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Abstract

Utilizing Unmanned Aerial Vechials (UAV)s for assisting in emergency response missions is already a fact, both in open landscapes like forests and in restricted areas like sewers. However, using them in road tunnels has not yet been realised, and could possibly provide a huge help for the first responders in the form of surveillance, providing network coverage or announcing self-help assistance to the victims. There are certain challenges which needs to be solved for this to be possible, some of them being lack of signal coverage, battery life and positional navigation in a Global Positioning System (GPS)-denied environment. In this thesis the feasibility of this will be put into consideration by surveying available software and hardware for this utilization, as well as setting up a generalised energy consumption model to check where the different drone configurations can be used. The results implies that the state-of-the-art drone configurations are very capable of being used to assist in emergency situations in road tunnels, both when it comes to response time and length coverage. However, the main restricting factor will be cost, as modern drone swarm configurations with a reasonable battery capacity and sophisticated sensors comes at a high cost.

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Contents

List of Figures

Abbreviations

FANET Flying Ad-Hoc Network

UAV Unmanned Aerial Vechials

INS Inertial Navigation System

UWB Ultra-Wideband

SMD Surface Mount Device

AHRS Attitude and heading reference system

IMU Inertial measurement unit

LiDAR Light Detection and Ranging

GNSS Global Navigation Satellite System

LoS Line of Sight

GPS Global Positioning System

D2D Device-to-device

RFID Radio Frequency Identification Technology

Chapter 1

Introduction

UAVs are widely used for a variety of different operations. Examples of such operations may include photography, filming, carrying out search and rescue operations and/or military operations. Furthermore, the utilization of drones for assisting the emergency response teams within tunnels is a subject which has been considered in various scenarios, i.e., [1] take on search and rescue operations in vehicular tunnels. Drones could assist in a tunnel environment in different manners, such as providing surveillance for the first responders, network coverage for communication if on-site infrastructure is damaged, or offer self-rescue guidance during a stressful situation.

However, there are a set of challenges connected to this, i.e. lack of signal coverage, signal attenuation and battery restraints. By using a swarm of collaborative drones throughout the length of the tunnel, where each drone works as a relay network, it might be possible to extend the signal coverage to such a degree that UAVs may work in this environment. This sets up a Flying Ad-Hoc Network (FANET), where having the furthermost drone work as the main surveillance drone and the other drones will work as backups in case of failure, as well as relaying the data to the base station on the outside. A visualization of this can be seen in 1.1.

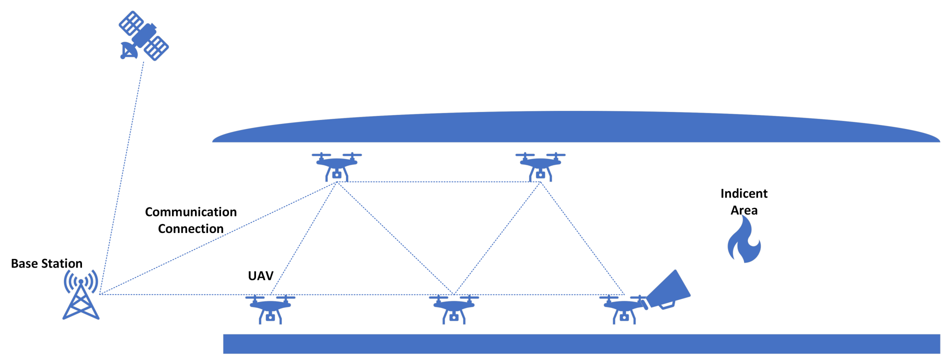

Figure 1.1: Visualization of how the drone swarm will communicate together

1.1 Problem Statement

The outcome of this research could help to set up a framework to see the potential and possibilities of utilizing drone swarms in road tunnels to assist the emergency response teams. With continued advancements in both drone and communication technology there might be a big potential for doing exactly this. The problem statement is as follows: *Is it feasible to utilize collaborative drones in roadside tunnels to assist the emergency response team?*

1.2 Objectives

The objectives of this thesis will be:

1. Figure out feasibility using a generalized mathematical model.
2. Decide which length of tunnels certain drones can be utilized in.
3. Find the main limiting factors for drones to be utilized in such an environment.

1.3 Research Questions

1. Is it feasible to use collaborative drones in roadside tunnels?
2. Which length of tunnels can certain drones be used in?
3. What are the main limiting factors for drones in a tunnel-like environment

1.4 Thesis Outline

The structure of the thesis will be as follows:

2. **Chapter 2 - Related Works**
   A literature review of related works, which involves key concepts.
3. **Chapter 3 - Methodology**
   Describes the approach to the thesis.
4. **Chapter 4 - Feasibility Study**
   Main part of the thesis, where the analytical and survey work is presented.
5. **Chapter 5 - Results**
   Presents the results from the feasibility study.
6. **Chapter 6 - Discussion**
   A discussion of the achieved results.
7. **Chapter 7 - Conclusion**
   A final conclusion with future work which can be done to improve the model.

Chapter 2

Related Works

2.1 Related Works

2.1.1 Drone Swarms

Drone swarms are increasing in popularity due to their huge range of application, as they are able to perform tasks which a single drone can not. [2] presents numerous different applications for aerial swarms, some of them being entertainment, security and surveillance, collaborative transportation and environmental monitoring. The authors also go into detail on which challenges still apply to aerial swarms, with real-world orientated development being the key to solving most of them.

As mentioned earlier, drone swarms working together in union form a FANET, and are able to communicate and act according to each other. In the paper from [3], there is presented a solution where the drones have no prerequisites when it comes to infrastructure or specific sensors. Instead, the drones position relative to others based on signal strength. Additionally, [4] takes deeper dive into the issues,, challenges, research problems and research directions of FANETs. Some of the issues presented include Security in Communication, Path Planning, multimedia routing and mobility models.

There has also been proven drone swarm architectures specifically developed for autonomous swarms with UAV-to-UAV communication. [5] , shows that there is a huge potential for utilization of drone swarm together with the upcoming 5G network.

2.1.2 Emergency Situations

Due to their fast and flexible deployment, drones could have a big impact on certain emergency situations, both outdoors and in constricted environments. The utilization could vary quite a lot, taking [6] as the first example. Here the authors consider a public safety scenario, where an emergency alert message is broadcast by the drone. Furthermore, they utilize a drone-initiated Device-to-device (D2D)-aided multihop multicast network to reach as many devices as possible, which will result in devices getting the emergency alert even if they're not in range of the initial alert from the drone.

Another utilization of drones in emergency situations could be when natural disasters happen, i.e. tsunamis, hurricanes or earthquakes. The latter is the focus in [7]. Here the topic of using drone swarms to perform rapid safety evaluations of building after there has been an earthquake.

2.1.3 Surveillance

Utilizing FANETs for different types of surveillance is a great way to ensure safety and flexibility. In [8] FANET surveillance is used to identify the presence of fire zones in forests, and transfers all data to a base station whenever they are in range. Furthermore, in [1] UAVs are used to help out in an emergency response situation, with surveillance being one of the factors of which the FANET can prove helpful.

2.1.4 Usage in tunnel-like environment

As previously mentioned, there has been done different research on utilizing drones in both vehicular tunnels and “tunnel-like” environments. [1], suggest using the drones to form a wireless ad-hoc network to support communication deep inside the tunnels, were the drones serves as a relay for data transmission. Furthermore, the drones would have cameras and sensors installed onto them, to be able to localise fires and survivors within the tunnels. According to [1] these drones could work together with a smart architecture of radars, cameras, and sensors, as well as utilizing Radio Frequency Identification Technology (RFID) for finding survivors.

Another application of drones is described by [9] , which goes into details on how drones are being used within the mining industry. There are two main advantages from utilizing drones being highlighted here, which are that drones fitted with sensors can be used for inspections of an area and used for unblocking of blocked box-holes and ore-passes. Other examples in this paper are connected to mine safety, 3D mapping, construction monitoring, rescue missions, gas detection, and several other applications.

