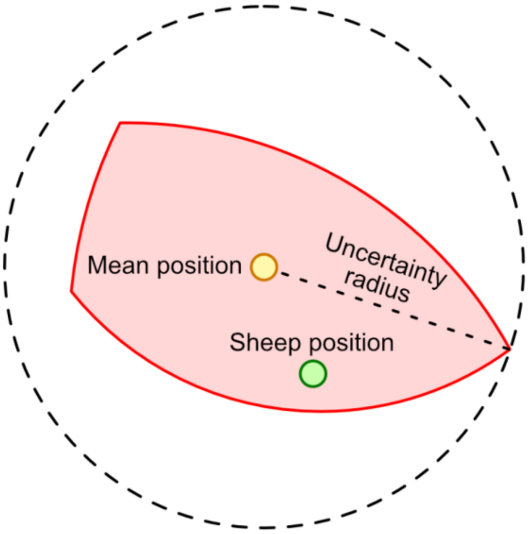


Figure 3.7: Illustration of the uncertainty area of multilateration. Taken from [4], with permission.

3.5 BLE Modules

The system can use two different BLE modules. The nRF52883 Development Kit (DevKit) by Nordic Semiconductor, and the Minew MS88SF23 module based on the nRF52883 System on a Chip (SoC) also by Nordic Semiconductor. Both modules offer the same in terms of functionality, but they differ in size, ease of reprogramming, and logging capabilities. This section presents the two modules and their preferred use cases.

3.5.1 nRF52833 Development Kit

The nRF52833 DevKit is a single-board development kit that supports BLE, Bluetooth Mesh, Zigbee, NFC, and Thread. It can be powered through USB, external power sources, or the built-in button-cell battery holder. The onboard SEGGER J-Link debugger also makes it easy to program and debug the DevKit [48].

The attributes of the nRF52833 make it the preferred module when developing, testing, and debugging the system. This module can be programmed to act as the central device attached to the UAV, enabling distance estimations and localization without using the UAV. This can be useful when performing ranging-accuracy tests or tweaking attributes to increase performance. It can also be programmed to be a peripheral device, acting as a sheep tag during testing. **Figure 3.8** shows the DevKit.

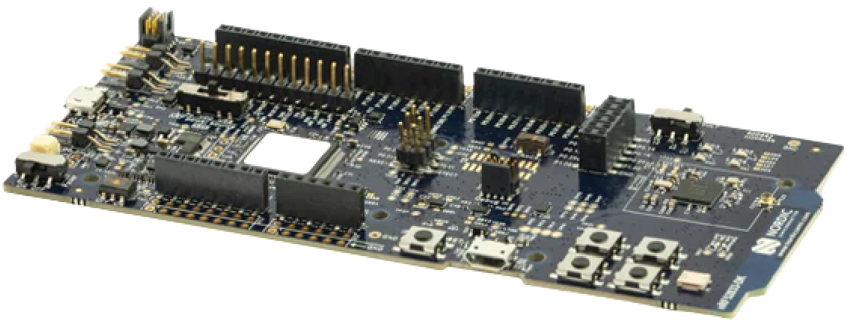


Figure 3.8: nRF52883 Development Kit. Picture from [49].

3.5.2 Minew MS88SF23 Module

The Minew MS88SF23 Module is a compact ultra-low-power BLE module based on the same SoC as the nRF52883 DevKit. It has no inbuilt USB or button-cell battery connection and therefore relies on other external power sources. The module also requires a custom-made connection for programming and offers no logging or debugging capabilities [50].

The small size and low weight of the Minew module make it the preferred module to attach to the UAV. The lack of an easy way to power the module is solved by connection to the power source of the UAV itself. Vucic and Axell [6] also used the Minew module to develop an early prototype of how the tracking equipment can be attached to sheep. Here, the module uses an external button-cell battery connector for power. **Figure 3.9a** shows the module, and **Figure 3.9b** shows the ear tag prototype using the Minew module.

(a) Minew MS88SF23 Module. Picture from [50]

(b) Ear tag prototype using the Minew module. Picture from [6].

Figure 3.9

3.6 Unmanned Aerial Vehicle

The system uses a Unmanned Aerial Vehicle (UAV) originally developed by Nerland [3] in 2021 and improved upon by Vucic and Axell [6] in 2022. This section gives an overview of how the UAV is constructed, the functionalities it provides, and how it is operated.

The UAV is a custom-built lightweight autonomous quadcopter with a Minew module for RTT measurement and a GPS module to determine its position when performing ranging measurements. The flight time of the UAV has not been measured but is expected to be around the same as the first iteration of the UAV that had a flight time of around 27 minutes [3]. The UAV can be operated manually using a UAV controller or by uploading a flight mission and having it perform its mission autonomously. A USB port on the UAV's flight controller is used to upload flight missions and download RTT-ranging data after finished flights. **Figure 3.10** shows a picture of the UAV.

Figure 3.10: Picture of the UAV.

3.7 Ground Control Station

The ground control station is called Radio Sheep GCS and was developed in 2021 by Steinsvik [4] and later improved by Vucic and Axell [6] in 2022. The current version is publicly available on GitHub [51]. Radio Sheep GCS is used to create flight missions and upload them to the UAV, download RTT-measurement from the UAV, and calculate and visualize the positions of the sheep encountered during a flight. Radio Sheep GCS communicates with the UAV over MAVLink.

3.7.1 Planning Flights

Radio Sheep GCS generates flight missions for the UAV based on the geographical area the user wants to search. Parameters like elevation, velocity, search radius overlap, and more can be input. A flight mission is then generated based on the principles of the implemented search pattern of the system.

Figure 3.11 shows an example of what a generated flight mission in Radio Sheep GCS might look like.

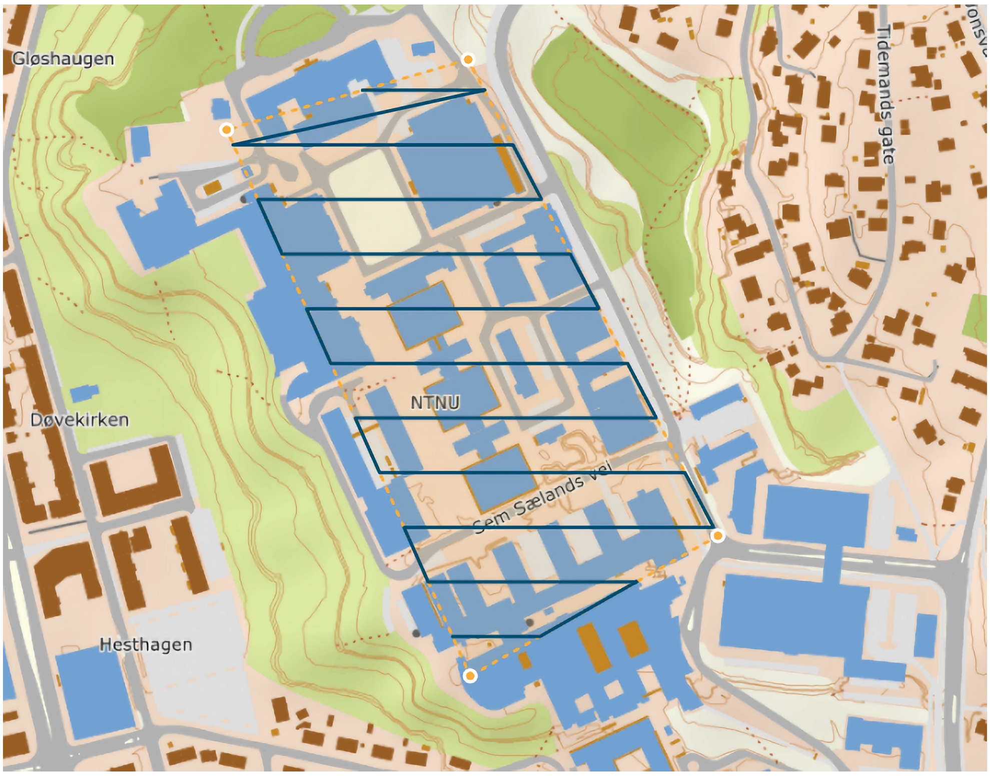


Figure 3.11: Flight path example from Radio Sheep GCS.

3.7.2 Visualization of Localization Data

Radio Sheep GCS can be used to visualize the estimated position of sheep after a flight is completed. The file containing the RTT measurements is uploaded, and the users choose between the Particle Filter method or the multilateration method. The GCS then displays all measurements visually on a map based on the GPS data of the readings, and the coordinates of each sheep are calculated and returned to the user. **Figure 3.12** shows how Radio Sheep GCS visualizes RTT measurements. Every circle corresponds to a completed RTT measurement.

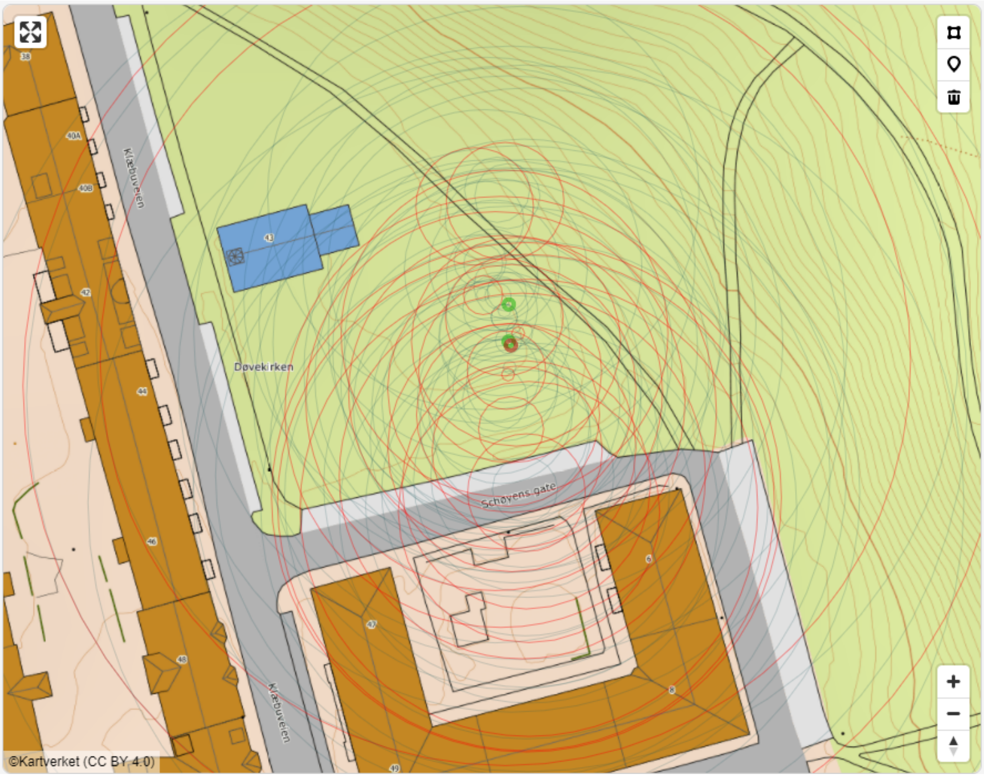


Figure 3.12: Visualization example from Radio Sheep GCS.

Chapter 4

Evaluation of the System

This chapter will address the evaluation of the system through several conducted tests that focus on how the system performs in dense foliage. All tests are presented with background, goal, method, results, discussion, and conclusion.

4.1 Preliminary Testing

During the autumn of 2022, several tests of the current system were carried out as a part of the preparatory project. This section will address the goal of the preliminary testing, how the tests were conducted, the results, errors that occurred during the testing, and a conclusion resulting from the tests.

4.1.1 Goal

The purpose of the preparatory project and preliminary testing was to get familiarized with the current system. Having an understanding of how to control the UAV, plan flight routes, display flight data, and how to interpret the data was necessary. Understanding the system and how it functions will provide the groundwork needed to conduct proper testing in a secure environment that closely resembles the real-life scenario. Another objective of the preliminary testing is to identify and address any potential problems with the current system to be prepared for the proper and realistic testing conducted later.

4.1.2 Method

Four system tests were conducted throughout the preparatory project, of which three have been conducted with active radio transmitters placed in the UAV ’s search area.

First Test Flight

The UAV and Radio Sheep GCS are quite advanced systems that are difficult to use without prior knowledge. Christian Axell from [6] provided guidance during our first test flight. He showed how the GCS worked, how to upload flight missions to the UAV, and how to fly the UAV with the predetermined flight path. For the first test, a small flight path was made over a flat open area by the grass lawn behind Hovedbygget at Gløshaugen in Trondheim. The UAV was put in automatic flight mode, and it started the flight path. However, it gradually lost altitude and eventually crashed into the ground. No nRF52833 DevKit were placed along the flight path during this flight, as only the UAV's ability to follow the flight path automatically was tested.

Test of Automated Flight in Høyskoleparken with nRF52833 DevKit

The second test was conducted in a flat open area in Høyskoleparken near Døvekirken below Gløshaugen in Trondheim with three nRF52833 DevKits placed on the grass along the flight path. A flight path was made in Radio Sheep GCS and uploaded to the UAV via Mission Planner. The approximate flight path and positions of the DevKits that were placed along the flight path can be seen in **Figure 4.1**. An error occurred when trying to upload the flight path using the Sheep GCS, and as a result, ArduPilot's Mission Planner software had to be used to upload the actual flight path to the UAV. As a result of the loss of altitude during our initial test, the altitude was set to a few meters above the preferred altitude. The UAV was flown manually up to a suitable altitude, and then the UAV was set to automated flight. The UAV had an approximate altitude of 3 meters and a relatively low flight speed during the flight. After completing the flight, the flight data was extracted through USB and displayed in Sheep GCS.

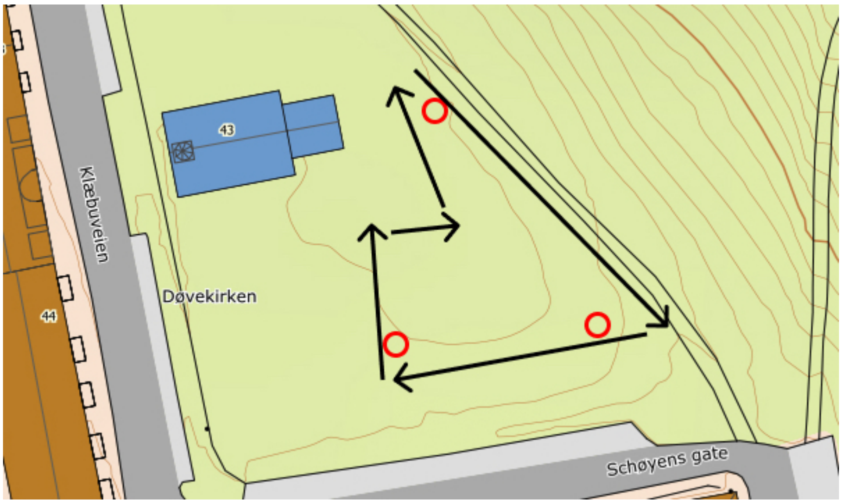


Figure 4.1: The map shows the flight path and the approximate positions of the nRF52833 DevKits that were placed along the flight path.

Large Scale Test at Dragvoll

After the test was conducted in Høyskoleparken with the DevKits, there was a need to test over a larger area for a more realistic test scenario. Two tests were conducted on an open field near Dragvoll idrettsenter. A flight path was created in Radio Sheep GCS covering a large part of the field, and four nRF52833 DevKits were placed in the search area, as seen in **Figure 4.2**. The flight path was uploaded to the UAV via Mission Planner, and the UAV was set to automated flight. The UAV had an approximate altitude of 8 meters and a relatively low flight speed during the test flight. During the test, high winds were encountered. However, the UAV handled it well in automated flight mode. The UAV completed the flight path and landed by itself. The test was repeated due to an error when displaying data in Sheep GCS.

