Final Report

Technical report on the conceptual design process for a wind and temperature sensing drone swarm

2021 Fall DSE group 3

Delft University of Technology

TU Delft

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by

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Student name	Student number
Vince van Deursen	4561066
Matti Hitzerd	4853644
Wikash Chitoe	4853253
Pooh Laohamethanee	4538420
Jacob Evans	4852397
Niklas Gebhardt	4850653
Andrei-Carlo Papuc	4772385
Lilien Madi	4836626

Project Tutor:	dr. ir. Dries Allaerts
Project Coaches:	dr. ir. Salua Hamaza
	dr. ir. Rudolf Saathof
Teaching Assistants:	Marko Rehbein
	Lorenza Motinelli
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TU Delft

Preface

This report is one in a series of reports written by a group of final year Aerospace Engineering students. It is part of the Design Synthesis Exercise in which the aim is to produce a complete design to meet a given project objective statement and stakeholder requirements. In this sequence of reports, the assigned directive is to design a drone swarm to map wind speed and temperature fields in and around a 100 $[km^2]$ wind farm, as to make a step towards more continuous data that can aid wind farm operators with performance and control optimization, as well as researchers with more detailed data sets.

To begin this project, a week was spent organizing the engineering team and developing an initial planning for the project over the coming 10 weeks. In the following weeks, time was spent conducting a detailed analysis of the relevant market, fully defining the requirements of the system and generating a set of preliminary concepts. They were then further explored and designed in greater detail to obtain estimates of performance, cost and power. This step allowed the informed selection of the local sensing system as the final concept to be designed deeper.

In this report specifically, we work through the final design phase of the system design process. In this phase, the local sensing concept selected, is broken down into sub-systems that can be designed in detail separately. The individual sub-system designs then come together to provide a full overview of the final system that can be analyzed against the initial technical and financial constraints, ensuring compliance with the stakeholders needs.

The reader is not expected to have prior extensive knowledge on wind farms, sensors or UAVs. However, a basic understanding of LiDARs and standard UAV configurations would be useful. A basic understanding of engineering components could also be useful to help visualize design choices.

Readers who want to gain an idea as to the design approach can find this in Chapter 2. Those who wish to learn on the final system design and its visualization can find this in Chapter 3 and Chapter 4. Readers more interested in the technical system analysis can read on this in Chapter 5 and those interested in the system's financial breakdown are guided to Chapter 6. Lastly, readers who want an idea on the approach developed for future work and production plans are guided to Chapter 7.

We would like to take this time to thank our coaches, dr. ir. Dries Allaerts, dr. ir. Salua Hamza and dr. ir. Rudolf Saathof, for providing direction and assistance whenever it is needed. We would also like to thank our TAs Marko Rehbein and Lorenza Motinelli for their guidance in the field of PM/SE.

An extra thanks needs to go out to dr. Mithu Debnath of the NREL for taking the time to talk with us, and provide valuable guidance on the capabilities of LiDAR.

Delft, Tuesday 25th January, 2022
DSE Group 03
Vince van Deursen, Matti Hitzerd, Wikash Chitoe, Pooh Laohamethanee, Jacob Evans, Niklas Gebhardt, Andrei-Carlo Papuc, Lilien Madi.

Summary

The goal of this report is to outline the sub-system design of the local sensing system chosen as the final concept in [1], to satisfy the mission need statement: **measure the atmospheric conditions with full three-dimensional coverage of a wind farm to optimize its operational performance and control**. This statement is derived from the need to improve the control and performance of wind farms through more informed processes and decisions, a task that meteorological masts would usually take on. However, the providable coverage is very low in comparison to the one a UAV based system could provide. UAVs have the potential to significantly increase the measurement coverage around an entire wind farm and in turn return to the user more valuable data.

To approach the finding of a solution to this problem, the project was divided into four: planning, concept definition, concept exploration and detailed design. From the first two phases came unique concepts exploring remote and local sensing options, combined with a range of UAV types including hybrid, fixed-wing and rotor. Through a detailed trade-off process and sensitivity analysis, the agreed upon final solution came to be a local sensing concept that makes use of many hybrid drones. In the fourth and final phase, where we now find ourselves, the detailed concept is unpacked and designed into a marketable system that is capable of satisfying the underlying MNS. In this stage the design was split into three design groups: UAV design, ground station design, swarm design.

The UAV department decided on an off-the-shelf UAV to ensure sufficient resources could be allocated to the design of the autonomous operations of the system. The final choice came to be the DeltaQuad Pro UAV, as this gives good endurance and ability to fly in windy conditions while being able to carry the chosen sensors: Trisonica mini (from Anemoment) for the wind speed and FST600-202 4-20mA PT100 (from Hunan FirstRate) for the temperature. These were selected for their compliance with the required accuracy and weight. The hybrid configuration is useful here as it allows the UAVs to take-off and land vertically whilst having efficient flight when measuring data.

The swarm department identified optimal flight routes with the chosen UAV, this allows the calculation of optimal number of ground stations and their placement. This was chosen to be a preset zig-zag path optimized for ground station positioning, later combined with a collision avoidance algorithm, making use of Rapidly-exploring Random Trees. This also allows the estimation of the spatial and temporal resolutions of 300 metres and 42 minutes respectively.

The ground station department worked to facilitate the autonomous operations of the system, to allow the UAVs to charge regularly and take shelter in non-operable conditions. To combat this, containers are designed to be constructed on the nacelle of the turbines (4 for charging the batteries and 17 for storage for a 100 $[km^2]$), providing covered space for the UAVs to charge and be stored. Inside of these containers a robotic arm is placed, capable of withdrawing empty batteries and swapping them with charged batteries that are stored inside the container.

These design choices resulted in a system cost of 18.4M [€], with a power draw of 16.9 $[kW]$. The system was then verified against the system's requirements and analyzed through the scope of a technical analysis and financial compliance review. With this insight, it became possible to determine full characteristics of the system as well as possible areas for further work. The final system from this design process is presented in Figure 1, and marks the end of the conceptual design phase.