Inspections of deep tunnels are both extremely challenging and dangerous, which is why UAV are preferred to be utilized for this, instead of having people perform such tasks. In [10], there is presented a smart UAV platform to be utilized inside the Deep Tunnel Sewerage System in Singapore. This tunnel system is very long and narrow, and requires routinely inspections of the tunnels structural integrity. Their solution enables effective tunnel inspection, by using a rotary image system to capture the entire tunnel wall surface.

Lastly, [11] describes yet another utilisation aspect of drones, which is inspection of tunnel lining surface. This aspect is similar to what was shown in the last paragraph, however, in this paper [11] developed a tunnel lining surface inspection system which utilizes an Edge-AI. Three major techniques were introduced, them being: *The YOLOv3 Detection Model with Sensor Fusion*, *Small Defect Detection using SAHI* and *Synthetic Image Creation for Training*.

2.1.5 Routing

Drone swarms need to have optimal algorithms for communication and autonomous flying, both for the sake of quality of service and battery life. [12], shows a comparison between flooding and routing techniques for drone swarms, taking into consideration energy consumption, range, and latency. In the comparison it is shown that the flooding technique seems to be the superior one, especially when it comes to robustness and its resistance to multi-path fading, because of no single point of failure.

[13], proposes an energy efficient algorithm (E-AntHocNEt) based on classical ant colony, which shows great tendency to reduce packet drop rate. This will improve network throughput and quality of service, and overall is a good routing protocol for a flying Ad-Hoc network. [14] also show routing and power management, but this time in a GPS-denied environment, via the widely known Dijkstra algorithm. By using a router-based navigation system it finds an optimum path and helps to control the drone traffic.

2.1.6 Collision-free navigation

Collision-free navigation is also quite important in making sure the UAV is kept safe whilst operating, especially when they are in unknown environments. [15] presents exactly this for quad-rotor UAVs in an unknown tunnel-like environment. Their solution presents a computationally light method which processes light from sensors' measurements to guide the UAV along the tunnel axis. From the results presented this seems to be a navigation algorithm which works quite well. [16] also proposes a collision-free navigation algorithm, by combining RRT-GD and the RRT*-Smart algorithms, they ended up with the RRT*-GD-Smart algorithm which resulted in a higher convergence rate. Together with low cost sensors, [16] concluded with a complete navigation system for an autonomous indoor UAV.

Chapter 3

Methodology

To figure out if it is feasible to utilize drone swarms for emergency response mission, there are certain aspect which needs to addressed and solved. This thesis will rely on two different methodologies. The first one being survey work, where surveying different data aspects of the drones, these include available hardware, software and more. Furthermore, an analytical approach will be performed where a mathematical model will be presented and evaluated.

3.1 Survey Work

3.1.1 Drone models

In there being a plethora of available drone models at the current marked, it was important to figure out which ones are applicable to usage in a tunnel environment.

Drone type

Firstly it was necessary to decide which type of drone is most suitable for this situation. For this, popular drone blog website where used, such as the likes of [17] and [18]. It was decided that a rotor drone would need to be used because of the ability to hover in place, compared to a fixed-wing drone which needs to keep moving. Furthermore, multi-rotor drones, or quadcopters, drones would be utilized, as they are more safe and are generally more affordable, compared to single-rotor helicopter drones.

Drone models

After the type of drone was established, different drone models needed to be evaluated. Again, looking to news outlets for drones was the strategy. The likes of [19] and [20] provided good insight into different drone models and their capabilities. To get specific information about each drone model, their official website and product specifications were used. Which drones were picked can be seen in 4.4.

3.1.2 Software

For the drone swarm to work in unison and be able to autopilot the fleet, there are software which needs to be implemented. To find such software [21] was a good start. The article provided Open Source projects which have been under development for a long time. This was an older article, however it provided information about such projects like Ardupilot [22] and Dronecode [23]. Both of these are open source, which is an integral part in making an affordable model.

3.2 Analytical Work

The analytical part consisted of making a mathematical model, and use that model to analyse if and when a certain drone swarm configurations is usable.

3.2.1 Mathematical model

The mathematical model is mainly comprised of evaluating energy used by drone flight and sensor usage, vs available energy for the drone. The aim was to make a generic model which could be easily used to check an approximate of how far a set of drones could reach, as well as leaving room for other energy models to be implemented for evaluation of specific setups. The basis of the model is in using Joule's Law and Ohm's Law to extract the power consumption of each phase and use the energy level of a drones battery (Power · Time), before subtracting the energy consumed by the different actions. A detailed explanation, with an example, will be provided in 4.3.

3.3 Tools

The tools utilized for this thesis was:

- Visual Studio Code with Python. This was used to write a script for the mathematical model, as well as plotting graphs for drone capabilities and tunnel length distributions.
- Microsoft Visio. This was used to visualize the drone within a tunnel, to easier explain the though process behind the mathematical model and communication model.
- Overleaf with Latex. Used to write and present the thesis.
- The literature search engines, Oria[1] and Google Scholar[2] were used to survey for relevant literature within the applicable fields.

[1]https://www.oria.no/
[2]https://www.scholar.google.com/

Chapter 4

Feasibility Study

4.1 Challenges

Even though there are plenty of positives with utilizing drones for emergency response within tunnels, there are first quite a few challenges which needs to be handled for the drone swarm to be effective and useful. These may include:

- Limited GPS signal: GPS signals may not reach inside tunnels, which can affect the drone's navigation and positioning accuracy. This can make it difficult to keep the drones in formation and can increase the chances of collisions.
- Signal attenuation: Tunnels are made of materials that can block or weaken radio signals, such as concrete and steel. As a result, FANETs operating in a tunnel may experience signal attenuation, leading to weaker and more unstable connections.
- Multipath fading: the signal from FANETs can reflect off the walls of the tunnel, leading to multiple paths that the signal can take. These multiple paths can cause interference and make it difficult for the receiver to accurately decode the signal.
- Interference: the confined space of a tunnel can result in interference

from other wireless devices, such as radios or Wi-Fi networks. This interference can result in a decrease in the signal-to-noise ratio, making it difficult for the receiver to distinguish the signal from the noise.

- Limited Line of Sight: FANETs rely on radio signals to communicate with each other, and radio waves cannot penetrate solid obstacles like the tunnel walls. As a result, the line of sight between the nodes is often limited because of the curves inside the tunnels, making it challenging to establish and maintain stable connections.
- Power Consumption: establishing and maintaining communication links inside a tunnel requires a significant amount of power, which can drain the battery life of the UAVs quickly. This limitation can impact the drones flight time, and reliability of the established network.
- Lighting: lighting can be an issue in tunnels, especially in poorly lit or dark areas. This can affect the ability of the drones to see and navigate, increasing the risk of collisions or crashes. Furthermore, it may reduce the effectiveness of the drones, as the information received may be less helpful.
- Airflow and turbulence: airflow and turbulence can be unpredictable and strong inside tunnels, which can affect the stability and maneuverability of the drones. This can also make it challenging to maintain the desired formation and speed.

4.2 Payload

The increase in payload will have a impact on battery consumption as shown in 4.3, which is why it is important to include it. The energy consumption model for payload for this thesis is on the basis of [24]. Here several different payload models are compared, both for larger drones and smaller drones. [24] concludes that for both smaller and larger drones the power consumption is close to linear, and has a 20-40% increase in energy consumption depending on which payload model is used.

