Kaunas University of Technology

Faculty of Mechanical Engineering and Design

Development of System to Increase Communication Distance between Drone and Operator

Master's Final Degree Project

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Project author

Researcher Dr. Linas Obcarskas

Supervisor

Kaunas, 2026

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Mechatronics (6211EX017)

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Development of System to Increase Communication Distance between Drone and Operator

Declaration of Academic Integrity

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Task of the Master's Final Degree Project

Given to the student – Vakarius Preimantas

1. Title of the Project

Development of System to Increase Communication Distance between Drone and Operator

(In English)

Sistemos, padidinančios ryšio tarp drono ir operatoriaus atstumą, kūrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to develop a system to improve drone communication distance.

Tasks:

1. to determine the most promising solution;
2. to simulate the performance of the solution;
3. to compare the system to existing solutions;
4. to evaluate the cost of the solution.

3. Main Requirements and Conditions

The antenna used should be 2,4GHz. Drone used should not be heavier than 20kg additionally the solution should be for a hexacopter. The implemented device should not add more than 2kg to the weight of the drone. Finally, the ground station would not weigh more than 15kg for ease of transportation. Perform simulations in order to receive data on the effectiveness of the solution.

4. Additional Requirements for the Project, Report and its Annexes

“Not applicable”

Project author	Vakarius Preimantas		02-03-2026
	(Name, Surname)	*(Signature)*	*(Date)*
Supervisor	Linas Obcarskas		02-03-2026
	(Name, Surname)	*(Signature)*	*(Date)*
Head of study field programs	Regita Bendikienė		02-03-2026
	(Name, Surname)	*(Signature)*	*(Date)*

Preimantas Vakarius. Development of System to Increase Communication Distance between Drone and Operator. Master's Final Degree Project, supervisor Researcher Dr. Linas Obcarskas; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: drone; wireless communication; tracking antenna system; range improvement; directional antenna.

Kaunas, 2026. 57 p.

Summary

A way to improve communication distance without greatly affecting other significant drone parameters is considered in this work. However, this is quite difficult as in drone parameters are co depended as altering one parameter can invertedly impact the drones' other characteristics. Which is why the study mainly focused on quantitative research since this allows to objectively estimate how much of an improvement is made and how big are the losses and downsides of implementation. This has given a good estimate on the feasibility of implementation as well as profitability. It was found that by using directional antennas along with antenna tracking directly on the drone the drone's range of communication could be boosted by about 20% with the tested setup. While for drone network this distance increased is proportional since the communication range is increased between each drone. The major trend found here was that as long as accurate antenna tracking is ensured the overall range of communication can greatly increase. Possibly even going beyond the determined range extension values with antennas featuring more focused signal beam. Additionally, the implementation is mean not to change the current design of drones meaning it could be widely utilized as long as the drone can carry an additional 0.6 kg of payload. While economically an investment of 184€ should be acceptable for applications where extended communication range is required. Additionally, from an economic view it must be taken into account that drones do not need to be redesigned and only minor modifications need to be done in order to allow use of the device discussed in the study.

Preimantas Vakarius. Sistemos, padidinančios ryšio tarp drono ir operatoriaus atstumą, kūrimas. Magistro baigiamasis projektas, vadovas m.d. dr. Linas Obcarskas; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: dronas; belaidis ryšys; antenos sekimo sistema; ryšio nuotolio pagerinimas; tiesinė antena.

Kaunas, 2026. 57 p.

Santrauka

Šiame darbe yra nagrinėjamas metodas leidžiantis padidinti ryšio atsntumą, nedarant žymios įtakos kitiems svarbiems drono parametrams. Tai yra pakankamai sudėtinga, nes drono parametrai priklauso vienas nuo kito. Todėl vieno paramatro pakeitimas gali neigiamai paveikti kitas drono charakteriistikas. Todėl tyrime daugiausiai dėmesio yra skiriama kiekybiniams metodams, nes jie liedžia objektyviai įvertinti, kokia yra pasiekiamas nauda ir leidžia pasakyti kokie nuostoliai gali būti pastebėti to pasekoje. Tai leido įvertinti, įgyvendinimo įgyvendinamumą ir pelningumą. Atliekant tyrimą buvo nustatyta, kad naudojant tiesines antenas kartu su antenos sekimu ant drono, gaunamas 20% susisiekimo astumo pagerinimas. Dronų tikle šis astumo padidėjimas yra proporcingas, nes maksimalus ryšio nuotolis tarp kiekvieno drono yra padidėjęs. Buvo pastebėta tendencija, kad užtikrinus tikslų antenos sekimą, bendras ryšio atstumas gali būti ženkliai padidintas. Galimai, net viršyti nustatytas ryšio atstumo padidinimo reikšmes naudojant antenas su stipresniu ryšio fokusavimu. Taip pat šis sprendimas leistų nekeisti esamų dronų konstrukcijos, todėl šis metodas galėtų būti plačiau naudojamas, jei tik naudojami dronai gali pakelti 0,6kg papildomą apkrovą. Šiam metodui reikalinga isvestiją siektų iki 186€ ekonominiu požiūriu tokia ivestiją turėtų būti priimtina tais atvejais, kai reikalingas maksimalus ryšio atstumas. Be to reikia atsižvelgti į tai, kad šiuo metu naudojamų dronų nereiktų pilnai perprojektuoti, o būtų reikalingi tik minimalų pakeitimai, kad būtų galima naudoti tyrime aptartą įrenginį.

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Introduction

Drone technology has been quickly expanding into multiple industrial sectors, driven by increased sensor capabilities and reduced economic costs. It has now become a commonly used tool. However, in order to fully utilize this technology in most cases line of sight and close proximity between controller and the drone being operated must be ensured. This poses a major limitation in many applications. For example, in long range survey and security applications, where close proximity and line of sight can be difficult to ensure. Additionally, signal loss is quite common in drone which can cause disruptions to automated and manually controlled processes alike and greater signal stability can decrease this parameter. This is especially important in drone networks where a drone’s consistent operation and range are extremely important. Since disruptions in one drones’ communications cause disruptions in the entire system. Furthermore, low communication range require use of more drones in a system to cover the same amount of area. Finally, as drones become capable of executing higher complexity task, the increased sensor data generated require a matching high data throughput. For this high frequency communication is desirable, however it results in lower possible communication ranges and more unstable signal connections.

In order to overcome this problem many parameters must be taken into account as drones are extremely constrained in their weight, power capacity and size. Which is why finding a suitable solution that does not negatively affect either of these parameters is nearly impossible. As there are trade-offs for each used method it must be ensured that the decrease of these parameters is worth the benefit of the suggested solution. Which can be incredibly difficult since these parameters and especially power capacity are extremely constrained in drone systems. Additionally, to implement most solutions changes is a drone’s design are be necessary, meaning that if several different types or designs of drones are already used for a certain application in order to improve their communication capabilities major changes of drone’s design or new drones altogether are be necessary. This can greatly raise the costs for the changes, rendering the solution economically unappealing. For this reason, a device that could be added to an existing drone without major design changes are be desirable as many types of drones could benefit from such a system. This is expected to result in lower overall prices of implementation as the drones themselves do not require to be changed. Which is why in this paper the creation of such device is explored. For determining how said system affects drone operations testing was performed to have quantifiable data on the expected benefit and potential drawbacks. Finally, the economic aspect of such a device was considered.

Aim: to develop a system to improve drone communication distance.
Tasks:
1. to determine the most promising solution;
2. to simulate the performance of the solution;
3. to compare the system to existing solutions;
4. to evaluate the cost of the solution.
Hypothesis: It is possible to create a system that could significantly increase communication range without altering the design of the drone in a major way.

1. Drone Technology Overview and Future Possibilities

Drone technology started in the military industry, where the first drone UAV (Unmanned Aerial vehicle) was first used in 1849 [1]. These do not resemble current drone's since they were helium balloons with bombs attached to them that were be dropped once in position [1]. Then the next know drones were little more than an aerial torpedo that could be controlled via radio waves by a pilot. That were utilized during WW1. However, since then a drone has become so much more as with each iteration the design of a drone took on different forms and provided increasingly better performance. The first drone type that truly made a breakthrough in drone military applications was the MQ1-Predator drone, which can be seen in Fig. 1. This was a fixed wing drone still quite similar to a traditional plane, however its efficiency and usefulness in field operations cemented the drone technology. As it was used not only for reconnaissance and strike missions but also search and rescue operations.

Fig. 1. Image of a MQ1-Predator Drone [1]

With time three main types of drones emerged that are categorized according to their construction: fixed wing, single rotor and multi-rotor. The type of drone used depends on the task since each of these types is used for different purposes. Fixed wing is perhaps the oldest type and is the most similar to traditional plane not only in its construction but also its utilization for long range flights. A single rotor drone construction is much like a helicopter with a single rotor that has exceptional power and therefore has higher lifting force than the multi-rotor. Finally, the most recognizable and familiar drone type today is the multirotor. Here the drone uses multiple rotors to ensure stability and allow for complex and agile movement of said drone. The last type has been of particular interest in recent years, simply due to its flexibility as it can be used in tight spaces and its capability of quickly making sharp turns. As this allows the utilization of these drones in urban settings and allows it to perform more complex tasks [2].

1.1. Drone Market Overview

This has allowed drone technology to become more than simply machines specialized for conflict or surveillance and to expand in other industrial sectors, while growth in military related sectors has not slowed down and due to the recent conflicts is even expected to be accelerated. The overall expected market change can be seen from Fig. 2. From this data it can be seen that a stable annual growth is predicted to be as high as 7.8% [3]. While in other sources the growth can be seen to be even higher reaching up to 12.5% predicted growth annually [2]. So, while the exact amount of growth is difficult to predict it makes it clear that it is quickly growing industry branch. This fast growth can largely be attributed to rapid technological advancements in sensing equipment, which allows drones to get more accurate and therefore useful data. In addition to that advancements in the drone battery life which allows these drones to function for longer and therefore perform more task.

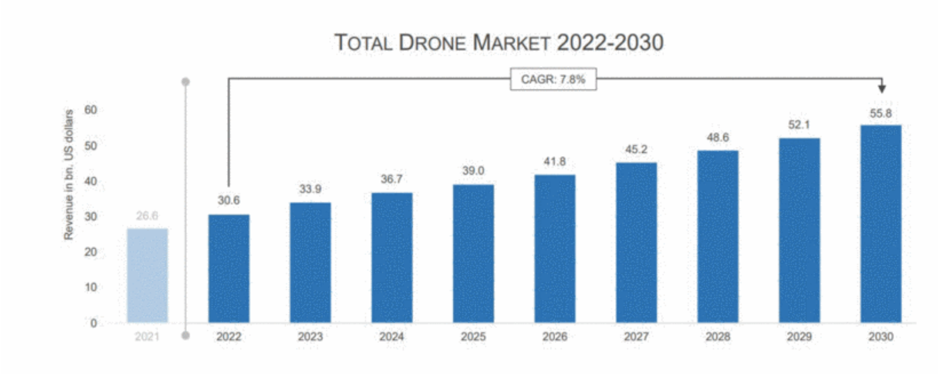


Fig. 2. Drone Market Trend Prediction [3]

Currently, the largest sector that takes advantage of drone technology is the construction sector. This can be seen from Fig. 3, where the market share for this sector reaches 36% [2]. While the runner up is agriculture. This is most likely due to the similarity of these fields. As the task here are performed within "controlled" environments. Meaning that the drones in these sectors have easier conditions for operation due to the smaller number of variables involved with navigating the drone. Additionally, in both cases the drone can usually establish a connection either by line-of-sight methods, due to the small numbers of obstacles, which allow for quick and stable transfer of data or when such methods can't be used either Wi-Fi or cellular connections can be used to make up for it due to the relatively small distances from the operator.

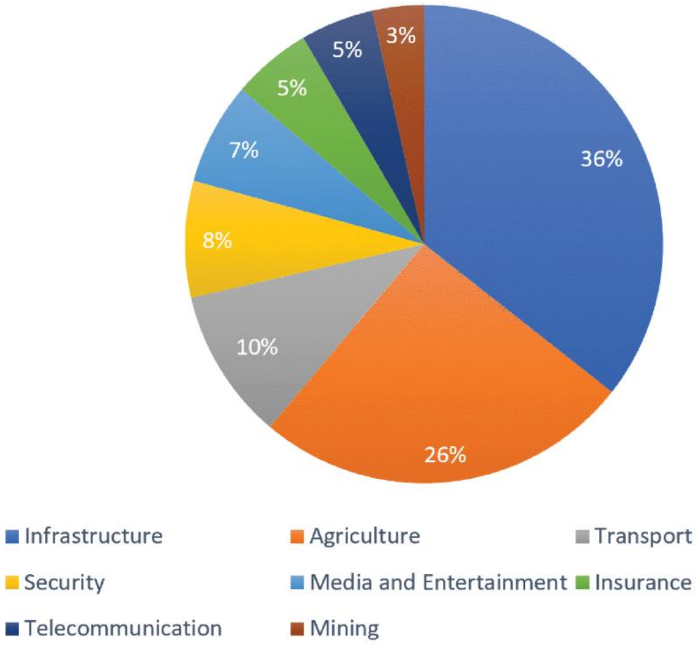


Fig. 3. Pie Chart of Civilian Use Drone Utilization [2]

The fact that infrastructure sector uses the most drones can be attributed to the point that a drone can get visual data on infrastructure many times faster than a person could. Mainly due to the fact that many spots can be difficult for a person to reach requiring additional equipment in order to inspect it. While a person operating a drone can quickly perform this with no additional preparation this way simplifying, increasing the speed of the process and also improving the safety of the operation. Additionally, while for a person to gather data many tools can be needed that could be cumbersome for said person. A drone however can have several of these tools preinstalled allowing to inspect several properties at once. As can be seen in Fig. 4. Here images of a drone with a camera, a LiDAR and a thermal sensor can be seen. This offers many benefits to maintenance inspections with drones most notably the decreased cost of this operation as a drone equipped with several sensors does not need to make several passes along the surfaces inspected and instead does it in one. Since the data from several sources is available a person can also review the data more accurately and allows for earlier detection of defects [2]. Additionally, in the infrastructure sector the drones are always controlled by a person meaning that these are constantly supervised since it is easier to check the required points in a building is by far easier than to automate it for every building. Additionally, this has the side effect of reducing the danger of accidents from happening on the site.

In the agricultural sector the drones have less restrictions in general since these are mainly used for monitoring crops, mapping fields and more recently spraying pesticides. While these are difficult task, the fact that fields are flat with no major objects that could cause collisions paired with the fact that people are not physically present in the fields and clear line of sight between drone and operator increases the simplicity of these tasks. Since the drone or the operator do not need to constantly account for many variables as is the case in other fields of industry. The automation in transport sector is limited precisely due to the number of variables. For example, if the task of last mile delivery via drones is considered then first the drone needs to receive the exact place where it can land, then to get to the location, avoid infrastructure, foliage and other obstacles, while also making sure it has enough power in order to get back to the landing area to charge. Since running out of power mid-flight can cause accidents or injuries. Which is why the implementation of this technology is currently limited.

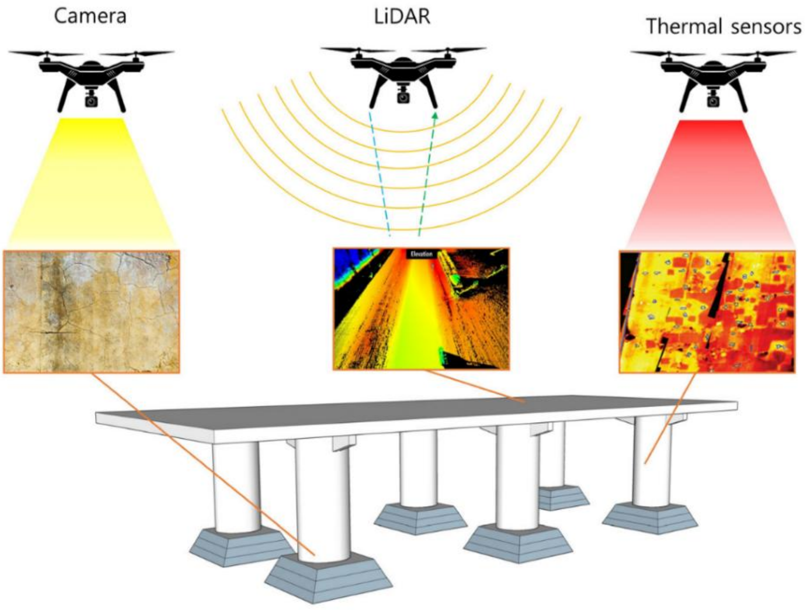


Fig. 4. Drone Equipped With Different Sensing Equipment [4]

This paper focuses more on the security and surveillance sectors. While this sector is currently not the largest [2] it holds large amount of promise for future expansion. This can be seen in Fig. 5 where the expected growth of surveillance industry is presented. By comparing the data from [3] it can be said that growth of surveillance using UAVs is be significantly faster than the average of drone market. This can be attributed to the rise of geopolitical conflicts as this has increased the demand for security measures globally. However, surveillance in more remote, less accessible regions can be incredibly human resource intensive as with more difficult terrains patrols naturally need more people to ensure full coverage of the region. Which is why drone technology is so important for this sector. Since drones have already proven their usefulness in search and rescue operations deployment of drone in the surveillance sector is nothing new. Additionally, their cost effectiveness and flexibility make their implementation highly desirable. As it is by far cheaper to provide tools such as drones to experienced personnel, than to hire large amounts of new personnel that have to be trained. Since by using drones, a single person can cover much larger sectors of land as the drones have better vision from above, that is not hindered by the terrain. In addition to that tools can be mounted on a drone that can assist in detection of intruders. As is the case in [4] where the drones can use not only a camera but also a LIDAR and also thermal imaging equipment, this provides the operators with large amounts of data that can simplify their jobs as with thermal imaging it can be easier to differentiate people from animals in low visibility environments. However, their deployment in this field is relatively new, which why there are many challenges that must be overcome in order to achieve widespread and large-scale implementation that is expected in the future.

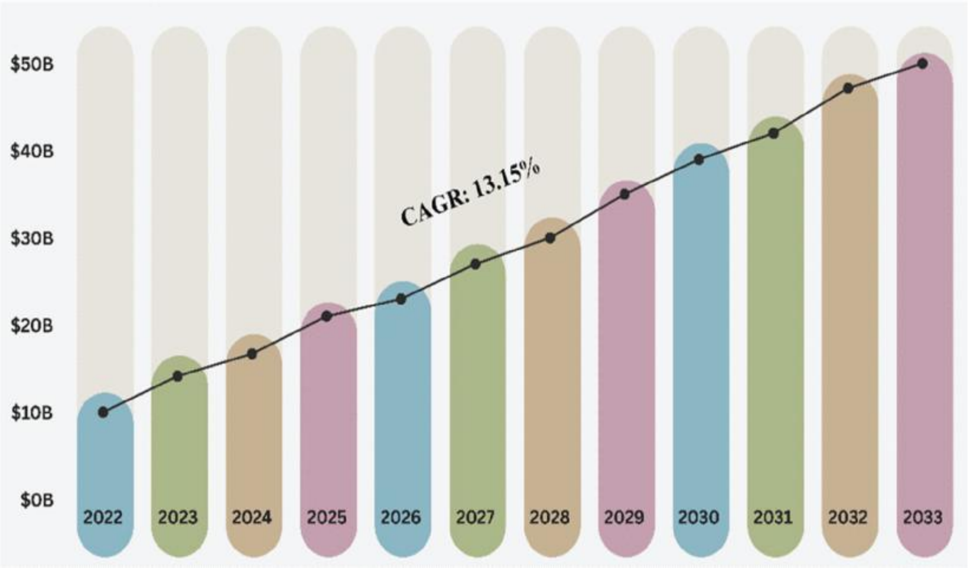


Fig. 5. The Expected Growth of Drone Surveillance Industry [5]

1.2. Risks and Limitations Associated with Drone Technology

While drones are already utilized in the security sector it is to a limited degree. This is can be attributed to the still existing risks and limitations that come from using drones. The main limitations in question are the need for recharging solutions, limited processing power of the drone and limited or unstable connectivity. To tackle these limitations many solutions have been developed with varying degrees of success. One work that has attempted to use UAV technology to provide seamless surveillance of an area along a national border took the charging as the main problem [6]. To solve the issue a suggested solution was to create a battery charging system that is built directly onto electricity lines. Drone can pass by these lines and recharge while flying. In this way recharging the drones in this process and allowing for uninterrupted surveillance to be performed in a specific area that has these lines installed [6]. The need for infrastructure has limited the implementation of said solution. However, automation of surveillance task could bring great benefits not only to the cost effectiveness, but also the security of a region. Since drones can cover ground faster than land vehicles on rough terrain and the fact that multiple of them can be sent periodically on the route and do not need to be controlled means that one person can supervise the same area that normally had required several people. Still there is room for improvement since drones here can only go through a predetermined route. Which is not ideal as from said route not all details can be seen that could be important. Drone needs to have the possibility of recognizing and investigating on their own. For example, drones could attempt to see intruders faces so that security personal could later recognise them.

To do more complex tasks drones computational power requirements increase. As drones have limited amounts of it and this limits many applications. While it may seem obvious to counter this issue of limited processing power by simply creating drones that have increased computational capabilities. However, this negatively affects the power consumption and, in this way, the productiveness of the drone is impacted. Since it can be performing useful tasks for smaller amounts of time. There exists ongoing research on how to connect drones to IOT (Internet-of-things) infrastructure in order to offload the task to the cloud for computations [7, 8]. This can be seen presented in Fig. 6 where the drones send the raw data through coordinator drones which upload the data to the cloud and from there the servers in ground stations process the data and send instructions back to the drone [8].