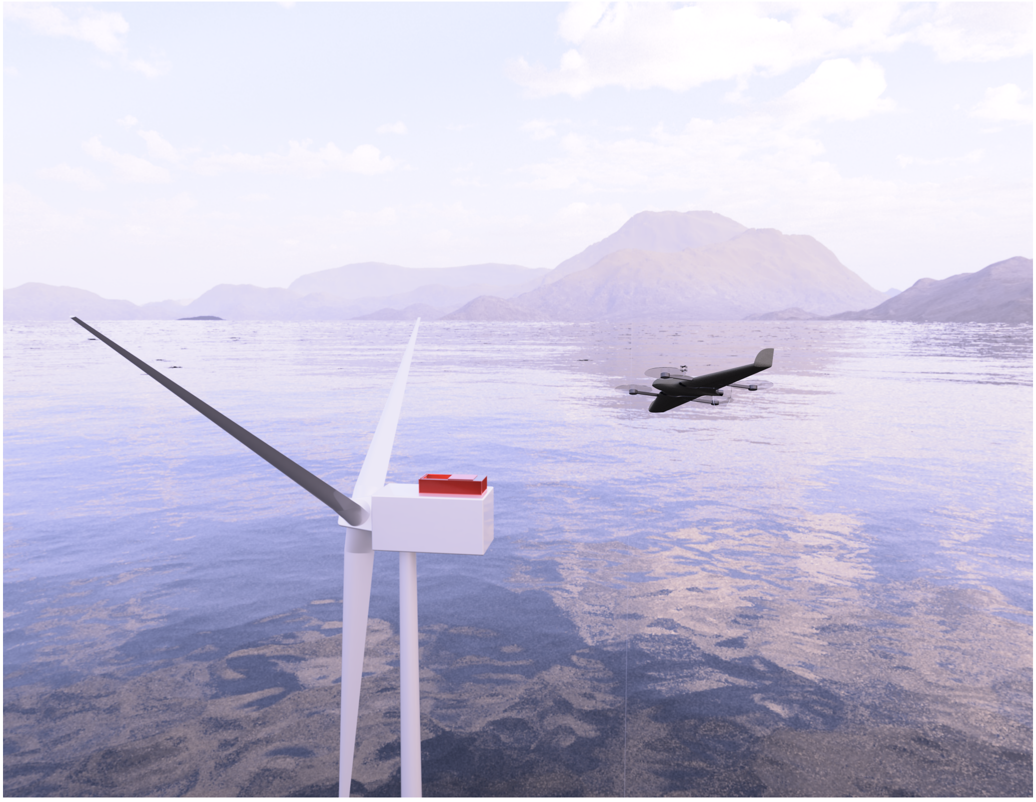


Figure 1: UAV coming in to land

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
API	Application Programming Interface
BEC	Battery Elimination Circuit
CAD	Computer Aided Design
CCW	Counter clockwise
CFD	Computational Fluid Dynamics
CW	Clockwise
DSE	Design Synthesis Exercise
DOT	Design Option Tree
EOL	End of Life
ESC	Electrionc Speed Controller
FS	Full Scale
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Unit
IC	Integrated Circuit
IP	Ingress Protection
k-CP	k-Chinese Postman algorithm
LCA	Life Cycle Assessment
LCOE	Levelised Cost of Electricity
LiDAR	Light Detection and Ranging
MVP	Minimum Viable Product
NAA	National Aviation Authority
NREL	National Renewable Energy Laboratory
PM/SE	Project Management / Systems Engineering
RAMS	Reliability Availability Maintenance and Safety
R&D	Research and Development
ROI	Return On Investment
RTD	Resistance Temperature Detectors
RRT	Rapidly–Exploring Random Tree
SNR	Signal to Noise Ratio
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TBD	To be Determined
TSP	Travelling Salesperson algorithm
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take-off and Landing

Symbols

Symbol	Definition	Unit
AR	Aspect ratio	$[-]$
C	Battery Capacity	$[Ah]$
Cd_0	Parasitic drag coefficient	$[-]$
E	Energy	$[J]$
e	Oswald efficiency factor	$[-]$
EN	Endurance	$[s]$
g	Gravitational constant	$[m/s^2]$
I	Current	$[A]$
n	Discharge parameter	$[-]$
n_{tot}	Total efficiency	$[-]$
n_{load}	Vehicle Loading	$[-]$
η_{turb}	Wind turbine efficiency	$[-]$
OEW	Operational Empty Weight	$[kg]$
P	Power	$[W]$
$P_{rat,turb}$	Rated turbine power	$[MW]$
$P_{avg,norm}$	Average wind farm power delivery (normal control)	$[MW]$
$P_{avg,impr}$	Average wind farm power delivery (improved)	$[MW]$
P_{norm}	Wind turbine power delivery (normal control)	$[MW]$
P_{impr}	Wind turbine power delivery (improved control)	$[MW]$
P_{rat}	Wind turbine rated power	$[MW]$
ρ	Air density	$[kg/m^3]$
R	Range	$[km]$
Re	Reynolds number	$[-]$
Rt	Battery hour rating	$[-]$
R_{turn}	Turn radius	$[m]$
S	Wing surface area	$[m^2]$
t	Time	$[s]$
t_{VTOL}	Time needed for VTOL flight	$[s]$
t_{turn}	Turn rate	$[rad/s]$
U	Voltage	$[V]$
V	UAV airspeed	$[m/s]$
v_{in}	Cut-in wind speed of turbine	$[m/s]$
v_{out}	Cut-out wind speed of turbine	$[m/s]$
v_{rat}	Rated wind speed of turbine	$[m/s]$
W	Weight	$[N]$

1
Introduction

To quantify and subsequently optimize the performance of an array of wind turbines, information is required about the wind conditions in the vicinity of each turbine. Traditionally, this has been provided by instruments (mainly anemometers) on one or two meteorological masts close to the wind farm. This has the major drawback that one mast can only provide point measurements at a few heights which may not reflect the true conditions close to individual turbines. UAVs have the potential to significantly increase the measurement coverage around an entire wind farm. This project is about the design of a drone swarm system equipped with measurement instrumentation to map the wind speed and temperature field in a wind farm [2].

The purpose of the final design phase and this report is to detail how the subsystems are designed in greater detail. This builds on the concept production and exploration phases found in [3] and [1], where an extensive design option tree is processed, removing infeasible ideas, leading to a shortlist of designs that are further explored and analyzed for the purposes of a concept trade-off that compares parameters such as system performance, cost, power, sustainability and risk. The result of this process is one final concept to design on a sub-system level, this concept being the local sensors mounted on hybrid drones.

In short, this concept fixes wind speed and temperature sensors to the body of each of the UAVs in the system. The system as a whole will comprise of many drones that through an organised flight path, take measurements of the wind farm. This is supported by ground stations spread throughout the wind farm that allow for autonomous charging and storage.

Sub-system design is clearly important to the overall design, however what is also important is the relationship between these sub-systems, and ensuring that the system is functional as a single unit that can be marketed to customers. Ensuring this requires clear definitions of each of the divisions of the system and at what points of their respective designs the sub-systems interact and need a more iterative approach to produce a workable design. With these dependencies established, independent design of the sub-systems becomes more straightforward. This in turn results in a cohesive design that can be analysed against the initial requirements and budget to ensure compliance with the stakeholders needs. From this point, an effort can be made to estimate: the robustness of the concept through a RAMS analysis, performance analysis, effect of the concept on the sustainability goals of the project, and the complexity of the design through a risk assessment and TRL analysis. With a fully rounded view of the design, an informed approach to a market analysis can be made in which it is discussed how the system can fit in today's market and what benefits it can provide to a potential customer. This closes off the final design phase, with only the recommendations for future work remaining inside which a production plan is included.