For this thesis the goal is, as mentioned, to make a general model, which is why as many specifics as possible are being left out. It has been decided to generalise from the study [24], and include a constant payload power consumption rate. The study presents 20-40% increase in energy consumption for 0g to 500g increase in payload, which is the relevant part as this thesis mainly utilizes small drones. The worst case scenario will be used in this thesis, which is 40% increase with 500g payload. This gives the equation below 4.2.

$$PayloadEnergyRate = \frac{40\%}{500g} = 0.08\%/g \tag{4.1}$$

This gives a constant percentage rate increase for every gram of payload on the drone. It is worth noting that this model does not take into account changes in aerodynamics, which increase in payload may cause, and the fact that different drone models may consume more or less energy with increased payload. Furthermore, the final equation with payload energy consumption utilized as a percentage increase will be as follows:

$$EC_{Payload} = \frac{Payload \cdot PayloadEnergyRate}{100} + 1 \tag{4.2}$$

4.3 Mathematical model

To figure out if it is feasible to utilize drone swarms for emergency response mission, there are certain aspect which needs to addressed and solved. Firstly, there is to be introduced three phases of the flight scenario. These phases are:

1. **Deployment**: this is the first phase of the mission, where the drones will autonomously fly into the tunnel one at the time, and stop whenever the first drone reaches the incident site. They will be deployed at certain intervals, which will vary according to the distance that is to be maintained between each drone.
2. **Hovering**: in this phase the drones have reached their designated positions inside the tunnel, and will only hover and transmit data.
3. **Returning**: this is the final phase of the mission, where the drones are returning to the base station. In reality, this phase is very similar to "Deployment", however it does not need to take into account deployment intervals.

Symbol	Meaning	Unit
T_{Flight}	Adding T_{Dep} and T_{Ret} together	min
T_{Dep}	Time to deploy	min
T_{Hov}	Time spent hovering	min
T_{Ret}	Time used to return	min
IL	Length from start of tunnel to incident area	m
SM	Safety margin to not deplete battery	unitless
$\overline{v}$	Average speed of drone	km/h
PC_{Sens}	Power consumption by Sensors	W
PC_{Flight}	Power consumption by Flight	W
PC_{Hov}	Power consumption by Hovering	W
PC_{Com}	Power consumption by Communication	W
E_{DB}	Energy of the drones battery	Wh
EC_{Flight}	Energy used when flying	Wh
EC_{Hov}	Energy used when hovering	Wh
EC_{Sens}	Energy used to power the sensors	Wh
$EC_{Payload}$	A percentage used take into account payload	unitless

Table 4.1: Meaning of symbols used in the following and previous equations.

Constraints:

1.
$$T_{Total} = T_{Dep} + T_{Hov} + T_{Ret} \leq \frac{IL}{(\overline{v} \cdot 1000) \div 60} \div 2$$

Assumptions:

1. In keeping with a generic model, wifi transmission specifics are not taken into account. As shown by [25], communication generally has a very low impact on energy consumption, especially on such short ranges. This resulted in a decision to put PC_{Com} equal to zero .

2. For most cases, $T_{Dep} \equiv T_{Ret}$

Energy level of a battery can either be taken directly from the drones specifications, or derived by using 4.3. Here Capacity is the battery capacity in

Ampere-hour.

$$E_{DB} = Voltage \cdot Capacity \tag{4.3}$$

Furthermore, there is Joule's Law to calculate power consumption in watts, where P is power consumption in watts and I is current drain in ampere:

$$P = Voltage \cdot I \tag{4.4}$$

E_{DB} being the amount of energy consumed or produced by system that operates at a constant rate of one watt for one hour, means that the power consumption for both flying and hovering can be derived by the following equation:

$$P = \frac{E_{DB}}{Time} \tag{4.5}$$

From normal specifications for different drones, where flight time and hovering time usually is given, the equation 4.5 can be used to calculate the power consumption from flight and hovering. This gives us PC_{Flight} and PC_{Hov} as follows:

$$PC_{Flight} = \frac{E_{DB}}{(MaxFlightTime \div 60)} \tag{4.6}$$

$$PC_{Hov} = \frac{E_{DB}}{(MaxHoveringTime \div 60)} \tag{4.7}$$

Additionally the power consumption from additional sensors will simply be added together, and then multiplied by the total time to get power consumption equation and energy consumption equation respectively:

$$PC_{Sens} = \sum_{i=1}^{n} PC_i \tag{4.8}$$

$$EC_{Sens} = \frac{(T_{Flight} + T_{Hov})}{60} \cdot PC_{Sens} \tag{4.9}$$

The energy consumption from each flying phase, which were **Deployment** and **Returning**, can be presented as single equation by using assumption number 2 from the earlier assumptions 4.3.

$$EC_{Flight} = \frac{T_{Flight}}{60} \cdot PC_{Flight} \cdot EC_{Payload} \tag{4.10}$$

Lastly the energy consumption from the **Hovering** phase will be as follows:

$$EC_{Hov} = \frac{T_{Hov}}{60} \cdot PC_{Hov} \cdot EC_{Payload} \tag{4.11}$$

This results in the Final Mathematical Model:

$$EC_{Flight} + EC_{Sens} + EC_{Hov} \leq E_{DB} \cdot SM \tag{4.12}$$

Utilizing equation 4.12 together with the other equations like 4.11 and 4.10, it is possible manipulate the to achieve different results. I.E. by setting a certain hovering time, it can be calculated which maximum flight time is possible, which in turn can be used to calculate how far the drone can travel by using the simple equation 4.13. In that equation, speed is in meters per minute, which gives the maximum distance the drone can travel in meters. It divides by 2, to ensure the drone can safely return to its starting position.

$$Max_{Distance} = \frac{Speed \cdot T_{Flight}}{2} \tag{4.13}$$

4.3.1 Example of mathematical model in practice

In this section an example, using the DJI Mini 3 Pro [26], will be performed to showcase how the mathematical model operates.

Furthermore, the sensors from 5.1.4 will be used. Then by using equations 4.2, 4.8 and 4.11, where 10 minutes of active hovering time is utilized, the models gives the following values:

Symbol	Value	Unit
Max Flight Time	47	min
Max Hovering Time	40	min
E_{DB}	28.4	Wh
SM	0.8	Unitless
$\overline{v}$	21.6	km/h

Table 4.2: Spec from a DJI Mini 3 Pro [26]

Symbol	Value	Unit
PC_{Flight}	36.25	W
EC_{Hov}	7.1	Wh
PC_{Sens}	0.21	W
$EC_{Payload}$	1.0192	Unitless

Table 4.3: Intermediate calculations

After these intermediate calculations have been done, the final model equation 4.12 can be utilized, and all that has to be done is rearrange for T_{Flight}. This gives the following equation:

$$T_{Flight} \leq \frac{E_{db} \cdot SM - EC_{Hov}}{PC_{Flight} \cdot EC_{Payload} + PC_{Sens}} \cdot 60 - \frac{T_{Hov} \cdot PC_{Sens}}{PC_{Flight} \cdot EC_{Payload} + PC_{Sens}} \tag{4.14}$$

Furthermore, by putting in the known values in equation 4.14 it gives us **25.17min**, which is very close to what is displayed in 6.1. There is a slight difference due to the value from 6.1 is from the mathematical model put into a python script, which is more accurate.

Lastly, to find the achievable distance, the flight time can be multiplied by the average speed of the DJI Mini 3 Pro [26] as shown in equation 4.13.

This results in **4529m**, which is very close to what is presented in figure 5.7.

In this example we got a flight time of 25.17 minutes and a max distance of 4529 meters, when we were hovering for 10 minutes. However, it is important to note that this is just an approximation, as other factors like wind, temperature and humidity, to name a few, might impact the battery consumption.

4.4 Software

There are currently quite a few software which are being used for drone swarms, and picking between them can be challenging. There are certain software which are open source, and could be used for the application described in this thesis. Some of them are:

Software	Open Source
Dronecode [23]	Yes
PX4 [27]	Yes
ROS [28]	Yes
Ardupilot [22]	Yes
FlytBase [29]	Yes

- Dronecode [23]: Dronecode [23] is an open source platform that provides a comprehensive solution for building, programming, and operating a wide range of autonomous vehicles, including drones. The platform includes several key components, including the PX4 flight stack, MAVLink communication protocol, and QGroundControl ground control station. Dronecode [23] is designed to be highly customizable, and it supports a variety of hardware platforms and operating systems.
- PX4 [27]: PX4 [27] is a popular open source flight control software for drones, which is highly customizable and designed to work with a variety of hardware platforms. It includes a real-time operating system, flight control algorithms, and support for various sensors and communication protocols. PX4 [27] is designed to be modular, which

allows users to easily customize and extend the platform to meet their specific needs.