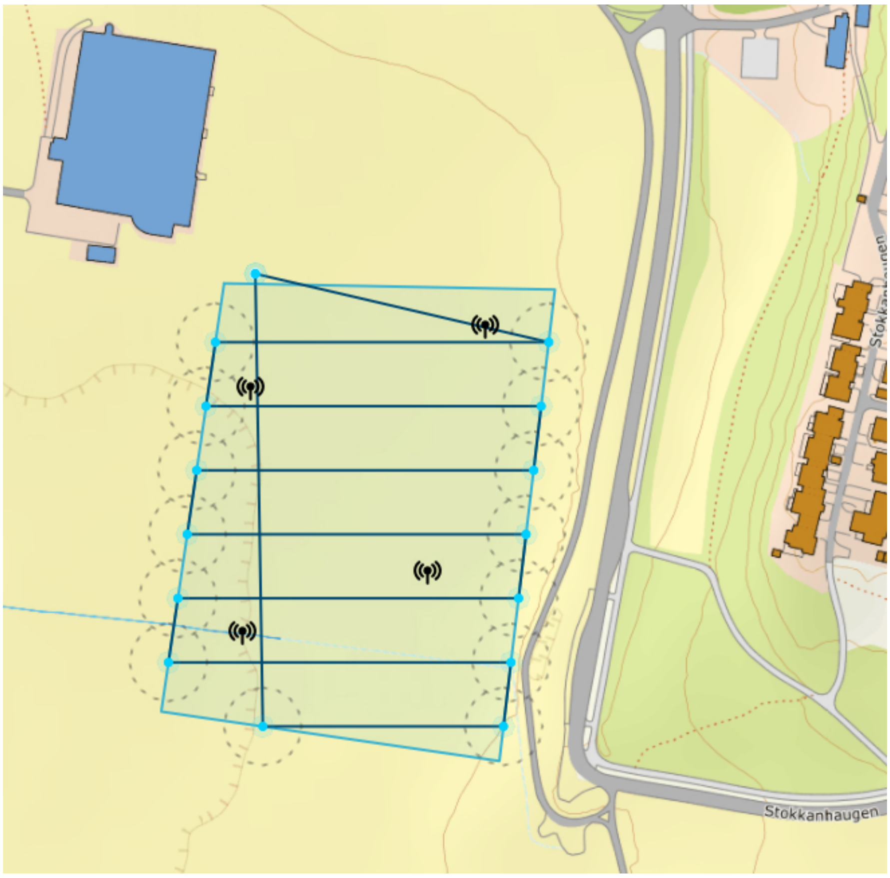


Figure 4.2: Sheep GCS showing the flight path and approximately where the radio transmitters were placed during the test.

4.1.3 Results

First Test

As a result of the UAV gradually losing altitude during the first test flight and eventually crashing into the grass lawn, the altitude in Radio Sheep GCS or Mission Planner had to be set to higher than the preferred altitude to prevent the UAV from crashing during the following tests. The reason for the loss of altitude is unknown, but it had a simple fix by setting the altitude higher than preferred. As the altitude of the UAV during a realistic scenario is higher than 15 meters, this will not pose a problem in the future.

Test in Høyskoleparken

The data was extracted from the UAV through USB and uploaded to Sheep GCS, as seen in **Figure 4.3**. All of the RTT ranging measurements that were made during the test had a distance estimate of 0 meters. An observation from the results is that the map's locations where the drone made signal readings from the radio transmitters are clustered together and near one another. Thus, the necessity to test the system across a larger area was recognized. By doing so, the test scenario would also be more realistic compared to the actual use case.

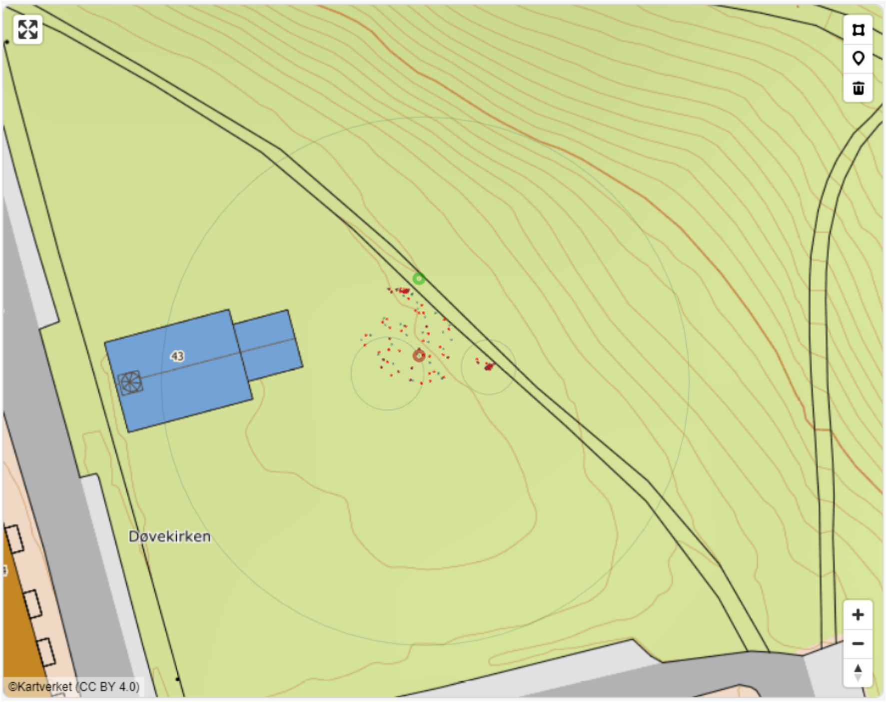


Figure 4.3: First test of automated flight in Høyskoleparken with nRF52833 DevKits

Large Scale Test at Dragvoll

An error occurred when extracting the data from the first flight, and Radio Sheep GCS would not display the flight data. Trying to fix the issue, the data was logged, and it was discovered that the data was transferred to the GCS. Therefore, the reason why the data would not be displayed is unknown. Vucic and Axell [6] also encountered problems with extracting data using Radio Sheep GCS, which could be related to the same issue.

The UAV flew the flight path one more time in an attempt to figure out how to fix the issue. During this test flight, the UAV did not receive any signals from the DevKits placed in the field. Some of the nRF52833 DevKits had known problems with staying powered, which led, in this case, to all of them turning off before conducting the second test flight. As a consequence, no RTT data was received during this flight.

During the landing on the second test, the UAV flew into a nearby tree. It seemed that the UAV suffered no damages from the crash, and a second test flight was conducted to see if everything worked as it should. During this test flight, one of the wires connecting the GPS module to the UAV was loose, and as can be seen in **Figure 4.4**, one of the wires was cut off by the rotor. This resulted in the GPS module malfunctioning and causing the automated flight mode not to work.

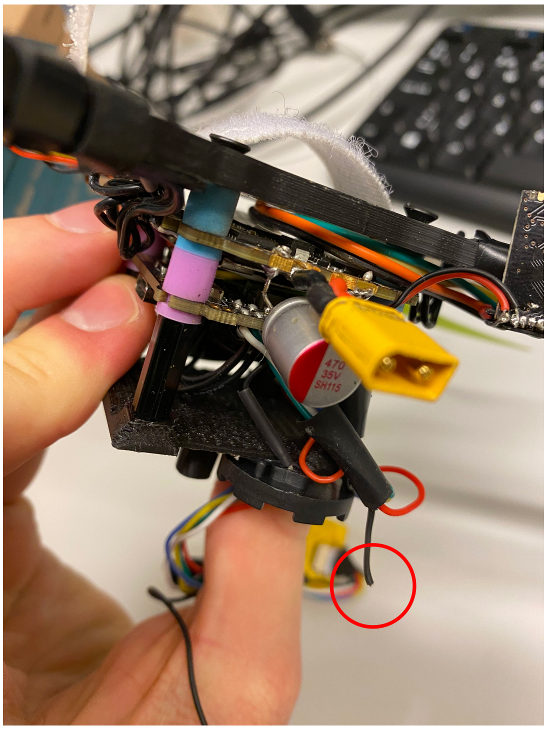


Figure 4.4: The wire between the UAV and the GPS module had been cut off as a result of the crash.

4.1.4 Discussion

During the preliminary testing, several issues appeared and showed how the system could be unreliable and the hardware of the UAV fragile. As a result of the different encountered issues, no usable flight data from the test flights was received. The encountered issues may affect the system's reliability and ease of use. In addition, certain functional aspects of the system must be enhanced to work as intended, meet users' requirements, and be simple to use.

Fragile Hardware

During the preliminary testing, the UAV was damaged several times, resulting in the malfunctioning of the GPS module and the UAV. The UAV was custom-made by Vucic and Axell [6] during their work on their master thesis in 2022. As mentioned in [6], they also experienced problems with the UAV hardware during testing and had to repair the UAV about a dozen times. The tests performed in this thesis gave a similar experience, showing how fragile the hardware is. Loose cables, lousy soldering, and other poor solutions contribute to the UAV hardware often needing repairs. This consumes valuable time that might be used to evaluate the system more thoroughly. For researchers doing similar work or students continuing with further work on this system, it is recommended that the UAV undergoes upgrades that make it more robust. Buying a robust commercially ready-made UAV that supports custom flight plans and can carry the RTT-ranging module would be most suitable.

GCS Performance Issues

Several software issues affecting the system's usability have been encountered. Problems with uploading flight paths and reading RTT data using Radio Sheep GCS have been experienced throughout the preliminary testing. There was an issue with GCS that prevented flight paths from being uploaded to the UAV, and as a consequence, the flight paths had to be uploaded via Mission Planner. After testing, the RTT data was extracted. However, an error in GCS prevented the display of the data. These software issues experienced with Radio Sheep GCS have affected the system's usability. These are just a few of the issues that must be resolved for the system to go into production in the future. As for further research on this topic, these issues should be fixed to make it less complicated to familiarize oneself with the system.

External Power Source

As mentioned in Section 4.1.3, issues regarding the power supply on the nRF52833 DevKit during testing were experienced. Some of the DevKits powered off during the test, resulting in no RTT data. The reason why the DevKits powered off during testing is unknown to us. To prevent this issue during testing, the DevKits had to be connected to an external power source, such as a power bank, to ensure that they stayed powered on. However, this issue will only be present during our testing and not in a realistic scenario where the ear tag prototype using the Minew module would be used since the power supply on the ear tag is functional.

4.1.5 Conclusion

Earlier work performed on the system was reviewed to identify any current issues and how to address them. The system was tested to identify areas where it may be enhanced. Several issues that affected the system's performance and ease of use were identified throughout the testing. Rather than extensively testing the system, much effort went into repairing fragile hardware that kept breaking. Issues were also encountered when uploading flight plans and extracting flight data through the Ground Control System. The preliminary testing gave a solid foundation for further work on the master's thesis by providing an understanding of how the system functions, current issues, and the modifications the system requires.

4.2 Testing Ranging Performance

As mentioned in **Section 3.3**, the ranging method used by the system is the Minimal Custom Protocol-Based (MCPB) method made by Swiderski [5]. This protocol does not run directly on the BLE stack but shares many attributes and can not be perceived as a pure BLE-ranging method. The results from testing BLE ranging in forests, performed in [43], and by Mathew *et al.* [44], give some insights into how well purely BLE-based ranging methods perform in forests.

Although the Minimal Custom Protocol-Based method shares many of its attributes with BLE, the difference in ranging performance in forests should be investigated to conclude whether the custom protocol outperforms other BLE-based ranging methods. Vucic and Axell [6] investigated the range of the Minimal Custom Protocol-Based method in 2022, but no testing of the method in forest environments was performed. Their investigation compared the MCPB method with a new commercially available RTT-based BLE ranging method created by Nordic Semiconductor. This involved testing the range of the MCPB method in a Line of Sight environment. They concluded that the commercially available method had a LoS range of 126 meters. In comparison, the MCPB method could complete RTT readings up to a distance of 823 meters. This clearly shows that the custom-ranging methods outperform BLE-based methods in LoS environments. However, this is not concluded when foliage is introduced, which is the basis of this investigation. The insights into the performance of the MCPB method in foliage will also be valuable when discussing Research Question 1.

4.2.1 Goal

This test aims to investigate and conclude how well the MCPB method performs in areas of high-density foliage. This will give valuable insight into how well and consistently the system can estimate the distance between the UAV and sheep located in forests and determine if the MCPB method outperforms standard BLE ranging methods in forests.

4.2.2 Performance Metrics

The performance of the MCPB method will be evaluated using ranging accuracy, precision, and Packet Delivery Ratio (PDR). These three metrics will indicate how well the method can estimate the distance between a transmitter and receiver in forests using RTT readings, but also (mainly at longer distances) say something about the range in which it can reliably perform these distance estimations. The accuracy and precision of ranging measurements are directly connected to how well the multilateration method for localization will perform and is, therefore, a crucial aspect of any radio localization system. The PDR is the ratio between the number of packets sent by the transmitter and the number of packets received by the receiver. The MCPB method requires at least four different RTT readings from the same position (it aggregates and uses the average of the four readings) to perform a single distance estimation, and a low PDR can therefore make it impossible to perform distance estimations. A lack of distance estimations will make the multilateration localization method inaccurate, lowering the system's overall performance.

4.2.3 Method

Setup

During this test, the nRF52833 DevKit from Nordic Semiconductor was used as both the transmitter (sheep) and receiver (UAV). This was chosen over the Minew MS88SF23 Module as it enables the use of the RTT Viewer software. This software is used for logging the RTT readings done by the receiver, allowing the extraction of the distance estimation data for further analysis. The Minew MS88SF23 could have been used as the transmitter for this test, but at the time of writing this thesis, the only available Minew module was attached to the physical UAV. Vucic and Axell [6] also used the nRF52833 DevKit in their range tests, and it is preferred to use a similar setup in this test, as the results are to be compared. The nRF52833 DevKit is used as the sheep in the other tests, as there is currently a lack of available Minew modules. It is therefore preferred to use the same physical transmitter for our range tests, as similar setups will ensure consistency in our results.

In order to also get an indication of how much the foliage affects ranging precision, accuracy, and PDR, every test was performed in both a LoS environment and a forest environment. Although the primary goal of this test is to investigate the performance of the MCPB method in foliage, it is also believed that LoS testing can act as a reference for the tests performed by Vucic and Axell [6]. A significant difference in LoS results compared to previously performed tests could indicate if the results from our foliage tests are reliable and valid.

All range tests were performed around Campus Gløshaugen, in the area presented in **Figure 4.5**. The LoS tests were performed in the area marked in red, and the forest tests were performed in the area marked in yellow. The nRF52833 DevKits were attached to a pole at a height of around 65 cm above the ground. This is the average withers height of sheep and was chosen as it most closely resembles a real use case for the system [52]. Each LoS and foliage test was performed at distances of 5, 25, 50, 75, and 100 meters. A forest is naturally a random medium, and the variation in distance between the tests could lead to an increase or decrease in foliage density. An effort was, however, made to perform all the foliage tests with a similar foliage density to ensure that a change in distance was the only variable factor.