The structure of the report can be broken down in the following way. This journey begins with an extensive explanation of the design process utilized in the final phase in Chapter 2, starting with a high-level description of the general design approach and subsequently focusing on each subsystem in greater detail. After this, the design work established is compiled into a single system design in Chapter 3, this is supported with a verification and validation analysis on a system level and a sensitivity analysis on the design iteration process. From this an effort is made in Chapter 4 to visualize this final system through renders of the system in operation as well as engineering diagrams to provide insight into the inner workings of the system. Chapter 5 can then focus on assessing technical analysis which includes: risk assessment, RAMS analysis, performance analysis and a sustainability analysis. This is followed by up with an analysis on the financial budget of the system in Chapter 6, which includes: cost breakdown structure, market analysis and estimations of the potential ROIs of the system. Following this can be found recommendations for future work in Chapter 7, this covers not only work to do in the near-future but also production plans as well as insights into more effective design approaches that could be used for a later version of the system. Finally, the report will be closed off with a wrap-up of the project, concluding all four stages of design in Chapter 8.

2
Iteratively designing the final system

Following the midterm review, it was decided that the local concept was to be carried forward to the final design phase, where the concept is to be worked out further. In the midterm review a conceptual design was presented, now the design team was challenged with designing the system in more detail.

This chapter discusses the preliminary design process of the local design concept in different levels of detail. Section 2.1 discusses the iterative design process on a high level and how each of the three design departments cooperated to come to specific system configurations. Then, Section 2.2 discusses the design process for the UAV department in more detail, namely the UAV design and the the windspeed/temperature sensor choice will be discussed. Section 2.3 will discuss the swarm department's design process in more detail. Topics such as route planning and obstacle avoidance will be addressed. Lastly, in Section 2.4, the design process for the ground department is presented. This includes for instance the battery charging system, UAV storage system and the data transmission system.

The following chapter, Chapter 3, presents and validates the results provided by the design processes explained in this chapter.

2.1. Iterative design procedure

With the scale of the proposed solution, it is important to be efficiently organised as a team to enable the detailed design of the system whilst maintaining overview of the project such that at the end of the project there is a viable solution to present to the clients. With this in mind it is thought best to divide the engineering team into the three main focuses of the project: UAV design, swarm design and last but definitely not least the ground station design.

In approaching the project in this manner, it is important to be very explicit in the tasks for each department:

- **UAV department** - responsible for the design of the UAV as well as sensor selection. The target for this group is a clear design of the integration of the sensor to the UAV.
- **Swarm department** - responsible for the design of the route plan for all of the drones in the system, this includes exploration of different methods and algorithms for route planning with the goal of defining an approach to best optimise the UAVs' endurance such that the best measurement resolution can be extracted from each UAV.
- **Ground station department** - responsible for making sure that the chose UAV and design route plan can be implemented. This includes the design of all charging stations and communication infrastructure to allow for both drone-to-ground station communication, as well as ground station-to-client communication (drone-to-drone communication is not needed for this system).

In practice, however, inter-department work is not always as clear cut, therefore it is important to define at a very low-level specific parameters of the design that each group has ownership of. It is also at this point it is possible to define an iterative strategy for the final system design. This iteration is crucial as while parameters may be calculable by one team, they may also not be feasible from the perspective of another group. It is for this reason that an N2 chart depicting the relationship between each of the departments has been formulated, as seen in Figure 2.1.

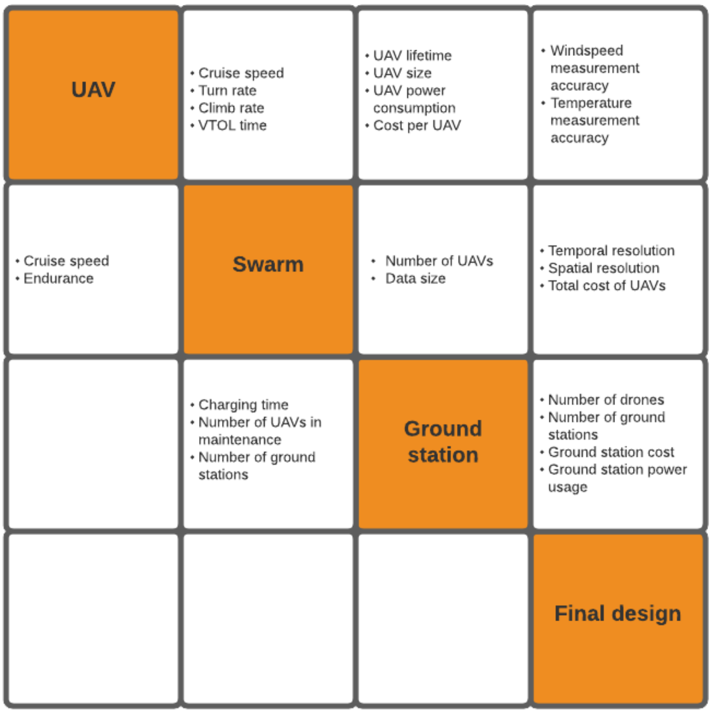


Figure 2.1: N2 diagram representing the iterative design process between departments

As shown in Figure 2.1, the dependencies between groups is clear, this further allows for more insightful planning for the time allowed for the final design. It is also important to take note of the final column in the N2 diagram, as this shows which parameters are of importance at a high level to the clients, and in turn those that are subject to compliance with the system requirements.

For further explanation of the design for each departments, sections 2.2-2.4 will provide further insight into the UAV, swarm and ground station subsystems.

2.2. UAV design

In this section UAV design processes will be explained, first starting with an overview of the different hybrid UAV choices and why the selected UAV was chosen. Next, the difficulties faced by the UAV to work in a wind farm environment are discussed. The calculation required for the full system design iteration concerning the UAV are then explained with all made assumptions stated. Finally the two sensor choices are explained and the reasons for selecting each are given.