- ROS (Robot Operating System) [28]: Although not specifically designed for drones, ROS [28] is a widely used open source platform for building robot applications and can be used for collaborative drone swarm applications. It includes a set of libraries and tools for building, simulating, and testing robot applications, as well as communication and visualization tools. ROS [28] is designed to be modular and distributed, which allows users to easily develop and integrate software components.

- ArduPilot [22]: ArduPilot [22] is another popular open source autopilot software for drones, which supports a variety of vehicle types including fixed-wing, multirotor, and VTOL. It includes a wide range of features, including support for GPS-based navigation, mission planning, and autonomous flight modes. ArduPilot [22] is highly customizable and can be used with a variety of hardware platforms.

- FlytBase [29]: FlytBase [29] is an open source platform for building drone automation and control applications that includes support for collaborative drone swarms. It includes features such as real-time video streaming, mission planning, and obstacle avoidance. FlytBase [29] is designed to be highly scalable, which allows users to easily deploy and manage large drone fleets.

When considering which open source software platform would be most suitable for drone swarms working inside tunnels, there are several factors to consider, as has been mentioned earlier in the thesis 4.1. Taking into consideration this, ROS [28] looks to be a very suitable open source software. ROS [28] is designed to be highly modular and distributed, which allows users to develop and integrate software components for specific tasks. This can be useful when working in tunnels where GPS signals may not be available, as it allows the drones to rely on other sensors such as Light Detection and Ranging (LiDAR) or Inertial Navigation System (INS) for navigation. Additionally, ROS [28] includes support for various communication protocols, which can be useful for maintaining communication between drones in a swarm.

ArduPilot [22] could also be a suitable open source software platform for drone swarms working inside tunnels, depending on the specific requirements of the application. ArduPilot [22] includes support for various vehicle types, including multirotors which are well-suited for navigating confined spaces such as tunnels. Additionally, ArduPilot [22] includes support for a variety of sensors, such as LiDAR and sonar, which can be useful for obstacle avoidance and navigation in GPS-denied environments. That being said, there are some potential limitations to using ArduPilot [22] for drone swarms working inside tunnels. For example, the performance of the autonomous flight modes may be affected by the quality of the onboard sensors, and communication between drones may be more difficult in areas with limited GPS and communication signal availability. As with any software platform, it is important to carefully evaluate the specific requirements of the application and choose the best tool for the job.

4.5 Assortment of drones

As stated earlier, there are quite a few drones which could be applicable for this scenario. Below there can be seen a table 4.4 which shows a selection of drones which could be used.

Drone	Flight Time [min]	Hovering Time [min]	Cost [nok]	Energy [Wh]	Average Speed [km/h]
DJI Mini Pro 3 [26]	47	40	8790	28.4	21.6
DJI Mavic 3 [30]	46	40	21999	77	32.4
DJI Air 2S [31]	31	30	11990	41.4	36
Autel Evo Lite+ [32]	40	38	21099	68.7	36
Autel Robotics Evo ll Pro [33]	40	35	16 013	82	37

Table 4.4: Assortment of applicable drones. This is not an exhaustive table. Prices are taken from www.elkjop.no and www.computersalg.no

4.6 Navigation

The question of navigation and control of the collaborative UAVs is also an important aspect to consider carefully. As mentioned in 4.1, GPS signals may not be available or reliable inside road tunnels due to the lack of direct line-of-sight with the GPS satellites. In such cases, other position systems can be utilized to enable navigation and control of the UAVs. Some of these other systems are listed below.

- Inertial Navigation Systems
  INS uses accelerometers and gyroscopes to measure the velocity and orientation of the UAV. It has a Kalman filter in it, which is how the sensor itself uses the information to estimate the position of the UAV relative to its initial position. INS can provide accurate positioning information in the absence of GPS signals, but it might be prone to drift over time.

- Ultra-Wideband (UWB) Positioning
  UWB is a wireless positioning technology that uses radio waves to measure the distance between a transmitter and a receiver. UWB can be used to estimate the position of the UAV relative to UWB beacons installed in the tunnel. This technology can provide accurate positioning information, but it requires careful calibration and placement of the beacons.

- LiDAR-based Navigation
  LiDAR uses lasers to measure distances and create a 3D map of the environment. This technology can be used to estimate the position of the UAV relative to the walls and other objects in the tunnel. LiDAR can provide accurate positioning information, but it is limited by the range and density of the laser scans.

- Magnetic Field-based Navigation
  Magnetic field-based navigation uses the Earth's magnetic field to estimate the position of the UAV. This technology can be used in tunnels with known magnetic field variations, such as those caused by steel reinforcement in the walls. However, it is less accurate than other position systems and is susceptible to interference from nearby metal objects.

Considering the effectiveness, battery consumption, and cost, an INS or a magnetic field-based system may be the most cost-effective options for determining the drone's position inside tunnels. However, INS is prone to drift over time, making it not suitable for longer mission, thus, combining these systems might be the better option. Examples where this is the case are can be seen in the table below.

Model	**Power consumption** [W]	**Weight** [g]	**Cost** [nok]
Ellipse2-N Micro INS [34]	0.4	10	Not received
VN-300 Global Navigation Satellite System (GNSS)/INS [35]	1.25	5 (Surface Mount Device (SMD)) 30 (Rugged)	57270
AHRS-M2 Micro Attitude and heading reference system (AHRS)/Inertial measurement unit (IMU) with AutoCal [36]	0.06	7	Not received
Inertial Labs INS-B [37]	2.5	220	Not received

Table 4.5: Variety of different INS.

Ellipse2-N Micro INS [34]is light weight (10 grams) with a 400mW power consumption, which would make it ideal for utilization on small drones. It has a built-in USB port for configuration and data transfer and can communicate via a variety of protocols, including NMEA, ASCII, and binary. This would be quite a good INS for smaller drones, especially because of the light weight.

The Inertial Labs INS-B [37] would also be a good option, but is slightly bigger (220g), and consumes more power (2.5W). It is designed for use in a wide range of applications, including land, air, and marine navigation. The INS-B [37] provides accurate and reliable position, velocity, and attitude information, even in areas where GPS signals may be weak or unavailable.

4.6.1 Obstacle Detection Systems

Furthermore, obstacle detection systems need to be implemented, as to keep the swarms from colliding with the walls or other objects is essential for mission safety. There are several obstacle detection systems that could be used, through surveying a few examples have been acquired, and listed below.

- LiDAR
  LiDAR (Light Detection and Ranging) sensors use lasers to create a 3D map of the environment and detect obstacles in the path of the UAV. LiDAR sensors are highly accurate and can detect obstacles at a range of distances, making them a popular choice for obstacle detection in UAVs.

- Ultrasonic Sensors
  Ultrasonic sensors emit high-frequency sound waves and measure the time it takes for the sound waves to bounce back from obstacles. These sensors are commonly used in parking sensors and can be used to detect obstacles in the path of the UAV.

- Infrared Sensors
  Infrared sensors detect the heat signature of obstacles in the path of the UAV. These sensors are commonly used in proximity sensors and can be used to detect obstacles in the path of the UAV.

- Stereo Cameras
  Stereo cameras use two cameras to create a 3D map of the environment and detect obstacles in the path of the UAV. These cameras can detect obstacles at a range of distances and can provide highly detailed images of the environment.

- Radar
  Radar sensors use radio waves to detect obstacles in the path of the UAV. These sensors can detect obstacles at long ranges, making them useful for obstacle detection in UAVs flying at high speeds.

When choosing which systems to use, and to make sure the best system is being used, there are several factors to take into account, Considering the effectiveness, cost, and reliability, cameras and ultrasonic sensors are the most cost-effective options for obstacle detection in tunnels. However, radar and LiDAR may be better options for applications that require higher accuracy and reliability, but at a higher cost. The specific choice of obstacle detection system will depend on the specific requirements of the mission, such as the range and accuracy of obstacle detection needed, and the available budget.