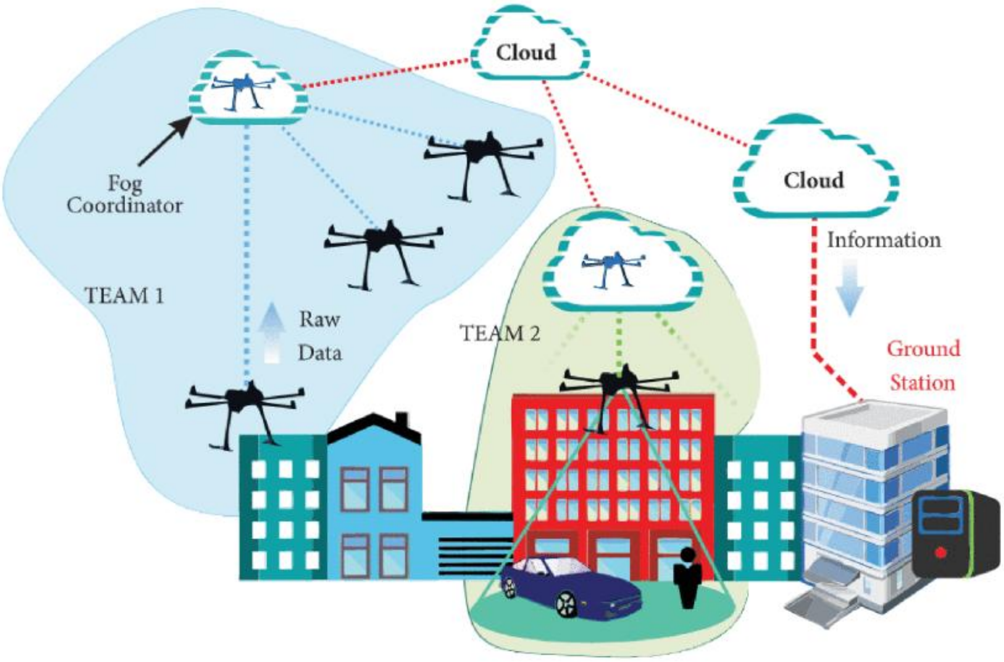


Fig. 6. Cloud-Based Communication Framework [8]

This can allow the cheap drones to perform far more complex task than these are equipped for hardware wise. While also allowing drones to benefit from the decision making of neural networks. However right now this technology is still in development mainly due the reasons being short battery life and lack of effective communication possibilities [8]. Which again leads to the limitation of connectivity. While the solution of offloading the difficult task onto the cloud to solve can work it has the risk of becoming useless if a connection can't be ensured to the drone, since then it won't be receiving any commands and stop performing useful work until the connection is reestablished or can even cause accidents due to lack of decision-making capabilities and lack of instructions. Which is a major downside to drone utilization with IOT which has been difficult to deal with. Since it is an incredibly complex topic, however by decreasing or eliminating the connectivity issues allow easier drone integration into IOT. This has many benefits for users and allow wider utilization of drones. However, lack of connection in not the only risk associated with drone technology.

The risks associated with drone technology are mainly divided into two sections external and internal risk as can be seen in Fig. 7. The most notable external risk being the risk of collisions, since it is the most frequent point of failure for a drone. This is due to the fact that in most cases drones are controlled by pilots and this means that a lot depends on a pilot's skills. Additionally, the lack of line of sight when UAVs are further away makes precise control more difficult as the only thing that can be relied on is the drone's camera. This leads to the next group of risk factors, namely internal ones. Here sensor failure, software failure and communication loss are the most important [9]. Since without getting data from the camera and other sensors an operator can't see what the drone's position or current condition is unless the drone is in line of sight. The camera in particular is quite prone to smudging which prevents the access to camera data. The results are more catastrophic when a drone is working autonomously since it lacks the data necessary to perform any action and to react to dangerous situations. While connection loss is by no means less dangerous since when signal is lost with a drone no actions can be performed by the operator and a drone has to rely on automated protocols if it even has such protocols installed. It does not mean that such landings are completely safe since most drones currently cannot ensure a 100% probability of safe landing, especially under difficult situations. Which are most likely the case when connection loss is experienced since, it often occurs in areas where many obstacles are between receiver and transmitter such as forests or towns. From this it can be inferred that ensuring a stable connection to a drone can greatly decrease the risks of drone technology.

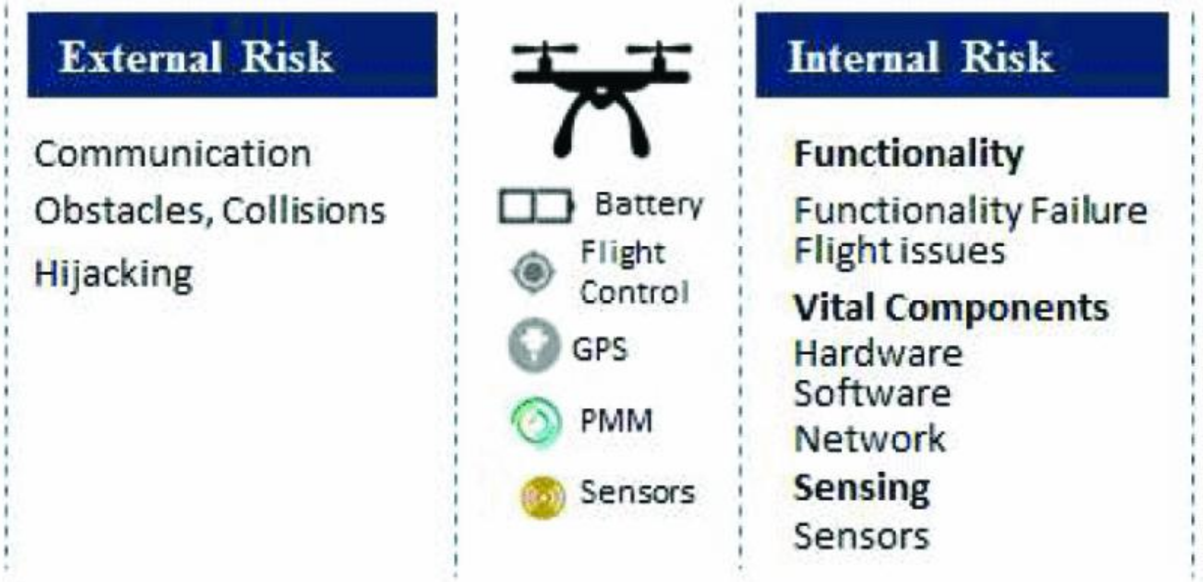


Fig. 7. Drone Technology Risks [9]

The risks associated with drone technology are also deeply connected to connection issues. In [9] it is recognised that communication related problems can be critical risk for drones. From one of the sources analysed there it was found that 11.53% of crashes occur due to poor or lack of communication [9]. This might seem like a small number it must be considered that here the data is mainly taken that from manually controlled drones, where drones are least sensitive to communication loss since a person is present in the general vicinity and is able to move to another place in order to reestablish communications. While in automated solutions this is not the case and potentially this percentile is predicted to be significantly higher. Additionally, in [9] it was reported that 15% of all crashes happen due to pilot error, however it is difficult to specify whether connection played no part in these crashes. As lag between the drone receiving data and the pilot receiving data can delay a pilot's reaction to certain dangerous situations. As even a slight delay in receiving information can greatly affect a pilot's decisions this could potentially mean that is responsible for higher percentage of crashes than it is believed.

1.3. Research Associated with Drone Antennas

Which is why the topic that is focused on in this study is drone communications distance. As with stable connection across a large distance between the drone and the operator or the ground station many more applications and benefits to existing applications can be seen. For this reason, large number of publications have been published since it is an important issue that has to be solved as can be seen from Fig. 8. Here the topic of antennas made up around 47% of all publications found on the Scopus database and the data seen has been collected from 2020 to 2023 [10]. It can be seen how prevalent the issue is since just almost half of all publications talk about the issue of communications.

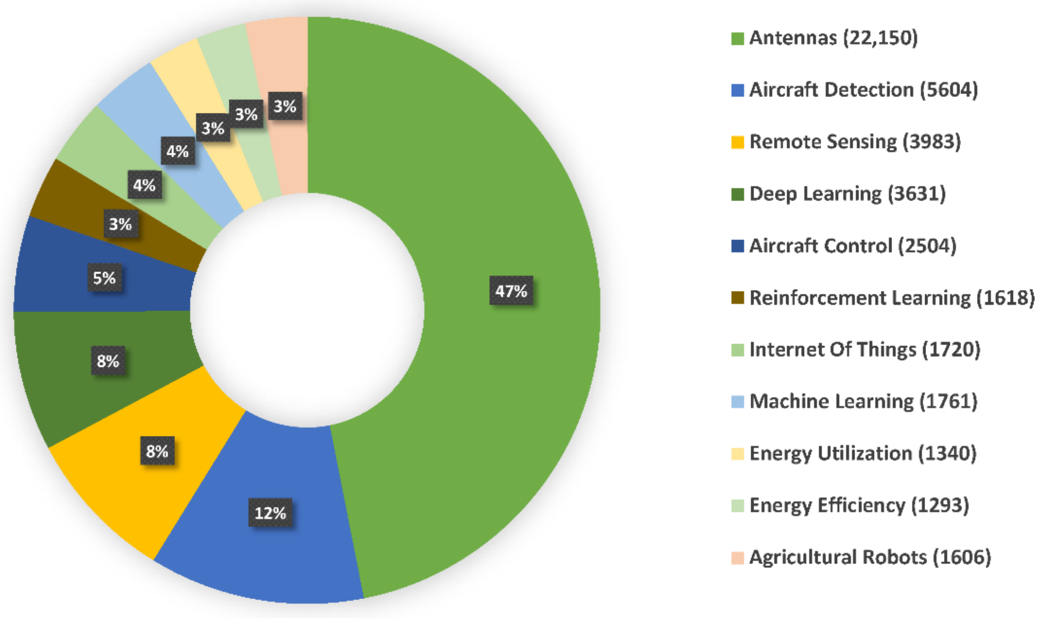


Fig. 8. Pie Chart of UAV Research Distribution [10]

Additionally, in [10] it is also discussed that that there is a large overlap between different areas of research most notably the antennas section. This is due to the high dependence of communication in drone technology since a drone can potentially collect incredible amounts of data ranging from simple visual data to point clouds created through LIDAR technology. However, the bandwidth, stability and sufficient range of communications are the limiting factors that still constrain the technology. As data collection and complex control for drones could allow it to perform more complex and useful task. This is illustrated in Fig. 9, where the previously mentioned overlap of research areas can be seen. Here the most notable section is the AI, which showed how computationally demanding the technology can be and how difficult it is to accommodate. However, it also signifies the importance of this technology for future drone control. As for drones to operate at least semi autonomously it is necessary for it to have object avoidance, which requires the drone to first understand the data provided to it and then decide how to avoid obstacles. As computer vision is categorized as a field of artificial intelligence.

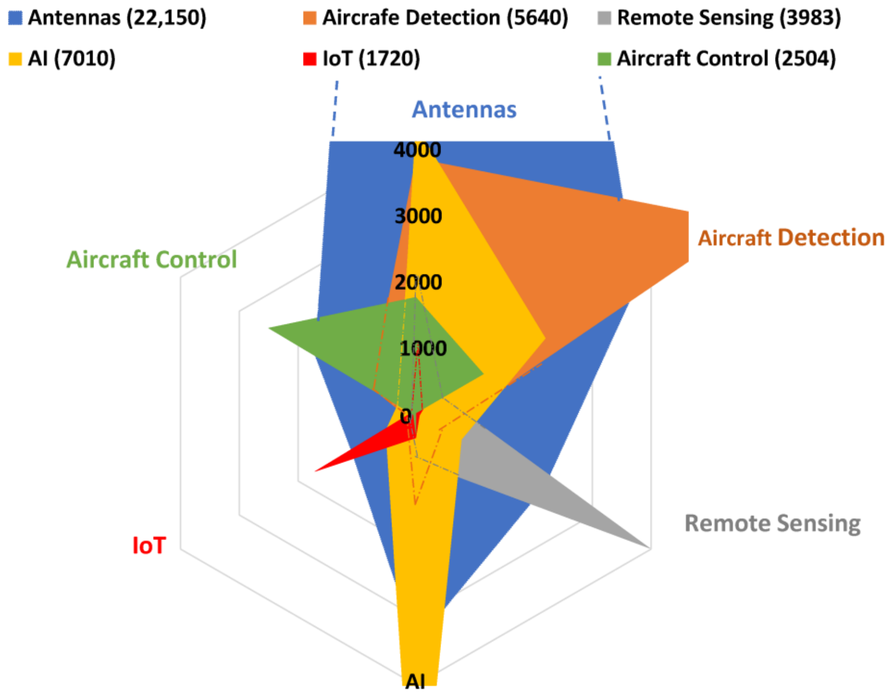


Fig. 9. Distribution of Overlap Among Different Topics for Drone Technology [10]

The implementation of such technology is expected to lead to development of many new sectors for drone technology and can revolutionise how it is used. For example, if precise and safe control can be achieved in drone technology many doors can open up for not only currently developing technologies, but also already implemented ones. One example of an already implemented technology is drone package or food delivery. While these technologies are currently only tested on a small scale the growth of at least the food delivery industry is set to rise 9% annually between the years 2025 and 2030 [11]. While reportedly in major cities the food delivery industry has already increased the congestion on the roads and has increased the emissions due to the frequent usage of cars to make deliveries. By making drones more reliable this problem can be significantly decreased since a drone is by far more efficient, when considering the energy required but it also allows for faster deliveries overall since drones do not use roads and therefore traffic does not affect them. Which can decrease some of the existing problems related to food delivery. Additionally, by pairing the potential market of drone package and food delivery sectors a real impact can be created in the environment. Since these can greatly reduce the emissions created by these industries, since the delivery industry alone makes up 7% of all greenhouse gasses emission in the USA [12]. While for package delivery drone usage is not always be suitable due to the size or perhaps the nature of the package as well as drone power storage limitations. There are suggestions to use them as an addition to currently utilized methods of delivery. The idea for this can be seen in Fig. 10. Here the drones are be used along with traditional trucks in order to make deliveries. The truck can drive where drones cannot deliver the required packages, while the drones automatically deliver packages to other points of delivery around the truck. This decreases the need for large energy storage for drones and results in increased efficiency of the entire process. However, to implement this object avoidance, precise landing and enhanced communication capabilities are required. Since the drone needs to leave the trucks, while avoiding the trees and houses that might surround the area around the truck. Then to land at customers location, which in most likelihood do not have a designated spot for drone landing in order to deliver the package. So, the drone needs to be capable of performing these decisions and afterward find the truck it left and go back to it again, avoiding the obstacles in the path.

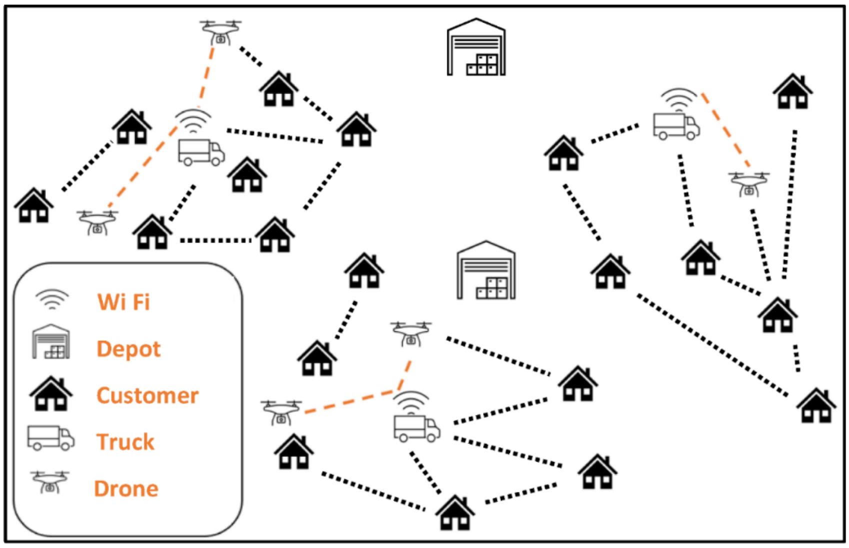


Fig. 10. Drone Delivery System Visualization [12]

This requires stable communication with the truck to be ensured. Which could possibly be achieved due to existing network infrastructure in urban areas. However, for scarcely populated places to implement this method of delivery can be incredibly dangerous and, in most likelihood, it is impossible with currently utilized methods. Since with no insurances that a stable signal can be received due to infrastructure the safe operation of the drone can’t be ensured. This requires the trucks to communicate with the drones directly and not through the use of cellular networks. Which again brings up the problem of antennas used for communication and is the reason why in this work the paper is focused on a solution that do not require infrastructure to increase drone operation range since this adds a lot more flexibility to the solution.

1.4. Chapter Summary

As the drone market is experiencing incredible growth in multiple sectors and is expected to grow by 12.5% annually. It is important to decrease the risks and downsides of drone technology. The main downside that is focused on in this study is the range and bandwidth of drone communications. Since by decreasing this problem drone technologies can be more widely utilized and offer more reliability along with expanding the drone’s capabilities. As with a stable and high bandwidth connections the use of neural networks and cloud computing is possible. Which is why improvements have to be made to drone communications in order to allow these technologies to see widespread implementation. In particular this is important for implementations in rural environments without cellular signal infrastructure and with obstacles that could block the signal.

2. Drone Connectivity Technologies

To solve the described problem, it is first very important to have a deeper understanding of the communication frequencies used in drone control. In general communication frequencies can be divided into three main types categorized according to their function:

- Control
- Telemetry
- Large data transfer

While there is some overlap in this classification due to several technologies being able to perform well under every category presented here, it must be said that each and every single one of the technologies have trade-offs and the there is no perfect communication type. Each communication type is highly situational, requiring to first analyse the situation before implementation can be performed. For drone control the most commonly used method of data transfer is RF (radio frequency) data transfer as this allows to control drones from a large distance. Since it can ensure good connectivity and small latency. Allowing for quick action execution even at significant distances. While control can be performed with most technologies that have high distance and low latency however none are as flexible as RF.

For transferring telemetry data in most cases RF is used as it typically ensures a good range of the connection, however the data transfer rate is quite small which makes it perfect for such implementation. For receiving the position of a drone in often cases LoRa connections are used since these have a typical range of up to 15km making it incredibly reliable for drone operation far from the pilot. In addition to this its power consumption is typically lower than even RF communication, however this type of communication has incredibly low bandwidth and high latency. This means that its usage is limited for providing low data telemetry data such as GPS data or drone’s operation status or simple commands to the drone.

Higher frequency RF connections can allow video feed or receiving constant data from other sensors. However, this results in higher power consumption and a decrease in effective range, making it more constrained but having greater capabilities in data transfer. A communication that easily achieves greater data transfer rate is Wi-Fi since this can provide up to 600Mbps speeds with low latency as well, however this is even more constrained in terms of range than high frequency RF connection. Additionally, the power consumption is a lot higher for Wi-Fi than RF. However, in terms of data transfer speeds neither can compete with 5G connection, however this results in equally significant limitations as infrastructure is required for this technology’s operation.

2.1. Types of Common Drone Communications

Drone communication types can be divided into:

- Ground-to-air
- Air-to-cloud
- Air-to-air

These types vary greatly from one another as their purpose, reach, data transfer rate and usage are quite different. The first type analysed is the ground to air control, since it is the most commonly utilized communication type. For this type of communication data exchange is established by using a ground station [13]. This type of communication is the simplest to establish. However, while this communication type has remained popular it has some limitations. The first limitation is that in most cases the communication range is lower than expected. This is because an operator on the ground can experience many obstacles that obstruct a connection to the drone [13]. For example, due to the lower elevation than the drone a forest can greatly decrease the distance of communications even if the drone is flying above it as direct line of sight is still blocked by the canopy. To counter this problem directional antennas are often employed to extend the range of communications when the need arises for large distance communications as otherwise the degradation of signal could quickly block the connection to the drone entirely.

The second type air to cloud communication that was briefly mentioned before relies heavily on cellular tower infrastructure or satellite networks. As the drones in this case require incredibly high bandwidth. Drones gather data and then send it to the cloud, where this gathered data is processed. A diagram of this control expressed schematically can be seen in Fig. 11. Here there are three layers that describe this method, the terrestrial network layer that provides access to internet and cloud servers, the aerial network that is made out of drones providing sensor data and the user layer where use cases of these drones are shown. This method allows for most complex control of a drone since machine learning and AI can assist in controlling a drone in order to achieve the best possible results. However, the technology hinges heavily on cell tower infrastructure or satellite networks. This is a problem since utilization of this technology in rural, scarcely populated areas with limited or no infrastructure is impossible without cell tower support. While satellite networks could be used to control drone these usually have high latency this can be problematic since it is unintuitive to fly such a drone as significant delays are experienced for every action which is why in most cases this is used to issue commands for the drone to perform while not having “direct” control over its movement. Additionally, this control method requires to ensure good sky visibility as any obstructions above the drone can lead to signal loss which can be problematic. This also means that for surveillance purposes it is be hard utilize this technology since signal loss in forests can be a major problem.