2.2.1. UAV overview

As decided previously, the UAV is designed with a hybrid VTOL configuration, meaning the UAV is a combination between a fixed wing and multirotor UAV. Within this hybrid configuration multiple categories can be distinguished: tail sitter, quad plane, and tilt rotor. For the mission design, certain criteria are of considerable importance: robustness, reliability, efficiency, cost and wind resistance. Robustness is mostly connected to the question if the UAV type is able to function with a failure of one of the propellers. Reliability is an important requirement, reflected in requirements **SR.rel.1**, **SR.rel.2** and **SR.rel.3**, as well as in requirements **SR.maint.4**, **SR.maint.5**, **SR.maint.6**. These requirements lead the design of the UAV to maximise the lifetime of the UAV, the ability for the UAV to fly without maintenance for 6 months as well as their capability to fly in harsh environments. The efficiency is connected the power usage of the UAV and how long it can fly with this power, given in requirements **SR.pwr.18.SUB.4** and **SR.pwr.18.SUB.5**. Lastly, cost is connected to requirement **SR.cost.20.SUB.1** and wind resistance is connected to **MR.adap.16**, meaning it has to be able to fly at wind speeds higher than about 12 m/s. For each hybrid UAV choice all criteria will be briefly discussed.

1. **Tail sitter** - The tail sitter is efficient as it does not carry so called dead weight or increased parasitic drag due to it using all its propellers in both vertical and horizontal flight. However, this option is less robust when compared to the other options, this comes from the combination of the higher wetted surface area when it is performing VTOL, due to the wing being perpendicular to the ground. This is also not helped by the low yaw control in VTOL, thus with a lot of wind it becomes unstable and has an increased chances of tipping over. Lastly the control and stability system is more complex since it needs to be able to facilitate the switch between VTOL and cruise conditions
2. **Quad plane** - This is a robust option, it is also the least complex since it combines a normal quad copter and a fixed wing UAV which are both proven and developed systems. It is however, the least efficient since it carries dead weight in the form of the booms and motors for vertical flight. The four motors used for VTOL are not used during cruise and cause extra parasitic drag. This can however be solved by making the arm and motors retractable.
3. **Tilt rotor** - This is the most efficient option as it reduces the parasitic drag caused by the extruding arms and from the vertical propellers in horizontal flight found on quad planes, instead has a set of tiltable motors to propel the UAV, disturbing the airflow less. However this adds a lot of complexity to the design caused by the gearing and servos needed to tilt the rotors, as well as the flight software needed to perform the tilting actions. This causes the design to be unreliable due to the larger amount of single failure points.

With the three different configurations for hybrid UAVs, its clear to see why the industry has so far favoured the quad plane over the other two options. When it comes to a commercial product the highest priority is that it works and is reliable, meaning the quad plane with its relatively simple and robust design is able to do the job more reliably and safely when compared to its counter parts. To further emphasize this point, a trade-off table was generated evaluating the different hybrid UAV design options, for each of the five criteria (reliability, robustness, efficiency, cost and wind resistance) a normalized score is given with one being the best and zero being the worst. Again the quad plane comes out on top due to its high reliability and relatively low cost. This has unsurprisingly flooded the market with quad planes having very little examples of either tilt rotors or tail sitters on the market. With both tail sitters and tilt rotors remaining in the exploration phase of design.

As it was decided that the UAV should be bought off-the-shelf, the UAV chosen was the DeltaQuad Pro cargo variant, Figure 2.2, [4]. The UAV was bought off-the-shelf for several reasons, the main being the: cost of producing a UAV, focusing on the performance of the UAV, focusing on sensor integration and also allowing a focus on other aspects of the system. It was decided that rather than focusing the teams time and effort on designing a drone from scratch, in that sacrificing the ability to focus on the UAV performance for the swarm design or the sensor choice and integration into the UAV, it would be the best use of time to find an off-the-shelf solution. This also allowed for a reduction in the UAV cost due to the lack of R&D costs as well as allowing the team to divide its time between the three subsystems. The DeltaQuad is a quad plane configuration meaning it benefits from all the above mentioned characteristics of quad plane designs, as well as the main body having a fixed wing configuration meaning that it is more efficient when comparing against other quad planes with a more conventional design.

Table 2.1: Trade off table showing the results for the different UAV design choices

UAV type	Reliability	Robustness	Efficiency	Cost	Wind Resistance	Total
Weights	**0.2**	**0.2**	**0.1**	**0.2**	**0.3**	
Tail Sitters	0.333	0.500	0.333	0.333	0.167	0.317
Quad Plane	0.500	0.333	0.167	0.500	0.333	0.383
Tilt Rotor	0.167	0.167	0.500	0.167	0.500	0.300

Figure 2.2: Image showing the Delta Quad cargo variant

2.2.2. Difficulties with flying in a wind farm

Another aspect in choosing a drone for this project is the environment that the drone will be flying in, with the drone flying in and around an offshore wind farm with all the hazards that comes with it, explaining the hazards and their effects more.

For any electronic device, one of the greatest hazards is salt water, as this aggressively corrodes away any exposed metal or wiring, meaning that special care has to be taken when choosing and weather proofing the electronics of the UAV.

The other large hazard to flying in a wind farm are the relatively strong winds, with the chosen UAV having a maximum operational wind speed resistance of $14[m/s]$. Meaning that the system is incapable of operating in wind speeds greater than $14[m/s]$. Wind turbines have three main operating regions, Figure 2.3. Briefly explaining each region, region 1 is where the wind speed is not sufficient to start the wind turbine and thus the wind farm will not generate any electricity, making this region rather uninteresting for our system. In the third region, the wind speed is so great that the wind turbines are running at their maximum power output and cannot produce more power without incurring extra risk to damaging the turbines, again meaning that the system is not useful in this region either. Region 2 is the most important for the system, as here the system can have the greatest effect on the efficiency of the wind farm. By carefully measuring the wind speeds in the wind farm, this data can be used to optimize the yaw of the wind turbine head as well as the pitch of the individual blades on each wind turbine. This results in the turbines reaching their maximum rated power at a lower wind speed.