Model	**Type**	**Power consumption** [W]	**Weight** [g]	**Cost** [nok]
Maxbotix I2CXL-MaxSonar [38]	Ultrasonic	0.0242	Not listed	545
HC-SR04 [39]	Ultrasonic	0.075	8.5	64
Benewake TFmini-S LiDAR Module [40]	LiDAR	0.7	5	463
Garmin LiDAR-Lite V4 Led [41]	LiDAR	0.425	14.6	679
LightWare SF45/B [42]	LiDAR	1.5	59	4726

Table 4.6: Variety of different LiDAR sensors and ultrasonic sensors.

4.7 Durability and Redundancy

During an emergency response situation, it is of the utmost importance to keep both the UAVs itself and communication between them operational throughout the entire mission. If this fails, it could end up making the emergency situation worse than it already is. To keep this from happening, there needs to be some form of redundancy for the drones.
The first thought that comes to mind when introducing redundancy in a drone swarm, would be to increase the number of drones in the swarm. As

mentioned earlier, the drone swarm would function as a FANET, meaning it would relay data between each drone. Intuitively, by having more drones there would be more nodes to relay to, resulting in redundancy if one of the drones were to fail.

However, taking into account how narrow tunnels can be and the cost of drones, flooding the tunnels with an abundance of drones would not be possible during a critical distress situation. The proposed solution would be to deploy enough drones such that any of the drones, at any time, has connection with 2 other drones. An example of how this would work can be seen in the figure 4.1 down below. This approach would create redundancy in the case of a UAV malfunctioning during the mission, and would ensure connectivity for the network.

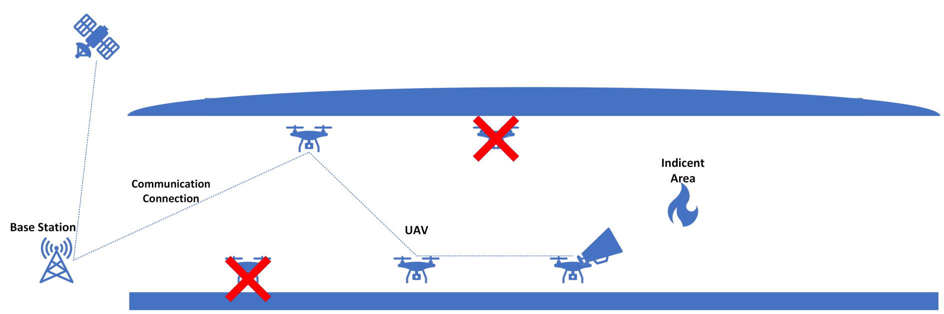

Figure 4.1: Visualization of how multiple drones will implement redundancy in case of some drones malfunctioning

4.8 Communication/routing

When inside a tunnel there are certain constraints, which was mentioned in 4.1, when it comes to communication for the drone swarm. Some of these challenges include:

To overcome the constraints that FANETs face when communicating inside a tunnel, several techniques and solutions can be implemented. Here are some possible ways to address these constraints:

- Use of directional antennas: Directional antennas can help to increase the range of communication and reduce interference. By focusing the signal in a specific direction, it is possible to establish stable connections with other nodes, even in the presence of obstacles. Beamforming techniques can also be used to further improve the signal strength and quality.

- Multi-hop communication: Multi-hop communication involves relaying data packets between multiple nodes to reach the intended destination. This technique can help to overcome the limited range and line of sight issues faced by FANETs in tunnels. In a multi-hop network, intermediate nodes act as relays, forwarding packets to other nodes until they reach the final destination. However, multi-hop communication may increase latency and reduce overall network throughput.

- Adaptive modulation: Adaptive modulation is a technique that adjusts the modulation scheme of the communication link based on the quality of the channel. By using a lower modulation scheme when the signal is weak or the channel is noisy, it is possible to maintain a stable connection and reduce the impact of interference and signal fading.

- Routing protocols: Routing protocols determine the path that data packets take in the network. In tunnels, where the network topology is highly dynamic and unpredictable, routing protocols need to be robust and able to adapt quickly to changes in the network. Proactive routing protocols, such as Optimized Link State Routing (OLSR), and reactive routing protocols, such as Ad hoc On-Demand Distance Vector (AODV), are commonly used in FANETs.

- Power management: To extend the lifetime of the UAVs and reduce power consumption, power management techniques can be used. These techniques may include dynamic voltage scaling, duty cycling, and sleep mode. By reducing the power consumption of the nodes, it is possible to improve the overall lifetime and reliability of the network.

As mentioned above, and in 2, there are several routing protocols can be suitable for FANETs operating in tunnels, depending on the specific requirements and constraints of the application.

- Optimized Link State Routing (OLSR): OLSR is a proactive routing protocol that maintains a global view of the network topology by exchanging link-state information between nodes. OLSR can work well in tunnels because it can quickly adapt to changes in the network and provide reliable routes even in dynamic and unpredictable environments. OLSR can also support multi-hop communication, making it a suitable choice for FANETs.

- Ad hoc On-Demand Distance Vector (AODV): AODV is a reactive routing protocol that establishes routes on demand as needed. When a node needs to send data to a destination, it broadcasts a route request (RREQ) message, and the nodes along the way forward the message until it reaches the destination or a node with a route to the destination. AODV can work well in tunnels because it can quickly establish routes to destinations and minimize overhead and latency.

- Dynamic Source Routing (DSR): DSR is a reactive routing protocol that uses source routing to establish routes. In DSR, each data packet carries the complete route from the source to the destination. When a node needs to send data, it looks up the route in its cache or broadcasts a route discovery (RREQ) message. DSR can work well in tunnels because it can support multi-hop communication and reduce the overhead of maintaining routing tables.

- Zone Routing Protocol (ZRP): ZRP is a hybrid routing protocol that combines proactive and reactive strategies. ZRP divides the network into zones, where each zone has a proactive routing protocol to maintain a local view of the network topology. When a node needs to send data to a destination outside its zone, it uses a reactive routing protocol to establish a route. ZRP can work well in tunnels because it can provide reliable and efficient routes while minimizing overhead and latency.

Chapter 5

Results

5.1 How far do the drones reach?

To be able to actually see in which length of tunnels each drone is able to be used in, it is necessary to plot it. By writing a simple script to use the proposed mathematical model, it is possible to cross reference the length of tunnels by the possible reach achievable of each drone.

There has been picked out four different configurations to evaluate, and can be seen in the table below 5.1. The reasoning for the different configurations are on the basis of covering different types of sensors, as well as a variety of compositions between the different sensors. Each configuration has two different sensors equipped, one for navigational purposes, and one for obstacle detection.

Furthermore, there will be a few different figures presenting different values. One will show how long each of the drone models can stay in active flight for a given active hovering time. Another one will show the distance possible distance each drone can cover for a given hovering time. Important to note, is that the distance take into consideration that the drones would need to return to its start position again. Lastly there will be figures to show possible response times according to maximum and minimum speeds, however the energy consumption model will not be used here as the energy consumption is derived from average speed from the different drones specifications. All the figures will be presented here, and then evaluated in 6.

Config 1	**Config 2**	**Config 3**	**Config 4**
VN-300 SMD GNSS/INS [35]	VN-300 Rugged GNSS/INS [35]	Inertial Labs INS-B [37]	AHRS-M2 Micro AHRS/IMU with AutoCal [36]
TFmini-S LiDAR Module [40]	Garmin Lidar Lite v4 [41]	LightWare SF45/B [42]	HC-SR04 Ultrasonic [39]
This uses a lightweight INS together with two light-weight LiDARs, with a total weight of 15g	This uses a light weight INS, together with two slightly heavier LiDAR sensor. Total weight reaching 60g	This is the more "rugged" build, which uses a heavy INS and two heavy LiDARs. Totalling in on 340g	A light weight build, this time a INS and two ultrasonic sensors with weight of only 24g.

Table 5.1: Configurations used.