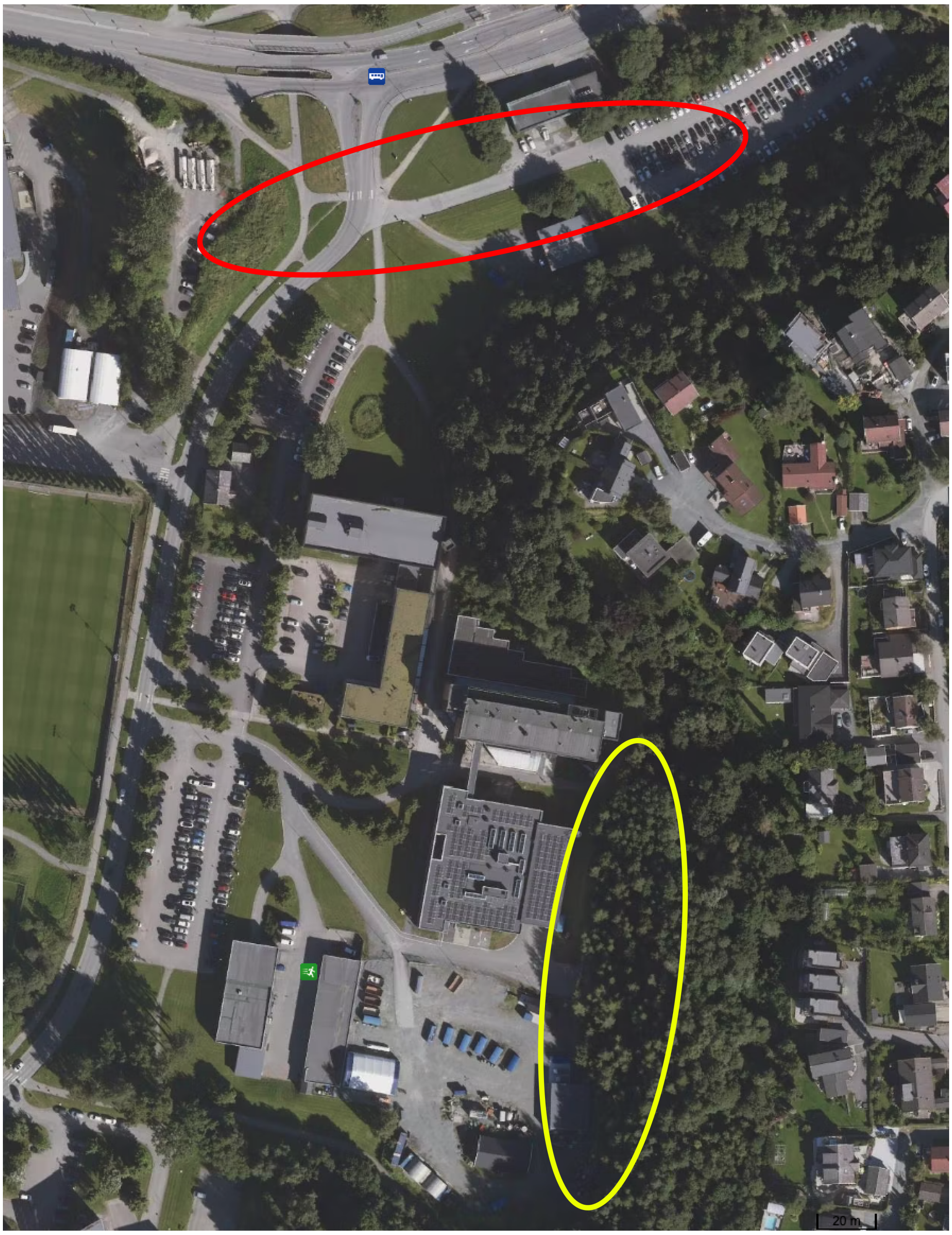


Figure 4.5: Area where range tests were performed.

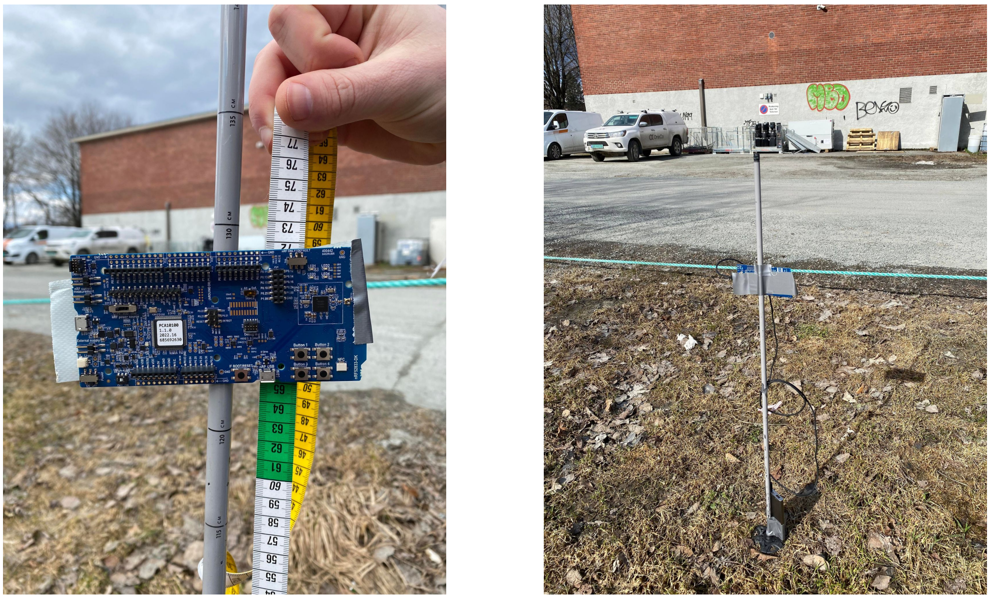
Execution

The test was performed through the following steps:

1. Mount both nRF52833 DevKits on a pole 65 cm above the ground.
2. Turn on and move the receiver away from the transmitter and measure to confirm that the distance is correct.
3. Turn on the transmitter and confirm in RTT Viewer that the receiver starts getting RTT readings.
4. Start logging and set a timer to 1 minute.
5. Stop logging after the timer is finished and download the log file.
6. Start again from step 2 using the next ranging distance until finished.

The nRF DevKits were attached to a pole as shown in **Figure 4.6a**. The receiver was powered through a USB cable from the computer that was also used for logging measurements in RTT Viewer. There were some problems where the DevKits would power off when using a button cell battery, and it was decided to use a power bank as the power source for the DevKit acting as the transmitter. This is shown in **Figure 4.6b**. The receiver used for the forest tests was placed as shown in **Figure 4.6c**. This test was performed in the spring, and the trees in the testing area were, therefore, without leaves. The correct distance for each test was confirmed using the GPS distance estimation functionality in Apple Maps. After successfully performing each test, the logged data was downloaded for later analysis.

A Python script was created, enabling efficient analysis of the log files. The script reads the raw RTT measurements and packet information from the log files and returns the average distance estimation, standard deviation, variance, and PDR.



(a) DevKit attached 65 cm above the ground.

(b) Transmitter using external power bank as power-source.

(c) Receiver set up in the forest.

Figure 4.6

4.2.4 Results

Table 4.1 shows the distance estimations from the Line of Sight tests. As the table shows, the MCPB method overestimated the distance for all of the distances used. The standard deviation also steadily increases with distance, indicating a decrease in precision as the distance increases.

	5m	**25m**	**50m**	**75m**	**100m**
Average Distance	12	31	57	82	104
Standard Deviation	8	8	10	18	23
Variance	69	66	103	308	512

Table 4.1: Performance of the RTT ranging method in a Line of Sight Environment

Figure 4.7 shows a graph of the estimated distances and the standard deviation range for each distance, with the standard deviation increasing at longer distances.

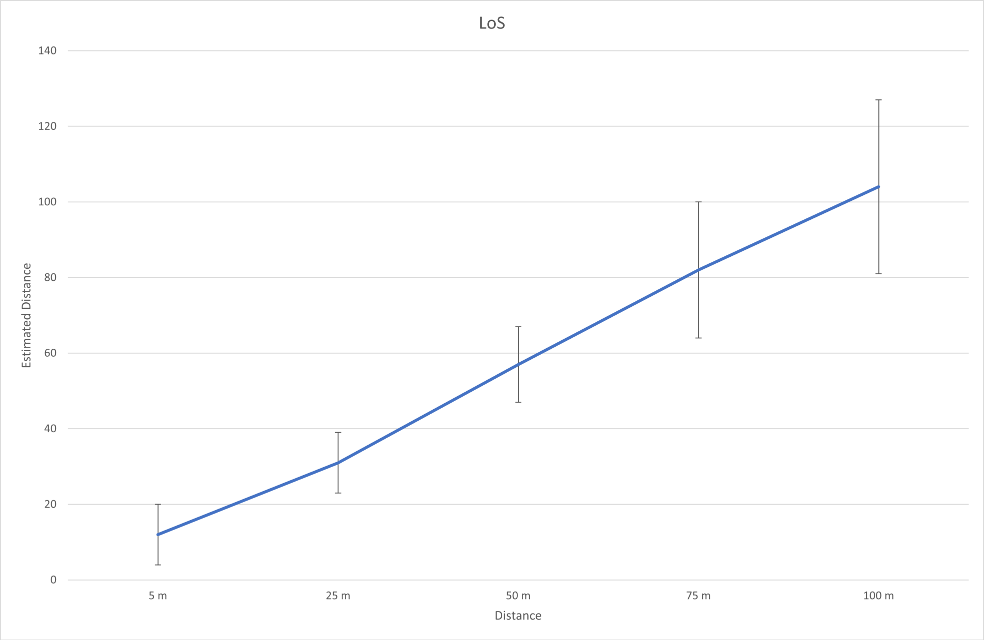


Figure 4.7: Estimated distance in LoS environment together with standard deviation.

Table 4.2 shows the distance estimations from the foliage tests. The MCPB method also seems to overestimate distances in forests, except when the distance reaches 100 meters, where it underestimated the distance. It was noticed during the tests that due to packet loss at 100 meters in foliage, each unsuccessful measurement was logged as having a distance of 0 meters. This explains the low average distance. Removing all unsuccessful measurements when calculating the average results in the MCPB method measuring an average distance of 99 meters at 100 meters in foliage, surprisingly outperforming the same test in a Line of Sight environment. The standard deviation in foliage is significantly higher in foliage, especially at distances of 50, 75, and 100 meters.

	5m	**25m**	**50m**	**75m**	**100m**
Average Distance	15	28	57	91	78
Standard Deviation	9	10	22	28	42
Variance	79	95	502	769	1796

Table 4.2: Performance of the RTT ranging method in a forest environment.

Figure 4.8 shows a graph of the estimated distances and the standard deviation range for each distance. The graph clearly shows how the standard deviation increases at longer distances.

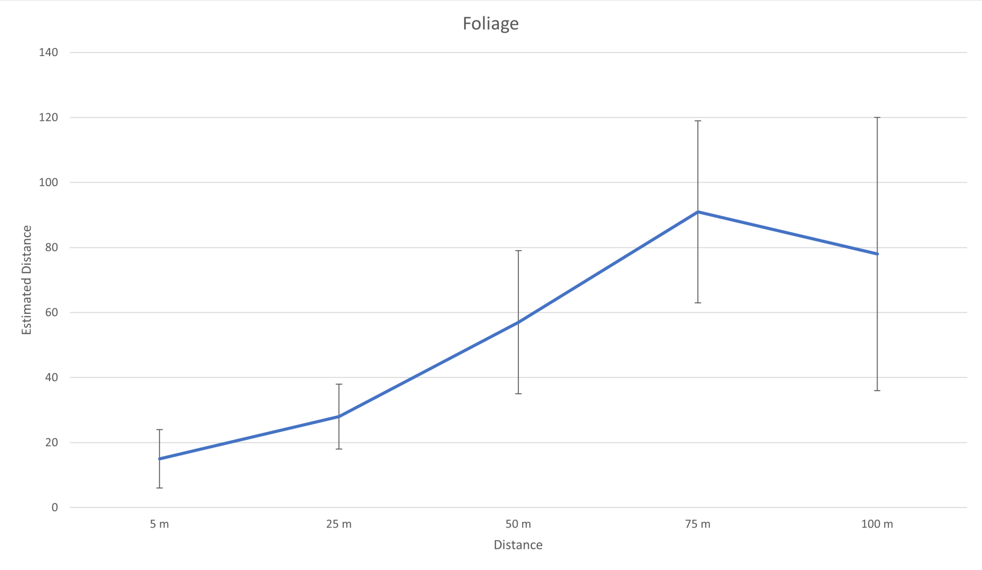


Figure 4.8: Estimated distance in forest environment together with standard deviation.

The graph in **Figure 4.9** shows the average absolute error for LoS and foliage for all test distances. The accuracy and precision of the MCPB method are greater in a Line of Sight environment, especially at greater distances. The absolute error in foliage shows a growing trend as distances increase, whereas the absolute error in LoS is relatively stable across all distances.

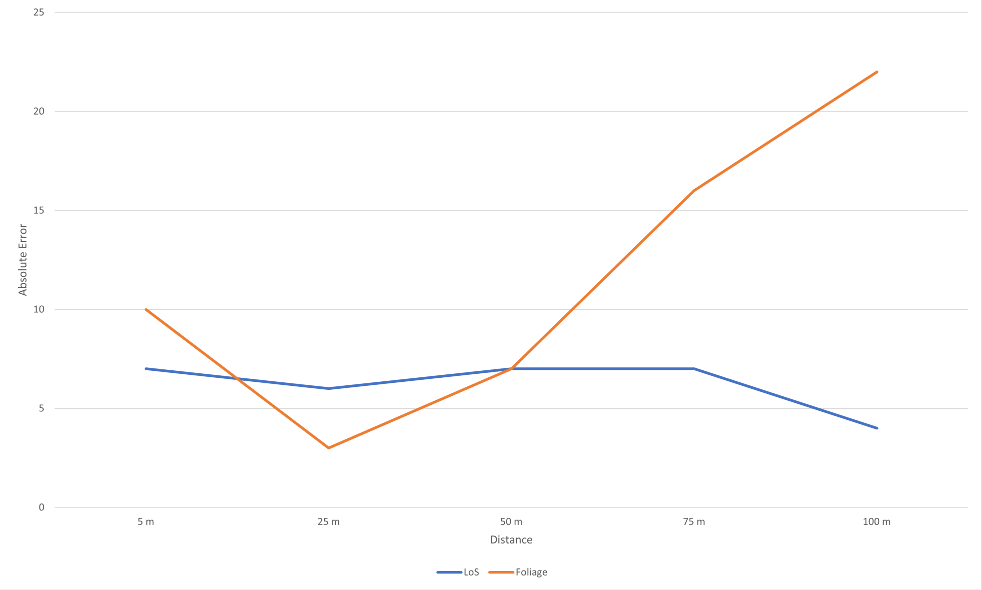


Figure 4.9: Absolute error for LoS and foliage.

Table 4.3 shows the PDR from the Line of Sight test. All transmitted packets were received at 5, 25, and 50 meters. However, some very minor losses were experienced at 75 and 100 meters.

	5m	**25m**	**50m**	**75m**	**100m**
Amount of Readings	252	248	212	232	232
Packet Delivery Ratio	1	1	1	≈ 0.97	≈ 0.99

Table 4.3: Packet Delivery Ratio of the RTT method in a Line of Sight environment.

Table 4.4 shows the PDR from the foliage test. The PDR in foliage seems to suffer heavily as the distance approaches 100 meters. A PDR of ≈ 0.67 means that one-third of all measurements are unsuccessful. This results in a large amount of measurement being logged as 0 meters.

	5m	**25m**	**50m**	**75m**	**100m**
Amount of Readings	264	276	468	468	380
Packet Delivery Ratio	1	1	≈ 0.98	≈ 0.93	≈ 0.67

Table 4.4: Packet Delivery Ratio of the RTT method in a forest environment.

The graph in **Figure 4.10** illustrates how to PDR changes at different distances. The PDR for LoS is stable for all distances and shows no clear sign of significant losses for distances up to 100 meters. The foliage PDR does, however, experience an evident decline after 50 meters. No PDR tests have been conducted at distances greater than 100 meters, but the graph shows a negative trend. The degree of this negative trend cannot be concluded, but it is believed that any more increase in the distance could significantly decrease the PDR in foliage.

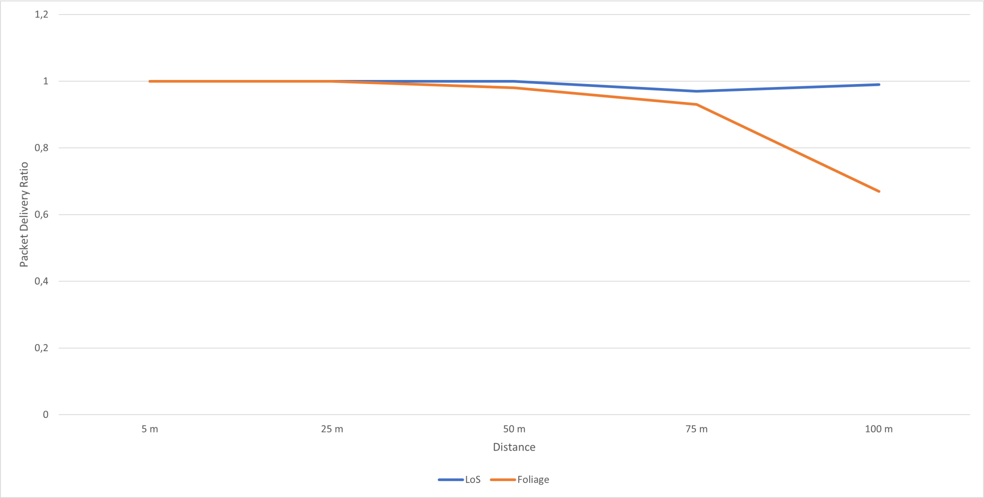


Figure 4.10: Packet Delivery Ratio at different distances for LoS and foliage.