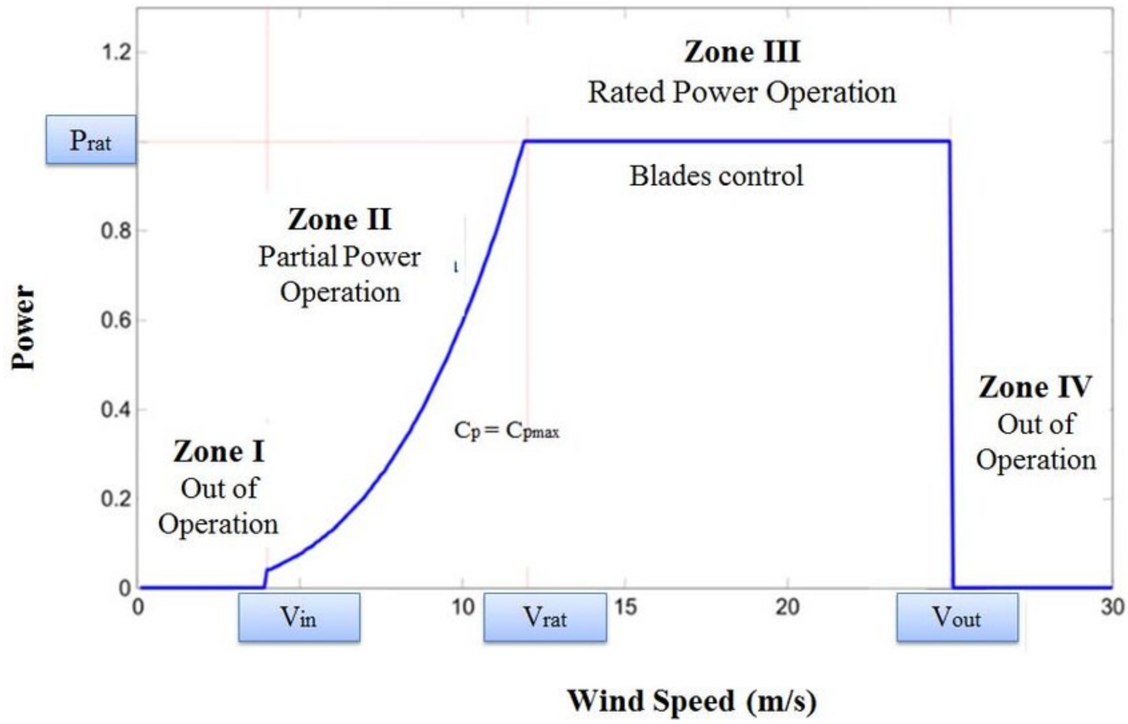


Figure 2.3: Graph showing the expected power from a turbine against the current wind speed

With the different aspects of flying in a wind farm explained it is clear to see that allowing the system to only fly in the region 2 wind speed range is both beneficial to the longevity of the drones as well as still being able to provide the required data to optimize the wind farm. Table 2.2 shows the wind speeds for the different regions of the wind turbine, with the cut-in wind speed corresponding to the start of region 2, and rather self explanatory the cut-off wind speed corresponds to the end of region 3. Cut-in speed is the speed at which the wind turbine is able to generate power and cut-off speed is the speed at which the wind turbine stops generating power. Looking at the rated wind speed which corresponds to the end of region 2, it's clear to see that the rated wind speed is on average 11.7 $[m/s]$, this is lower than the maximum wind speed resistance of the chosen UAV, meaning that the chosen UAV is suitable for the task at hand. It is also easy to see that the more efficient a wind turbine, the lower the rated wind speed should be, meaning as wind turbines become larger and more efficient the rated wind speed will drop, this is advantageous to the system.

Table 2.2: Table showing the different aspects of wind turbines

Name	Rated power [MW]	Rotor Diameter [m]	Cut-in wind speed [m/s]	Rated wind speed [m/s]	Cut-off wind speed [m/s]
NREL offshore 5-MW baseline wind turbine	5	126	3	11.4	25
HTW5.0-126	5	126	4	13	25
Gamesa G128-5.0MW	5	128	2	14	27
Goldwind 6s GW175 8mw	8	175	3	12	25
Goldwind 6s GW184	6.45	184	3	10	21
Goldwind 5s GW 165	5.6	165	3	11	24
Goldwind 5s GW 165	5.2	165	3	10.7	24
Goldwind 5s GW 165	6.0	165	3	11.4	24

2.2.3. Calculations made

With the UAV taken off-the-shelf it is very hard to obtain a complete picture on the capabilities of the UAV, with only limited information on the capabilities of the UAV when it comes to the flight characteristics. With a some correspondence, a little more information was gathered but not sufficient information to completely model the UAV without making some assumptions, thus in Table 2.3 all the available information about the UAV, required for this project, is shown.

Table 2.3: Data for the UAV supplied by the supplier

Name	Values found or received from the supplier
Max endurance	110 [minutes] at 1 [kg] payload
Max range	100 [km]
Cruise speed	16 [m/s]
Max speed	25 [m/s]
Stall speed	13 [m/s]
Climb rate	2.2 [m/s]
Climb angle	Do not exceed 10 [deg]
VTOL take-off speed	1.5 [m/s]
VTOL landing speed	Min 0.6 [m/s], max 1.2 [m/s] close to ground and 1.5 [m/s] not close to ground
Battery weight	1.7 [kg]
Battery type	LiPo 4s (14.8 [V])
Battery capacity	33 [Ah]
Charging time	1 [h] at 20 [Amps], recommended is 4.6 [h] atm 5 [Amps]
OEW no battery	3.3 [kg]
OEW with battery	5 [kg]
Payload weight	0.4 [kg]
MTOW	6.2 [kg]
UAV length	0.9 [m]
UAV wingspan	2.35 [m]
Max altitude	4000 [m]
Antennas	Pinecone S1 antenna and Sunhans SH-RC24G3W amplifier
Telemetry sensors	Accelerometer, Gyro, Compass, Level Horizon
Material Composition	Carbon Fiber for spars and propeller and EPO foam for the body
Operating temperature range	-20 [° C] to +45 [° C]
Wind resistance	9 [m/s] in VTOL and 14 [m/s] in cruise
IP rating	Can take drizzle
Lifetime	Recommended maintenance every 12 months with replacing most electronic components
Cost	Base is €9,999 with additional extras
Average pitch angle	6 to 8 [degrees]

With not enough information on the UAV given, a few assumptions have to be made. Below all the assumptions made for the calculations concerning the UAV have been given:

- It is assumed that the drone is stable, this comes from the fact that the drone is a flying wing which can be unstable, but it is assumed that the supplier ensured that the final product would be dynamically stable.
- It is also assumed that the endurance and range values given by the supplier were calculated for stall speed. The optimum value is not chosen as can be seen in Figure 2.4 both the optimal range and endurance lie below the stall speed. This allows for the comparison of the data

given by the supplier and the data calculated by the UAV team. By matching the values from the manufacturer at stall speed to the ones generated at stall speed, the UAV can be modeled more accuractly.

- It has also been assumed that all the unknown coefficients for the UAV are similar to other hybrid UAVs in the same weight class.

Thus with the given information and the assumptions made, the calculations required for the iterative process can be made. The three main values needed to be calculated for the iterative design are the endurance of the UAV in $[hrs]$, the range of the UAV in $[km]$ and the maximum power required for the flight in $[W]$. These allow for an estimation of the spatial and temporal resolution of the system for both temperature and wind speed, as well as a power estimate for the system. With all the calculations being used from either [5] or [6]. Explaining each of these one at a time, the first being the endurance of the drone.