5.1.1 Configuration 1

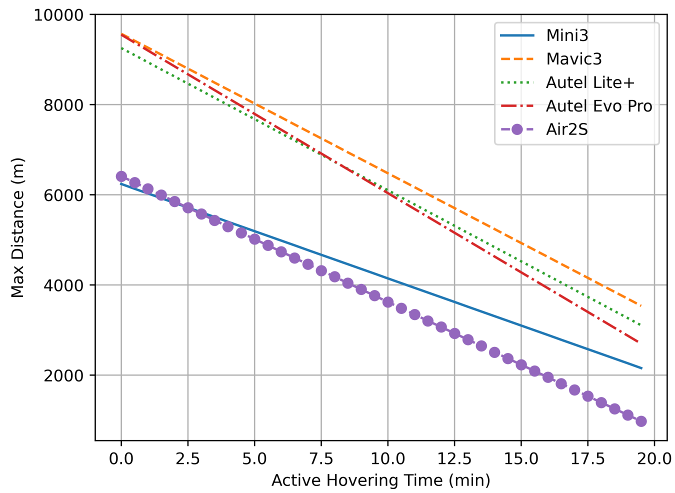

Figure 5.1: Configuration 1 Max Distance

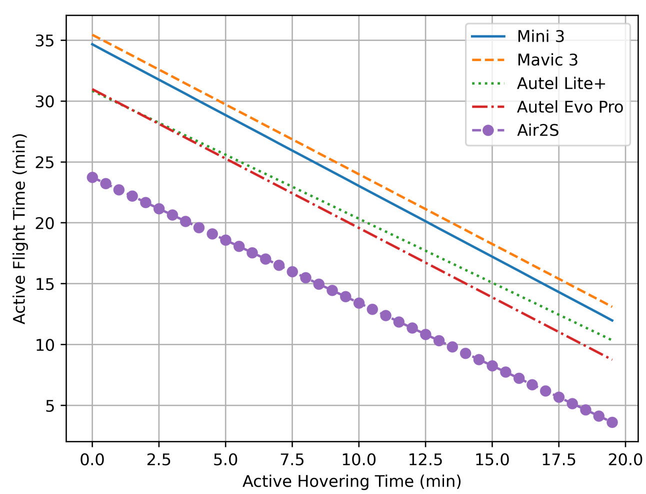

Figure 5.2: Configuration 1 Max Active Flight Time

5.1.2 Configuration 2

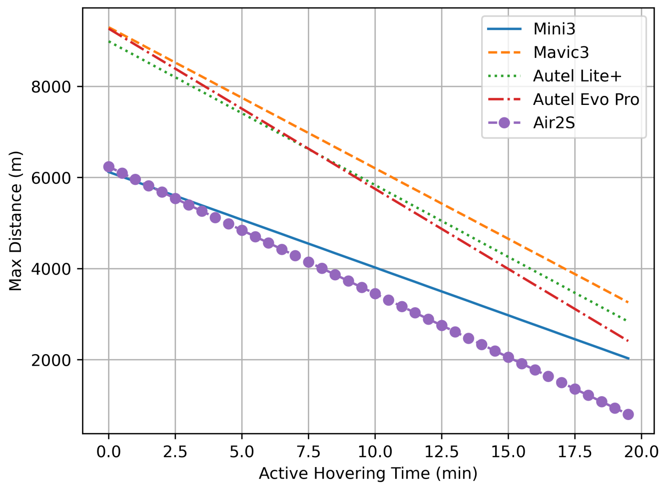

Figure 5.3: Configuration 2 Max Distance

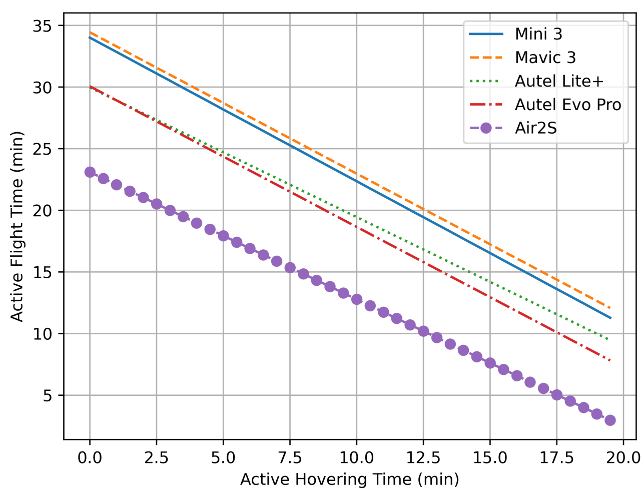

Figure 5.4: Configuration 2 Max Active Flight Time

5.1.3 Configuration 3

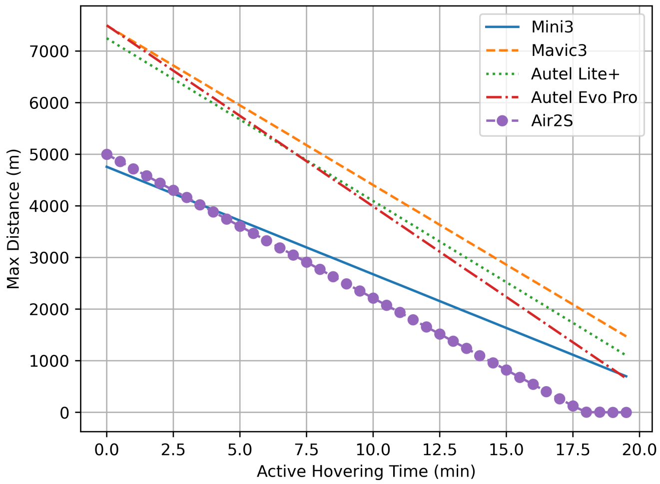

Figure 5.5: Configuration 3 Max Distance

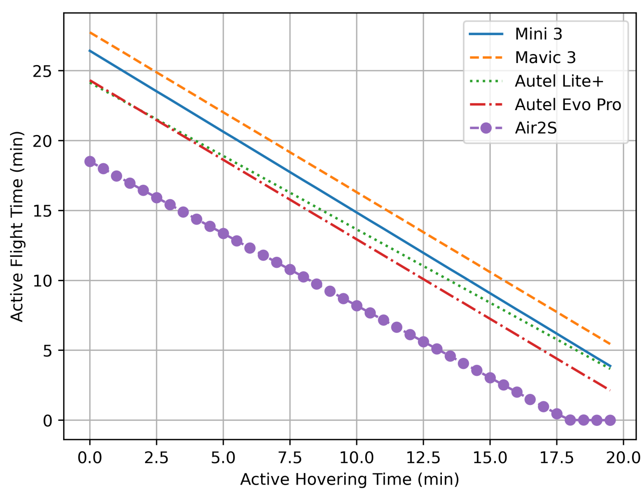

Figure 5.6: Configuration 3 Max Active Flight Time

5.1.4 Configuration 4

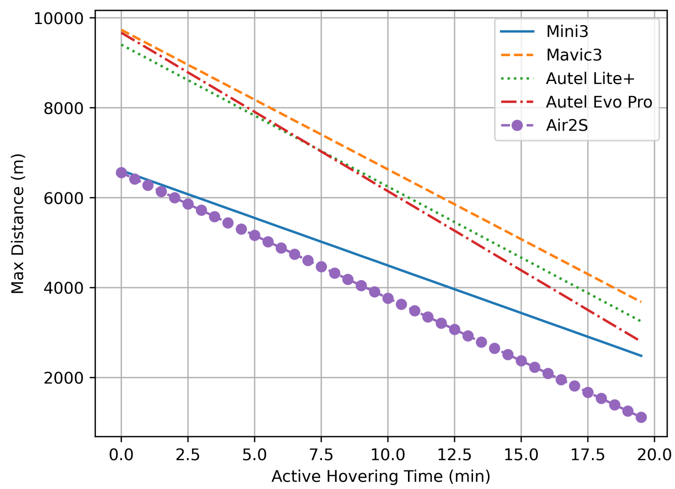

Figure 5.7: Configuration 4 Max Distance

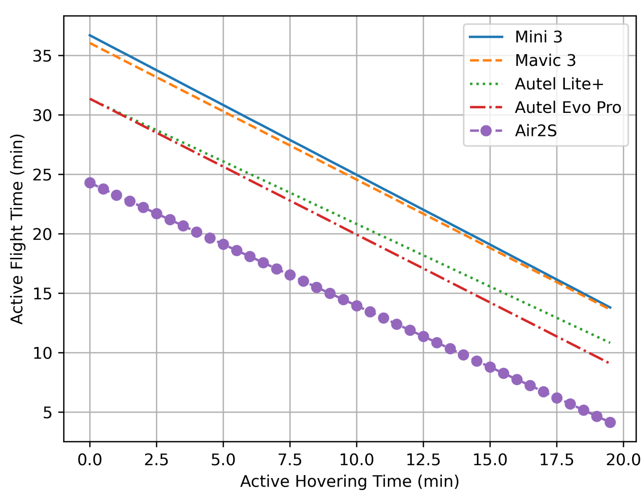

Figure 5.8: Configuration 4 Max Active Flight Time

5.2 Response Time

A critical factor to consider when utilizing drones for emergency response missions is how quickly they are able to provide useful information to emergency response teams. This makes it so that the speed of which the different drones can fly is important, and not just how long it can stay airborne. The figure will show response time for each of the drones mentioned in 4.4, where the distance is set to 2000m, which covers 86.2% of the Norwegian tunnels. It is also important to note that this is the average and fastest listed speeds for each drone model taken from their respective specifications.

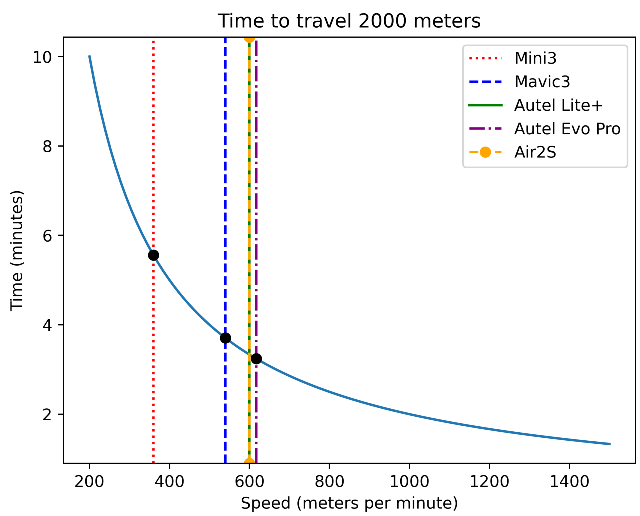

Figure 5.9: Average Response time for each drone from the table 4.4

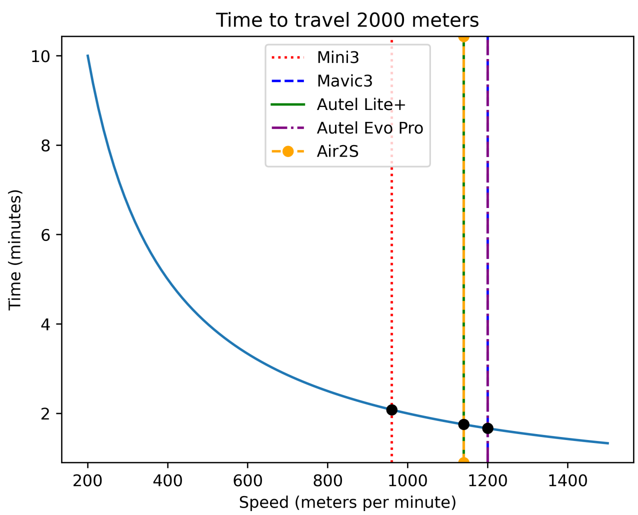

Figure 5.10: Fastest Response time for each drone from the table 4.4

Chapter 6

Discussion

6.1 Evaluation of Results

When evaluating the results, there are certain metrics which needs to be taken into account. The main metrics which have been showcased in 5 were "Active Flight Time", "Achievable Distance" and "Response Time", and these will be discussed in the paragraphs below.

6.1.1 Evaluation of active flight time

The active flight time of each drone and configuration is an important metric when looking at the feasibility, as a good active flight time opens up for the possibility to have a longer active hovering time, which results in better coverage for the emergency response team.

By evaluating the different configurations, it can be seen that the DJI Mini 3 Pro [26] and DJI Mavic 3 [30] on general has a higher active flight time. This can be explained either by the drones having a higher energy total, or by being more energy efficient, which by looking at 4.4 it can be derived that the DJI Mavic 3 [30] has the higher energy total, whilst the DJI Mini 3 Pro [26] is the more energy efficient of the lot. Likewise can be said about the Autel drones [33] [32], where they are very similar in available active flight time, generally about 1 minute apart from each other. The weakest of the drones was DJI Air 2S [31], which can be seen from the different figures 5.2, 5.4, 5.6 and 5.8, as the purple dotted line is noticeable lower compared to the other drones.