4.2.5 Error Sources

Several potential error sources have been identified during the execution of these tests, and their existence could impact the reliability and validity of our results.

All ranging tests were performed in a forest-to-forest configuration. The main goal of the thesis is to evaluate the system as a whole, and it is preferred to test the ranging aspect of its performance in the configuration it is meant to be used. Performing these ranging tests in a forest-to-air configuration was not doable with the available hardware. The nRF52833 DevKit is the only module that allows measurement data logging. Performing these tests in a forest-to-air configuration would demand the use of the UAV, but this is not doable as the UAV is only compatible with the Minew module. The use of the forest-to-forest configuration results in the radio waves propagating mainly through the trunk layer of the forest, as described in **Section 2.6.1**. The forest-to-air configuration mainly consists of propagation through the canopy layer of the forests, and the difference in propagation mediums could impact how the system performs. The use of the forest-to-forest configuration is similar to the configurations of the previously performed ranging tests, making it easier to directly compare our result to that of Vucic and Axell [6] and Mathew *et al.* [44].

Another potential source of error is using the nRF52833 DevKit as both the transmitter and receiver during the tests. The Minew module is used during the large-scale test, and it would be ideal to conduct all tests using the same hardware to ensure consistency in the results. As previously mentioned, there was no opportunity to perform these tests using the Minew module as the receiver, as there was a need to be able to log distance measurements. The difference in performance between the Minew module and the nRF52833 DevKit has yet to be concluded. However, as with the configuration, using the nRF52833 DevKit ensures a similar setup to the ranging tests performed in Vucic and Axell [6], making it easier to compare the results with previously obtained results.

The use of GPS for determining the true position of the transmitters will inherently be a source of error, as GPS measurements may be inaccurate. GPS was not used to determine any true positions during these tests directly but was used to confirm that the distance between the transmitter and receiver was correct. It can, therefore, not be guaranteed that each test was performed using exactly the correct distance. However, the potential error in the distance is low relative to the 25 meters increase in distance between tests. Therefore, the results will clearly indicate the effect of an increase in transmission distance regardless.

Although an effort was made to ensure each distance test was performed with a similar foliage density, this proved challenging in practice. The natural randomness of a forest environment will affect the ranging results regardless of our efforts. Therefore, it must be accepted as a part of any test performed in a forest environment.

As previously stated, all the ranging tests were performed during spring. The time limitation of this thesis made it impossible to perform tests in the late summer when sheep gathering typically takes place. This resulted in the tests being performed in a forest environment consisting of trees without leaves. It would be preferable to perform all tests in the same environment the system is meant to be operated, and the lack of leaves could impact the system's performance. The degree of impact this would have cannot be concluded, but it is believed that this would have a minimal impact on the results obtained in this test.

4.2.6 Discussion

The tests show that the MCPB method performs well in LoS and forest environments. One important observation is that the method's precision drops significantly in forest environments. The increase in measurement standard deviation for distances greater than 50 meters can induce problems during real use cases, as an insufficient amount of reading may lead to less accurate distance estimations. This can be combated by lowering the flight speed of the UAV and using flight paths with closer sweep lines, allowing the UAV to aggregate more distance estimations for each transmitter. The results show that the accuracy decreases in forests as the distance approaches 100 meters. As discussed, this is due to unsuccessful readings being logged as having a distance of 0 meters. This significantly skews the average estimated distance, but after removing these values, the MCPB method has excellent accuracy in forests, even at 100 meters. Changing the system to discard unsuccessful readings would significantly increase the system's accuracy and precision in forest environments.

The packet delivery ratio in the LoS environment is excellent, and the packet loss at more considerable distances will likely not cause usability issues. It is, however, observed that the MCPB method suffers from decreasing PDR at distances approaching 100 meters in foliage. This currently results in low accuracy in distance estimations, reducing the system's overall performance. As previously discussed, a solution to this problem is already identified. The degree to which the PDR is reduced at more significant distances is unknown. However, the system is believed to be still usable with even lower PDR values, although with lower accuracy. In theory, only one single measurement needs to be successful for multilateration to be performed. However, the low precision in foliage will negatively affect accuracy if the number of distance estimations is too low. During one minute of testing, the system performed approximately 254 successful readings at 100 meters in foliage. An average of 4 successful readings each second is sufficient for reaching an accurate average during a fly-by of the UAV. The same cannot, however, be said for greater distances if the PDR continues decreasing at the same rate.

Another observation from the PDR results is the significant increase in the number of readings performed at 50 meters and greater in foliage. Analysis of the log files has not given any insight into why this happened, but it is believed this is due to the low PDR, as there is a clear correlation between PDR and the number of readings performed. This is, however, not an issue, as a larger amount of readings is preferred when the system suffers from a lower PDR.

The different testing distances impact precision and accuracy, and although forests vary significantly in height, some assumptions can be made. As discussed in **Section 4.2.5**, this test was performed in a forest-to-forest environment. A real use case for the system would be in a forest-to-air configuration, where the radio waves would need to propagate horizontally, mainly through the canopy layer of the forest. Spruce, birch, and pine are the main types of trees in Norwegian forests, with a maximum height of 45 meters, 15 meters, and 40 meters, respectively [53][54][55]. Most of this distance consists only of the tree trunk, and the radio waves would only need to penetrate the tree crowns. A flight altitude of around the height of the forests plus 10 meters would lead to an approximate maximum foliage propagation distance of 50 meters. Precision, accuracy, or PDR were not issues in 50 meters of high-density foliage, and foliage is not believed to introduce significant performance problems in real use cases.

Our testing shows a lower accuracy and precision in a Line of Sight environment compared to the tests performed by Vucic and Axell [6]. The previous tests show a mean absolute error of approximately 0.83 meters for all distances up to 100 meters, whereas our tests report a mean absolute error of approximately 6.2 meters. It is unknown why this significant gap in accuracy exists, as the same testing setup was used. The purely BLE-based ranging method from Nordic Semiconductor has a mean absolute error of 1.89 meters across the same distances, outperforming the MCPB method in LoS environments. Compared to the results in [43] and [44], the MCPB method is superior in foliage. The tests performed in [43] show a PDR of 0.33 at 110 meters. Although tests were only performed at 100 meters, it is believed that the PDR of our system would not drop by 0.33 when increasing the distance by another 10 meters. Mathew *et al.* [44] reported that BLE had a maximum practical transmission range of 20 meters in high-density foliage. Our tests have revealed that the MCPB method can accurately estimate distances up to 100 meters.

4.2.7 Conclusion

The Minimal Custom Protocol-Based RTT ranging method performs well in LoS and forest environments. Our tests have reported a mean average error of 6.2 meters across distances up to 100 meters in Line of Sight environments and a mean average error of 7.4 meters across the same distances in a forest environment. An increase in transmission distance has a minimal effect on the Packet Delivery Ratio in LoS but is prevalent in foliage as the distance approaches 100 meters. This is, however, believed not to cause any usability issues. Previously performed tests indicate that this system can perform even better in LoS environments. Furthermore, the MCPB method outperforms the purely BLE-based methods in forest environments regarding range and PDR.

The tests were performed in a forest-to-forest configuration, and it is believed that the MCPB method will perform even better in a forest-to-air configuration that more closely resembles the real use case of the system.

4.3 Large Scale Tests

The tests performed in this section are the primary evaluation of the system's ability to locate sheep in areas of high-density foliage. These tests are meant to imitate the actual use case of a sheep localization system and will indicate how well the current system performs. These tests will give results in terms of the performance metrics and can be used to identify any usability issues tied to the system's operation. A sheep localization system is ultimately meant to be used independently by farmers. Although the system is still under development, apparent usability issues will also be valuable for evaluating the system's ability to consistently and accurately locate sheep in foliage.

Vucic and Axell [6] performed several actual use case tests of the system in 2022. These tests were performed at different scales and environments, including tests at a sheep farm using real sheep equipped with a Minew module integrated into their ear tag. A system test was also performed in a forest environment, but no localization performance was evaluated. These tests focused on the maximum range the UAV could receive signals from the sheep.

The tests performed in a farm environment report an average localization error of 15 meters across all sheep and flights. The localization error was calculated by finding the true position of the sheep using GPS and comparing it to the estimated mean position calculated by the system, as shown in **Figure 3.7**. However, their results do not mention the uncertainty area of the system's calculated sheep positions.

4.3.1 Goal

These tests aim to investigate and conclude how well the MCPB method and the implemented multilateration method can perform sheep localization in areas of high-density foliage. In addition, these tests will uncover any major usability issues in the system, resulting in suggestions for how the system can be modified for increased usability. The insight provided by these tests will help in discussing and concluding RQ2 and RQ3.

4.3.2 Performance Metrics

The system's performance will be evaluated using the average localization error and uncertainty area. These metrics will indicate how well the system can accurately locate sheep in forests. The maximum range the system can locate sheep will indirectly also be a performance metric. The maximum range will not be tested directly, but potential failures in locating sheep at a given distance will implicitly indicate the maximum operable distance. PDR would also be a valuable performance metric, but as explained in **Section 4.2**, using the Minew module on the UAV hinders the logging of packet information.

4.3.3 Method

Setup

As described in **Section 3.4**, the system has already been implemented with two localization techniques: multilateration and the Particle Filter method. Compared to multilateration, the localization accuracy of the particle filter approach is lower. Steinsvik [4] concluded that multilateration had a smaller error and uncertainty radius than the particle filter approach after extensive testing. As a result of this, multilateration will solely be used rather than a combination of the two localization methods.

A technique for locating the sheep's actual location must be used to evaluate the system's accuracy. It can be challenging to pinpoint an exact location, but GPS is utilized to pinpoint the precise location of the transmitters acting as sheep during tests. Although GPS technology is precise and dependable, it may be less accurate and dependable in places with dense foliage. Therefore, the testing should be carried out in the best conditions possible, preferably with clear skies with little cloud cover, as this element may also impact the GPS's accuracy and precision. In addition to the GPS, landmarks and other visuals are utilized to confirm a precise position considering the usage of GPS might be a significant source of error.

Vucic and Axell [6] had to wait until the end of May 2022 to test the prototype ear tags on living sheep, and the system with a realistic use case. The sheep are typically released late in the spring, and as a result, no tests will be performed on living sheep. A Minew module mounted on the UAV is the receiver during all tests. The time constraints of this thesis made it challenging to perform these tests using real sheep, and nRF52833 DevKits will be used as sheep replacements. As with the range tests, the DevKits will be mounted on a pole at a height of 65 cm, which matches the average withers height of sheep. Vucic and Axell [6] performed tests of the system using both nRF DevKits and Minew modules acting as sheep, but as previously stated, the lack of available Minew modules made it impossible to perform tests using both types of transceivers.

Sheep are typically gathered during September or October, and it would be preferred for the tests to take place during these months to simulate a realistic scenario. Due to time limitations, this is not possible. Radio signals can be impacted by snow on the ground in various ways, including attenuation, reflection, absorption, and diffraction. Both the weather and the state of the ground might introduce errors in the testing. As a result, the tests are carried out after the snow has melted in the testing areas.

Three sheep were used during each test, which is believed to generate enough data to make a qualified conclusion about the system's performance. A total of six flights were planned, with three being done in a Line of Sight environment and three being done in a forest environment. However, the low quality of the collected data during these flights made it necessary to perform more flights. As with the range tests, it was decided to perform tests in LoS environments to reference how much the foliage affects performance. Most of the tests performed by Vucic and

Axell [6] were also performed in LoS environments, and the results from these tests can also be used to ensure consistency in results for the same environments.

All tests were performed around Dragvoll Idrettssenter, as shown in **Figure 4.11**. The LoS tests were performed in the area marked in red, and the foliage tests were performed in the area marked in yellow. The setup used for the nRF DevKits acting as sheep are shown in **Figure 4.12a** and **Figure 4.12b**.

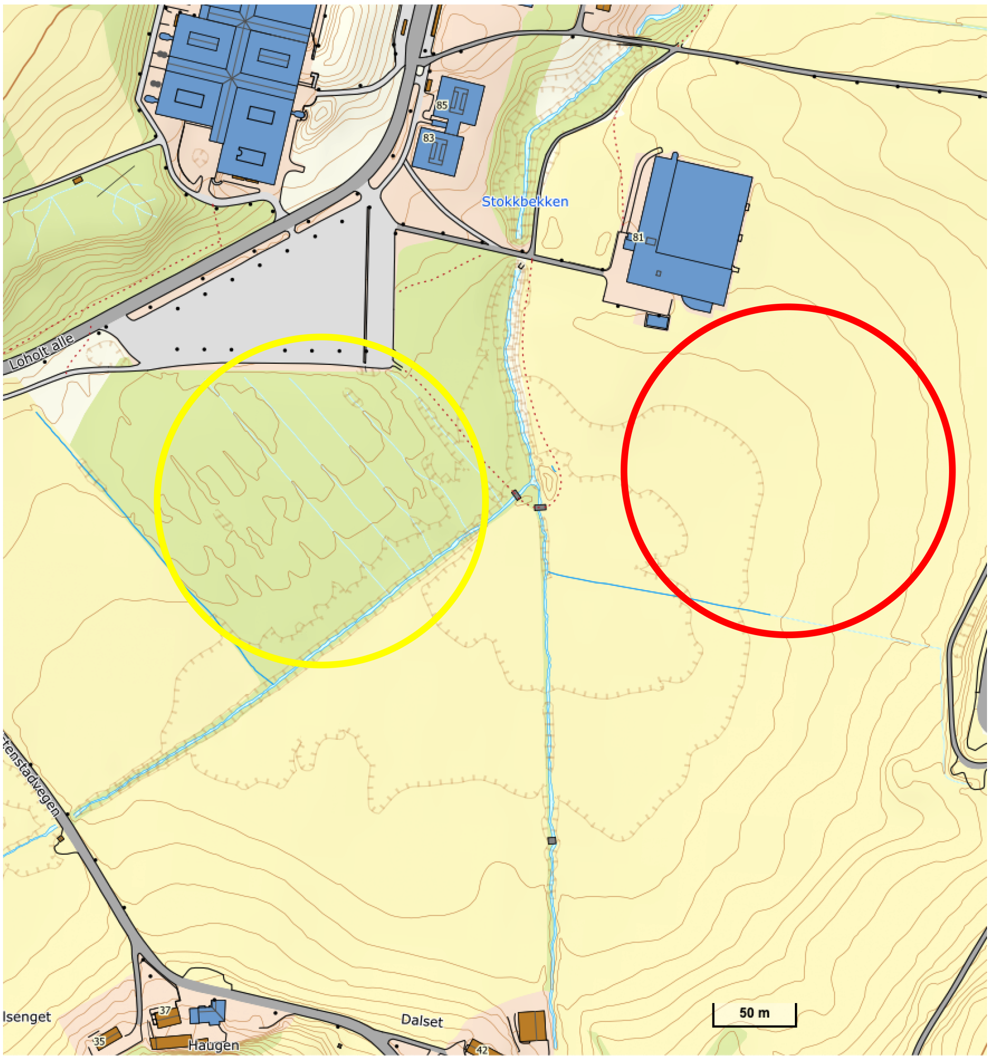


Figure 4.11: The area where the tests were performed.

(a) Sheep setup for LoS tests.

(b) Sheep setup for foliage tests

Figure 4.12

Execution

The tests were performed through the following steps:

1. Mount all four nRF52833 DevKits on a pole 65 cm above the ground.
2. Turn on and place all DevKits in different locations in the search area.
3. Create a flight mission and upload it to the UAV
4. Manually perform the UAV's lift-off and put it into "auto" mode after successful lift-off.
5. Download RTT data after the UAV has landed.
6. Input RTT data into Sheep GCS and perform multilateration.

As previously discussed, errors during RTT measurements will lead to the UAV logging a distance of 0 meters. Therefore, all RTT measurements with a distance of 0 meters were removed before analyzing the results.

4.3.4 Results

Flight 1: LoS

The flight was performed without any problems. All three sheep transmitted RTT data, and the UAV followed the flight path displayed in **Figure 4.13**. All RTT measurements collected during the flight are visualized in **Figure 4.14**. Every circle corresponds to one completed RTT measurement, where the center of a circle is the position of the UAV at the time of the reading, and the circle's radius is equal to the measured distance from the UAV to the sheep.