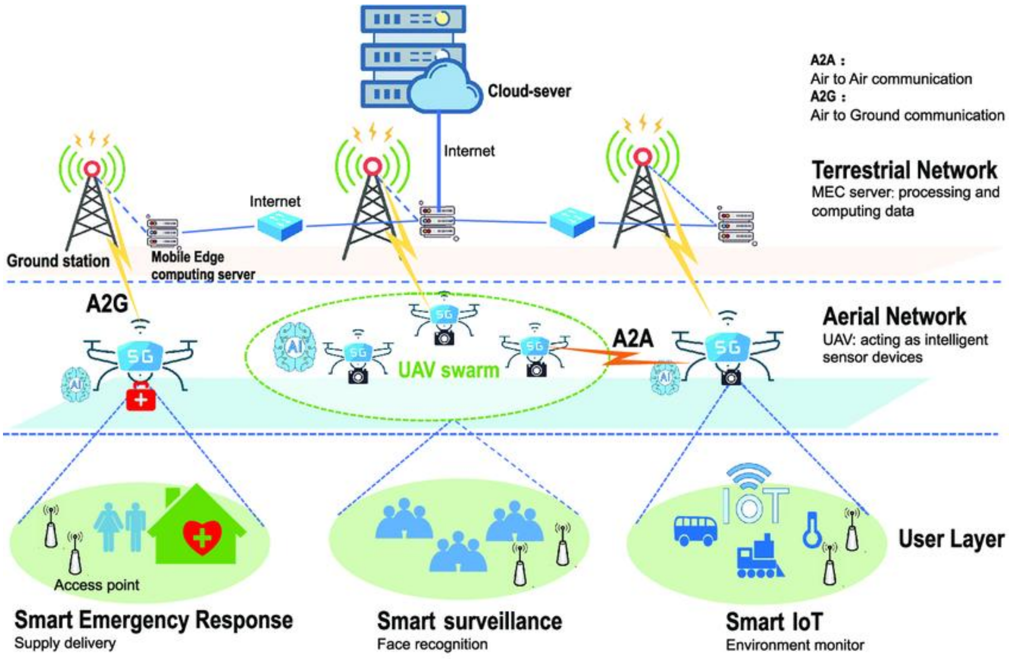


Fig. 11. Air-to-Cloud Communication [14]

The third type Air to air refers to the direct communication between drones in order to transfer data or provide commands. This type of communication has begun to quickly gain traction as the technology allows for the communication and coordination of drone swarms [13]. In the scenario of drone swarms, the drones can communicate in short range communication methods such as Wi-Fi in order to transfer large amount of data through drone made networks. This method can be quite useful when multiple drones are used as the coverage of signal can be ensured over a wider area. This can be seen in Fig. 12 where at the highest layer there are fewer drones providing instructions to other drones in the network and this data is shared from one drone to the next until every single one of these drones has received the data. This also increases the efficiency of drone communications, since the drones do not need to have high power antennas that can extend the range for receiving and sending signals by expending more electrical power for communication. However, this method requires complex control of the drones to make sure that sufficient coverage is ensured for all drones and that no collisions between devices can happen. As this has been a problem that has plagued drone swarms for a very long time it also affects drone-to-drone communication. This means that safety of the technology is difficult to ensure for large scale implementation. While the fewer drones are used the less dangerous it is be but the problem will not be resolved completely. Another problem that may arise from said technology is the difficulty in establishing stable connections. Finally, the main difficulty is ensuring this communication over large distances, since if the drones have overall low communication distance and communications that need to be performed over great distances can be problematic as latency and packet loss can be significant.

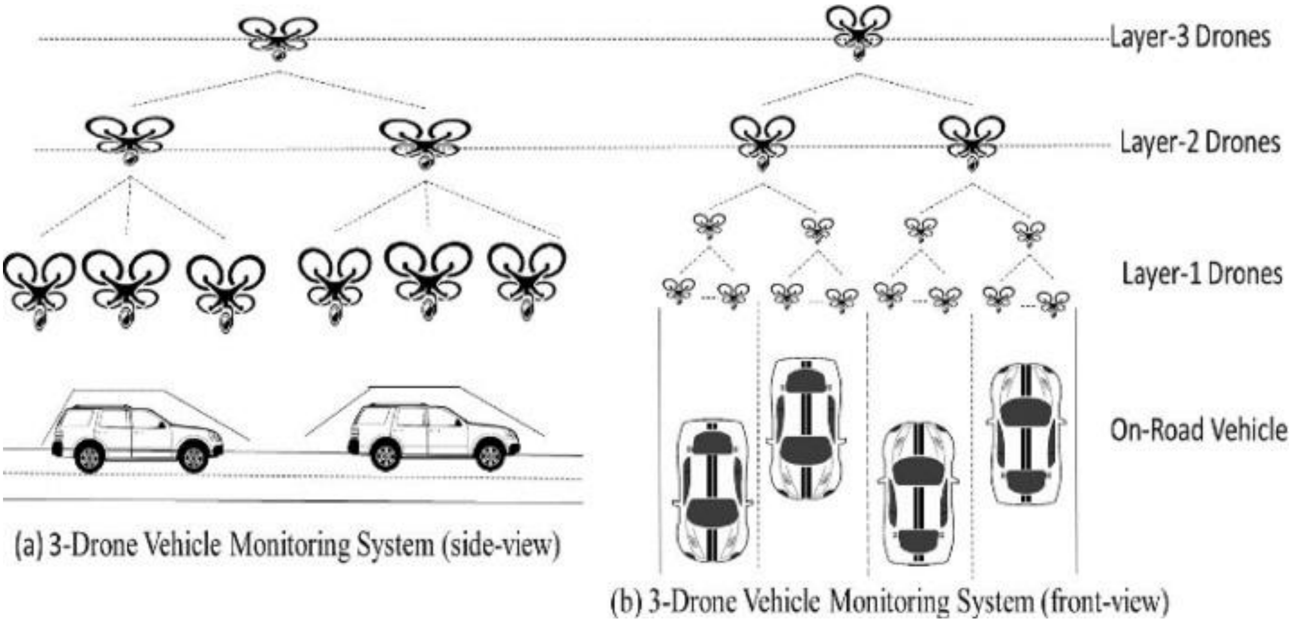
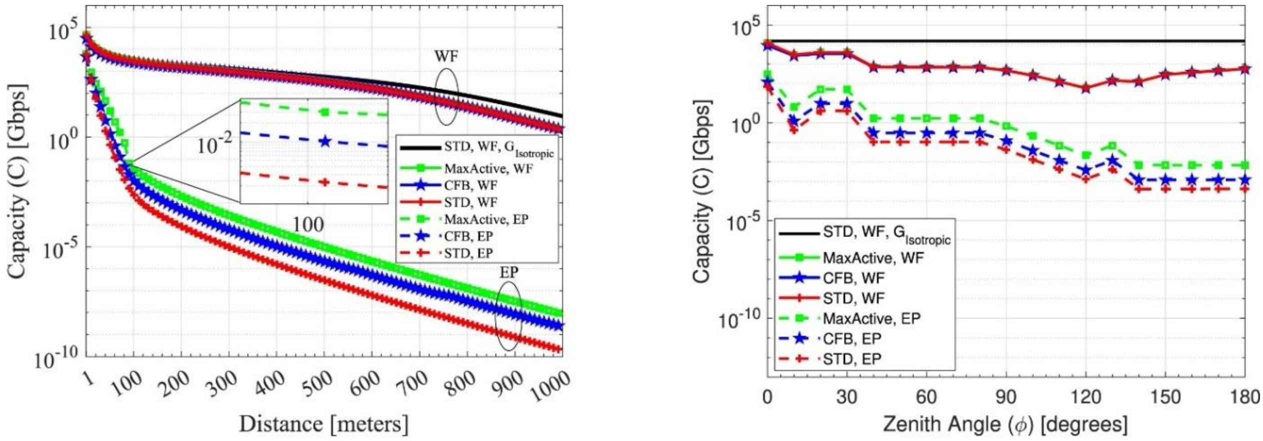
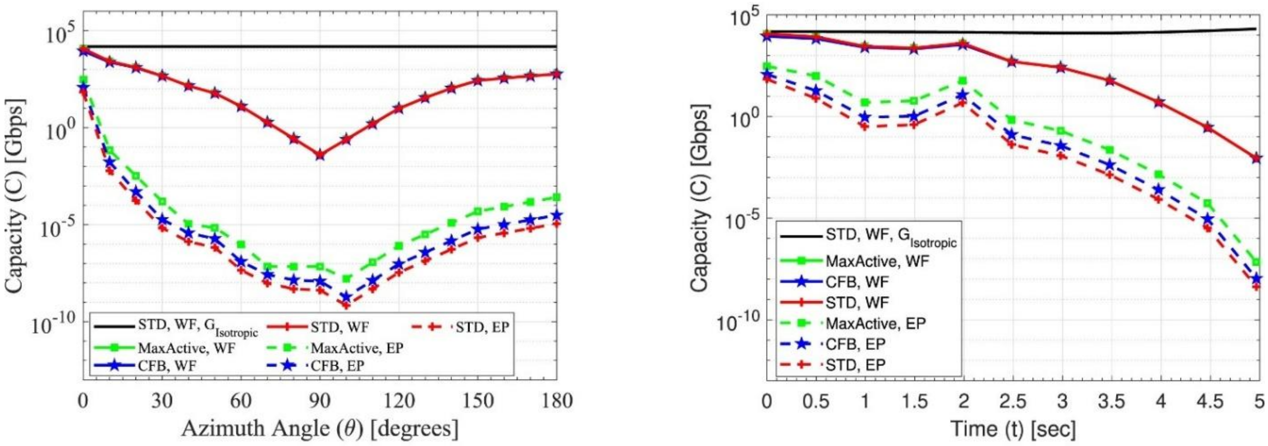


Fig. 12. Air-to-Air Communication [15]

To better understand how big of role is played by distance and drone positioning in this technology an illustration of the effect of drone's bandwidth under different situations is presented in Fig. 13. Here it can be seen that, while under small distances the bandwidth of the connection is incredibly large, while each meter of distance can greatly decrease this value. The most dramatic communication capacity decrease can be seen after 100m. While within very close proximity Gbps transfer rates are achieved at this distance it drops to Mbps capacity. This means that close proximity is vital especially since drones can fly at 10-20m/s speeds depending on the drone construction. This can result in incredibly inconsistent communication speed as one second it is in the Gbps range another in Mbps range. Then it is needed to pair it with misalignment losses since these are quite significant as well and it can quickly become a problem of complete signal loss. The only exception that can be seen from the example data is for WF (water-filling) signal allocation, which is incredibly power consuming and is deemed not suitable for implementation with current power storage solutions [16].



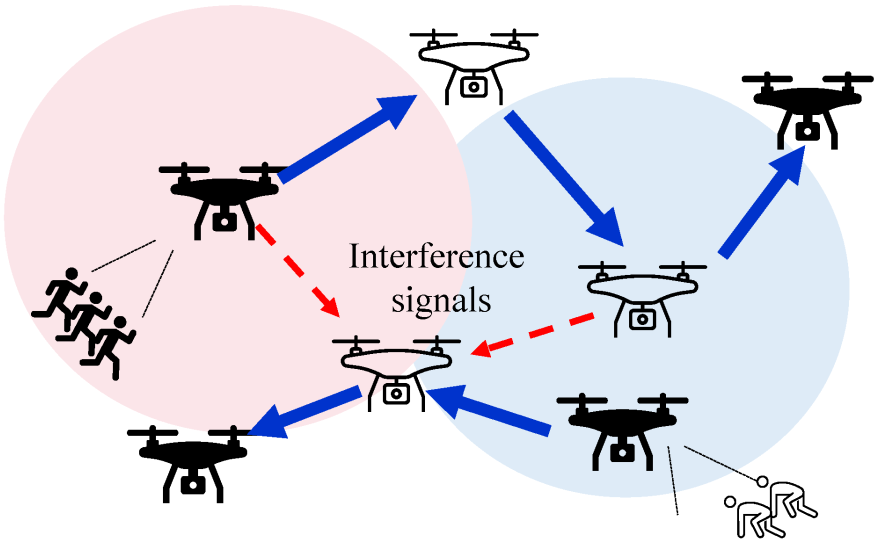
(a) Aligned (b) Misaligned via elevation



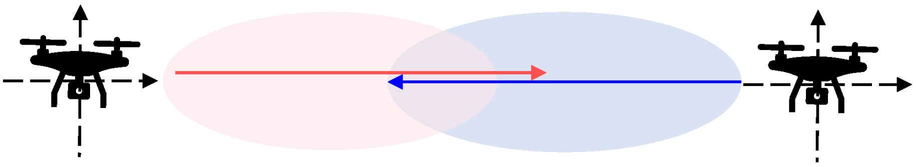
(c) Misaligned via azimuth (d) Misaligned via real mobility traces

Fig. 13. Drone-to-Drone Communication [16]

In most cases of drone-to-drone communication implementation, the method used of communicating with drones far away is to form chains of drones. Here a drone relays information from a ground station to the next drone in the line and the drones then transmit the signal in this manner until the signal reaches the intended target. However, this greatly increase the latency depending on the number of drones that make up said chain and signal interference due to other drone communications can become substantial problem. To decrease this latency and interference it is needed to increase the range of drone communication. This can either be done by increasing the gains of the antennas by increasing their power consumption which can be a problem in of itself, or by using a more targeted approach by using directional antennas. The comparison between the two methods can be seen in Fig. 14 where the a) approach uses omnidirectional communication and the b) approach uses directional beams. The distance of communication and gains of the antennas are significantly increased due to the narrowed beam width. However other problems arise due to this communication. Since here the beam is narrower that means that the beams must at all times point at each other otherwise the data transition rate can be severely decreased due to disconnection of signal [17].



(**a**) How to use a relay network.



(**b**) Relay method using directional beams.

Fig. 14. Comparison Between Omnidirectional Antennas and Omnidirectional Antennas Used in Drone-to-Drone Communications [17]

Which is why the implementation of directional antennas is quite difficult since the misalignment of antennas can be quite common. Especially considering that the drones themselves move and are not stationary in most implementation cases. This creates the problem of how to ensure alignment between two drones since misalignment can happen even if the drones are stationary simply due to the wind swaying the drones and changing their tilt. This added consideration results in the high difficulty of solution implementation as reliability is imperative for wide spread implementation. In general, the most straight forward way of decreasing these dangers hinges on the design and performance of the antenna. Since either the antenna beam must quickly and precisely react to the drone's position changes or it must have increased signal spread angle which in turn decreases the effectiveness of the solution and precise signal correct is still required even if to a lesser extent.

2.2. Antennas

In general, to solve the problem of drone communication UAV antennas are a pivotal part that defines a drones communication capability. In order for a drone to function properly many factors must be taken into account. This is because an antenna defines a drone's efficiency, bandwidth and polarization. Which is why when designing an antenna, it is important to take into account its mechanical properties such as size and weight must be kept at a minimum in order to have good efficiency. Additionally, the antenna must be aerodynamic since it can create drag that can slow down a drone during operation otherwise. Then the operating frequency dictates the overall range of communications and the bandwidth. While the polarization defines whether the signal is sent only directionally or in all directions around the drone affecting the range and the efficiency of communication, which makes the task of designing a suitable antenna a difficult one. Since optimizing every parameter is incredibly difficult. Then the placement of antenna on the drone must be considered, which can also affect the range as some interference can be experienced due to the other parts shielding the antenna.

To select an appropriate antenna for the solution, first an in-depth review must be performed for each antenna type. To ensure good performance many conflicting factors must be analysed not only on the performance parameters but also the physical size and weight since these are sensitive parameters for drones. The gain parameter shows how focused the communication beams are. While bandwidth describes how much information can be sent with the antenna. Radiation pattern describes how the radiation wave travels in space and polarization describes the orientation of the antenna’s waves. In general, the most common antennas used are:

- Monopole
- Dipole
- Horn
- Patch
- Yagi-Uda

Design wise the simplest antennas are the dipole and monopole antennas since these feature two straight conductive elements for the dipole and one for monopole. Electromagnetic waves are produced from them when current passes through the antenna. An example of a monopole antenna can be seen in Fig. 15. It is a simplistic design, however integrating this design into a drone is not always practical since these antennas tend to be fragile under vibrations and are difficult to integrate into the chassis design of drones. Much more common in drones are variations of these antennas that are planar and are omnidirectional. Such as the bow-tie design antenna that is an omnidirectional antenna that is far more compact allowing easier integration and its weight is reduced considerably. However, in most cases these antennas are not directional which makes them less efficient at long distances. Additionally, these antennas are sensitive to nearby existing structures such as the drone’s body which can make these difficult to implement [18].

Fig. 15. Dipole Antenna [18]

Horn antennas boast high gain of the antennas due to the extremely high directionality of the produced signal. This also makes them incredibly efficient as less power is required to receive high gain values of the antenna. Their shapes are most commonly conical, sectoral or pyramidal (this type can be seen in Fig. 16) as this structure optimizes the distribution for electromagnetic waves. However, this type of antenna has the downsides of having high weight and size which are extremely limited for drones

[18]. Additionally, due to the fact that these are directional these antennas have to be physically moved as the drone moves in order to ensure a stable connection between the sender and recipient.

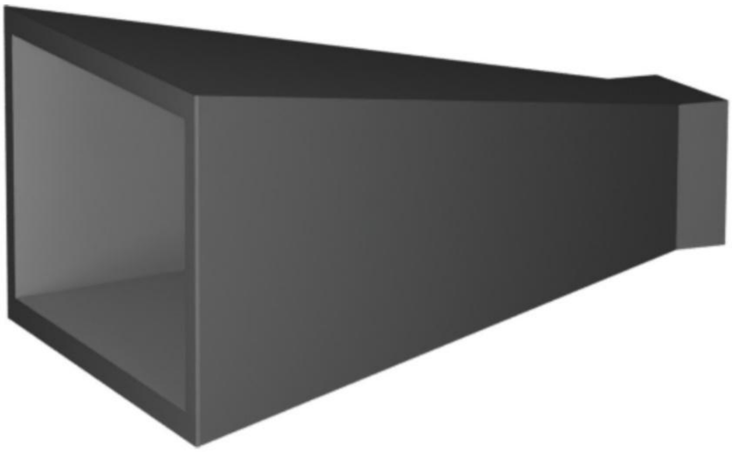


Fig. 16. Horn Antenna [18]

Yagi-Uda antennas offer high gain and low cost. This type of antenna can be seen in Fig. 17. In general, the design of the antenna is light however its dimensions are quite big. If comparing the horn antenna and Yagi-Uda antenna the horn antenna has higher gain, however it also has much higher weight. While the Yagi-Uda antenna is in general larger in size than the horn antenna. It is also highly directional however less so than the horn antenna. In general implementation of both of these antennas on a drone are quite difficult due to their size and weight, however these offers some of the highest communication distances with the lowest power consumption due to their power efficiency.

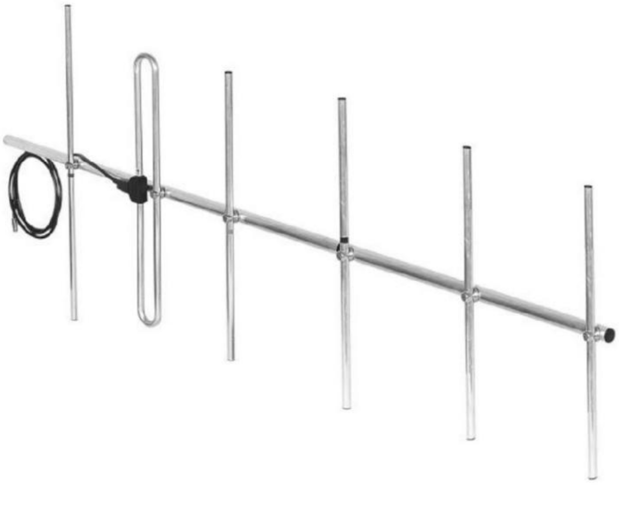


Fig. 17. Yagi-Uda Antenna [19]

Patch antennas are two dimensional antennas since these are mostly flat conductive elements as example of such an antenna can be seen in Fig. 18. These antennas are made from four main components. The patch is component that radiates electromagnetic waves its shape and size determine the antennas key characteristics. The part that supplies electric power to said patch is called a microstrip feed. While a substrate holds these elements and insulates them from the ground plane. The ground plane is on the opposite side of the patch and it reflects magnetic waves in order to form desired radiation patterns. Due to the manufacturing methods used these antennas are incredibly cheap, small and lightweight, this comes at a cost of coverage, bandwidth capacity and limited antenna gains. This makes these antennas most suitable for low-cost mass manufacturing as their performance is smaller as compared to the other described antennas. However, these antennas offer unique benefits such as conformal shape of patch antennas allowing to integrate them directly along curved surfaces of a drone improving aerodynamic performance of the drone. The fact that these antennas can be made to be reconfigurable is also a big advantage as it can allow the antenna to change their properties during operation without the need to physically change the antenna’s design in order to get different properties of operation [18].