When looking at the different configurations of sensors, configuration 45.1.4 looks to be the superior one in terms of highest achievable active flight time, and configuration 3 5.1.3 seems the worst. Consider an active hovering time of 10min gives the results listen in 6.1, where the first rows is the results for configuration 4 and the second being for configuration 3

DJI Mini 3 Pro	**DJI Mavic 3**	**DJI Air 2S**	**Autel Lite+**	**Autel Evo II pro**
24.96min	24.55min	13.95min	20.82min	19.93min
14.86min	16.31min	8.20min	13.65min	12.94min

Table 6.1: Active flight time when Hovering time set to 10min for config 4 and config 3 .

Comparing these results, it shows a difference in the range of 33.5-41%, which is quite a substantial amount. The reason for the big difference is because of the higher payload, 24g vs 340g, as well as the higher power consumption of the sensors for configuration 3. The specifics for each sensor can be viewed in 4.5 and 4.6.

6.1.2 Evaluation of achievable distance

Another metric which needs to be evaluated is the length each of the drone configurations can achieve with its listed speed and total energy levels. This gives a set distance, which can be evaluated against which tunnels the configurations are usable in. In the table below it is assumed an active hovering time of 10min, and then the Max Distance value from 5.1, 5.3, 5.5 and 5.7 is retrieved.

DJI Mini 3 Pro	DJI Mavic 3	DJI Air 2S	Autel Lite+	Autel Evo II pro
4145m	6477m	3623m	6102m	6037m
4024m	6201m	3450m	5835m	5750m
2674m	4403m	2213m	4095m	3990m
4493m	6628m	3766m	6246m	6145m

Table 6.2: Achievable distance for the different drone configurations. From top to bottom config 1 -> config 4

From the table 6.2 it can be seen that DJI Mavic 3 [30] has the longest reach, closely followed by both Autel drones [33],[32], with DJI Mini 3 Pro [26] and [31] being second last and last respectively. Even though the DJI Mini 3 Pro [26] did well on the Active Flying Time parameter, it lacks the speed compared to the other drones, as can be seen from 4.4, which results in a lower max distance.

Furthermore, it can be seen that configuration 3 and 4 are again the worst and best case scenario, which reflects the outcome of the previous subsection 6.1.1. However, configuration 1, 2 and 4 are very similar in terms of achievable length, with configuration being the one which stands out. Hence, picking one or the other between 1, 2 or 4 wont have much of an impact on the achievable distance, and other factors like price, compatibility and efficiency can be the deciding factor instead.

Using the DJI Mini 3 Pro [26] together with configuration 3, it gives a max distance of approximately 2600m. This can be cross-referenced by using the NVDB API, to find out the length distribution of available tunnels with the distance of 2600m. Figure 6.1 shows the tunnel length distribution of all tunnels in Norway with a length of less than 2600m, which results in 90.4% of all the tunnels in Norway.