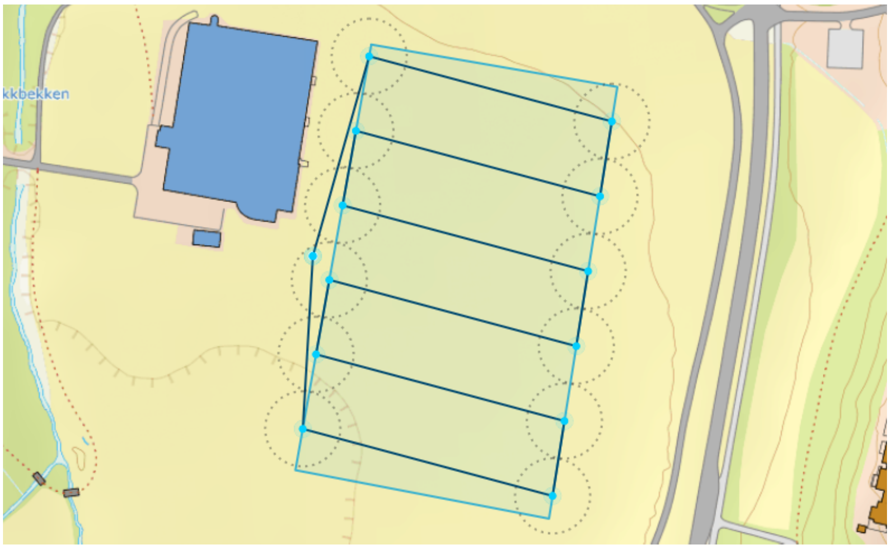


Figure 4.13: Flight path from flight 1.

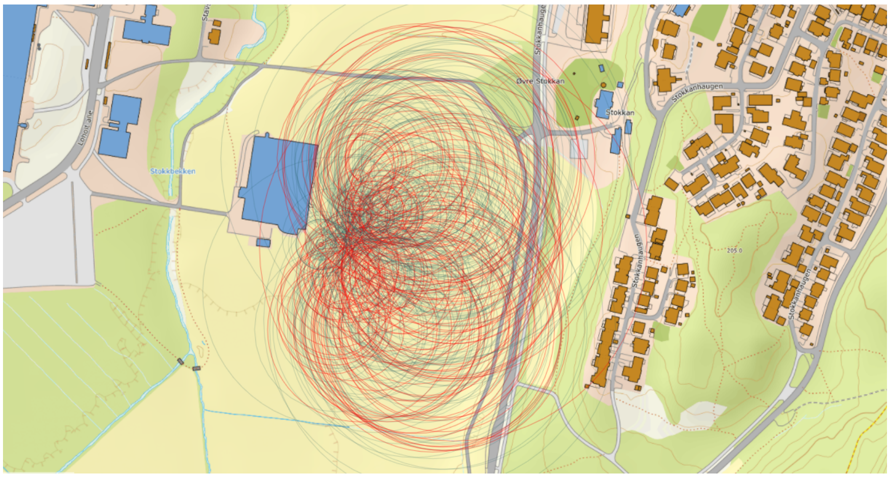


Figure 4.14: All RTT measurements from flight 1.

Table 4.5 show the results from flight 1. Each sheep's localization error and uncertainty area are visualized in **Figure 4.15**. The points marked in red represent the systems estimation position of the sheep, and the green points represent the true positions of the sheep. Each red point is the mean point of its corresponding uncertainty area.

	Localization Error	**Uncertainty Area**	**Number of RTT Readings**
Sheep 1	19.4 m	319.0 m^2	135
Sheep 2	54.6 m	442.5 m^2	157
Sheep 3	43.2 m	2 266.1 m^2	143
Average	36.1 m	1 009.3 m^2	145

Table 4.5: Results from flight 1

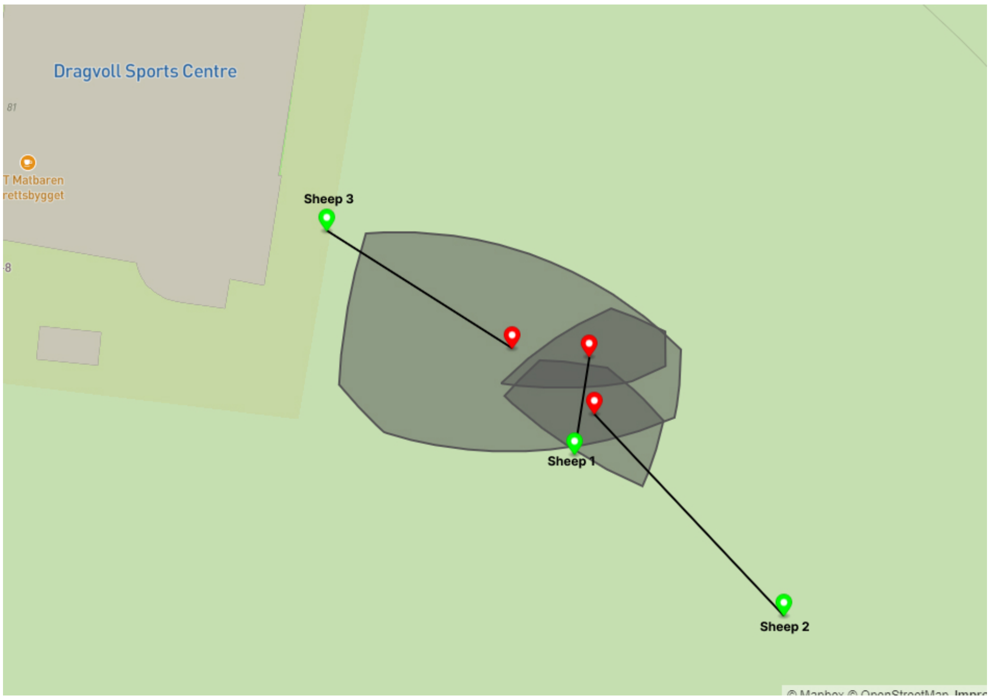


Figure 4.15: Results from flight 1. Generated using GeoJson.io [56].

Flight 2: LoS

Flight 2 was performed using the same flight path shown in **Figure 4.13**. Several problems were encountered during this flight. The UAV was set to automated flight mode and started its path, but it shortly after started to display a *BATTERY FAILSAFE* warning. Vucic and Axell [6] encountered the same problem, and they concluded that a sudden drop in battery voltage caused this. The drop in voltage causes the Minew Module on the UAV to stop performing RTT measurements. In addition to this, the nRF52833 DevKit representing Sheep 3 lost power and did not transmit any data during the flight. These problems resulted in minimal RTT measurements collected during the flight. The collected RTT measurements are shown in **Figure 4.16**.

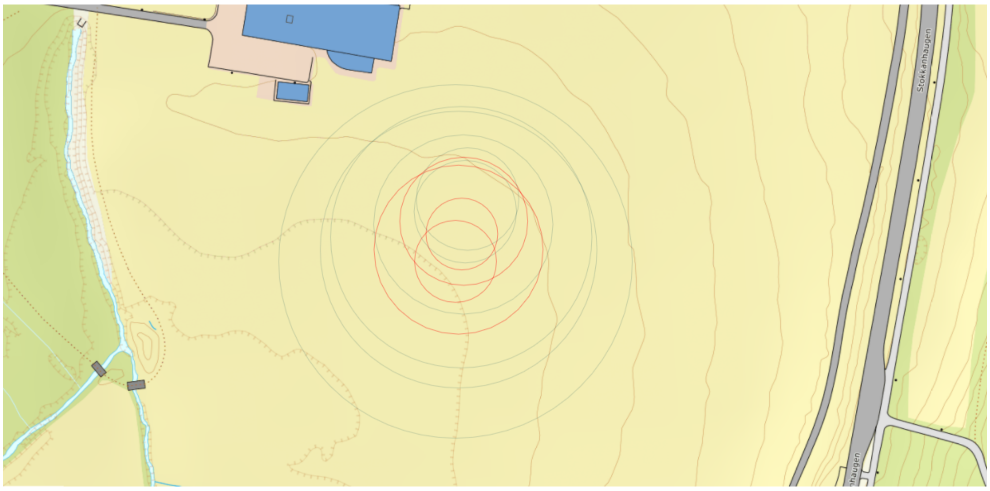


Figure 4.16: All RTT measurements from flight 2.

Table 4.6 show the results from flight 2. Each sheep's localization error and uncertainty areas are visualized in **Figure 4.17**.

	Localization Error	**Uncertainty Area**	**Number of RTT Readings**
Sheep 1	40.5 m	7 991.5 m^2	6
Sheep 2	76.0 m	5 910.7 m^2	4
Sheep 3	N/A	N/A	N/A
Average	58.3 m	6 951.1 m^2	5

Table 4.6: Results from flight 2

Figure 4.17: Results from flight 2. Generated using GeoJson.io [56].

Flight 3: LoS

Flight 3 was performed using the flight path shown in **Figure 4.18**. Several problems were also encountered during this flight. As with the previous flight, Sheep 3 did not transmit any data, and no RTT measurements were collected for Sheep 3. The RTT measurements in **Figure 4.19** show that all measurements were performed at the starting point of the flight path, resulting in insubstantial intersection areas. The reason for this has not been concluded.

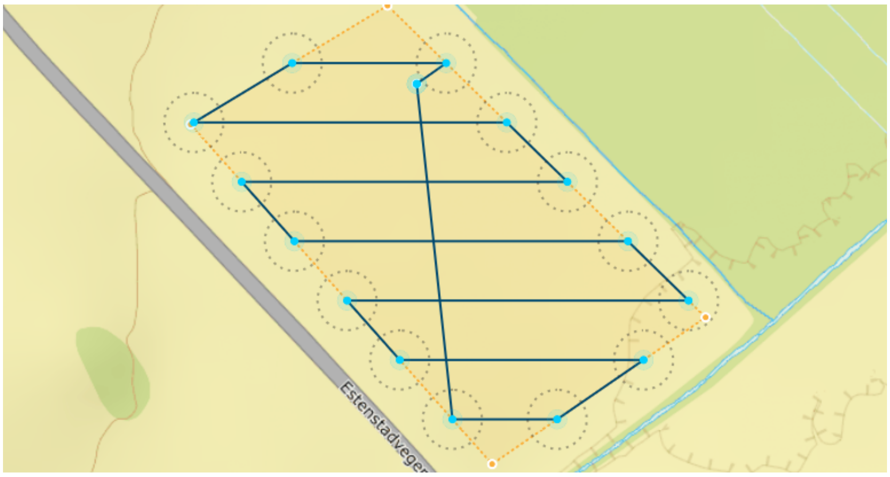


Figure 4.18: Flight path from flight 3.

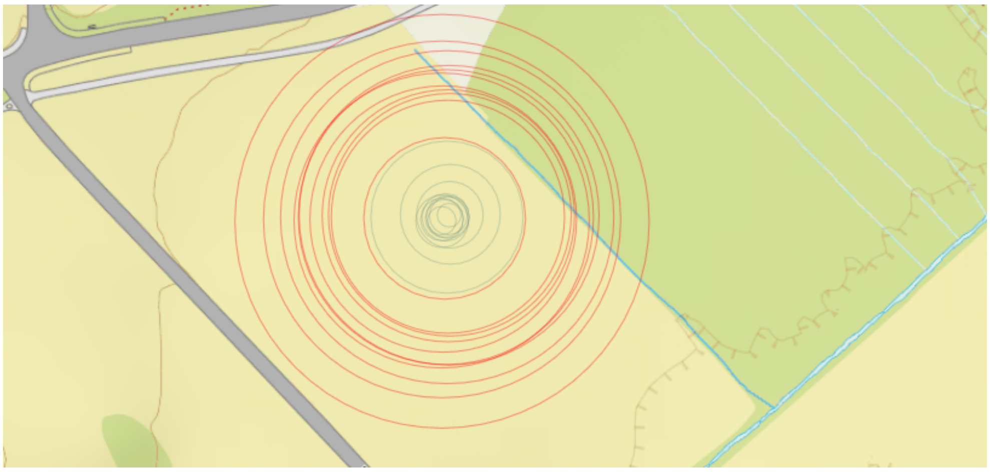


Figure 4.19: All RTT measurements from flight 3.

Table 4.7 show the results from flight 3. The localization error and uncertainty areas of Sheep 1 and 2 are visualized in **Figure 4.20**.

	Localization Error	Uncertainty Area	Number of RTT Readings
Sheep 1	80.7 m	14 655.5 m^2	11
Sheep 2	53.7 m	3 856.5 m^2	11
Sheep 3	N/A	N/A	N/A
Average	67.2 m	9 256.0 m^2	11

Table 4.7: Results from Flight 3

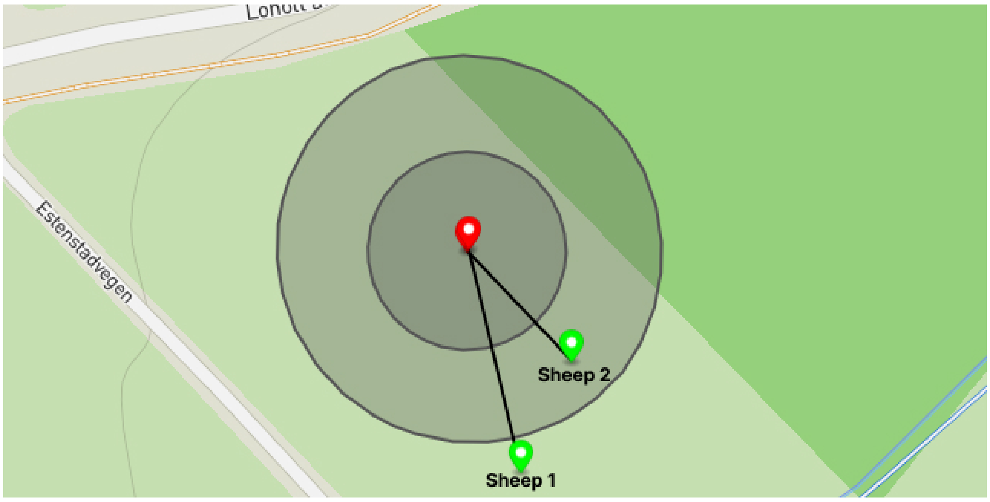


Figure 4.20: Results from flight 3. Generated using GeoJson.io [56].

Flight 4: Foliage

Flight 4 was conducted in dense foliage using the flight path shown in **Figure 4.21**. The UAV was flown up manually and then set in automated flight mode. During the flight, when the UAV flew to the outermost part of the flight path, the UAV and the UAV controller lost connection, which resulted in the UAV automatically returning to the landing. All three sheep transmitted RTT data during the flight, and the measurements collected during the flight can be seen in **Figure 4.22**. As a result of the shortening of the flight time due to the UAV not completing the flight path, the amount of RTT readings is limited.

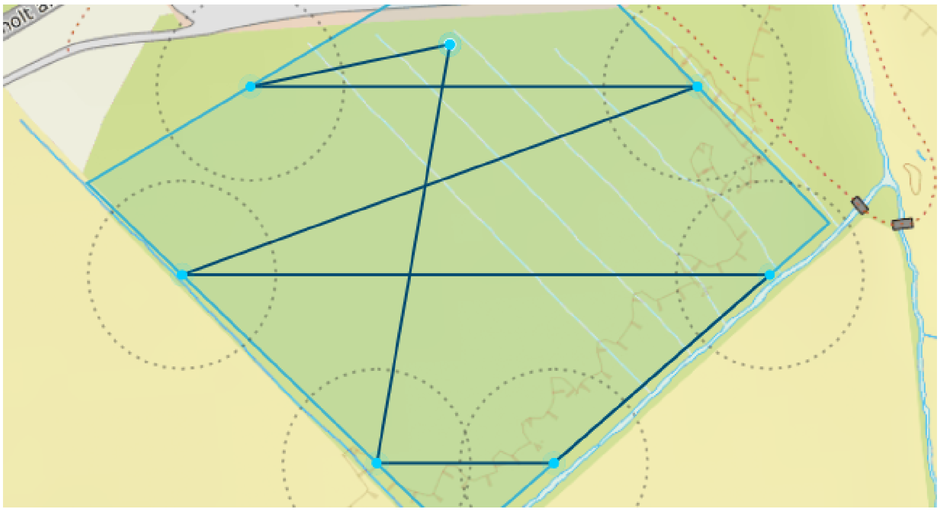


Figure 4.21: Flight path for flight 4.