UAV endurance

The endurance of the drone is calculated using the Equation 2.1. Explaining the parameters: Rt is the battery hour rating set to 1 $[hour]$, n is the discharge parameter of the battery and is dependent on the number of cycles and temperature of the battery, a value of 1.3 was chosen for the discharge parameter for lithium polymer batteries taken from [6]. n_{tot} is the overall efficiency of the drone and was set at 0.6, U is the voltage of the battery dependent on the battery cell configuration with the battery chosen having a voltage of 14.8 $[V]$, C is the capacity of the battery on the UAV having a value of 33 $[Ah]$. ρ is the air density of the surrounding air given a value of 1.225$[kg/m^3]$ due to the proximity to sea level, V is the speed of the UAV given in $[m/s]$ this value was iterated on to provide Figure 2.4. S is the surface area of the wing of the UAV and was estimated to be 0.9 $[m^2]$, Cd_0 is the parasitic drag coefficient of the UAV given a value of 0.06, W is the weight of the UAV which was calculated from the given mass having a value of 60.8 $[N]$. k is the slope of the drag coefficient equation and is calculated using Equation 2.2 where e is the Oswald efficiency factor and AR is the aspect ratio of the UAV's wing, given values of 0.65 and 6.14 respectively, this gives k as 0.08.

$$EN = Rt^{(1-n)} \cdot \left(\frac{n_{tot} \cdot U \cdot C}{0.5 \cdot \rho \cdot V^3 \cdot S \cdot Cd_0 + \frac{2 \cdot W^2 \cdot k}{\rho \cdot V \cdot S}} \right)^n \tag{2.1}$$

$$k = \frac{1}{\pi \cdot e \cdot AR} \tag{2.2}$$

UAV range

Calculating the range of the UAV is much simpler using Equation 2.3, where V is once again the speed of the UAV and multiplied by 3.6 to get range in $[km]$. Hence plotting both these values against UAV speed gives the graph shown in Figure 2.4. Here it is clear to see that the maximum range and endurance of the drone happen at speeds below stall.

$$R = EN \cdot V \cdot 3.6 \tag{2.3}$$

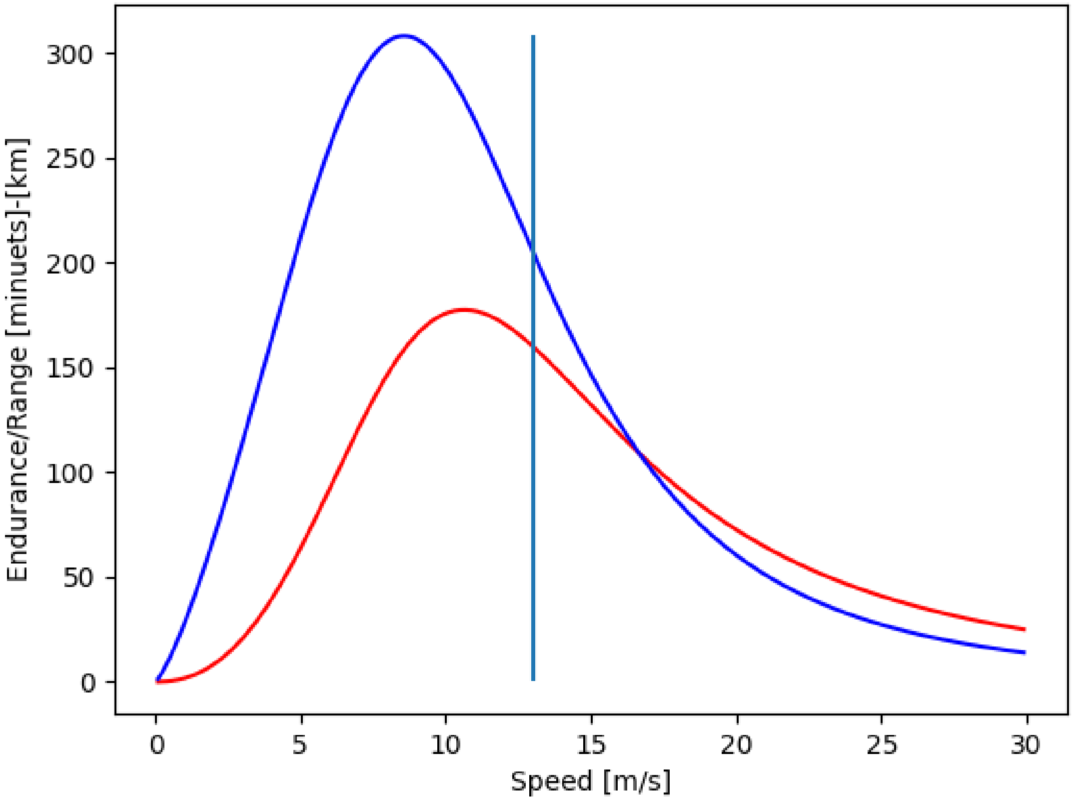


Figure 2.4: Graph showing Endurance and Range against UAV air speed, Endurance given in blue and range given in red, with the cyan line being the stall speed [1]

UAV power consumption

The other aspect of the calculations is the power consumption of the drone, this is calculated using the very simple principles, highlighted by Equation 2.4 and Equation 2.5, where I is the current in A, U is again the voltage, E is energy given in joules and t is time given in seconds. These then combine to provide the maximum power required of the system, shown by Equation 2.6. Where once again C is the capacity of the battery and EN is the endurance of the drone. The first half of the calculation calculates the average power required during horizontal flight from the current drawn from the battery, the second half calculates the energy needed to go 30 meters up and down then dividing this by the time it takes to do this maneuver, giving the power required for VTOL flight.

$$P = I \cdot U \tag{2.4}$$

$$P = \frac{E}{t} \tag{2.5}$$

$$P = U \cdot \frac{C}{EN} + \frac{2 \cdot W \cdot 30}{\frac{30}{1.5} + \frac{30}{1.2}} \tag{2.6}$$

The final values calculated were the turn rate and turn radius, given in $[rad/s]$ and $[m]$ respectively. These were not used in the final iteration process for the project but rather in the more complex pathing algorithms developed in the swarm department Section 2.3. The equations for which are given by Equation 2.7 and Equation 2.8 for the turn rate and turn radius respectively. Where g is the gravitational acceleration equal to $9.81[m/s^2]$ and n_{load} is the loading experienced by the UAV in a banked turn.

$$t_{turn} = \frac{V}{R_{turn}} \tag{2.7}$$

$$R_{turn} = \frac{V^2}{g \cdot \sqrt{n_{load}^2 - 1}} \tag{2.8}$$

2.2.4. Tool Verification

All of the equations shown in Section 2.2.3 were calculated using a python script, allowing the calculations to be iterated on easily. However this python script has to be verified before it can be used in the iteration process. The midterm report [1], gives a clear outline on how the tool verification should be carried out, with the verification methods for a python script being given by: verif.tool.I.2, verif.tool.T.2, verif.tool.A.3, verif.tool.A.4 and verif.tool.T.3. Each of these methods were carried out and the results of which were given in Table 2.4. Quickly explaining each of these verification methods again, to provide a better overview of the verification process:

verif.tool.I.2 - Visual inspection and comparison between the code and written formulas.