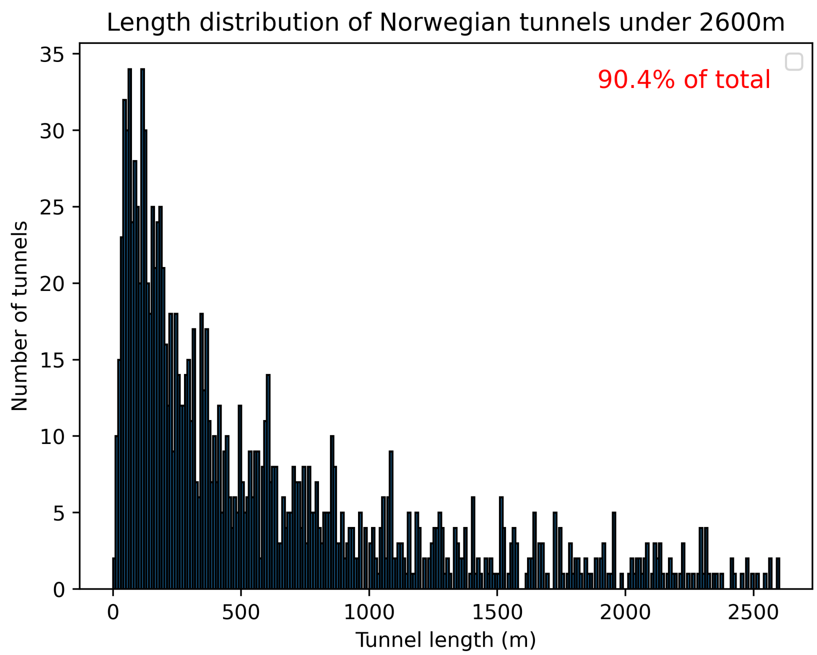

Figure 6.1: Plot over which length of tunnels each drone can be utilized in. Thanks to Aitor Martin Rodriguez for providing the python script to retrieve tunnel length distribution from the nvdb api.

6.1.3 Evaluation of Response Time

When utilizing drones in an emergency response mission, making sure they arrive in a timely manner is critical. Looking at figure 5.9 it can be shown that the DJI Mini 3 Pro [26] has the slowest average and maximum response time at 5.56min, due to being the slowest of the drones, which is to be expected as it is also the cheapest of the sample drones. Furthermore, the DJI Mavic 3 [30] has the second slowest average response time, but the joint fastest, together with DJI Air 2S [31], The average speed resulting in a response time of 3.70min, which is approximately 33.45% faster compared to the DJI Mini 3 Pro. The remaining three drones, DJI Air 2S [31], Autel lite+ [32] and Autel Evo II Pro [33], have a a very similar average response time at 3.33min and 3.24min, both being just over 40% faster than the DJI Mini 3 Pro.

Evaluating the second figure 5.10 for maximum response time, the DJI Mini 3 Pro [26] again comes out as the slower if the drones, with a maximum response time of 2.08min. The other drones have maximum response times of 1.67min and 1.75min, which is very similar, and probably wont have too much of an impact in an actual emergency response situation. However, comparing the DJI Mini 3 Pro to the other drones, the increase in response time is 15.87% and 19.71% which is minor, but may be an improvement of significance.

To summarize, it can bee seen from 5.9 and 5.10 that the DJI Mini 3 Pro [26] is the weakest when it comes to response time, both in average and on maximum. The other drones are very similar, and if response time is the main metric when evaluation which drone to utilize, the best option would be to not use the cheaper DJI Mini 3 Pro [26].

6.2 Evaluation of feasibility

To able to say that utilizing drones in emergency response mission in road tunnels is feasible, there needs to be evidence of a good balance between the different metrics described in the sections above.

When it comes to active flight time, all of the different configurations gave all the different drones quite a high active flight time. This means that there is room to decide how long the active hovering time will be. Furthermore, having a good active flight time will correlate with the maximum distance achievable, as the only restriction will be the actual flight speed. With the drone technology in such rapid development, the cruising speed of drones will continue to increase, which will result in both better maximum distance reach, as well as a good response time.

On the basis of these results it implies that utilizing drones for emergency response in road tunnels is indeed feasible.

Chapter 7

Conclusion

7.1 Conclusion

7.1.1 Research Question 1

The first research question was "Is it feasible to use collaborative drones in roadside tunnels". The short answer to this, if the results in 5 is used as the basis, is yes. From the different figures in 5 and the figure 6.1 it can be seen that with the configuration which performed second worst, it still covers 90% of the length of the Norwegian tunnels, and this even takes into consideration that the incident happens at the opposite end of the tunnel from where the drones are stationed. Furthermore, utilizing drone swarms to relay data to create a FANET can negate the challenges like signal attenuation and multipath fading. However, the long answer would take into account the price of setting up such a drone swarm, which could be too costly for the local authorities and needs to be evaluated on a situation to situation basis.

7.1.2 Research Question 2

Furthermore, the second question was "Which length of tunnels can certain drones be used in". This question is easily answered with figure 6.1, where the "worst case" scenario from the different configurations is taken as an example. In this figure it can be seen that if a drone configurations can achieve a max length of 2600m, it will cover 90.4% of all the tunnels in Norway. By using a more optimized configuration, it is possible to extend this range even more, but of course that will come with an extra cost to acquire more drones to ensure network connectivity between the drone swarm.

7.1.3 Research Question 3

Lastly, the question regarding limiting factors was "What are the main limiting factors for drones in a tunnel-like environment". This exact question was addressed in 4.1, however it was slightly rephrased as "challenges". One of the main factors was limited GPS signal, which seems to be able to be solved using a sophisticated INS. Another factor was lighting, but by using either LiDAR or Ultrasonic sensors a big impact of poor lighting can be negated. Power consumption has been covered to great lengths in this thesis, and with the simplified energy model provided, it seems that the modern drones are energy efficient enough and capable of operating in tunnel-like environment without big difficulties. There are still more limiting factors from 4.1 which have not been solved in this thesis, and should be investigated in future research.

7.1.4 Summarize

To summarize, this thesis has provided a generalized mathematical model to check energy consumption for drones, which can be utilized to find out the achievable length a drone can reach. The results from using this model implies that utilizing drone swarms in road tunnels is highly feasible, but to ensure connectivity throughout the entire tunnel due to Line of Sight (LoS) problems it might prove to costly for local authorities to set up. Furthermore, there are still challenges which needs to be solved to make it completely feasible, but current technology and the continuing advancement suggests that it will be possible.

7.2 Future Work

The result from this thesis will hopefully help in establishing a framework to see the potential and possibility of using drone swarms in emergency response missions in road tunnels. There are still certain aspects which needs to be addressed before complete feasibility can be proven. Deployment intervals are important to make sure that LoS do not become a problem and needs to be addressed, and together with signal attenuation and multi-path fading make feasibility difficult

Furthermore, the power consumption from wind and network communication has not been taken into consideration in this mathematical model, which of course will have an impact on the metrics like travel distance and active flight time due to the increased power consumption. With further research it would be ideal to expand the current mathematical model with inclusions like that, and other relevant metrics.

It would also be highly beneficial to make simulations, and conclude real-life experiments to further test the feasibility of UAV swarms in road tunnels. The simulations, specifically network simulations, would provide a good ground work to test for LoS and signal attenuation, and find out how to counteract this. The real-life experiments is probably more challenging, as it would need to be coordinated with the local authorities.

Lastly, the biggest constraint is the cost. Setting up drone swarms with the appropriate sensors and software is expensive, especially as the high-end usually are the ones with enough battery capacity to be able to handle this kind of mission. To counteract this, it might be possible to utilize inductive charging. This may allow for cheaper drones to be acquired, as they can be charged throughout the mission, and the risk of power depletion would be lower.

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Attachments A

Source Code

The code used to make the python scrips regarding Active Flight Time, Max Distance and Response Time can be found at this GitHub Repo

For access to the tunnel length distribution which was used, please contact Aitor Martin Rodriguez directly.