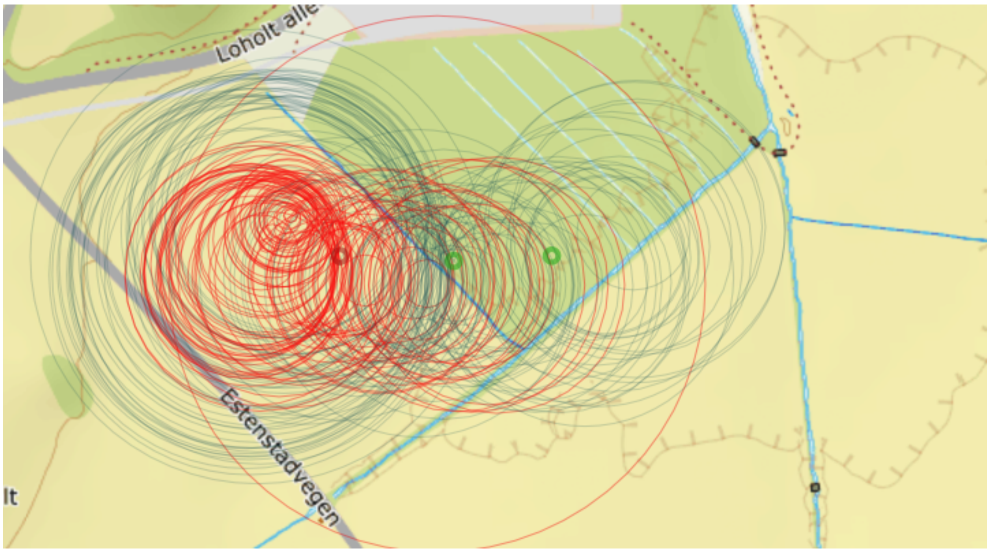


Figure 4.22: All RTT measurements from flight 4.

Table 4.8 shows the results from flight 4. The sheep's localization error and uncertainty areas are visualized in **Figure 4.23**.

	Localization Error	**Uncertainty Area**	**Number of RTT Readings**
Sheep 1	52.2 m	3 446.0 m^2	102
Sheep 2	42.2 m	3 662.0 m^2	24
Sheep 3	49.9 m	2 016.0 m^2	94
Average	48.1 m	3 041.3 m^2	73

Table 4.8: Results from Flight 4

Figure 4.23: Results from flight 4. Generated using GeoJson.io [56].

Flight 5: Foliage

It was decided to decrease the search area during flight 5 to combat the loss of connection between the UAV and the UAV controller experienced in flight 4. The UAV followed the flight path shown in **Figure 4.24** without problems. A *BATTERY FAILSAFE* error was reported after a short time, resulting in the Minew Module stopping to perform RTT measurements right after lift-off. This resulted in the small number of readings shown in **Figure 4.25**.

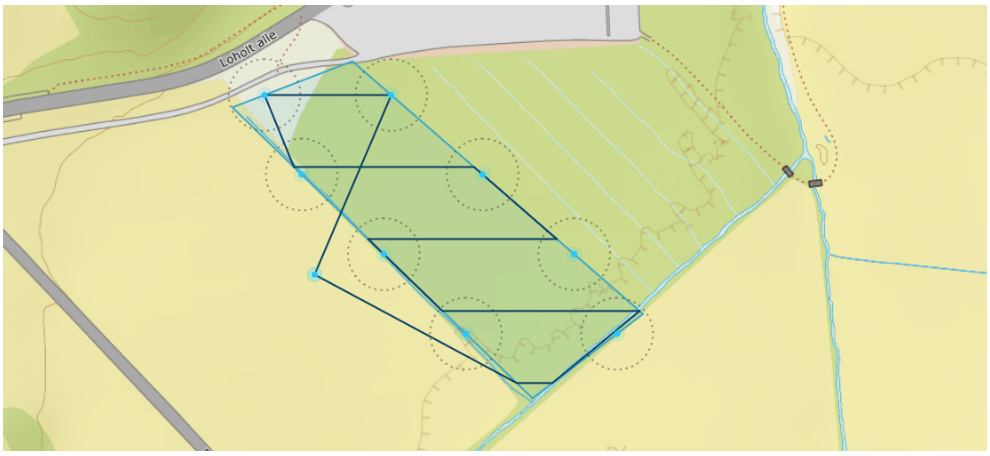


Figure 4.24: Flight path for flight 5.

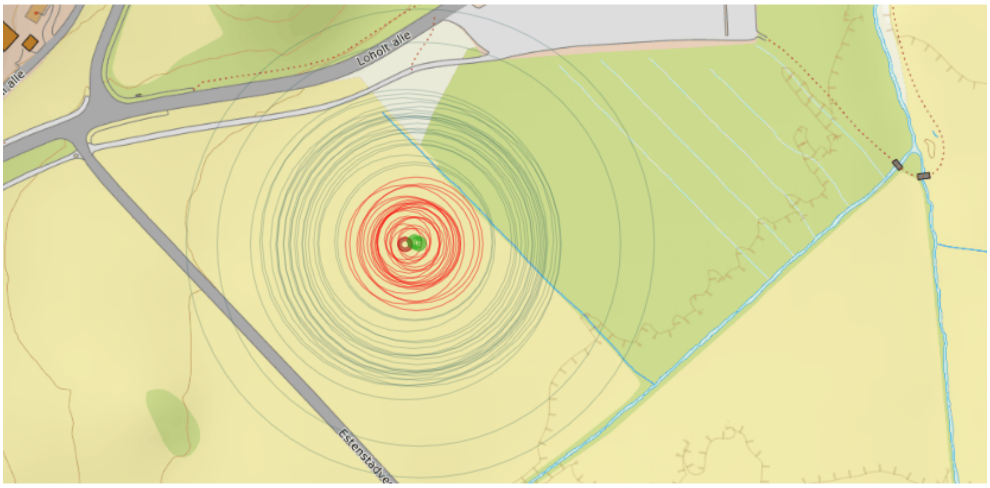


Figure 4.25: All RTT measurements from flight 5.

Table 4.9 show the results from flight 5. The sheep's localization error and uncertainty areas are visualized in **Figure 4.26**.

	Localization Error	**Uncertainty Area**	**Number of RTT Readings**
Sheep 1	51.5 m	5 821.0 m^2	25
Sheep 2	93.4 m	14 558.0 m^2	23
Sheep 3	138.4 m	39 493.0 m^2	2
Average	94.4 m	19 957.3 m^2	16.6

Table 4.9: Results from Flight 5

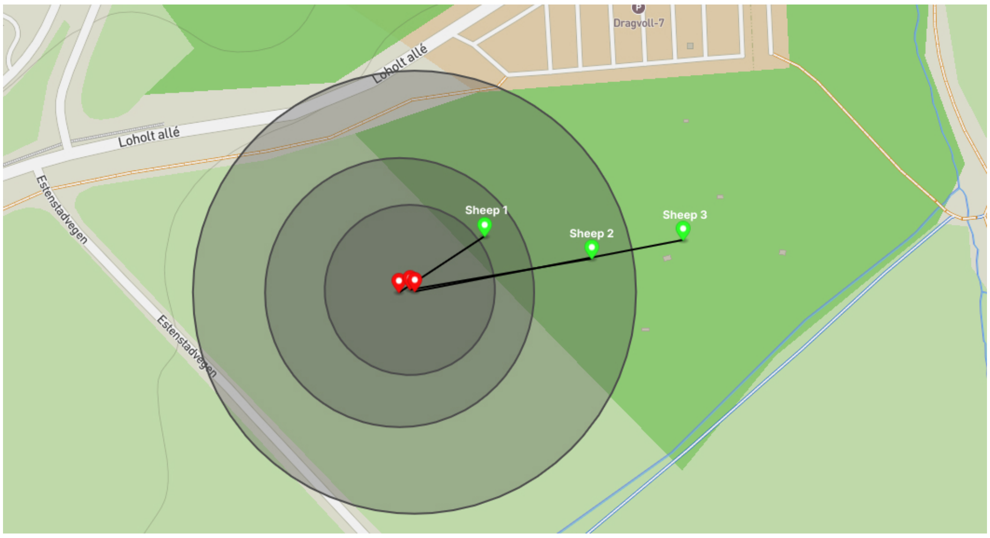


Figure 4.26: Results from flight 5. Generated using GeoJson.io [56].

Flight 6: Foliage

Flight 6 was performed using the same flight path shown in **Figure 4.24**. Several problems occurred during this test flight. When trying to set the UAV to automated flight mode, the UAV controller reported a BAD GYRO HEALTH error, resulting in the system preventing the UAV from being set to automated flight mode. After unplugging the battery several times, the UAV could finally be set to automated flight mode. A short time after, a BATTERY FAILSAFE error was reported, resulting in the Minew Module stopping to perform RTT measurements right after lift-off. Due to the error, the number of RTT measurements is quite limited, as shown in **Figure 4.27**. Sheep 3 did not transmit during this flight.

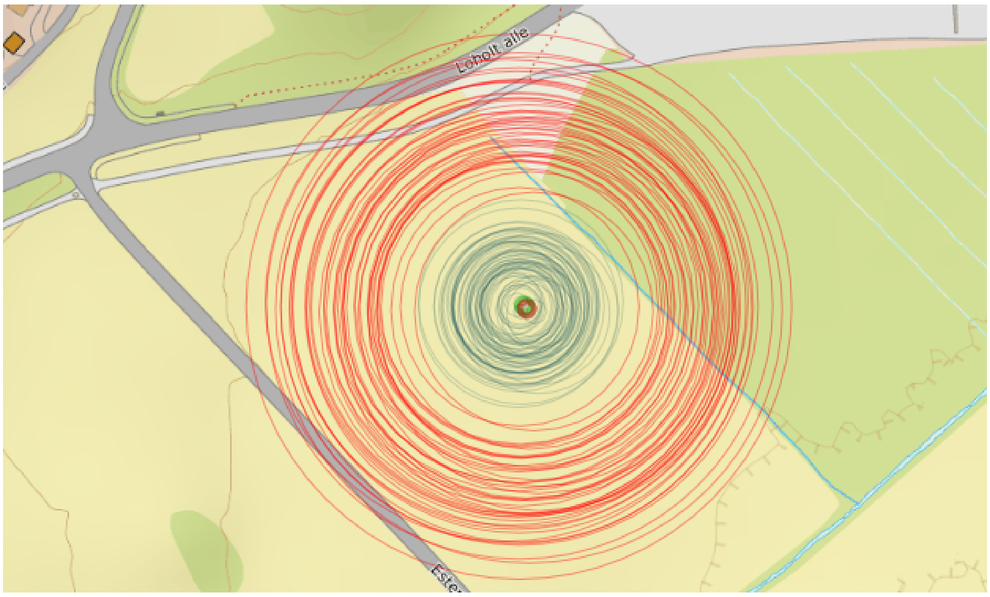


Figure 4.27: All RTT measurements from flight 6.

Table 4.10 shows the results from flight 6. The sheep's localization error and uncertainty areas are visualized in **Figure 4.28**.

	Localization Error	**Uncertainty Area**	**Number of RTT Readings**
Sheep 1	48.4 m	5 037.5 m^2	68
Sheep 2	96.2 m	6 961.7 m^2	46
Sheep 3	N/A	N/A	N/A
Average	72.3 m	5 999.6 m^2	57

Table 4.10: Results from Flight 6

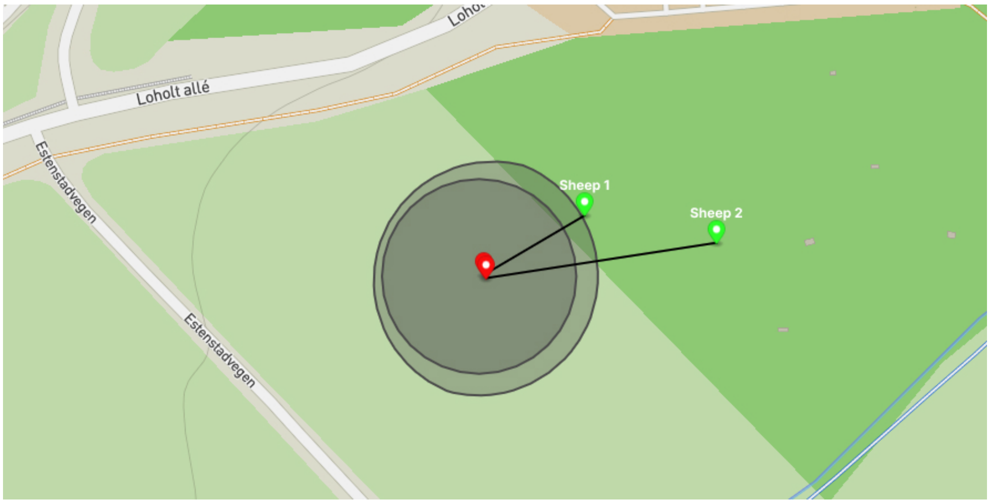


Figure 4.28: Results from flight 6. Generated using GeoJson.io [56].

Flight 7: Foliage

Flight 7 was performed using the same flight path as flight 5 shown in **Figure 4.24**. The UAV was flown up manually and set to automated flight mode. The UAV completed the flight path without any problems. Due to power issues, only two of the three sheep transmitted RTT data during the flight. All RTT data collected during the flight can be seen in **Figure 4.29**.

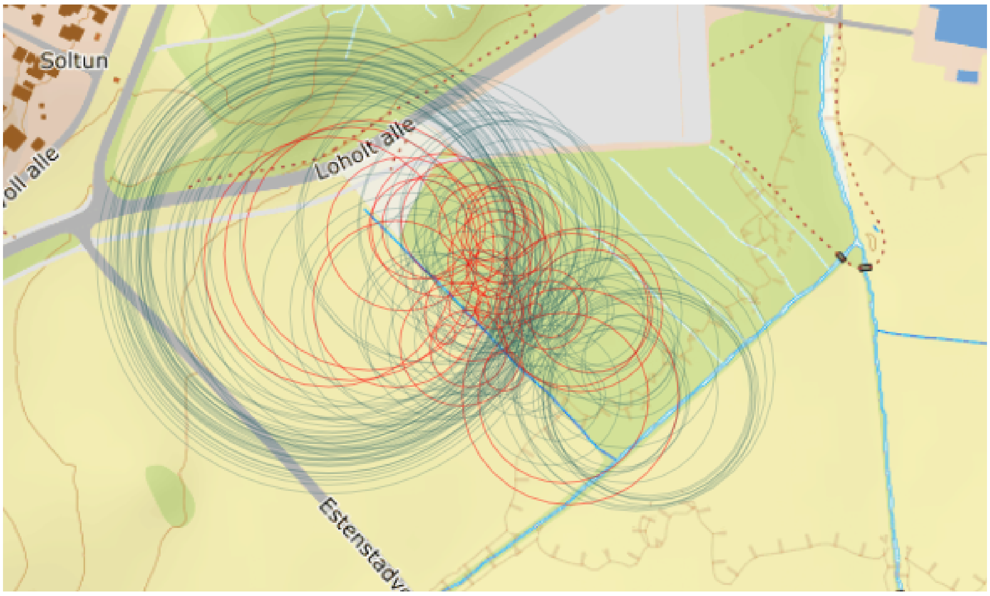


Figure 4.29: All RTT measurements from flight 7.

Table 4.11 shows the results from flight 6. The sheep's localization error and uncertainty areas are visualized in **Figure 4.30**.