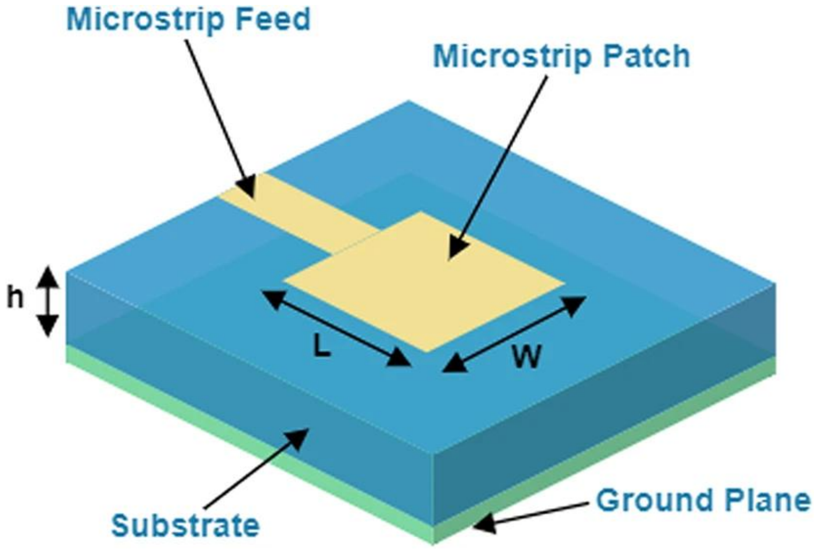


Fig. 18. Patch Antenna [20]

Under varying conditions reconfigurable antennas can achieve the best results. This is because antennas can change some of their properties depending on the current needs or the environment of the drone. These are categorized depending on how the antenna properties can be changed. In Fig. 19 reconfigurable antenna types are presented.

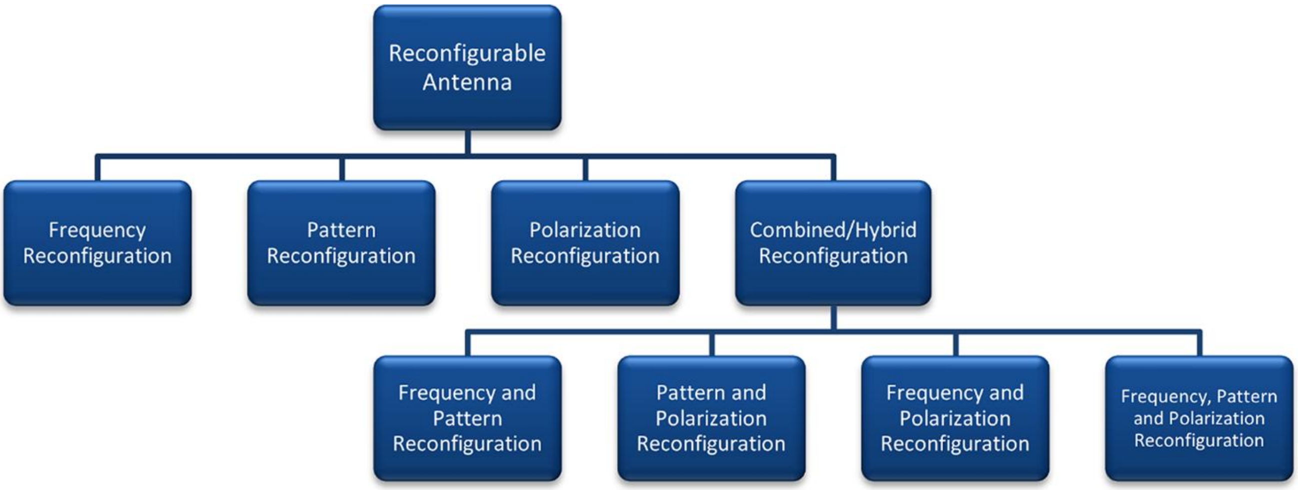


Fig. 19. Reconfigurable Antenna Types [20]

The first type frequency reconfigurable antennas allow to freely change the frequency. This gives the communication adaptability as if the drone is close by the frequency can be kept high in order to have high data transfer, however when it is further away it may be better to switch to lower frequency that allows for longer communication distance at the cost of better data transfer. The antenna does this by switching different parts of the antenna on or off or by physically changing the length of the antenna in order to get the required frequency. Pattern reconfigurable antennas are mostly used to change the radiation patter of the antenna. This enables better connectivity as when the pattern is towards the receiver a more stable connection can be achieved. To perform this in most cases either the dipoles or the antenna itself is rotated in order to tune the signal. For polarization reconfigurable antennas the antenna polarization modes can be changed. This allows for more stable connection as it allows it to account for the mismatch that is created due to the drone’s movement. Finally, the combined or hybrid reconfigurable antennas allow to change multiple parameters in order to ensure the best possible working conditions. As the antenna can change multiple working conditions in order to get more precise beam steering, to ensure better frequency tuning and making the radiation patterns match with the receiver [20]. However, these antennas are not widely utilized due to the complexity of their usage, their high production cost and their often-higher power consumption. Which is why the availability of these antennas is quite low.

2.3. Antenna Tracking

Antenna tracking is a very convenient tool that allows use of directional antennas for communication. Most drones have patch or panel type antennas imbedded in them these are considerably weaker than larger directional antennas such as Yagi type or parabolic dish antennas. This is because these antennas are much more power efficient and can ensure signal at larger distances. The antennas concentrate the signal and spread it at a much smaller angle. However, this narrow beamwidth introduces a challenge to the system. As high-speed tracking is needed due to the high drone speeds. Additionally, after losing the signal it can be difficult to reestablish communications since the narrow beamwidth means that if signal is lost the tracking antenna can no longer know the targets position and correct the heading of the antenna. Which is why various approaches are used to accurately direct the antennas in the correct position and ensure that the target devices are followed closely. This is why these are typically implemented in ground stations rather than the drones themselves. Nevertheless, two main approached are considered for antenna tracking operations. Ground-to-air the most common one, where a ground station relies on sensor measurements and comparison of signal strength to the UAV [21]. The second approach is air-to-ground tracking this approach is not as popular since the tracking is performed by an airborne platform. In one particular example to simplify this process two antennas are utilized one omnidirectional antenna used for antenna tracking and a directional antenna for the actual communication [22]. Still due to limitations such as requirement of line of sight between sender and receiver the approach has not reached wide spread implementation.

For antenna steering it is also worth mentioning the mechanical steering is not the only available option. While it is the most popular method it has its downsides. It suffers from high energy consumption and wear since it has to constantly move requiring additional power and maintenance. These downsides can be solved by using electrical steering, since here instead of physically moving parts, electrical control is used to direct the signal. This is done by controlling the phases of antenna elements, this allows signal to combine in one direction while destroying signal in other directions. This makes the approach must faster, since no mechanical parts must turn and decreases maintenance costs. However, its disadvantages are its high complexity, high signal losses and low efficiency.

An example of a commonly used ground-to-air systems that uses mechanical steering can be seen in Fig. 20. Here the antenna uses a RF (Radio frequency) in order to communicate with the UAV. This is done by the use of a steering system that can rotate the antenna so that it can constantly keep the UAV aligned with the antenna order to get the best possible connection between the ground station and the UAV. To direct the antenna strength-based steering is utilized this means that it constantly adjusts its position in order to achieve the highest possible signal strength. In order to do this the system has two degrees of freedom. One is for adjusting the device in the azimuth while the other accounts for elevation.

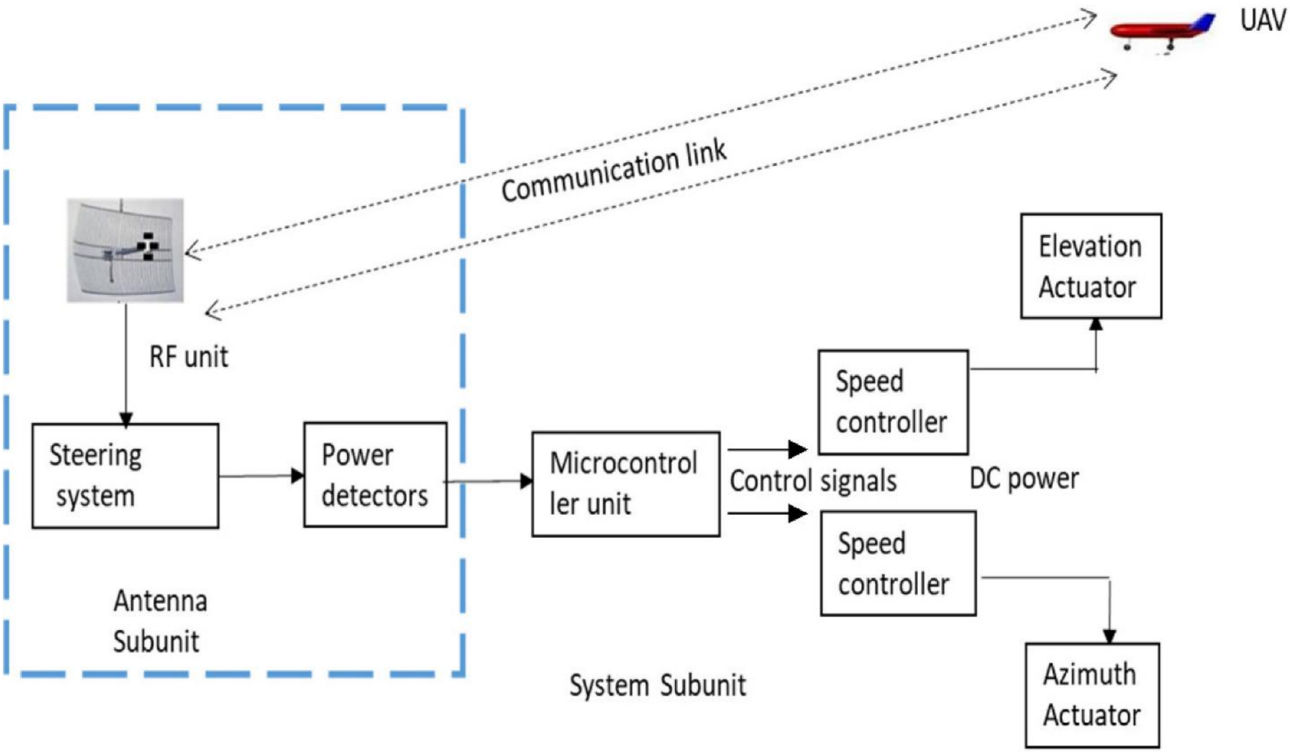


Fig. 20. Directional Antenna Steering System [21]

Another example of a successfully implemented antenna tracking system is described in [23]. The implementation is quite similar to the previously discussed method, however here the system uses its own GPS and the telemetry received from the drone in order to correct its position in comparison to the previous system [23]. This allows it to maintain more accurate alignment with the target. A Pixhawk controller is mounted directly on the moving part of the antenna tracker so that the controller is pointed in the same direction as the Yagi antenna that is mounted on the moving mount. The Pixhawk controller is used to directly control the servo motors used for the operation. A compass is used to know the current bearing of the antenna and a GPS is used to determine the position of the ground station. The device can then be connected to a computer in order to control the drone and to track its position via the received drone telemetry data. Its construction allows for 180 degrees of rotation on the horizontal axis in both directions ensuring 360-degree coverage and a total of 180 degrees pitch control. For controlling the antennas pitch two methods can be used with said setup, one using only GPS tracking and another using barometric tracking. This is done by using air pressure sensor on the drone, this allows the drone to transmit its altitude to the ground station, which can allow to determine drone’s position in the vertical plane even without drones GPS signal allowing to increase connectivity of the solution under thick canopy.

2.4. Tethered Drone

A unique technology that has branched off from the drone technology is tethered drone technology. Here a drone is physically connected to a ground station. Research of aerial tethered systems has been in use since the 60s. This includes the use of balloons, fixed wind air craft and air foil UAVs with tethers, however the simplicity of multirotor UAV’s have made these the most prevalent in recent years. The most common issue with drones is the limited flight time of a drone. Since a drone flight can take up to 40 minutes at the upper limit after this the batteries of a drone requires recharging. This process of recharging is incredibly time consuming and the time a drone can’t operate highly depends on the construction of the drone. Since some batteries can quickly be replaced, which allow to use a drone more frequently and the second type has batteries that can’t be physically replaced without disassembling parts of a drone. This can lead to downtime of several hours between flights greatly decreasing the effectiveness of drone solutions. However, by utilizing cables from a ground station flight of a drone can be sustained almost indefinitely since recharging of batteries in not required. This allows consistent performance of the system since the drone only needs to land in order to do routine maintenance or if there is problem with the function of a drone. However, tethers not only provide electrical power but also signal. Since in most cases the tether consists not only of the power cable but also includes an optical fibre cable ensuring maximal bandwidth and stability. An example of such a cable can be seen in Fig. 21. Here two copper cables are used to supply electricity and optical cable is used for connectivity. These are then enveloped by an external insulation that provides protection and Kevlar harness that provides tensile strength to the tether since for smooth operation it should always be pulled taut. This is done in order to avoid oscillations and make the control of the entire drone more predictable.

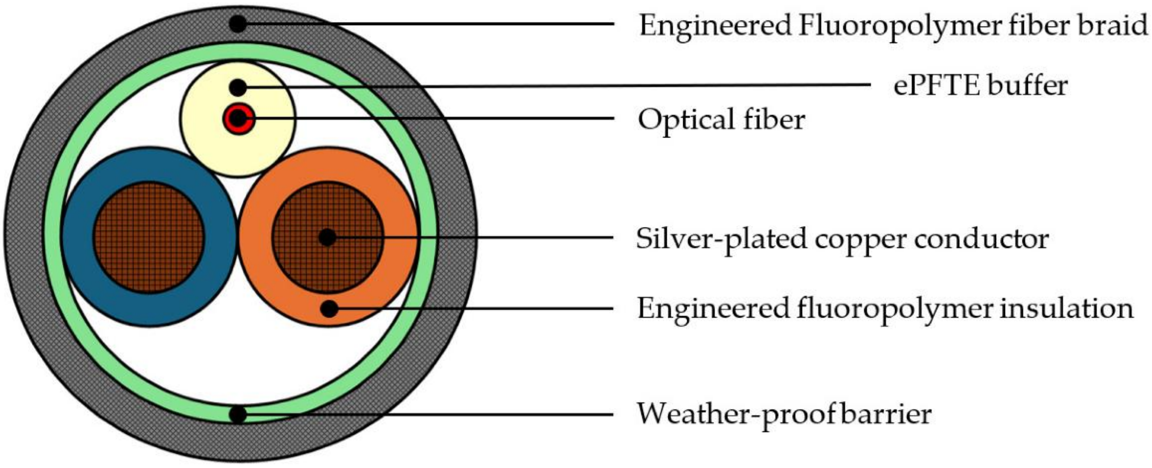


Fig. 21. Tether Construction [24]

For the purposes of this paper the focus is on the usage of drones as relays as in [22]. Since drones can function as small network tower alternatives. Their main advantage is that these can be easily redeployed to other locations. This allows to get widespread connection with no existing infrastructure in the area. Since tethered drone can be lifted 100m or even more depending on the drone. This way avoiding most ground obstacles that could hinder the propagation of signal in the area. Drones in this case mostly use omnidirectional antennas that spread the signal almost evenly across a wide area. Additionally, the drones can move and this way correct its position in order to either avoid obstacles that could be blocking a signal in one direction or to change the altitude of the drone this way either decreasing the effect that wind could have on the drone or to increase the spread of signal. A simple scheme of how the system could look like is presented in Fig. 22. Here the is receiving power and is connected to the internet via the ground station. This signal is then spread in an area and can form networks either with network towers or other tethered drones.

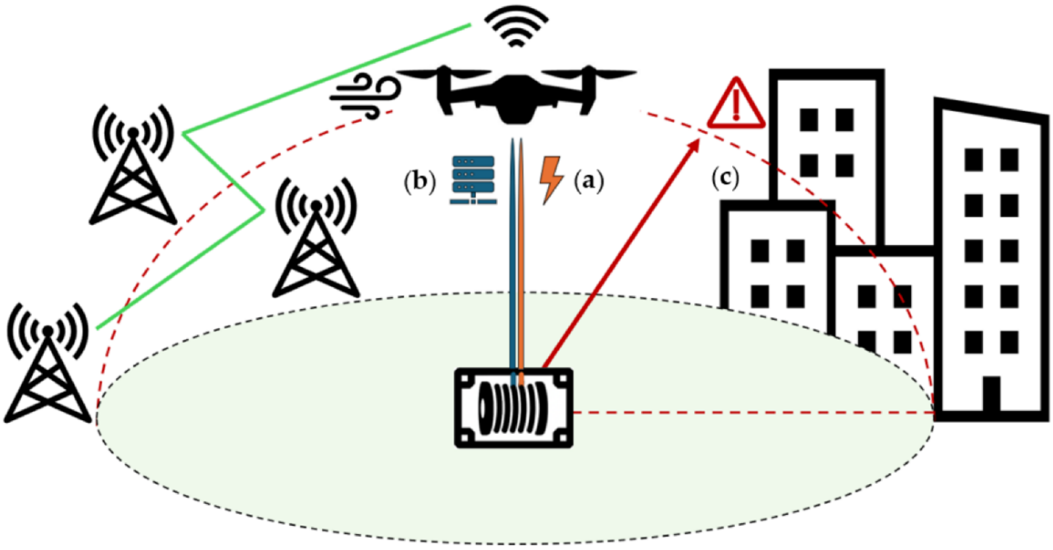


Fig. 22. Tethered Drone System [24]

However, this technology has some drawbacks since the drone has to be able to have a large payload capacity in order to be able to carry the wire. The tether can weigh several kilograms depending on the length of it. The drones themselves are restricted to a spherical area above the ground station. Additionally, the winch that pulls the tether taunt requires complex control since it has to always keep it in tension so that the stability of the drone can ensured.

2.5. Chapter Summary

This section described the methods used for drone control, discusses advantages and disadvantages of different antenna types while also overviewing ways how communication range could be extended. The main communication types found were ground-to-air, air-to-air and air-to-cloud. Each of these have different advantages and disadvantages that must be taken into account. While ground-to-air often has greater range, greater signal reliability and more available power at least for the ground station. It also is highly dependent on line of sight and has coverage limitations. Air-to-air could offer dynamic networks, potentially large coverage and efficient drone communications. While also having incredibly complex control and multiple possible points of failure as failure of one drone could disrupt the entire network. While the last type air to cloud can allow for complex control and boasts highest processing power due to cloud access. While having the disadvantages of high latency of communication, direct control unavailability and requiring incredibly stable and high bandwidth communication which is difficult to ensure. From this it was found that ground-to-air and air-to-air methods offer the greatest communication distances depending on the situation. For the solution many antenna types were overviewed and it was determined that for the solution using highly directional antennas offer the greatest signal strength increase. Antenna tracking methods for directional antennas were analysed in order to implement similar methods in design section as these can allow to steer the directional antennas in order to ensure a constant and stable connection. Finally, while tethered drone applications were analysed since it constrains the drone it is not suitable for implementation in this case.

3. Drone Antenna Tracking

To increase the communication distance, it was decided that a directional antenna setup is the most suitable since it could greatly increase the communication range without increasing the power consumption. As changing the transmitter and receiver power values is undesirable (except for ground station antennas) and change of used frequency greatly affects the bandwidth for data transfer, which can dramatically affect the data sharing capabilities of a drone. The described values are the main parameters affecting antenna power as can be seen in Eq.1. This power relationship dictates that by increasing antenna gain it increases the received power proportionally [25]. Which is why instead of increasing the power supplied to the antennas it is more beneficial to increase the concentration of this power in the desired direction in order to improve its performance.

$$\frac{P_{Rx,FS}}{P_{Tx}} = G_{Tx}G_{Rx}\left(\frac{C_0}{4\pi f d}\right)^2, \tag{1}$$

where: P_{Tx}- the transmitter power; $P_{Rx,FS}$ – received power in free space; G_{Tx}- antenna gain of transmitter; G_{Rx}- antenna gain of receiver; C_0- speed of light; f- frequency of signal; d- distance between antennas.

Most existing setups have directional antennas with tracking systems on the ground. Since these can be relocated and can have large power capacity or direct connection to power allowing these to work without many power constraints that drones face. In this work the use of directional antennas installed on moving drones is explored. This allows the antennas to be positioned above foliage or infrastructure that could potentially block the signal and to ensure more consistent line of sight with the targeted drone. Additionally, because these antennas are installed on drones the added benefit would be that these can be positioned freely at desired locations. As compared to ground stations that are mostly stationary and can only be moved manually. This offers improved sensor functionality that can allow for more accurate measurement and ensure uninterrupted data collection. In particular this applies to GPS systems and magnetometers since GPS modules can experience signal loss due to obstacles and nearby infrastructure and electrical lines can affect the data from magnetometers due to their high sensitivity to the magnetic field.

The use of directional antennas on drones is not a new concept [26]. However, these are not commonly utilized due to the constant changes in drones' orientation that could result in signal loss. To counter this, it becomes necessary to implement tracking systems that could allow antennas to follow their targets. This requires the use of systems similar to those found in ground stations. These tracking systems therefore add additional weight, power consumption and also significantly increase the complexity of the solution. Additionally, this introduces additional points of failure for the drone. As for drones' communication failure even with omnidirectional antennas is quite common it creates significant problems. The stability of a drone can also be significantly affected due to quick turning of the tracking system depending on the design of said system. As the quick turning of large antennas can create additional oscillations that can affect the drones' performance. Then it must be considered that for many drones to install such antennas heavy modifications of the drone's structure must be performed. This is why the goal is to have a device that is easily installed on to existing drones without greatly impacting the drone's capabilities. Which is why it is preferable to mount the finished device underneath the drone in between the landing gear. Since this allows to achieve more widespread use since mounting the device at some other location requires extensive design changes, while at most the device here can require changes in the landing gear.