verif.tool.T.2 - Unit test doing hand calculations along side the python code and comparing the results to find any discrepancies between the two.

verif.tool.A.3 - Input change verification, changing the input from 0 to infinity (or very large number), check if the output still makes sense when comparing to the calculations.

verif.tool.A.4 - Continuity test, have a range of inputs and check that the calculation is continues

verif.tool.T.3 - The use of Pytest to get a minimum coverage of 75%

Table 2.4: Table showing the results of the verification on the python script used for the UAV iterations process

ID	Power tool
verif.tool.I.2	✓
verif.tool.T.2	X (see **A**)
verif.tool.A.3	✓
verif.tool.A.4	X (see **B**)
verif.tool.T.3	✓

A - This test found there was a discrepancy with the range calculated by the python script and the range calculated by hand, it seamed that there was a constant difference between the two values. After much deliberation and checking of the units used in the calculation it was seen that the UAV speed used to multiply with the endurance, was not in fact in $[km/h]$ but instead was in $[m/s]$, but as the endurance was given in $[hours]$. Rectifying this my multiplying the UAV speed by 3.6 to convert it to $[km/h]$.

B - The next error was gained from using the optimal endurance and range air speeds, Equation 2.9 and Equation 2.10 respectively, for all the continues calculations this lead the endurance and range to not changing over different air speeds. Fixing this by using the current air speed for all the calculation and gathering the optimum air speed from the peak of the graph produced.

$$V_{EN_{opt}} = \sqrt{\frac{2 \cdot W}{\rho \cdot S} \frac{k}{3 \cdot Cd_0}} \tag{2.9}$$

$$V_{R_{opt}} = \sqrt{\frac{2 \cdot W}{\rho \cdot S} \frac{k}{Cd_0}} \tag{2.10}$$

2.2.5. Sensor choice

In order to fulfill the mission need statement and all mission performance requirements **MR.perf.1** up until **MR.perf.9** and the requirements **SUB.UAV.7** and **SUB.UAV.7**. A wind sensor, also called an anemometer, and a temperature sensor have to be mounted on the UAV. In this section the choice of sensor is explained and the integration with the UAV is explored.

Wind speed

The first sensor choice that will be explained further is the anemometer. The types of available sensors and the criteria that are taken into account while choosing an anemometer are explored. These criteria are based on requirements given in Section 3.4. A selection of the most suitable anemometers is presented and finally a small trade off is performed to make the final choice.

When deciding which sensor is best for the wind farm monitoring system, first a list of the available sensors is compiled:

- Cup anemometer
- Propeller anemometer
- Sonic anemometer
- Hot-wire anemometer
- Pitot tube
- Multi hole probes
- UAV attitude
- Laser-Cantilever-Anemometer
- LiDAR

This list then has to be explored based on criteria stemming from requirements and the chosen UAV design. From the UAV design it is concluded that the maximum mass of the complete payload system could be 400 $[g]$. The client's requirements provide an accuracy and three dimensional measurement capability, found in **SUB.UAV.7** and **SUB.UAV.7**. Moreover, ability to survive in extreme weather conditions, lifetime and sustainability were considered for all anemometers. Considering this, the list was brought down to three options, which are shown in Table 2.5. The other sensors were not suitable for a variety of reasons, most of these reasons are based on research from [7].

Some of them had mechanical elements that are moved by the wind, such as the cup and propeller anemometer. The main disadvantage of these sensors is that they have a lot of mechanical, moving components which are susceptible to breakage. This is especially true in harsh environments with high wind speeds, that exist in an offshore wind farm. Moreover, they could over-speed in turbulent conditions, which are also very common in a wind farm. Some sensors are too heavy to be placed on a UAV, like a LiDAR or a Laser-Cantilever-Anemometer. The hot-wire anemometer simply did not meet the range requirements, since it can only measure up to 15 $[m/s]$. Next to that it is too delicate to operate in an offshore environment. Lastly, the pitot tube is dismissed because it can only measure in one direction whilst a two-dimensional, 360 $[°]$ range is required.

Eventually the sonic anemometer, multi hole probe and the UAV attitude measurement systems are explored further. The upsides and downsides of these three sensing methods are summarized in Table 2.5.

Table 2.5: Up and downsides of three wind measuring systems

Type	Sonic anemometer	Multi-hole pressure probe	UAV attitude
Upsides	+ Accurate (0.2 $[m/s]$) + Wide range	+ Lightweight + Cheap	+ No extra sensors required + No extra drag + Accurate (0.2 $[m/s]$)
Downsides	- Expensive - Extra drag	- Less accurate (1 $[m/s]$) - Less accurate with lower speeds - Corrections to transform to appropriate coordinate system	- Extensive algorithm required - High development cost

Finally, the sonic anemometer is considered as the best choice because of its high accuracy at both high and low wind speeds. Another reason to support this choice is that it does not require an extensive algorithm to process the data, only calibration is needed. Next to that, the sonic anemometer is also capable of measuring temperature. Although its accuracy is less than required: 2 $[°C]$ instead of 1 $[°C]$, it can still function as a control group and as a redundancy. Additionally, the Trisonica Mini has a number of additional sensors integrated: a humidity sensor, pressure sensor, accelerometer and a magnetometer. These sensors are not required for this project, but could be used to extend the use of the drone swarm to make better weather predictions. Moreover, dew point could be calculated from the temperature and humidity values and air density can be calculated using values for the speed of sound and pressure. This is something to consider in later design stages.