	Localization Error	Uncertainty Area	Number of RTT Readings
Sheep 1	4.1 m	3 379.7 m^2	37
Sheep 2	18.7 m	4 060.9 m^2	120
Average	11.4 m	3 720.3 m^2	78.5

Table 4.11: Results from Flight 7

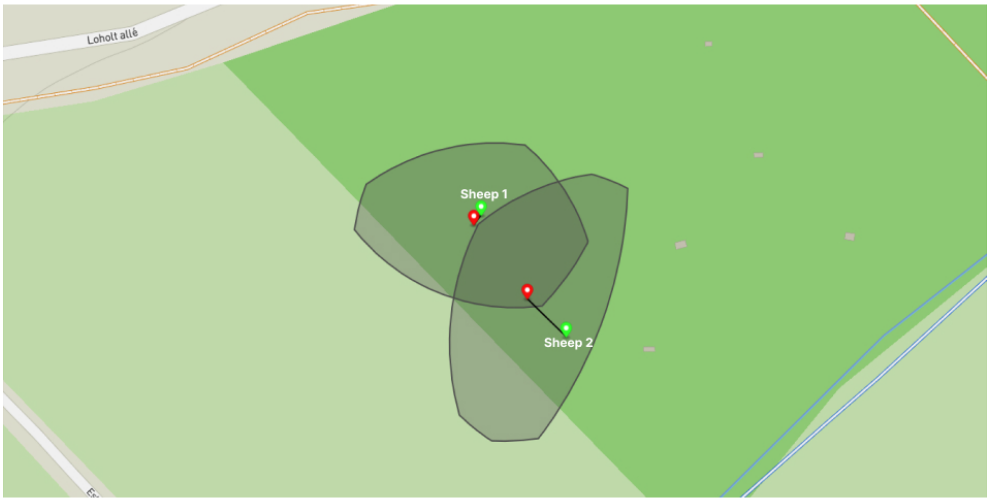


Figure 4.30: Results from flight 7. Generated using GeoJson.io [56].

Flight 8: Foliage

This flight was performed using the same path as in Flight 5, and no problems occurred. Only two sheep were transmitting RTT data during the flight, and all RTT measurements are shown in **Figure 4.31**.

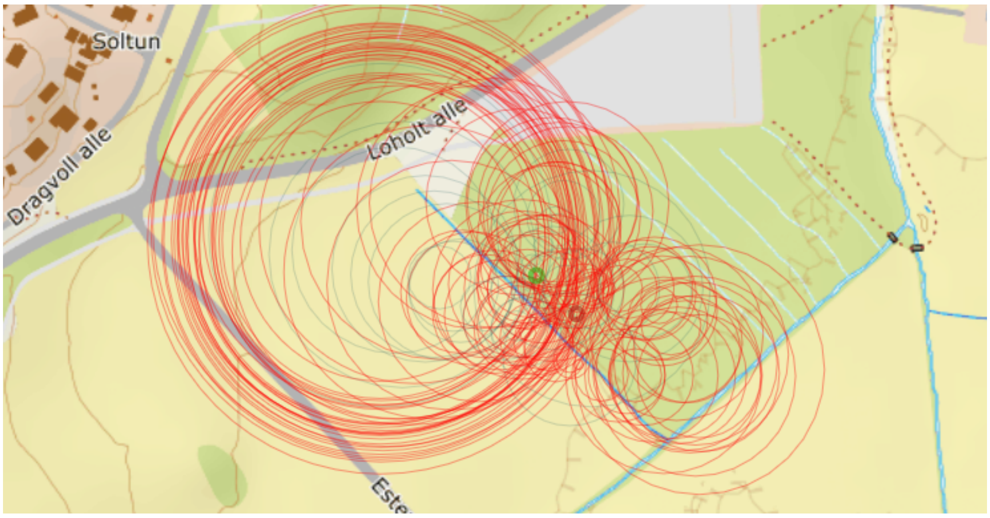


Figure 4.31: All RTT measurements from flight 8.

Table 4.12 shows the results from flight 6. The sheep's localization error and uncertainty areas are visualized in **Figure 4.32**.

	Localization Error	Uncertainty Area	Number of RTT Readings
Sheep 1	9.6 m	3 470.8 m^2	34
Sheep 2	17.9 m	29 064.6 m^2	108
Average	8.8 m	16 267.6 m^2	71

Table 4.12: Results from Flight 8

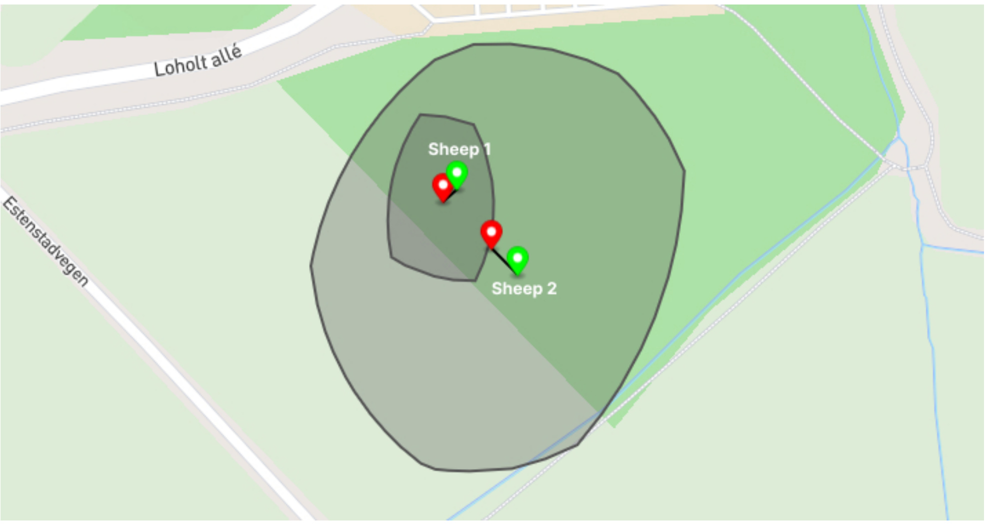


Figure 4.32: Results from flight 8. Generated using GeoJson.io [56].

Flight 9: Foliage

Flight 9 was performed using the same path as presented in Flight 5. No problems were encountered during the flight, and Sheep 1 and Sheep 2 were transmitting RTT data throughout the flight. All collected RTT measurements are shown in **Figure 4.33**.

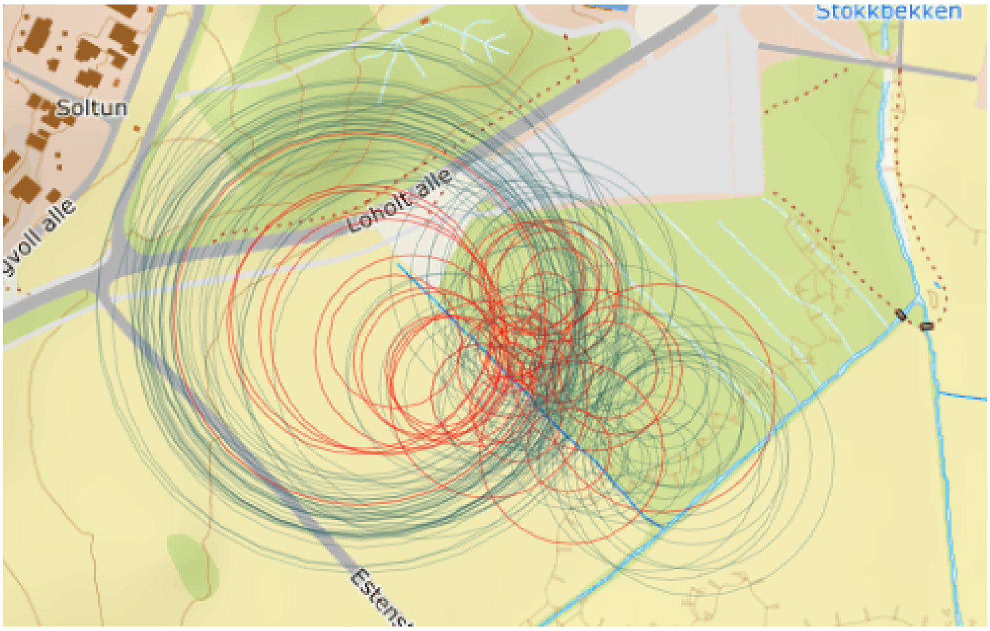


Figure 4.33: All RTT measurements from flight 9.

Table 4.13 presents the results from the flight, and **Figure 4.34** visualize the localization error and uncertainty area for both sheep.

	Localization Error	**Uncertainty Area**	**Number of RTT Readings**
Sheep 1	12.9 m	3 256.4 m^2	42
Sheep 2	15.7 m	3 237.9 m^2	119
Average	14.3 m	3 247.1 m^2	80.5

Table 4.13: Results from Flight 9

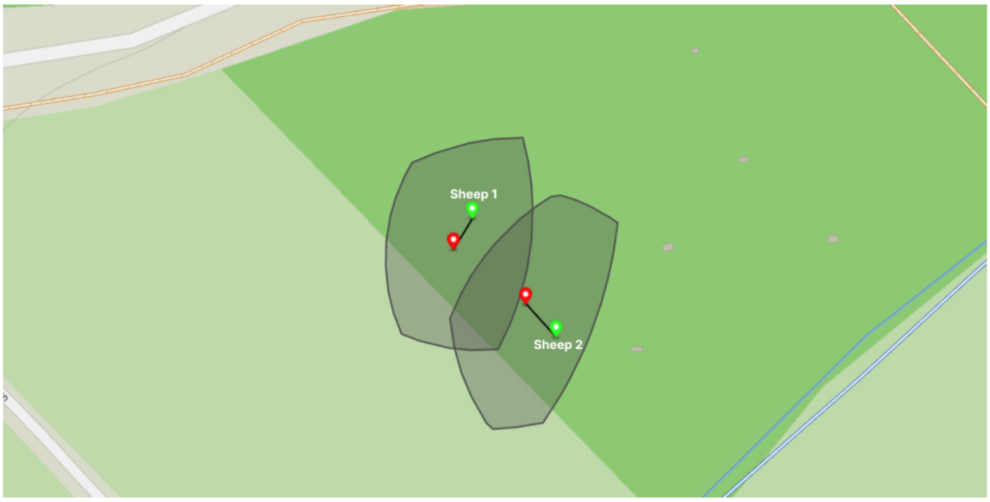


Figure 4.34: Results from flight 9. Generated using GeoJson.io [56].

Results From All Valid Foliage Flights

The results from flight 4 and flight 7-9 are the only results considered valid in foliage, as the other flights did not produce enough anchor points to perform multilateration properly. The averages across the valid flights are presented in **Table 4.14**.

	Localization Error	**Uncertainty Area**	**Number of RTT Readings**
Flight 4	48.1 m	3 041.3 m^2	73
Flight 7	11.4 m	3 720.3 m^2	78.5
Flight 8	8.8 m	16 267.6 m^2	71
Flight 9	14.3 m	3 247.1 m^2	80.5
Average	20.7 m	6 569.1 m^2	75.8

Table 4.14: The average from all valid foliage flights.

4.3.5 Error Sources

Some potential error sources have been identified that may affect the results obtained during the tests.

Using GPS to obtain the actual position of the sheep will inherently be a potential source of error in all performed tests. GPS measurements have some uncertainty, and this may lead to incorrect results. The measured actual position of the sheep is compared to the system's calculated position to get the localization error for each test, and inaccuracies in the GPS-measured position will affect our results. It is hard to conclude the exact positional error from GPS measurement, and the GPS-measured position will be perceived as correct during the tests. Foliage affects the signals used in our system and GPS signals. Therefore, the inaccuracy in the GPS-measured positions is expected to be greater during these tests. As previously discussed, landmarks and other visuals were used to cross-check that the GPS measurements were not entirely off the actual positions of the sheep.

The UAV needs to know its position to act as a single mobile anchor enabling multilateration. This is done by using a GPS module mounted on the UAV that saves the position of the UAV when an RTT measurement is performed. The UAV is equipped with a Matek M8Q-5882 GPS module with a positional accuracy of 2.5 meters [57]. The uncertainty in the GPS's position is, therefore, an error source and can influence the localization performance of the system.

As with the ranging tests, these tests were conducted during spring. The trees in the test area had no leaves, which may have affected the results. Therefore, it would be best to test the system during September or October using an environment resembling the intended environment for a sheep localization system. However, it is challenging to conclude what degree of impact this had on the results, but it is believed that it would only have a minor effect on the system's performance.

4.3.6 Discussion

The results from **Table 4.14** report an average localization error across all flights of 20.7 meters in foliage. Flight 1 reports a localization error of 36.1 meters for Line of Sight. The LoS results are not perceived as reliable, as only one successful LoS flight was conducted. Vucic and Axell [6] reported an average localization error of 15m for LoS environments from their tests. This is believed to be a more reliable result due to the larger sample size. This shows a 38% increase in localization error when foliage is introduced. The spread of localization errors across the valid flights shows a standard deviation from the mean of 17.2 meters, meaning the system also has low precision in foliage.

Table 4.14 reported an average uncertainty area of the sheep's positions of 6 569.1 m^2 across all valid flights in foliage, and Flight 1 reports an average uncertainty area of 1009.3 m^2 in LoS. Again, the small sample size in LoS makes it hard to conclude how foliage affects the uncertainty areas. An interesting observation is a significant increase in uncertainty area for Sheep 2 in flight 8. The uncertainty area of around 29 000 m^2 is much bigger than all other uncertainty areas, but the localization error is still relatively similar to the other results. It was noticed that if the system performs only a couple of RTT measurements entirely off the rest, it can significantly increase the uncertainty area. As explained in **Figure 3.6**, the multilateration method will incrementally increase the radii of RTT measurements until it finds an intersection between all measurements. A distance estimation much lower than the rest of the measurements taken from the same relative area will therefore result in the multilateration algorithm increasing all radii until the faulty measurement intersect all other measurements. Although this dramatically increases the uncertainty area, the results show that this does not move the mean point of the uncertainty area significantly, resulting in a localization error similar to other flights. As mentioned in **Section 4.3.3**, all RTT measurements with a measured distance of 0 meters were removed before analyzing the results. These measurements are faulty and would lead to an extreme increase in all uncertainty areas if not removed. The multilateration algorithm would need to increase the uncertainty areas to intersect all positions where a faulty RTT measurement was collected. A significant variation in the number of RTT measurements for each sheep across flights makes it interesting to investigate if there is a correlation between localization performance and the number of RTT measurements conducted. For flights 5, 7, 8, and 9, an increase in localization error can be observed for the sheep with the largest number of RTT measurements. Still, the sample size needs to be larger no conclude if there is a clear connection between localization accuracy and the number of RTT measurements for a sheep. As concluded in **Section 4.2**, the precision of the MCPB method for ranging is low in foliage. This leads to many RTT measurements being necessary to get an accurate average. Still, a growing number of RTT measurements increases the chances of inaccurate measurement occurring, significantly increasing the uncertainty area of the system. The ideal scenario is to perform enough RTT measurements to get an accurate estimation without excessive measurements that can decrease the accuracy. The ideal number of RTT measurements has not been further investigated.

During flights 2, 5, and 6, a BATTERY FAILSAFE error occurred. This resulted in the Minew module stopping to perform RTT measurements right after lift-off. The RTT measurements during all flights affected by this error were relatively limited and concentrated near the lift-off area. As the RTT measurements are only collected near the lift-off area, the calculated positions of the sheep will be within the lift-off area; the smallest intersection of all circles will be the area of the largest circle, as all other circles are within the largest circle. As a result of the concentrated positions of the UAV during the RTT measurements, the system could not produce enough anchor points to perform multilateration properly, giving an inaccurate position estimation of the sheep. It will, therefore, affect the accuracy and performance of the system.

During flight 4, the UAV lost connection with the UAV controller at the outermost part of the flight path, resulting in the UAV automatically returning to its landing location. This happened early in the flight, making the UAV only complete a single sweep line. When the distances are measured from only a single sweep line, it can lead to geometric dilution of precision as seen in **Figure 3.1**, resulting in inaccurate position estimations.

4.3.7 Conclusion

A total of nine test flights have been performed to collect RTT data to analyze the performance of the sheep localization system. Of these nine flights, only five are seen as having valid results. The tests report an average localization error of 20.7 meters and an average uncertainty area of 6 569.1 m^2 in foliage. The tests performed in a Line of Sight environment report an average localization error of 36.1 meters and an average uncertainty area of 1 009.3 m^2. However, the sample size used to calculate the LoS averages is believed to be too small to be used as a reliable result. It is concluded that even a few wildly inaccurate RTT measurements during a flight can lead to significant uncertainty areas. The results show a correlation between performance and the number of successful RTT measurements, but the sample size is too small to give a conclusion.

Problems with the UAV during flights will lead to the system performing poorly. For example, geometric dilution of precision or a lack of evenly spread anchor points for multilateration are problems that occur if the UAV cannot fly its designated path or if the UAV does not perform RTT measurements throughout the flight.