3.1. Component Selection

In order to validate the use of directional antennas in a standalone device that is mounted on a drone testing was performed. The experimental circuit made in order to test preliminary performance can be seen in Fig. 23. Here the sensors are powered via the Arduino itself and the servo motors that are used for adjusting the angle of the antenna are powered by a battery pack that provides a supply of 6V. For testing an Arduino mega board was used as the control and processing unit. However, the use of batteries is only used for testing purposes. For implementation power should be supplied to the drone itself with step down converters used to power Arduino and the motors as the voltage of a drone's power supply has higher voltages than it is allowed for selected components. This way greatly decreasing the weight of the device since additional batteries are heavy. Additionally, it should be noted that the final device directly transfers the data through ethernet connection to the drone.

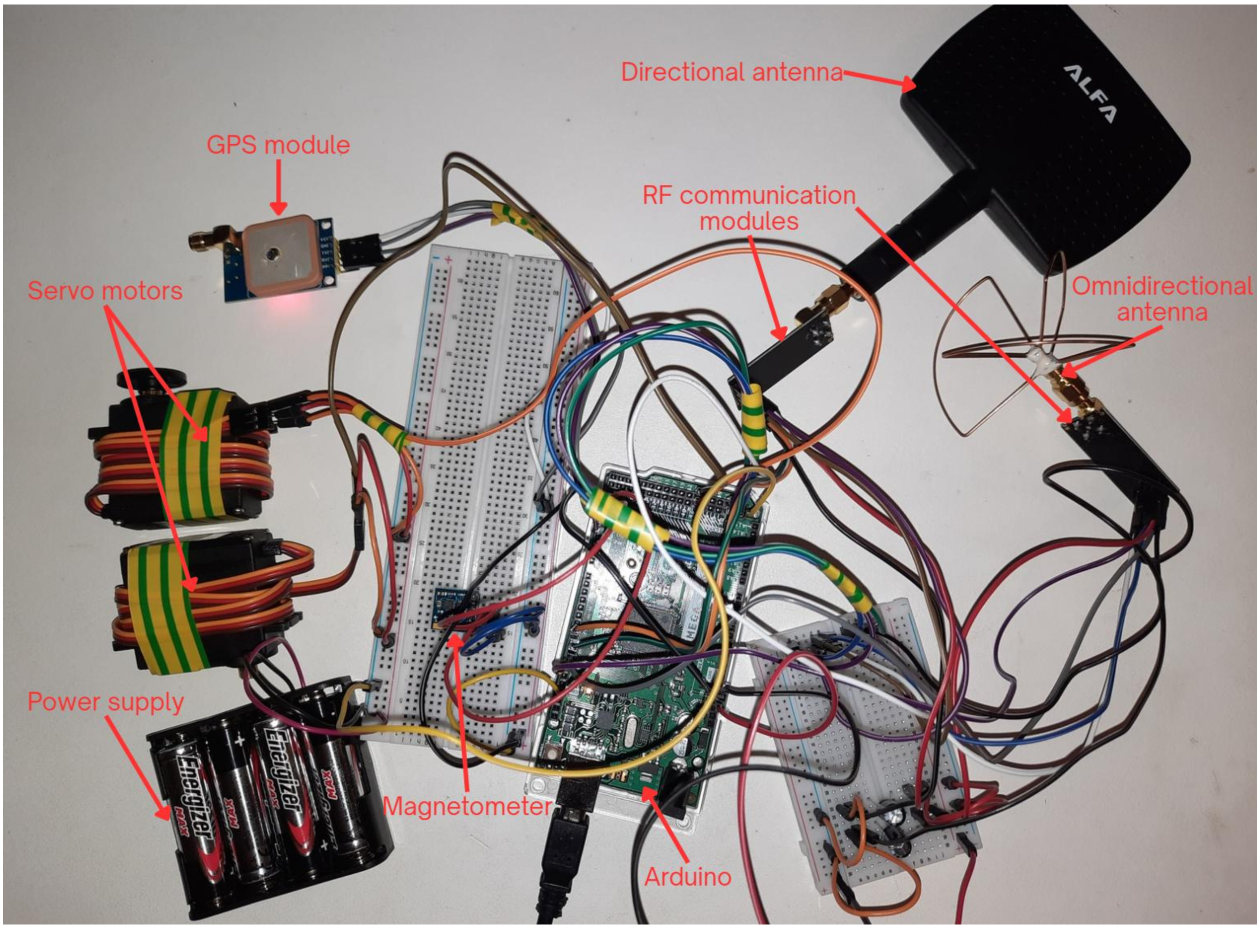


Fig. 23. Experimental Circuit

In order to make an antenna tracking system first it was important to determine the most suitable method for antenna tracking. In general, the main tracking methods are:

- Signal strength-based tracking
- Array based tracking
- Inertial tracking
- Geometry based tracking

Signal strength-based tracking is one of the simplest methods of tracking solutions. It is based on RSSI (Received Signal Strength Indicator) where it is assumed that a stronger signal means that the transmitter is closer to the receiver. This can either mean that these are physically closer or that the directional antenna is pointing more accurately at the receiver. These systems are easy to implement in existing systems since changes are only required at one end of the connection to improve connection. This is because the system does not require any additional data from the paired device as RSSI is measured at only one end of the connection and the antenna is moved in accordance where the maximal signal strength is recorded. This is done by slightly moving the antenna in different directions and then moving said antenna to the direction that offers the largest increase of signal values until a maximal value is reached. However, this method is not useful in this case since fast response times are necessary for drones, which can be difficult to achieve. Additionally, since no data from the paired device is provided for this system, it is susceptible to multipathing effect such as signal bouncing off nearby objects and confusing the antenna on where the paired device actually is. This can make accurate positioning difficult to achieve and thus was not selected for implementation.

Array based tracking uses an array of antennas to determine the direction of the signal source. The system works by comparing data from multiple antenna elements in order to estimate the source of the signal. The determination is done either by using the phase difference of these antennas or the difference in the arrival time of the signal. By using this data, the signal angle of arrival can be calculated. With it the antenna can be moved to point more accurately toward the recipient or transmitter. Which is why these types of systems can achieve greater accuracy, however this comes at the cost of higher complexity, costs and most importantly for this implementation higher power consumption and larger volume. So, while implementation is possible with said method it has several downsides, which makes their implementation on drones quite difficult.

Inertial tracking is a method based on internal sensor reading rather than radio signal or GPS. This is done by utilizing accelerometers and gyroscopes in order to determine the current position compare to the starting position. This method boasts fast response time and high reliability due to lack of reliance on external signals. This allows it to function in areas where stable connection could not be ensured. However, it has one major drawback, which is signal drift. This occurs even if sufficient filtering of data is performed due to the continuous integration of sensor measurements. As it introduces tiny errors that over time build up and can create large drift of values. Which is why in most cases these are utilized with GPS tracking to correct the position and magnetometers to correct the bearing of the drone. The fact that for implementation, accurate positioning for both the receiver and transmitter are needed complicates this approach. Since accurate antenna positioning can only be ensured by continuously sharing accelerometer data and then correcting it with GPS data. This will increase the bandwidth required for positional data exchange.

Finally, geometry-based tracking uses known geometric relations in order to measure distance and angles of elements in the system. These systems often use GPS data to determine the absolute position of the objects and can then be used to determine the relative angle between the two points on the absolute plane. To get the relative bearing between the two points, magnetometers are often used to determine the magnetic bearing which allows to calculate absolute bearing between the two points based on both GPS and magnetometer readings.

From reviewing the different methods, it was determined that for this work geometry-based tracking is most suitable and thus was used. This is because signal-based tracking can’t ensure high accuracy of tracking as it is much more suitable for slower systems with less possible interference. Array based tracking increases the power consumption which is not desirable as the power consumption is increased just due to the fact that motors require to physically move the antennas, therefore increasing it further is detrimental. While inertial tracking offers extended functionality, where signal loss is experienced, it can still experience connection loss with the secondary drone with which data must be exchanged. In order to establish where the antenna should be pointing radio connection is required since the drone is not a stationary object. Assuming it is stationary and that it will stay in the exact same place introduces uncertainty into the system. Meaning that while this approach can increase the accuracy, it makes implementation more complicated, while adding little benefit, since for implementation over long distances a small amount of positional inaccuracy does not greatly affect the process. This makes the geometry-based tracking the most attractive option since it requires fewer components, while still ensuring good accuracy of the system. For the system, the three main components for operation are a GPS, magnetometer, and RF module in order to ensure operation.

The selected magnetometer for this is the HMC5883L that can be seen in Fig. 24. The main purpose of this module is to give the magnetic bearing of the device. The magnetometer is a digital compass so it can be used as such to determine the magnetic field along three axes X, Y and Z. This way the yaw angle of the device can be determined by the micro controller. Which can be used along with relative bearing between the two devices in order to correct the antenna positioning system. Additionally, the module is of a small size of 14x18,5mm. Making it quite suitable for this implementation since space is limited. However, the module requires to be positioned further away from other components or metal objects, since it is sensitive to electromagnetic fields and could end up using the other component’s magnetic field as the reference point, which can make it useless or can greatly skew the data. This distance should as large as possible since the module can have interference from any metal parts and other electronics and its values should be calibrated to reduce said interference. Under favourable conditions this magnetometer has an accuracy of around 1-2°. Its supply voltage can be 3-5V, which is perfect for Arduino mega since it operates on 5V logic.

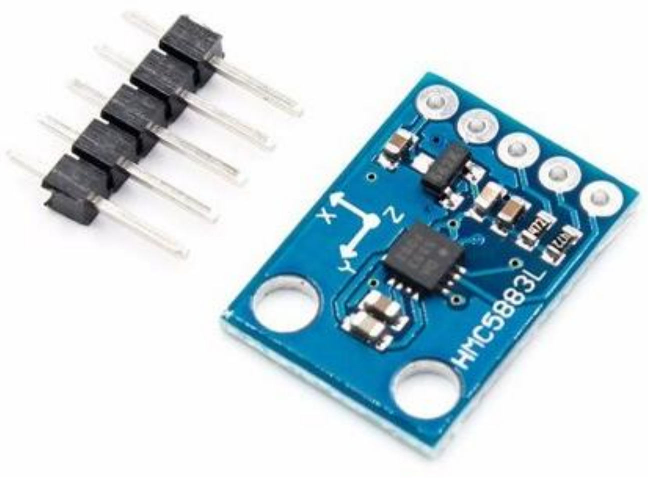


Fig. 24. Magnetometer HMC5883L [27]

To determine the drone absolute position GPS is be used (Fig. 25). This module is used receive signals from GPS satellites and by using their signals the position of the device can be triangulated. To do so signal from at least 3 satellites is necessary although the more satellites that the module can reach the better the accuracy of the received data is. This means that indoors the module could either give very inaccurate GPS data or it can be incapable of determining GPS data at all. However, in the reviewed situation drones are always be working outside so as long as obstacles are not overhead the module performance should be satisfactory.

Fig. 25. Neo 8M GPS Module [28]

This module sends the data to the controller and the controller then shares the recorded data with the secondary drone in order to get an absolute bearing. By having a magnetic bearing from magnetometer, we can get the relative bearing to the paired drone. The process represented schematically can be seen in Fig. 26. This is done at both ends of the connection so that each drone can know where the antenna should be pointing at. If the connection between the drones is blocked or no GPS signal is received then this bearing is not changed until new values are received. This way it is assumed that the position of the secondary drone does not change. While the change of position is almost unavoidable it does give the drone opportunities to possibly receive data as the new position of the drone is expected to be nearby and by doing so get the new position of the drone.

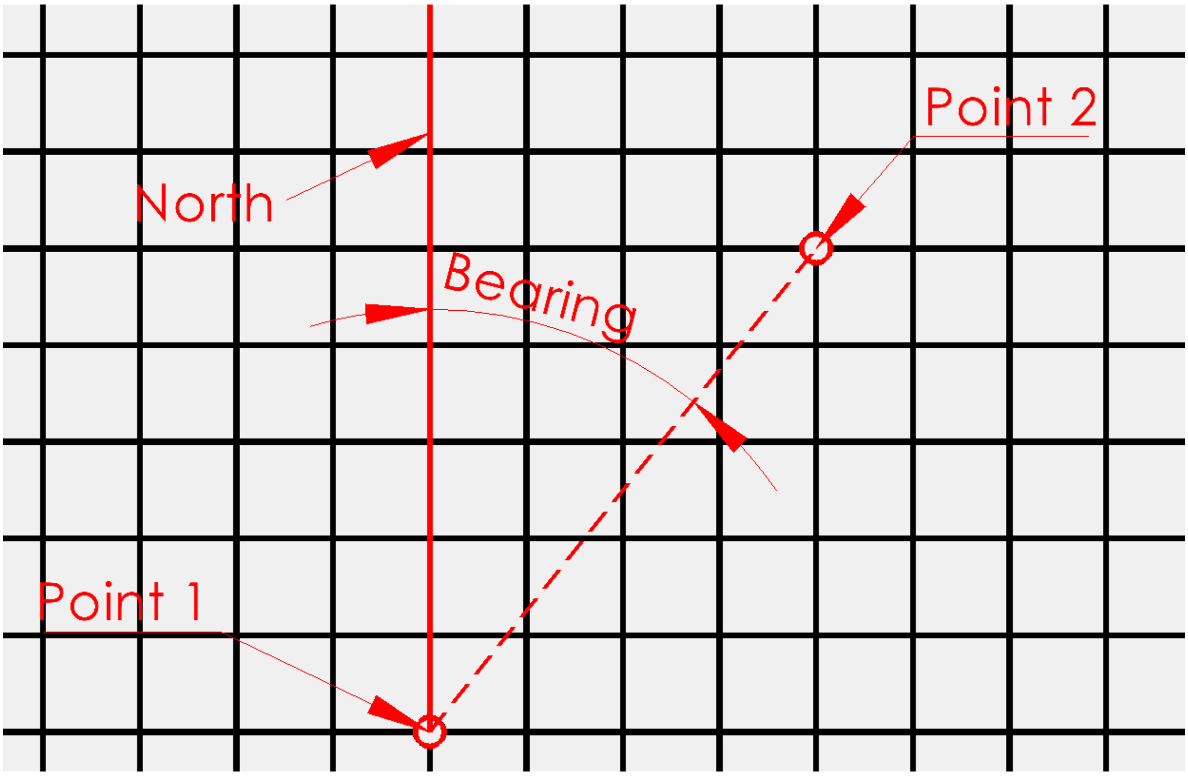


Fig. 26. Relative Bearing

In general, the module positional accuracy is 2m. For very close-range applications this can be problematic since the total error could be 4m, since data from both of the devices is necessary. However, for long range application this sort of error is not expected to create problems. This is because this distance becomes insignificant at higher distance. This can be seen in Table 1, where the maximal theoretical error angle is calculated according to the errors inherent to the magnetometer modules and the GPS. With the calculated data we can see that for ensuring stable communication between the two devices the angle of the directional antenna should be at least 10° as even highly directional antennas are not perfectly directional and this can allow communication under such close distances even if the radiation pattern is directional and not aligned with the target device. This allows to "overlook" the angular error that is received at 10m distance.

Table 1. Angular Error Angle Change

L (Distance), m	10	50	100	500	1000
T (Error), °	23,8	6,57	4,29	2,46	2,23

This angular error is calculated by using the Eq. 2. It should be noted that the positional error that is created due to the GPS is multiplied by two because the absolute angle is calculated both the initial drone's position and the second device so the error can be two times larger. While the magnetometer is not multiplied since for calculations only the devices own magnetometer reading is used.

$$T = \arctan\left(\frac{X*2}{L}\right) + A, \tag{2}$$

where: T-maximal error angle (°); L- distance between drones (m); X is the position error due to the GPS (m); A is the angular error angle of the magnetometer (°).

For easier understanding a visual representation of the formulas values was created in Fig. 27.

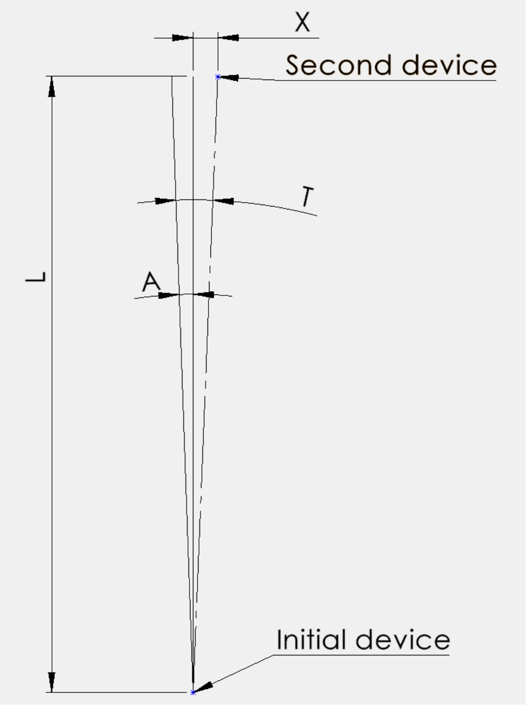


Fig. 27. Visual Representation of Eq. 2 Values

3.2. Communication

For the drone's communication the attached devices use two antenna NRF24L01 modules. One of these communication modules is fitted with an omnidirectional antenna that is not moved and the other is fitted with a directional antenna that can be moved by motors and can be used to follow a drone's movements. This is necessary since even in a multiple drone setup it is required to first get the signal from the ground station in order to relay the signal to the paired drone. An omnidirectional antenna is used here since adding another mechanism that follows and rotates according to the paired device's position can greatly increase the difficulty of the solution. Additionally, a drop in the overall performance of the system and it is expected that such a system can have sever limitation in utilization. Since the two moving antennas need to stay out of each other's way during operation as these can block each other's signal counteracting the possible benefit of such a system. So, this limits the device into certain configurations such as that the drone's back needs to always be toward the ground station and its front facing the target drone. This is simply not possible in most cases due to the terrain or other obstacles and is expected to be extremely impractical. While the possibility of using these antennas one on the top and one on the bottom of the drone is seen as possible. However, this can result in significant increase in complexity and is expected to require heavy modifications of the drone's structure instead of being a device that can be attached or taken off the drone if necessary. Which is why only one antenna is directional and performs antenna tracking in this case. By doing this a chain of communications such as the one shown in Fig. 28 can be established. Here the ground station sends and receives data from an omnidirectional antenna of the device, while the device then shares the data and its position with the next device in the chain until the end of the chain. In essence, the drones in the middle between the ground station and the final drone act as relays that can be freely positioned in order to increase line of sight. Finally, the last device in the communication chain receives and sends data only through the directional antenna this way greatly increasing the possible communication range, while the omnidirectional antenna is not used allowing to save power. However, this is not the only possible configuration as any number of devices can be used here and even a single device can be used which communicates with only a directional antenna with the ground station directly. While this is possible it must be considered that one of the main advantages of the system would be lost. Namely the use of a drone as a relay point that increases the line of sight of the connection.

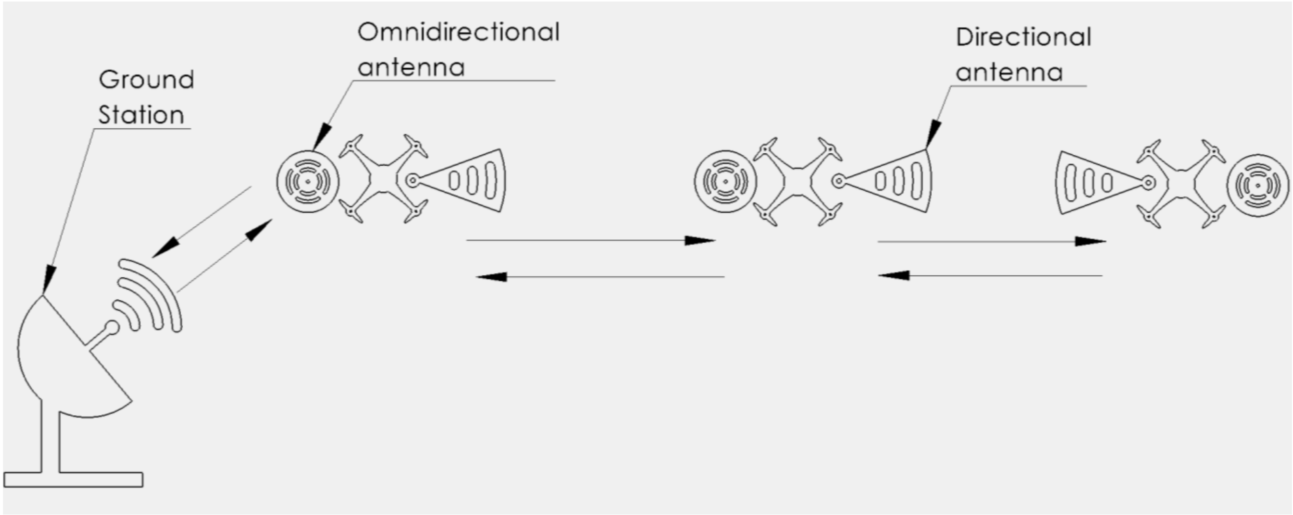


Fig. 28. Devices Communication Scheme

For easier understanding of how the entire process works and what processes are performed by the device a function block scheme was made. It can be seen in Fig. 29. Here first the data is received from the ground station or another device. This data contains instructions for the drone as well as sensor data that provides the position of the sender. Which is necessary if the device is the last in the communication chain so that it could accurately point to the targeted device. Any instructions addressed to the device are transferred via an ethernet cable to the drone. The device itself records its magnetic bearing and positional coordinates in order to perform the necessary calculations for antenna positioning. Then the microcontroller provides bearing on the horizontal and vertical planes to the servo motors in order to correct the antennas position. The device can send the instructions further down the chain through the directional antenna if it is necessary and it sends its positional coordinates so that the next device knows the position of said drone and if necessary (in cases where the drone is last in the communication chain), adjust the position of the directional antenna to point it to said drone.

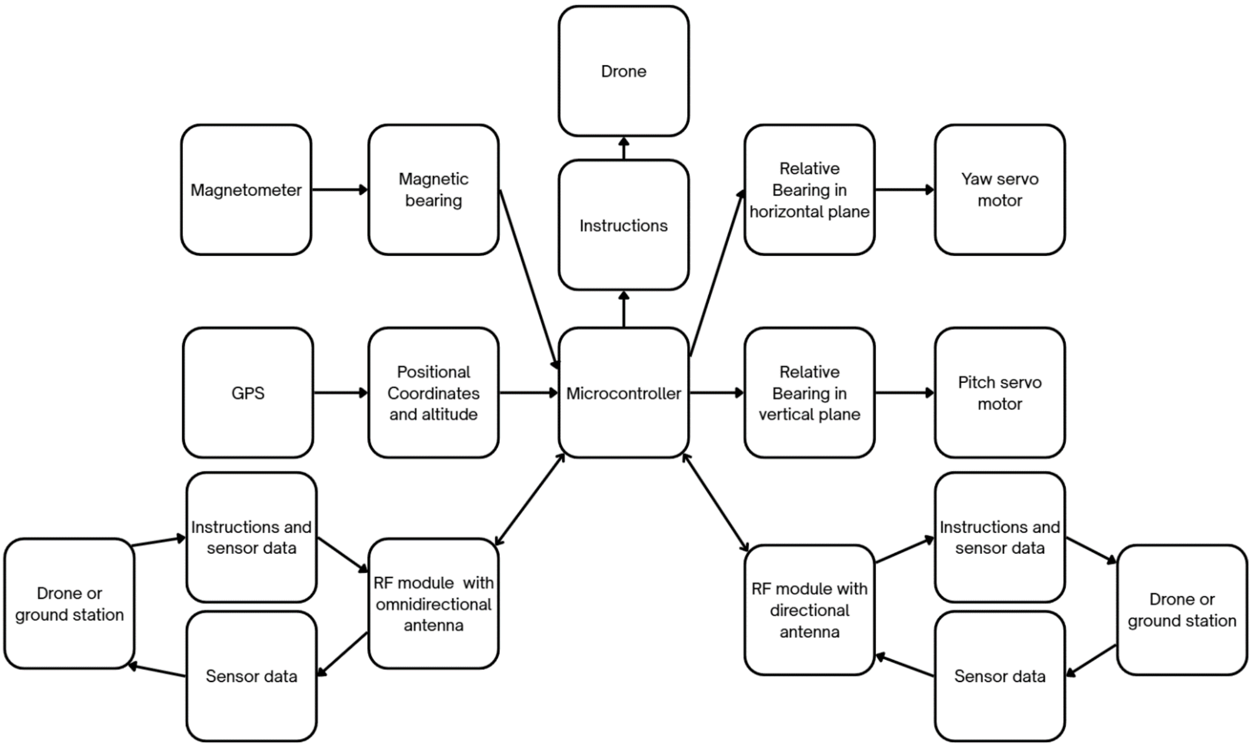


Fig. 29. Devices Functional Block Scheme

3.3. Motion Analysis

To determine whether the selected servo motors are suitable for antenna tracking a “MATLAB” program was made. This program was used to simulate the tracking behaviour of the system in order to determine the suitability of selected motors. Additionally, it was used in order to determine under what conditions could said motors ensure accurate alignment of the directional antenna. For this purpose, the calculations are based on motor turning speed data. Eq. 3 was used to calculate maximal linear velocity of the drone at which the error of values due to turning speed is zero. This ensures that the servos turning speed would always be faster than the drones relative bearing change with respect to the paired drone. Since otherwise accurate tracking is not possible. In said formula radius is used since the greatest angular velocity is seen if the secondary drone is turning around the primary drone in circular motion.

$$v = \omega * r \,, \tag{3}$$

where: v is the linear velocity of the drone (m/s); ω is the angular velocity of the drone (rad/s); r is the radius of drone movement (m).

A graph based on the received data of the selected motor can be seen in Fig. 30. This graph shows the appropriate speed of the drone based on the distance between the two drones. The relationship between the two values is linear and any values on or underneath the shown line result in the positional error of 0. From the graph it can be seen that at 1 meter distance the maximum speed of drone could only be 6.5 m/s, but at 20 meters could be around 130 m/s. So, the only problematic area is when the drones are close together. As these get further apart the speed at which the servo motors should turn decreases greatly.

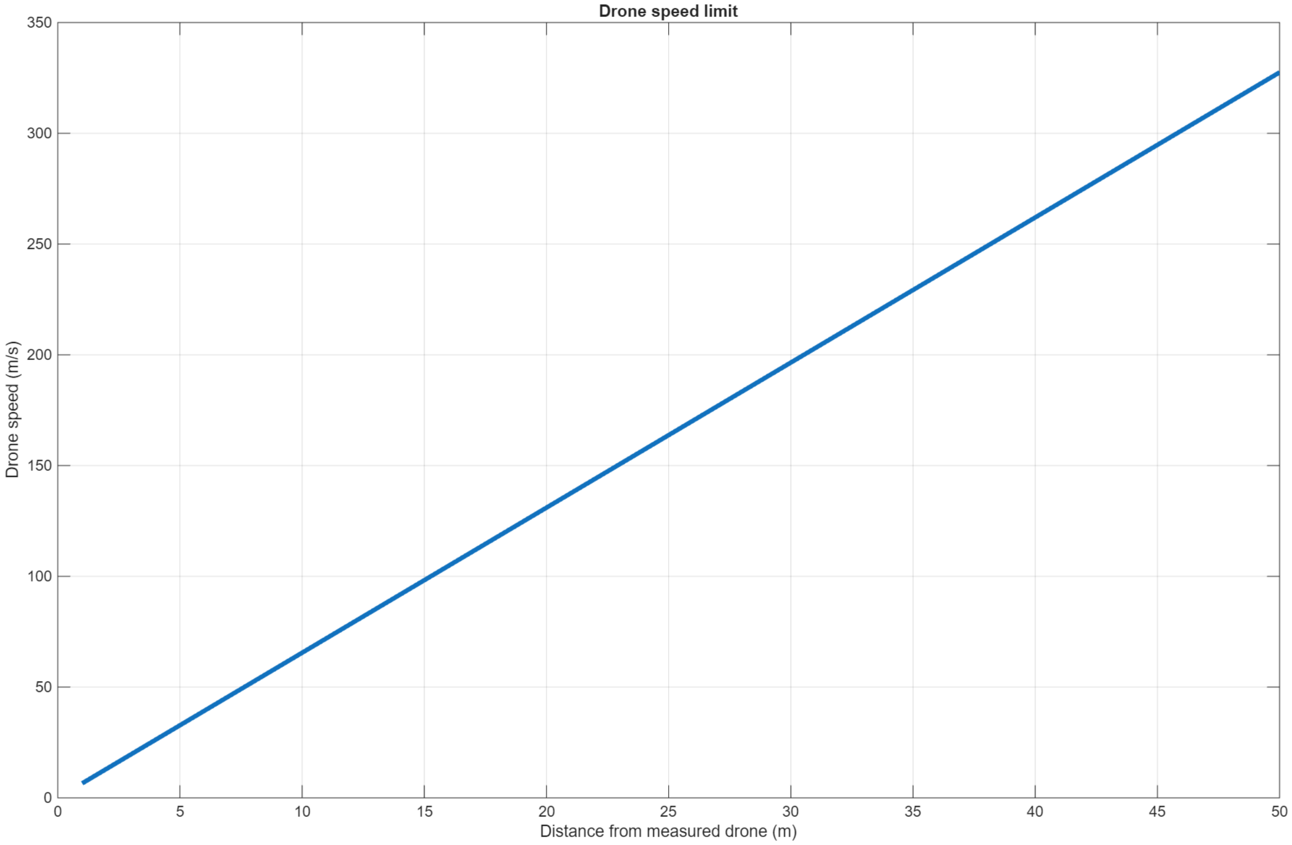


Fig. 30. Drone Speed Graph

By inputting the turning speed of various servo motors the selected motor was COM-Motor02. This servo motor has a turning speed of 60°/0.15s. With this data a simulation of the drones and servo motors movement was made based on the servo motor data and drone speed data. The common maximal speed for consumer grade drones is 50m/s [31, 32]. However, since two drones can move in opposite directions and therefore counteracting the drone positioning antennas movement this speed value in calculations is doubled. This speed means that accurate tracking can only be ensured for at least 15m of distance. This means that drone speed should be limited when these are close together. So ideally when the devices are close together their speed decrease and the speed is increased as these get further from each other. For visualization purposes the tracking data was simulated at 10m distance in Fig. 31. It can be seen that by the time a drone makes a half circle orbit around the primary drone the error for the antenna tracking if the speed is kept at 50m/s can exceed 60°. This can results in loss of signal between the two drones and highlights the need for speed control depending on the distance between devices.

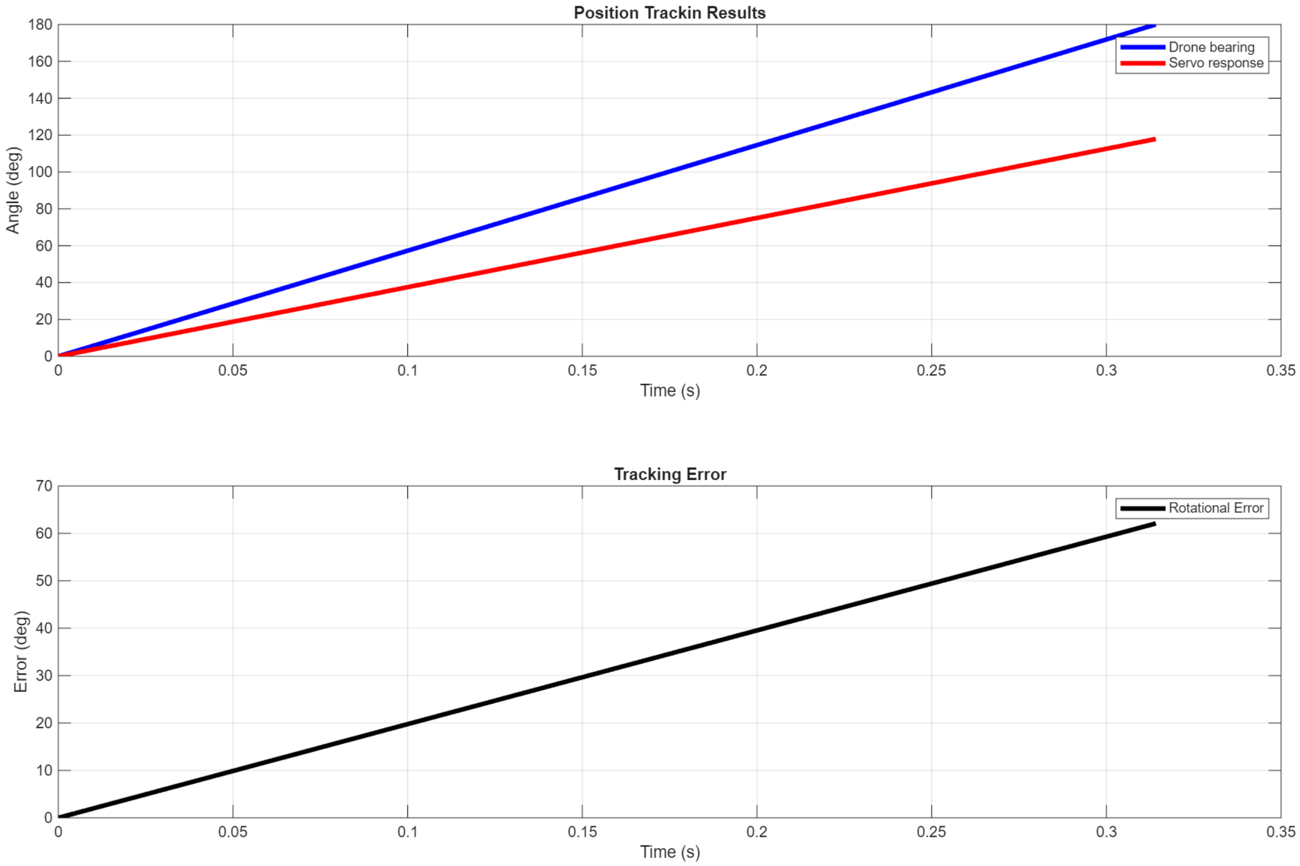


Fig. 31. Turning Error at 10m Distance

3.4. Antenna Performance

To establish communications the selected RF module was NRF24L01. This module works in the 2,4Ghz band and can have the data transfer rate of 2Mbps. With the monopole antenna that is provided the module can operate in distance of up to 1100m and achieve peak gain of around 2 dB. Which is sufficient for testing purposes. Additionally, this distance can theoretically be increased when directional antennas are used. This module was selected since it has multi-pipe communication which can be used to communicate with multiple devices at once. This is because it has 6 data pipes that allow it to accept packets from multiple different addresses simultaneously. While this is not required for this study for implementation in drone networks this feature can prove to be incredibly useful. As this allows to receive data from multiple drone which can allow different configuration of the drones to be possible for example multiple drones can send signal to a single drone in order to increase the signal reliability or to allow distributed sensing utilization of the system.

For the directional antenna APA-M04 antenna was selected and can be seen in Fig. 32. The antenna was selected due to its wide availability and directional gain. Additionally, the weight of the antenna is only 45g this would mean that for turning the antenna not require a large turning moment. This reduces the motor torque requirements and would allow to use smaller and less powerful motors. Additionally, this would mean that the oscillations of the drone would be minimal due to the effect of turning said antenna.

Fig. 32. APA-M04 Directional Antenna [29]

The antennas radiation patter can be seen in Fig. 33. The antenna has the largest gain in the forward direction in the beamwidth of around 60°. While for further implementations an antenna with an even narrower beamwidth can provide a greater increase in communication distance. The narrower it is the better, however for stability’s sake the antennas beamwidth should be kept at of around 30° since this is expected to give the best overall results. While leaving a large area for error so that communication loss does not occur due to lag of motors and the sensor errors.

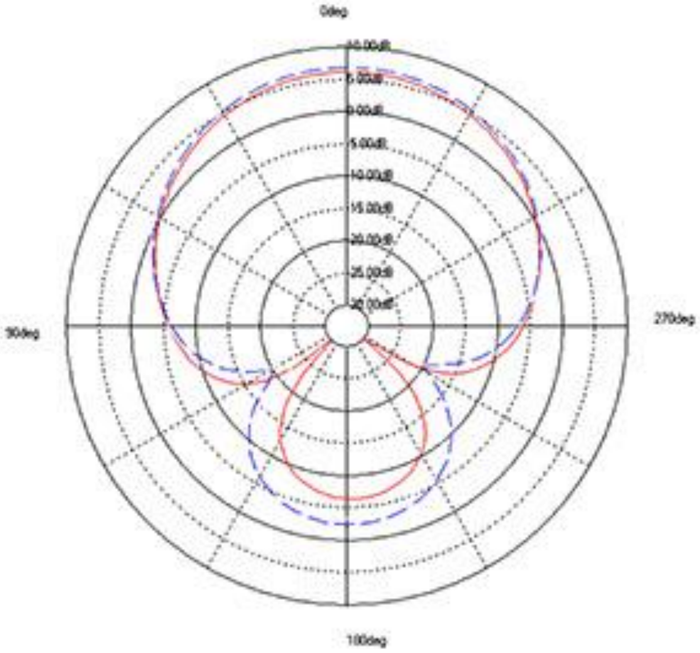


Fig. 33. Radiation Pattern [29]

For additional comparison results the antenna module was also tested with a circular polarized antenna. This antenna is quite commonly used in drone communications due to low sensitivity of antenna orientation and increased performance in environments, where multipathing can be an issue. It is used since monopole antennas are omnidirectional in the horizontal plane, but not in the vertical plane as their radiation patters are donut shaped. Compared to that circular polarized antennas have more even radiations patterns that can possibly lead to different real-world results.

Fig. 34. Circular Polarized Antenna [30]

To test the antennas the packet loss was tested. This was performed since the nRF24L01 module does not measure RSSI (Received Signal Strength Indicator), which could be used to measure the connection strength directly. This is why instead the packet loss was used since it can show the reliability of the RF link. This can be done by showing what amount of sent data packages are obtained by the receiver. By comparing the values between directional and omnidirectional antenna values the difference in possible communication distance was received. To do so different antennas were all tested under the same conditions. The distance was approximately 150m and the RF module was set to low power mode in order to increase data packet loss during testing. This was done in order to more reliably test communication performance under smaller distances than the maximal operating range of the RF module and the antennas.

In order to test the package loss one of the controllers was set as the receiver and the other as a transmitter and a matching pair of antennas were installed. The microprocessor set to be the receiver compared the times transmitter sent the values to the times it has successfully received said values. This was done by having the transmitter send the number of times it has already tried to send data to the receiver modules and the receiver values are only increased when readable data was received. By taking the difference between sent and received values packet loss is calculated and, in this case, it is expressed as a percentage. The testing results of a 1000 sent packets for each antenna can be seen in Table 2. From the results it can be seen that monopole and omnidirectional results are almost identical, while the measured packet loss for the directional antenna is around 20% lower, which is the expected result since the directional antenna has a more focused beamwidth capable of ensuring a more stable connection as long as the antennas on both ends are pointing at each other to get the maximal radiations pattern.

Table 2. Packet Loss of Different Antennas Comparison

Antenna used	**Measured packet loss**	**Radiation pattern**	**Peak gain**
Monopole antenna	37,8%	Omnidirectional	2 dB
Circular polarized	33,5%	Omnidirectional	7 dB
APA-M04	13,9%	Directional	8 dB

The test shows that using a directional antenna can greatly increase the effective range of the system. Since a 20% increase in range is a considerable amount. The total distance increase is expected to increase even more since in the implementation drone communication chains are used as each of said drones experience individual increase in communication distance greatly boosting the total range. Additionally, this percentage does not account for the increase of line of sight for the antennas. As line-of-sight links are by far stronger than non-line-of-sight connections. The line-of-sight increase is the results of using a drone as a relay between the ground station and the drone receiving commands, significantly increasing the line of sight. Which in turn can increase the communication range by several times depending on the conditions of utilization since the propagation conditions would be far more favourable. For example, for 6G wireless networks the difference between the signal's strengths can be up to 100 times depending on whether line of sight is established or not [33]. This is due to non-line of sight signal relying on reflection from surfaces in order to establish a connection an example of this can be seen Fig. 35. This leads to lower signal strength and decreased communication range. While for RF networks the increase due to line of sight is lower than for 6G networks it would still considerably increase the maximal communication distance.

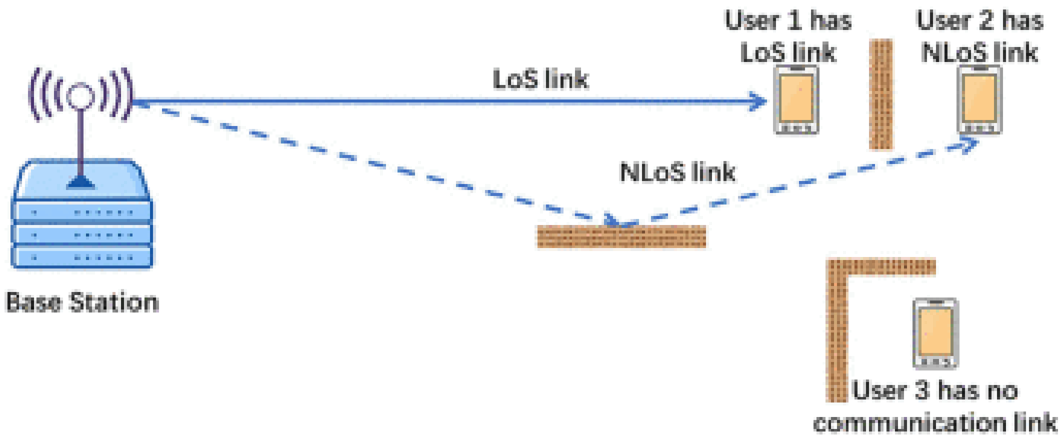


Fig. 35. Line of Sight and Non-Line of Sight Communication [33]

For comparing potential signal strength increase several scientific sources were analysed to compare the received results of packet loss reduction. In [34] directional antennas and omnidirectional antennas are directly compared and from the paper it is seen that directional antennas coverage probability is around 20-30% bigger. While this does not mean that these antennas allow to extend the communication range by the same amount as signal coverage. It does, however provide a strong indication that directional antennas can significantly and positively impact the communication distance. In another example the average transmit power required to achieve reliable coverage for a drone network was found to be 21.46% higher for drones using omnidirectional antennas as compared to directional antennas for the same coverage [35]. Additionally, the coverage of antennas can overlap and cause signal interference, which can severely decrease their effectiveness. While directional antennas can concentrate transmission power to a small area. By utilizing directional antennas conic areas that provide signal coverage are made and the theoretical results from [36] show that system coverage probability is improved by 41%. Overall while from the analysed research papers direct comparisons can't be made it can be seen that directional antennas can significantly increase the performance of drone communication systems.