Chapter 5

Discussion of Research Questions

5.1 RQ1: Is Bluetooth Low Energy the Best Radio Technology for Localization of Sheep in High-Density Foliage?

The discussions in this section are based on the theory presented in **Section 2.6**. It is important to remember that radio technologies must prove feasible to use in a localization system with a similar architecture to the current system, in addition to having good localization performance in foliage.

The research on foliage propagation shows that a radio wave's wavelength and frequency significantly impact its ability to penetrate objects. A radio wave's ability to penetrate objects is the highest when its wavelength matches the size of the obstruction it must penetrate. Using a forest-to-air configuration for transmissions results in the forest's crown layer being the most prevalent propagation medium for the radio waves, and attenuation in the crown layer is lowered when using frequencies between 30MHz and 1.2GHz.

Section 2.7 presents LoRa, Bluetooth Low Energy and Ultra-Wideband. LoRa operates with a frequency of 868MHz and should theoretically be the best radio technology for foliage penetration. The literature shows that LoRa has a maximum effective range in forests of around 250 meters and suffers from a PDR between 0.4 and 0.8 at 150 meters in foliage. Our research and previous research on BLE in forests show similar performance to LoRa. The tests performed in **Chapter 4** show that BLE can be used for fairly accurate foliage localization despite using a higher frequency. LoRa and BLE outperform UWB in foliage, and UWB will not be discussed further.

LoRa has a superior transmission range in a Line of Sight environment. Still, the tests performed by Vucic and Axell [6] conclude that the low theoretical range of BLE does not introduce any usability issues for the localization system. No research on the accuracy of LoRa for locating objects in foliage has been found at the time of writing this thesis, and this should be performed to compare BLE and LoRa's performance in the same scenarios. However, due to the time constraints of this thesis, no tests using LoRa were performed.

Although LoRa is the theoretical best choice of technology, the upside of switching technologies may not be that great. The potential increase in localization accuracy by changing to LoRa will likely not have any significant positive effect on end users of the system. The practical use case of this system is to narrow down the geographical area farmers need to search for their sheep manually. However, this does not require high localization accuracy. Moreover, the potential increase in accuracy by using LoRa would likely not give farmers any advantages, as the accuracy of BLE is high enough that farmers can visually locate sheep within the estimated intersection area regardless. The change in radio technology would require significant research, development, and testing to create a localization system that outperforms the current system in terms of usability, cost, and accuracy.

5.2 RQ2: How Well Does the UAV and BLE-based Localization System Perform in High-Density Foliage?

The system's performance is measured by the average localization error when estimating the position of sheep located in high-density foliage and the average uncertainty area of each estimated sheep position.

5.2.1 Results

The ranging tests have shown that the Minimal Custom Protocol-Based RTT ranging method developed by Swiderski [5] can accurately estimate distances in both Line of Sight and forest environments up to a distance of at least 100 meters. The MCPB method has a mean average ranging error of 7.4 meters across all tested distances in foliage and a mean average ranging error of 6.2 meters for LoS. The Packet Delivery Ratio of the system declines in foliage at transmission distances of 50 meters or more, while no significant reduction in PDR for LoS was found. A reported PDR of 0.66 at 100 meters in foliage demonstrates that the MCPB method struggles with performing measurements over large distances. It is also believed that the PDR will drastically decrease if the transmission distance is above 100 meters.

The large-scale tests show that the system can locate sheep in high-density foliage with an average localization error of 20.7 meters and an average uncertainty area of 6 569.1 m^2. The valid flight performed in a LoS environment reports that the system has an average localization error of 36.1 meters and an average uncertainty area of 1 009.3 m^2. These values are calculated using a small sample size, and the reported accuracy of 15 meters in LoS concluded by Vucic and Axell [6] will be used instead. The failed flights during the tests show that the system is prone to calculate inaccurate location estimations if the UAV is unable to complete its full flight path or if it is unable to perform RTT measurements throughout its flight.

5.2.2 Effect of Foliage

The theory presented in **Section 2.6** and **Section 2.7** suggest that foliage should have a significant impact on propagating radio waves. The various multipathing, diffraction, and refraction effects affecting transmitted signals should negatively impact any signal sent in foliage, especially over longer distances. The 2.4GHz frequency used by BLE makes the theoretical foliage penetration ability of BLE relatively bad. Still, our tests indicate that the effects of foliage may not introduce any significant usability issues.

The ranging and large-scale tests were performed in both LoS and forest environments. Comparing the results from the same test in different environments can indicate how much foliage affects performance. The ranging tests show that foliage does not significantly impact accuracy for distances up to 100 meters but that precision and PDR are reduced considerably as transmission distances increase. The mean average ranging error across all distances increases by 1.2 meters when foliage is introduced, but this is believed to have a minor impact on localization performance. The significant increase in standard deviation across all distances when foliage is introduced shows that the precision of the MCPB method is reduced in forest environments. Still, this decline in precision will not negatively impact accuracy as long as the UAV can perform enough RTT-ranging measurements to get an accurate average. The foliage has a considerable negative effect on the Packet Delivery Ratio. Introducing foliage reduces the PDR by 0.02 at 50 meters, 0.04 at 75 meters, and 0.32 at 100 meters.

The large-scale test demonstrates a 38% increase in the average localization error when foliage is introduced. There is not enough data to conclude how foliage affects the size of the uncertainty areas, but introducing foliage can lead to substantial uncertainty areas. The drop in ranging precision in foliage can result in outliers in the RTT measurements, and as previously explained, this makes the multilateration algorithm calculate an extremely large uncertainty area. The reduction in PDR in foliage will also lead to packet loss, where all unsuccessful measurements are saved as having a distance of 0 meters. These 0-meter values are outliers in the RTT measurements and will increase the uncertainty areas if not removed before analyzing the results. Foliage can also lead to the UAV losing its connection to the UAV controller, forcing it to return to landing prematurely. This happened during flight 4, where the UAV could only complete one sweep line. The geometric dilution of precision when only using a single sweep line will result in the system performing poorly in foliage.

5.2.3 Real-World Feasibility

An important aspect to discuss is how the system's real-world feasibility is affected by foliage. Swiderski [5] states that a localization accuracy of ±100 meters is acceptable for sheep localization systems. Farmers are forced to gather their sheep manually, and a localization accuracy higher than ±100 meters will not greatly increase the value provided by the system. The sheep are also not completely stationary while the farmer searches. The system's value, therefore, lies in its ability to narrow down the whole grazing area to a single smaller search area for each sheep. The average localization error of 20.7 meters in foliage is well within the accepted localization accuracy, and the system can provide value to farmers in areas of high-density foliage.

5.2.4 Limitations

The research on the system's ability to locate sheep in high-density foliage has limitations. All foliage tests were performed in the same forest area, meaning there has been no variation in the type of foliage during tests. It is not believed that forests with other foliage compositions would significantly impact performance, but this can only be concluded by performing more tests. The foliage tests were also performed in the spring before the trees had bloomed. The amount and density of foliage during the tests and the sheep gathering period differ, which could impact the system's performance. Testing during September and October would need to be conducted to give a conclusion on the impact of changes in foliage density. No real sheep were used during the tests, and all nRF DevKits were stationary during flight. Sheep would not be completely stationary, and the system's performance with moving targets is unknown. Still, the introduction of moving sheep is believed not to increase the system's average localization error beyond the accepted ±100 meters threshold. The UAV used during tests does not have the battery capacity needed to perform flights covering very large geographical areas. Testing the system's performance on significantly larger search areas would be valuable, but this demands replacing the UAV with an aerial vehicle with a longer maximum flight time.

5.3 RQ3: How Can the Existing System Be Modified to Increase Its Performance in High-Density Foliage?

The discussion of this research question will address the experiences gained throughout the work on this thesis and focus on how the system can be altered to enhance its performance in foliage without decreasing its performance in Line of Sight environments. Issues were encountered with the system's hardware and software during the testing. Therefore, recommended changes to these areas will be presented.

5.3.1 Hardware Changes

Battery Failsafe

The tests have revealed that the UAV is prone to enter a BATTERY FAILSAFE state during flights. A sudden voltage drop causes the issue, but why this happens is unknown. When this happens, the Minew module stops performing RTT measurements, which reduces the system's performance. As a result of the concentrated RTT measurements nearby the lift-off area, the system can not produce enough anchor points to perform multilateration properly, giving inaccurate position estimates.

As a suggestion to enhance the system's performance, increasing the RTT module's resistance to low voltages or making it entirely independent of the drone's power supply could prevent the UAV from entering a BATTERY FAILSAFE state during longer flights. Doing so would increase the number of RTT measurements and anchor points during the flight, enabling multilateration to be adequately performed and producing a more accurate position estimation for the sheep.

Connection Loss

Connection loss between the UAV and the UAV controller was experienced during the large-scale testing. The connection loss occurred when the UAV was on the outermost point of the flight path, resulting in the UAV automatically returning to its landing location. If this occurs early during a flight, it could result in the UAV only completing a single sweep line. When the distances are measured from only a single sweep line, it can lead to geometric dilution of precision, as seen in **Figure 3.1**, resulting in inaccurate position estimations or ambiguity in the sheep's position. Another point to consider is that an early flight cancellation could result in fewer RTT readings, producing few anchor points for the multilateration algorithm and inaccurate position estimations.

A possible solution to prevent connection loss during flight is to upgrade the antenna on the UAV or the UAV controller with an antenna providing a higher range limit. Thus the UAV would maintain its connection to the UAV controller during the whole flight, and it would be able to perform longer flights without losing connection, increasing the maximum search area of each flight.

5.3.2 Software Changes

Faulty RTT Measurements

Transmission of RTT data over large distances in foliage can lead to the Minew module on the UAV not receiving all transmitted packets. The measurement is regarded as unsuccessful if the UAV receives insufficient RTT packets. Unsuccessful RTT measurements are currently registered as having a distance of 0 meters, reducing the system's performance. The Minimal Custom Protocol-Based RTT ranging method uses the average of several distance estimations to combat imprecise reading. However, the introduction of 0-meter values will have a significant impact on the calculated average distance. The system's performance relies heavily on the MCPB method's accuracy, and 0-meter values will make the system less accurate.

It is therefore suggested to change the MCPB method to automatically discard any unsuccessful RTT measurements to ensure that no 0-meter values are registered. Estimating tiny distances can lead to valid 0-meter values being registered due to the rounding down of values, and accidentally removing valid RTT measurements could happen. Still, the system's intended use case would improbably lead to a valid 0-meter estimation being registered during a flight, and it is believed all 0-meter values can be seen as faulty.

Changes to Multilateration Method

The large-scale tests have shown that a small amount of imprecise RTT measurements can lead to the multilateration method returning extremely large uncertainty areas. As previously discussed, introducing foliage reduces the system's precision when performing RTT measurements. Low precision can produce anomalies in the registered RTT measurements, reducing the system's performance. The implemented multilateration method will incrementally increase each distance estimation if no intersection between all measurements exists. This is usually a practical approach when dealing with inaccurate data. However, anomalies in the measurements result in the multilateration method having to drastically increase the uncertainty area to ensure an intersection with the anomalies.

Changing the current method or implementing a new multilateration method that can identify and remove anomalies in the RTT measurements can significantly decrease the average uncertainty area of the system, further reducing the geographical area farmers need to search for sheep manually.

Chapter 6

Conclusion

This thesis evaluates the third iteration of a sheep localization system developed by master's students at the Norwegian University of Science and Technology. The system consists of an autonomous UAV and a lightweight radio transmitter. The UAV follows a predetermined flight path covering a search area. It uses a custom Bluetooth Low Energy (BLE) Round Trip Time (RTT) ranging method and multilateration to calculate the position of sheep in the search area.

A literature study has been conducted to research the best radio technology for propagation in high-density foliage. Several tests and field trials have also been performed to evaluate how well the sheep localization system can consistently and accurately locate sheep in forests. Finally, the experiences gained throughout the work on this thesis have resulted in several suggestions on how the system can be modified to increase localization performance in high-density foliage.

The literature shows that LoRa is theoretically the best radio technology for locating sheep in high-density foliage. A change to using LoRa is, however, not recommended as the potential upside of LoRa does not justify the amount of work needed to develop a new system with better performance using a new radio technology.

The system can locate sheep in areas of high-density foliage with an average localization error of 20.7 meters and an average uncertainty area of 6 569.1 m^2. The introduction of foliage increases the average localization error by 38%, but this is still within the accepted accuracy for sheep localization of ±100 meters.

It has been discovered that the system's reported performance in high-density foliage could be increased by removing faulty 0-meter RTT values, changing the multilateration method to calculate uncertainty areas better, or by making changes to the hardware that ensures that the UAV can complete its flight path and perform RTT measurements throughout all flights.

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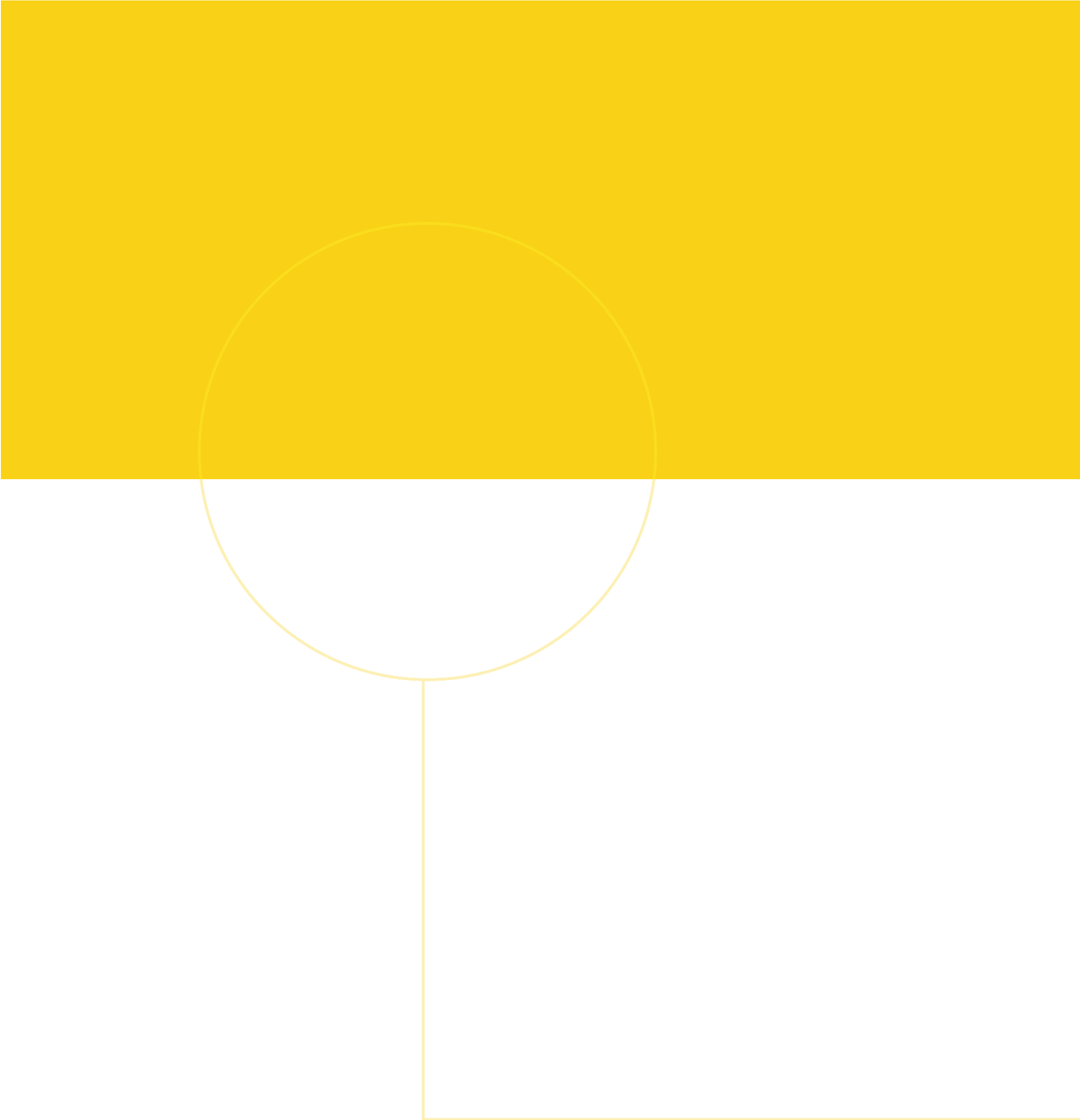

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