3.5. Devices Effect on Drones' Power and Mass

In order to determine the changes in the drone's performance with the added device it is important to determine the power usage of the device and then to see how significantly it affects the drone's flight. While in most cases communication takes about 10% of a drone's power for the added module it must be seen if this value is greater and if so by how much. To do this Table 3 was create. Here the basic parameters of the devices used are noted as well as the number of these devices along with the mass, since it is also a very important factor for the drone. To get this some assumptions are necessary since the hull for drone was not designed and so it is assumed to be a plastic ABS box, which dimensions are 150x150x60mm with a uniform thickness of 2mm. With this assumption the total mass of the assembly was determined to be around 0,6kg this means that the solution is quite lightweight. Only affecting the drone's performance in a minimal way since many medium sized drones have allowed carrying capacity of around 1kg. Additionally, this value is below the goal of keeping the device lighter than 2kg which was one of the goals for the study.

Table 3. Component Power Usage and Mass

Component	Amount	Voltage, V	Current, A	Power usage (total)	Mass (total)
Arduino Mega 2560	1	5	0.1	0,5W	37g
HMC5883L	1	5	0,003	0,015W	2g
NEO- 8M	1	5	0,03	0,15W	18g
COM-Motor02	2	6	0,1	1.2W	144g
NRF24L01	2	3,3	0,014	0.1W	12g
MP1584	2	-	-	0.9 efficiency coefficient	6g
Capacitor 10 µF	2	-	-	-	2g
APA-M04 antenna	1	-	-	-	45g
Circular polarized antenna	1	-	-	-	6g
SPT 200 Pan & tilt kit	1	-	-	-	155g
Plastic hull	1	-	-	-	170g

The power of usage of each component was calculate using Eq. 4. If all of these values are added together the total power consumption of 2.13W is found.

$$P_A = \frac{U*I*n}{\eta}, \qquad (4)$$

where: P_A is the power draw of the added device (W); U is the voltage of the device (V); I is the current (A); n is the number of components; η it the efficiency coefficient of step down converter.

Then it is needed to get the power draw of the drone to do this a 6S Lipo battery with the capacity of 0.7Ah and the voltage of 22,2V is assumed to be used. To get the energy capacity of the battery formula in Eq. 5 is used. From this it is calculated that total energy stored reaches 15.5 Wh. It is assumed that total possible flight time of the drone with this power capacity is 30 minutes after which the battery would be empty. This way the total power draw of the drone can be approximated to be double the battery capacity and is 31W.

$$E = Ah * U, \tag{5}$$

where: E is energy (Wh); Ah is battery capacity (Ah).

Now if these two values are added together and the new flight time is calculated with Eq. 6. The value was found to be 0.47h. The total flight time reduction was calculated with Eq. 7.

$$t_n = \frac{E}{P_D + P_{New}}, \tag{6}$$

where: t_n is the new flight time (h); P_D is the drone base power usage; P_{New} is the devices power usage (W).

$$F = \frac{t - t_n}{t} * 100\%, \tag{7}$$

where: t is the base flight time (h); F is the flight time reduction (%).

The values were inserted into Table 4. It was found that flight time is decreased by only 3 minutes. The overall decrease of flight time was determined to only be 6% of total flight time this does not pose a significant problem since decrease for drone flight is minimal. Which is why the solution should be appropriate as it decreases flight time by a small amount, while increasing communication distance between drones by around 20%.

Table 4. Devices Effect on Flight Time

Battery	**Voltage, V**	**Capacity, Ah**	**Battery energy Capacity, Wh**	**Flight time, h**	**Power draw of drone, W**	**Maximal power draw of added device, W**	**Flight time with added device, h**	**Flight time reduction, %**
6S Lipo battery	22,2	0,7	15.5	0,5	31	2.13	0,47	6

3.6. Ground Station

For implementation of the system, it is preferable to use a ground station with directional tracking. This results in communication range extension even if only one drone is used in the system since then the directional antenna can be used to track the ground stations position. Additionally, having a directional antenna with tracking on a ground station significantly boosts the connection strength without affecting the overall performance of a drone. Which is also the reason why these types of solutions are so widely utilized. Additionally, power storage is not a significant problem in this case since weight is generally not a major limiting factor. As these ground stations often feature simple designs that are moved manually by a person. Meaning that the only limitation to weight is to make relocation more comfortable for the drone pilot. This allows to add much larger energy storages and even though in general the rule is that if a antennas power is increased by 4x the effectiveness only doubles. Which is the reason why such a configuration is not be acceptable for many drones. For the ground station this is not the case since in general the ground station energy consumption is not high since here power is consumed only by the communication system and the motors that are used to turn the antenna. Furthermore, the energy storage can be much greater than the drones due to the fewer constraints on the weight of the system allowing for larger number of batteries to be used. Which is why by comparing to common systems where omnidirectional antennas are used for both the drone and the ground station the increase in communication distance is significant. While the proposed solution greatly benefits drone networks it still provides significant benefit even if a lone drone is used. This stems from the increase in range achieved due to the usage of directional antennas on both the drone and the ground station. Additionally, the ground stations antennas power can be increased resulting in greater power consumption but also increased communication distance.

For the described approach a ground station similar to the one implemented [23] can be used. Since it utilizes the GPS data the same way as the drone module minimal changes would be required to use said system. The only thing that should be changed would be the used antenna module and subsequently the antenna since the frequency of these would be different to the required one of 2.4Ghz. Additionally, its effectiveness has already been proven by physically implementing said system and utilizing it. Meaning that it should provide satisfactory results as long as the working principle of the system is kept. The basic setup of this system can be seen in Fig. 36.

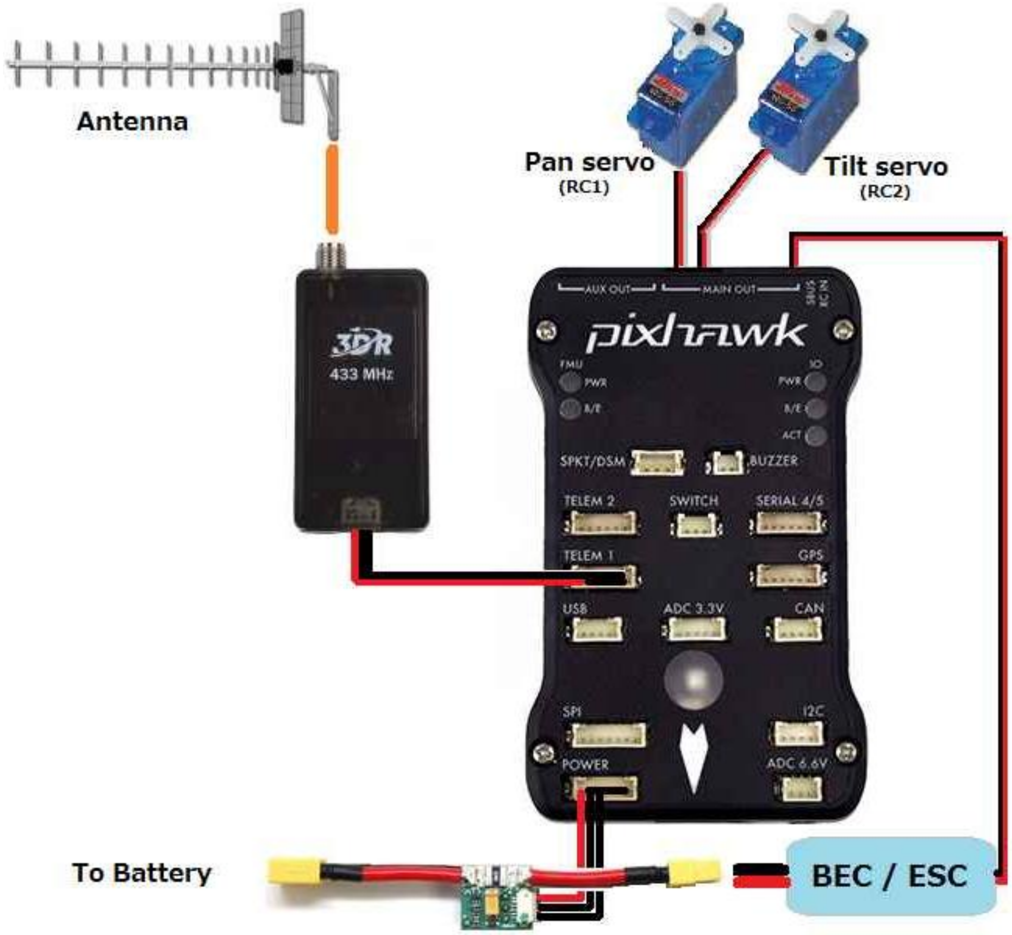


Fig. 36. Ground Station Setup [23]

To determine the ease of transportation for this assembly the weight of it was determined and can be seen in Table 5. The goal here was to keep the weight of the ground station below 15kg to ensure the portability of the system and ensure that deployment of it would not require specialized equipment. Even by incorporating a heavy, high-capacity battery it can be seen that the mass of the entire assembly is around 9.5kg this is a lot lighter than the parameter set as the constraint of the device. The low mass improves the practicality of the system in real-world deployment. Since it allows for a single operator to transport and deploy the device without assistance. Additionally, it allows for rapid repositioning which can be important for drone surveillance operations.

Table 5. Preliminary Components of Ground Station

Components	**Purpose**	**Mass, kg**
PT785-S Pan & Tilt System	To allow tilt and pan movement (motors included)	0.82
6dBi Yagi antenna	Extend the range of communication	0.28
Pixhawk controller	Perform logical task and computations	0.05
Radio module	Allow communication	0.1
Laptop	Controlling the drone	3
Tripod	Hold the entire assembly	1.5
Battery 12V 12Ah	Power storage	3.65

3.7. Programming

A program was created for controlling directional tracking antennas orientation and the logic that said program follows can be seen in Fig. 37. Here a flowchart is used to describe the devices actions. The program starts by initializing the components such as the GPS, magnetometer and antenna modules. This also sets the initial values of variables used in the program. Then the first action the program takes is to check if there is any available radio signa that it should read. For the configuration used for testing only the directional antenna is used. However, in full implementation data from both antennas should be checked. If this signal is available, it checks the received values and store them for calculations, while also providing its own values to the paired device.

The module uses pin-pong communication meaning that the paired module gives a response only after receiving some data this can lead to issues when communications are lost. For this reason, if there is no available radio signal it sends a signal unprompted with its data this way reestablishing communications as the second drone that receives this sent data back ensuring constant data exchange. Then the device checks if the GPS module has received new positional data and if so, it stores this positional data. Then with GPS data and magnetometer data the bearing in horizontal plane is calculated regardless if the GPS receives new navigational data or not. This is because while the position of the drone may not change the magnetometer bearing still can. Additionally, if GPS connection is lost this means that the drone assumes that the last position of the paired drone does not change which could help in reestablishing connection. For the bearing in vertical plane the calculation is performed only when vertical position changes. Finally, with said data servo angles are calculated.

Since the servo motors used in this case can only turn 180° it is checked if the value is withing said range and if it is not the servo is set to the closes allowable value and gives indication that the drone itself should turn for accurate antenna tracking since the servo cannot point in the required position. Then it is seen if the change in servo position is larger than 2° since this is the determined value of angular error due to sensors. This means that the angular error is ignored this way greatly increasing the stability. Only if the new value of the servo angle is different from the current position angle is changed. This approach should greatly decrease the jitter of servo modules and preserve their durability since location corrections are less common resulting in less movement for the servo motors. Then either the entire cycle is repeated or the drone in landed and the device turned off finishing the process.

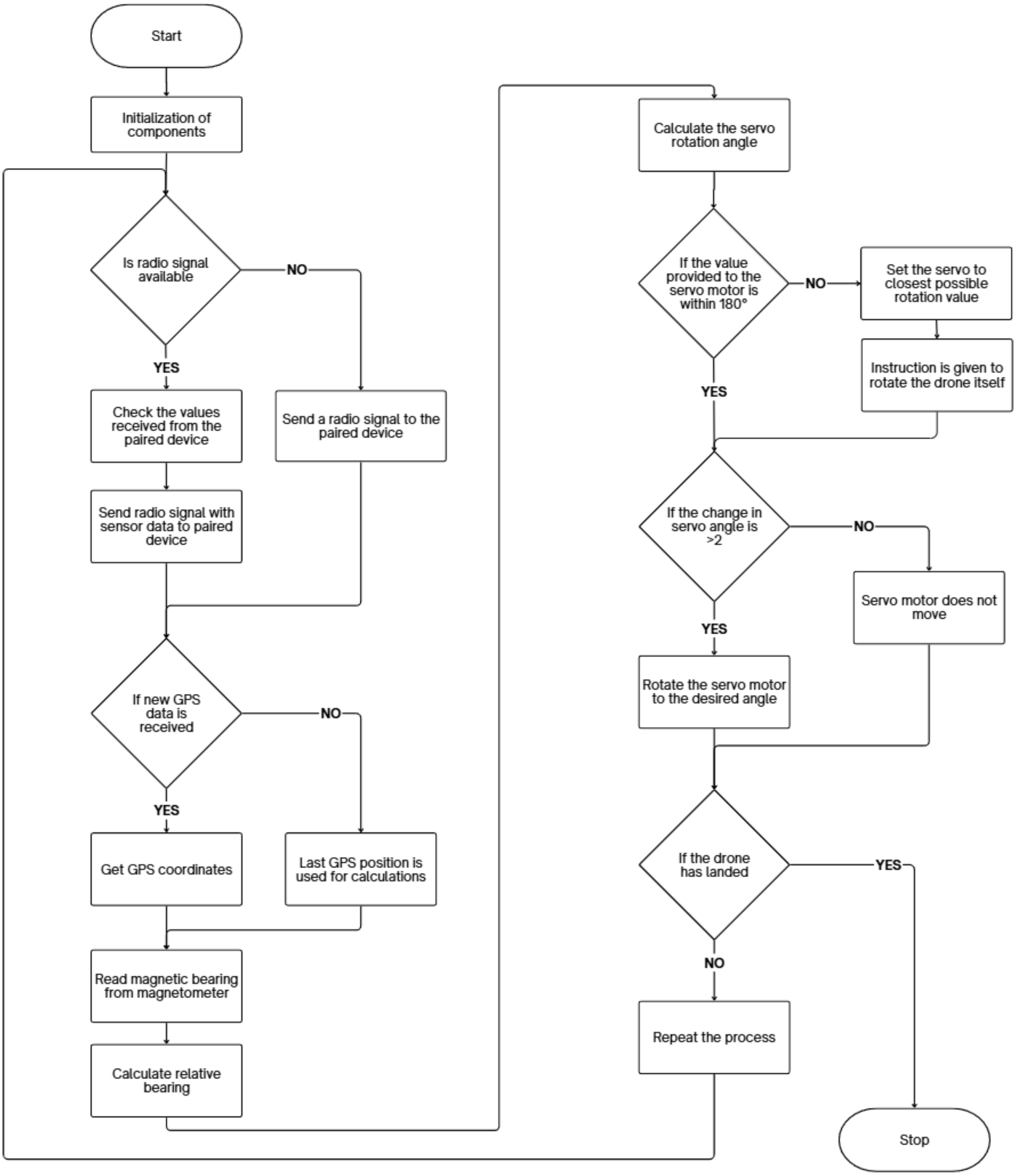
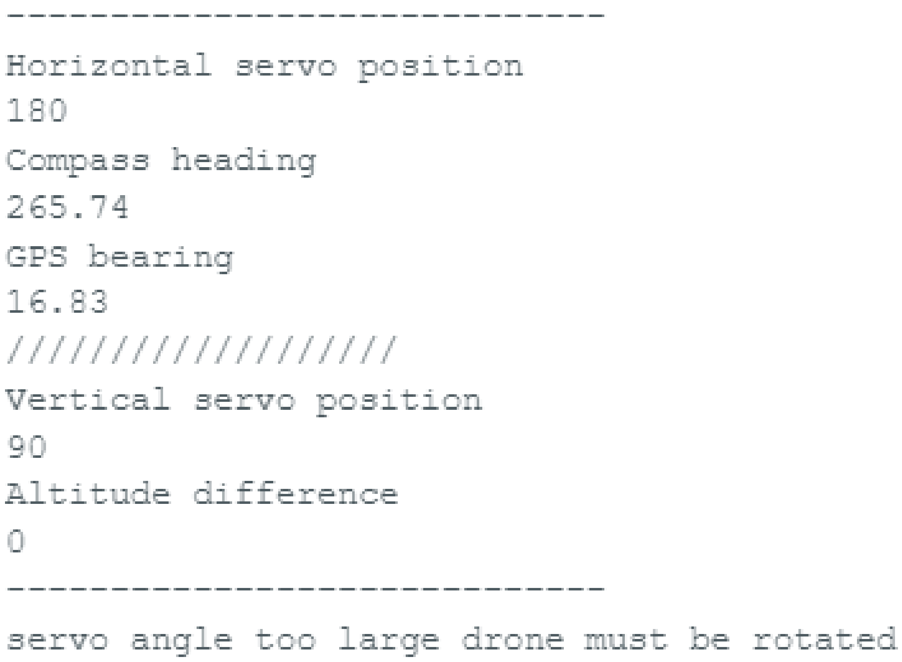


Fig. 37. Process Flow Chart

A program was made to test the connected system. It was programmed in "Arduino IDE". The results of the program can be seen in Fig. 38. This shows the horizontal servo position that for this case the required servo angle exceeds the maximal movement angle of the selected servo motor. Which is why it is set to the maximal angle that is closes to the target one, while still being withing the allowable angle. The compass heading and relative GPS bearings are also provided for testing purposes. Then the current servo position of vertical plane servo is shown in this case since both of the devices are on the same table the altitude difference was determined to be 0 which is why the servo is pointing at its initial point which is 90°. Additionally, the program notifies that the angle of servo motor is found to be too large which is why the drone should be rotated so that the antenna could be rotated to the target position.



```
-----------------------------
Horizontal servo position
180
Compass heading
265.74
GPS bearing
16.83
///////////////////
Vertical servo position
90
Altitude difference
0
-----------------------------
servo angle too large drone must be rotated
```

Fig. 38. Arduino Program Output

3.8. Chapter Summary

The chapter describes the reason why for drone communication range expansion a tracking antenna is useful. The antenna tracking uses geometric tracking meaning that it uses GPS and magnetometer data in order to know its and the secondary devices position. While other methods could potentially be used this approach uses only a small number of components, is highly suitable for outdoor use and isn’t complicated. For communication two RF modules are used in order to ensure stable communication. One RF module uses a directional antenna for tracking the secondary device allowing to extend the communication distance by 20% according to the performed packet loss testing. Additionally, in drone network utilization one drone acts as relay above the obstacles present in the surrounding environment. This increases the line of sight for communication which can lead to increasing communication range by several times. The other RF module is used to receive data from the primary device to add flexibility and not overcomplicate the system it uses an omnidirectional antenna. Depending on the implementation the mentioned primary device could either be the ground station or another drone in a communication chain. The preliminary power usage of the device was calculated and from calculations it is believed that the device decreases flight time by only 6 %. Additionally, the mass of the device was calculated to be around 1kg and the ground station mass to be around 9.5kg both being appropriate according to the set conditions of the work. Finally, the working process and programming are explained in this section.

4. Economic Overview

While most of the components can be easily bought directly, the only exception used in this project is the plastic hull used to cover the electric components and hold these in place. In order to estimate manufacturing cost of the hull, injection moulding tool and general production costs must be considered. Generally, the price of a moulding tool is in the range of 10000€ -20000€ per mould the price depends heavily on the complexity of the production tool. Since the main requirement of these parts is to hold the components in place the complexity of moulds is not expected to be especially high. However, another important parameter is that device should be capable of operating under rainy weather conditions. For this, a seal is required between the two parts to prevent water leaking in and damaging electrical components. In order to ensure seal integrity, the seal must be under constant compression. In order to ensure suitable conditions for the seal and to simplify assembly snap fit connections are desirable. An example of such a connection can be seen in Fig. 39. Here the component can quickly be assembled and be flush with the surface of the assembled body.

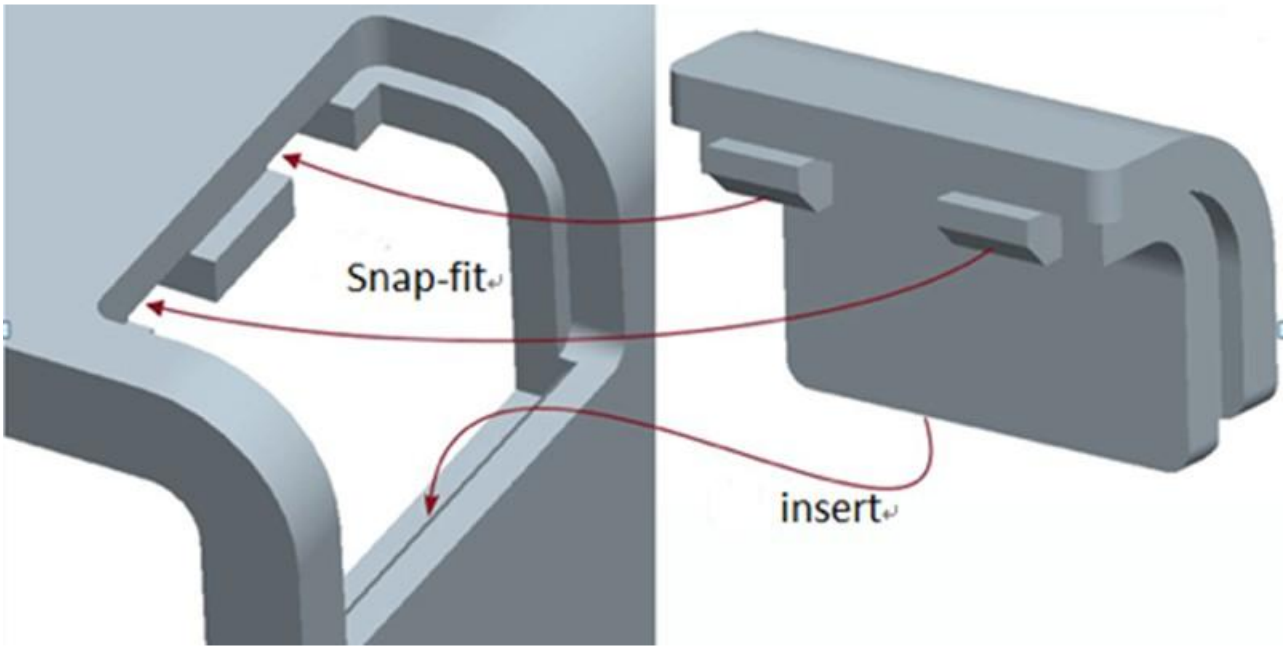


Fig. 39. Snap-Fit Example [37]

These connections allow to simplify and drive down the cost of assembly while also decreasing the overall weight of said assembly. In order to form snap fits on the parts sliding units are required in the mould. These can increase the overall cost of manufacturing by 10% per sliding unit. To ensure proper connections two of these sliding units are needed on each side for one of the plastic moulds increasing overall price of a mould by 20%. Assuming that the two parts required are of medium complexity for manufacturing the cost of said moulds is estimated to be 15000€, while the mould with sliding units' cost is around 18000€.

The normally expected lifetime of such equipment is 100000 cycles producing the equivalent number of parts. This results in the cost of 0,33€ per part in order to cover the cost of this equipment. To calculate the total cost, the price of the machine used must be determined. For smaller machines with a maximal clamping force of 50 tons these can cost 40000€. Resulting in an additional part price increase of 0,4€. Finally, the material costs for production are determined. Here electrostatic ABS is used, the cost for a kilogram of such material is 3€. This means that material cost for one part is expected to be 0.5€. The material is used because it is electrically non-conductive and this way damage to the sensitive electronics contained within can be avoided. To take into account unforeseen cost of operation such as equipment repairs and maintenance cost a 20% overhead cost is applied meaning that the total calculated cost of the part is increased by this percentage in order to get the final cost of a single part for production. By adding all of the values together and applying the overhead percentage, the total cost for producing the part is 1.5€. The summed-up data can be seen in Table 6.

Table 6. Plastic Hull Price

Injection mould total price	33000
Expected produced part amount	100000
Injection mould per piece price	0.33€
Moulding machine cost	40000€
Price increase due to cost of moulding machine	0.4€
Plastic price per kg	3€
Price of plastic per part	0.5€
Overhead percentage	20%
Total price per set of parts	1.5€

With this the total price of components needed to create the system can be summed and this is performed in Table 7. The total calculated cost of parts comes up to 184€.

Table 7. Component Cost

Component	**Amount**	**Cost of a single part, €**	**Total cost, €**
Arduino Mega 2560	1	49.9	49.9
HMC5883L	1	4.82	4.82
NEO- 8M	1	20.57	20.57
COM-Motor02	2	14	28
NRF24L01	2	7.3	14.6
Capacitor 10 µF	2	0.1	0.2
APA-M04 antenna	1	4.8	4.8
Circular polarized antenna	1	8	8
SPT 200 Pan & tilt kit	1	46	46
MP1584	2	2.8	5.6
Plastic hull	1	1.5	1.5
Total cost of parts	184		

To calculate the cost of assembly first the time required to solder the selected electric components must be determined. For estimation’s purposes, it is taken that each joint requires around 10s for forming a connection. Since there are 42 joints that need to be soldered it should take around 7 minutes making it the most time-consuming process of assembly. Since for assembly the sensors should be placed inside of the plastic hull and would need to be fixed to it. This can be done either by fastening with screws for most of the components, while magnetometer and seal would require the use of adhesives. It can be estimated then that the assembly by hand takes around 12 minutes. Assuming an average labour cost of 10€/h for such operations the labour cost adds up to additional 2€ per part. Bringing the total cost of production to be approximately 186€.

If the use of the system with the ground station is considered, the total cost can greatly increase. Since if [23] is taken as the example the cost of raw material, which can be seen in Table 8 reach 960€ for the ground station alone which is considerably larger than just the price of the device that is attached to the bottom of the drone. While many ground stations already come with directional antenna tracking this expense can be unnecessary in some cases since already existing systems can be utilized and adapted. However, for the sake of clarity the total cost of utilization of the system comes up to 1146€.

Table 8. Ground Station Price

Component	**Price, €**
PT785-S Pan & Tilt System	350
6dBi Yagi antenna	37
Pixhawk controller	410
3DR Radio module	86
Tripod	44
Battery 12V 12Ah	33
Total	960

In order to understand the solutions economic benefit a real example of drones utilization is necessary. A DJI Matrice 300 drone can cost 8500€ its default range of communication is 15km for unobstructed view. While for the DJI Matrice 350, drone an incredibly similar drone that costs 11500€ the communication range with unobstructed view can be as high as 20km. The cost difference between the two drones is 3000€ and the maximal communication distance is increased by 25% between the two models. If the new Matrice 350 model is used to replace the Matrice 300 model solely based on the communication range increase. The implementation of the described system seems to be an advantageous solution since if the 20% range increase is achieved the difference communication wise would be minimal. While the overall cost is much cheaper. Additionally, it should be considered that the device is suitable for drone network communication which can add more utility to the solution.

4.1. Chapter Summary

During the economic analysis, it was determined that the total cost for production of the drone system is around 186€. This price includes the cost of custom parts, namely as the frame components needed to house the electric components. As for these components injection moulding is suitable the detailed prices of the process have been determined with the assumption that snap fit joints are used for assembly. If it is considered that ground station implementation is used in tandem with the described system, which in most cases is unnecessary since ground stations are often equipped with directional antennas or antenna arrays that offer beam steering. However, for this case if we consider that the ground station is used the total cost is approximated to reach 1146€. This cost is not incredibly large since larger drones can cost tens of thousands. While comparing two similar models of drones solely based on their communication distance. The range extension added to the older drone is found to be similar to the newer drone, while being significantly cheaper. This offers a more economically viable solution than replacing an older drone with a newer model.

Conclusions

1. The most promising solution for increasing range of communication was found to be the use of a directional antenna with a tracking system in the ground station and also on the drones themselves.
2. By simulating the system, it was found that at a speed of 50m/s the device can only work properly if the distance between two of these devices is at least 8m as otherwise the servo motors will not be able keep up with the drone’s movement. This requires to control the drone’s speed based on the distance.
3. It was found during testing that the communication distance is increased by at least 20%. In found similar solutions results suggest that the range increase of directional antennas can provide even larger benefit. However, the solution does have the added benefit of increasing line of sight of communication with the potential to increase communication range several times.
4. The estimated cost of the solution was found to be 186€ per device. While for configuration with the ground station the total cost is 1146€. By comparing communication distance of drones, it was found that even though the cost is not small the added range and functionality makes system implementation viable.

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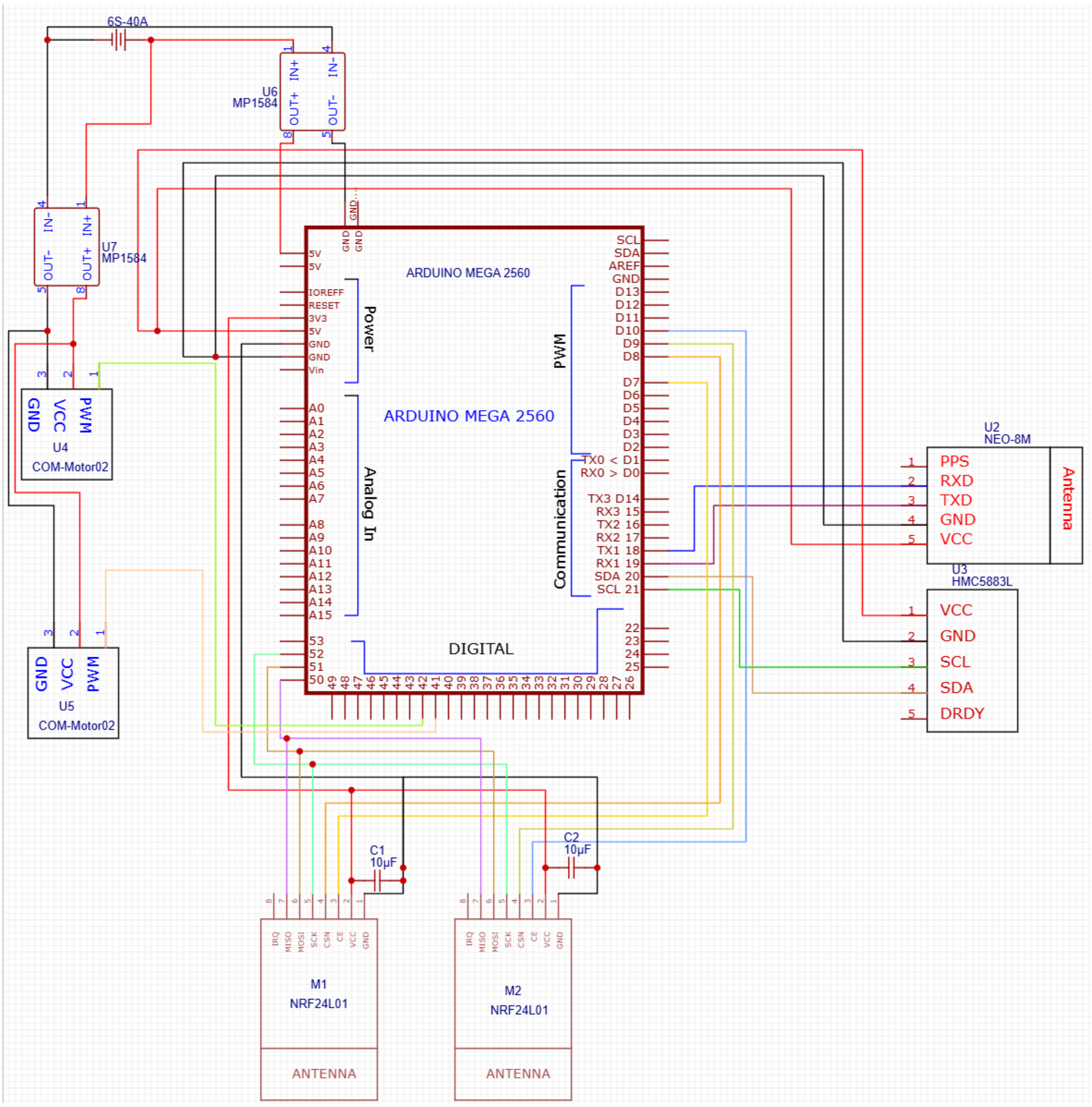
Appendices

Appendix 1. Wiring Scheme



Appendix 2. Devices Program

```
#include <SPI.h>
#include <nRF24L01.h>
#include <RF24.h>
#include <TinyGPS++.h>
#include <TinyGPSPlus.h>
#include <SoftwareSerial.h>
#include <math.h>
#include <Servo.h>
```

```
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_HMC5883_U.h>
//---------------------------------------------------------------------------------------------
Adafruit_HMC5883_Unified mag = Adafruit_HMC5883_Unified(12345);
Servo servo1;
Servo servo2;

TinyGPSPlus gps;

RF24 radio(7, 8); // CE, CSN
RF24 radio2(9, 10); // CE, CSN

byte read_address[6] = "00002";//current drone adress
byte write_address[6] = "00001";//targeted drone adress

int lastReceivedPacket=0;
int lostPackets=0;

uint32_t Disconnections = 0;

static unsigned long LastReceive = 0;
static unsigned long LastReceiveL = 0;
int ButtonPin=13;
bool Record=false;
double nextbearing=100;
float headingDegrees;
float elevationDeg;

void Radio_init();
void NormalOperation();
void InitialConnection();
void ServoControl();
void ReceiveGPSData();

//-----------------------------------------------------------Data structure used for transmission
struct Packet {
  int32_t lat;
  int32_t lon;
  int16_t h;
};

Packet received={0,0,0};
Packet sent={0,0,0};
Packet empty={0,0,0};
//---------------------------------------------------------------------------------------------
```

```
void setup() {

  servo1.attach(43);
  servo2.attach(44);
  Serial.begin(9600);//start serial comunication
  Serial1.begin(9600);//comunication for GPS module
  delay(1000);
  Radio_init();
  pinMode(ButtonPin, INPUT_PULLUP);
}

//-----------------------------------------------------------------------------------------------
void loop() {
  ReceiveGPSData();
  NormalOperation();
  ServoControl();
}
void NormalOperation(){ //Normal Operation
  InitialConnection();
  NoConnectionOperation();

  if (radio.available()) {
    radio.read(&received, sizeof(received));
    radio.stopListening();
    radio.write(&sent, sizeof(sent));
    radio.startListening();
    LastReceive=millis();
    LastReceiveL=millis();
  }

}

void InitialConnection(){
  if (millis() - LastReceive >= 3000) {//when a return signal is not received for a certain amount of time
    LastReceive = millis();
    radio.stopListening();
    radio.write(&sent, sizeof(sent));
    Serial.println(F("Establishing connection"));
    radio.startListening();
    Serial.println(millis() - LastReceive);
  }
}

void NoConnectionOperation(){//First connection and error sent if no signal is received for more than 5s
```

```
  if (millis() - LastReceiveL >= 5000) {//Disconnected operation
    LastReceiveL = millis();
    LastReceive = millis();
    radio.stopListening();
    radio.write(&sent, sizeof(sent));
    Serial.println(F("WARNING: No signal for 5+ seconds"));
    radio.startListening();
  }
}


void ReceiveGPSData(){
  static bool FirstTime=true;
  if (Serial1.available() > 0){
    gps.encode(Serial1.read());
    if(FirstTime==true){
      FirstTime=false;
      Serial.println(" GPS initialized");
    }

    if (gps.location.isUpdated()){
      sent.lat=gps.location.lat() * 100000;
      double l=sent.lat/100000.0;
      sent.lon=gps.location.lng() * 100000;
      double lo=sent.lon/100000.0;
      sent.h=gps.altitude.meters(), 2;
    }
  }
  RotationAngle();
}

void RotationAngle(){

  double currentLatRad=sent.lat * M_PI / 180.0/100000;
  double targetLatRad=received.lat * M_PI / 180.0/100000;
  double deltaLonRad=(received.lon - sent.lon)* M_PI / 180.0/100000;
  /////////////////////////////////////Bearing on the X and Y plane
  double x = sin(deltaLonRad) * cos(targetLatRad);
   double  y  =  cos(currentLatRad)  *  sin(targetLatRad)-  sin(currentLatRad)  *  cos(targetLatRad)  *  cos(deltaLonRad);

  nextbearing = atan2(x, y)* 180.0 / M_PI;

  if (nextbearing < 0) nextbearing += 360;

////Bearing in the vertical plane
```

```
  double R = 6371000; // Earth radius in meters
  double Lat = (received.lat - sent.lat) * M_PI / 180.0 / 100000;
  double Lon = (received.lon - sent.lon) * M_PI / 180.0 / 100000;
  double a = sin(Lat/2)*sin(Lat/2) +cos(currentLatRad)*cos(targetLatRad)*sin(Lon/2)*sin(Lon/2);

  double c = 2 * atan2(sqrt(a), sqrt(1-a));
  double horizontalDistance = R * c;

  double deltaH = received.h - sent.h;
  double elevationRad = atan2(deltaH, horizontalDistance);
  elevationDeg = elevationRad * 180.0 / M_PI;

}

void Radio_init() {
  radio.begin();
  radio.openWritingPipe(write_address); //define writing adress
  radio.openReadingPipe(1, read_address);//define reading adress and pipeline
   radio.setPALevel(RF24_PA_LOW); //set the power amplifier leve MAX is allows for largest distance
  radio.setDataRate(RF24_250KBPS); //set data transfer rate
  radio.setChannel(108);
  Serial.println("\nInitialization of antena complete");
  radio.setPayloadSize(sizeof(sent));
    if(!mag.begin())
  {
    Serial.println("no HMC5883 detected");
    }

}
void bearing(){
  sensors_event_t event;
  mag.getEvent(&event);

  float heading = atan2(event.magnetic.y, event.magnetic.x);

  float declinationAngle = 7.0 * PI / 180.0;
  heading += declinationAngle;

  if(heading < 0){
    heading += 2*PI;
  }
  if(heading > 2*PI){
    heading -= 2*PI;
  }
  // Convert received radians to degrees.
```

```
  headingDegrees = heading * 180/M_PI;

}
void ServoControl(){
  bearing();
  static int initial=0;
  static float BearingErrorH=0;
  static float BearingErrorV=0;
  static int timers=0;
  static int servoAngleH=90;
  static int servoAngleV=90;

//////////////////////////////Servo controll for Horizontal plane
  if(abs(BearingErrorH-(nextbearing - headingDegrees))>2||((BearingErrorV-elevationDeg)>2)){
    BearingErrorH=nextbearing - headingDegrees;
  if (BearingErrorH > 180) BearingErrorH -= 360;
  if (BearingErrorH < -180) BearingErrorH += 360;
  servoAngleH = BearingErrorH+90;


//////////////////////////////Servo controll for Vertical plane

  BearingErrorV= elevationDeg;
  if (BearingErrorV > 180) BearingErrorV -= 360;
  if (BearingErrorV < -180) BearingErrorV += 360;
  servoAngleV = BearingErrorV+90;
  }

  servoAngleH=constrain(servoAngleH, 0, 180);
  servoAngleV=constrain(servoAngleV, 0, 180);
  servo1.write(servoAngleH);
  servo2.write(servoAngleV);
  if(BearingErrorH+90>180){
  Serial.println("servo angle too large drone must be rotated");

  Serial.println(BearingErrorH+90);
  Serial.println(">>>>>>>>>>>>>>>>>>>>>>>>>>>>>");
  Serial.println("-----------------------------");
  }
  if(BearingErrorH+90<0){
  Serial.println("servo angle too small drone must be rotated");
  Serial.println(BearingErrorH+90);
    Serial.println("<<<<<<<<<<<<<<<<<<<<<<");
  Serial.println("-----------------------------");
  }
  if(nextbearing!=0){
```

```
  Serial.println("Horizontal servo position");
  Serial.println(servoAngleH);
  Serial.println("Compass heading");
  Serial.println(headingDegrees);
  Serial.println("GPS bearing");
  Serial.println(nextbearing);
   Serial.println("////////////////////");
  Serial.println("Vertical servo position");
  Serial.println(servoAngleV);
  Serial.println("Altitude difference");
  Serial.println(received.h - sent.h);

  Serial.println("----------------------------");

  }
}
```

Appendix 3. Mathlab Code Used for Simulation

```
clc;
clear;
v=200;% drones speed m/s
v_servo=375.3; %servo speed rad/s387 * pi / 180 375.3
R=20;
t_total = pi * R / v;

%get drone positional data while it is moving around the object
[x, y]=drone_trajectory(v, t_total, R);
degrees=rad2deg(atan2(y, x)); %calculate the bearing to drones position and convert to degrees
%calculate servo bearing to see if it can keep up with the drone
[servo_degrees]=antenna_trajectory(degrees, t_total, v_servo);
angle_servo=rad2deg(servo_degrees);%convert to degrees


t = linspace(0, t_total, length(degrees));

error = degrees - servo_degrees;%calculate if there is a difference between servo and  the drone headings
%plot the servo and antenna angles along with positional error
figure;
subplot(2,1,1);
plot(t, degrees, 'b', 'LineWidth', 3);
hold on;
plot(t, servo_degrees, 'r', 'LineWidth', 3);

xlabel('Time (s)');
```

```
ylabel('Angle (deg)');
title('Position Trackin Results');
legend('Drone bearing', 'Servo response');
grid on;

subplot(2,1,2);

plot(t, error, 'k', 'LineWidth', 3);

xlabel('Time (s)');
ylabel('Error (deg)');
title('Tracking Error');
legend('Rotational Error');
grid on;


%plot maximal drone speed allowed for varying distances according to servo
%motor speed
angular_servo = v_servo * pi / 180;   % rad/s

R = linspace(1, 50, 49);

v_max = angular_servo .* R;

figure;
plot(R, v_max, 'LineWidth', 3)

grid on;
xlabel('Distance from measured drone (m)');
ylabel('Maximum drone speed (m/s)');
title('Max Drone Speed vs Distance');

function [x, y] = drone_trajectory(v, t_total, R)

    n = 500;
    t = linspace(0, t_total, n).';

    angular_v = v / R;
    angle = angular_v .* t;

    x = R .* cos(angle);
    y = R .* sin(angle);
end

function servo_degrees = antenna_trajectory(degrees, t_total, v_servo)
```

```
n = numel(degrees);

sample_t = t_total / (n - 1);
servo_rotation = v_servo * sample_t;

servo_degrees = zeros(size(degrees));
servo_degrees(1) = 0;

for t = 2:n
    angle = degrees(t) - servo_degrees(t-1);
    angle = max(min(angle, servo_rotation), -servo_rotation);
    servo_degrees(t) = servo_degrees(t-1) + angle;
end

end
```