The next step in choosing a wind speed sensor is choosing which specific anemometer was going to be used. Three light weight anemometers have been found, the Trisonica sphere and the Trisonica Mini from Anemoment and the FT742 Surface Mount from FT technologies. A trade off is performed and the Trisonica Mini and FT742 score equally. The criteria used in the trade off and their corresponding requirements are listed below:

- **[SUB.UAV.8] -** vertical measuring range
- **[SR.cost.20.SUB.2] -** cost per year
- **[SR.mass.19.SUB.2] -** mass
- **[SUB.UAV.6] and [SUB.UAV.7] -** accuracy
- **[SR.rel.3] and [sr.sust.14] -** sustainability

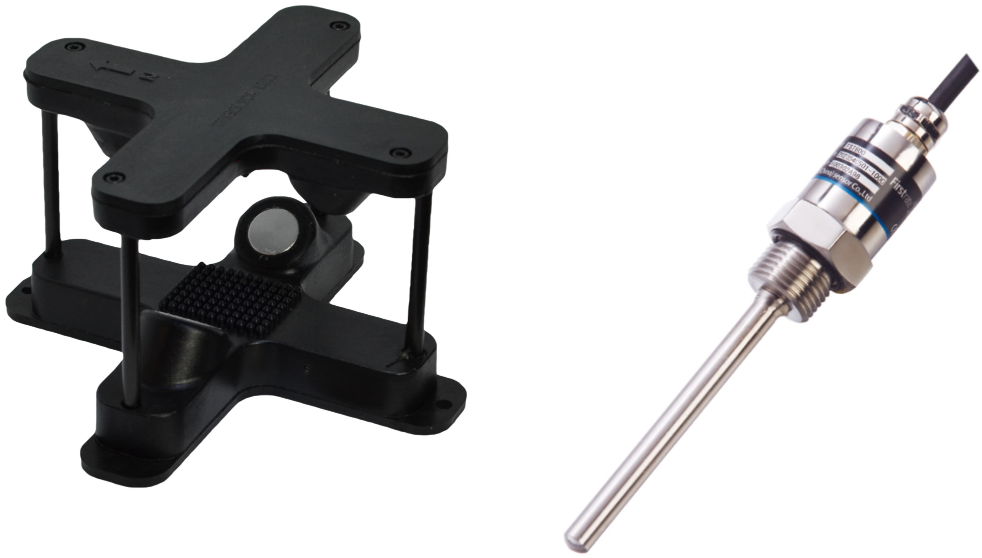
The data for each of the sensors on these criteria is given in Table 2.6. These values are then normalized and given weights as can be seen in Table 2.7. The FT742 is scored higher in sustainability, because it has a longer lifetime, and is thus more durable. It is also more sustainable, because the material of its body has a better recyclability compared to that of the Trisonica Mini. Finally, the Trisonica Mini is chosen over the FT742, because it can measure up to 15 $[°]$ vertically. This is a useful feature, because measurements will still be able to be performed if the UAV changes its pitch angle. The Trisonica Mini is shown in Figure 2.5a.

Table 2.6: Data on the trade off criteria of the Trisonica sphere, Trisonica Mini and FT742

	Range (° in w direction)	Cost per year (€)	Mass (grams)	Accuracy (m/s)	Sustainability
Trisonica sphere	60	930	225	1	6 year lifetime, injection molded glass filled nylon
Trisonica mini	15	290	50	1	5 year lifetime, injection molded glass filled nylon
FT742	0	185	252	0.6	10 year lifetime, anodized aluminium body

Table 2.7: Trade off between Trisonica Sphere, Trisonica Mini and FT742 anemometers

Trade off - Criteria Weight	Range	Cost	Weight	Accuracy	Sustainability	Total
Weights	0.2	0.15	0.15	0.3	0.2	1
Trisonica sphere	0.56	0.11	0.16	0.27	0.13	0.26
Trisonica mini	0.33	0.35	0.73	0.27	0.06	0.32
FT742	0.11	0.54	0.11	0.45	0.33	0.32



(a) The Trisonica Mini from Anemoment

(b) RTD PT100 from Firstrate

Figure 2.5: Wind speed and temperature sensor

Temperature

In this section the choice of temperature sensor is discussed. Since the implemented temperature sensor in the anemometer did not meet the requirement, **SUB.UAV.7**, of accuracy provided by the client. A different temperature sensor is needed for the design to meet the requirement. In order to find the best temperature sensor a list of criteria is made that the sensor should comply with.

- **Accuracy** - the sensor needs to meet requirement **SUB.UAV.7**, and have an accuracy of max 1 $[°C]$.
- **Weight** - the sensor should not be too heavy and fit within the requirement **SR.mass.19.SUB.2** maximum payload weight of 400 grams.
- **Robustness** - The sensor should be able to withstand temperatures of at least the temperature range of the UAV itself: -20 $[°C]$ to +45 $[°C]$
- **Cost** - The sensor price should lay within the requirement for the price of the sensors **SR.cost.20.SUB.2**, combined with the cost of the anemometer.
- **Integration** - It must be easy to integrate on the UAV itself and the size of the sensor should increase the aerodynamic drag by a reasonable amount.
- **Range** - The temperature sensor should be able to measure accurately between -30 and 40 $[°C]$, given as requirement **SR.maint.5**

Four different categories of temperature sensors are taken into consideration; Thermocouple, RTD (resistance temperature detectors), Thermistor, and IC sensors (Integrated Circuit). A short description of the differences is given in Table 2.8.

The categories: resolution, sensitivity and linearity, are all connected to the accuracy requirement **SUB.UAV.7**. The resolution at least has to be equal to 1 $[°C]$ in order to meet the accuracy requirement. Sensitivity can be described as the time it takes to register a change in temperate. As the UAV is moving, the time it takes to measure a temperature influences the accuracy of the measurement at a certain location. Linearity also influences the accuracy, as it changes drastically if the temperature moves outside of its prescribed linear temperature range. Although the operation range can be high, the linearity differs throughout this range. It may be only linear for certain parts of this range making the accuracy low if looked at the entire operational range.

Table 2.8: Overview characteristics temperature sensors[8] [9]

	Accuracy	Resolution	Cost	Range (°C)	Sensitivity	Robustness	Linearity
Thermocouple	Medium	Low	Low	-270 $\sim$ +3500	Low	High	High
RTD	High	Medium	Medium/High	-250 $\sim$ +750	Low	High	High
Thermistor	Low/Medium	High	Low	-80 $\sim$ +180	Best	Low	Low (Nonlinear)
IC sensor	Medium	Medium	Low	-55 $\sim$ +200	High	Low	High

In addition to Table 2.8 the main advantages and disadvantages per sensor will be discussed; type[10].

- **Thermocouple** - come in a wide variety and have a wide temperature range however their sensitivity and resolution is low.
- **RTD** - best performance regarding stability and accuracy. However, these sensors are expensive and have a lower sensitivity and they have a slower response time.
- **Thermistor** - have a limited temperature range, but it is within the operation temperature of our mission design. It shows strong non linearity and only accurate on a specified small temperature range. The sensors are lightweight but fragile.
- **IC Sensor** - will just meet the performance requirement regarding accuracy, but these type of sensors are fragile and it is more difficult to isolate it from board computer temperature.

For all sensors the temperature range would not be a limiting factor in the choice. The thermistor is eliminated in the choice because it does not meet the accuracy requirement and shows nonlinear data for temperatures out of its small specified temperature range. It would also be hard to implement the fragile sensor in the UAV design. The IC sensor is also not suitable because of its medium performance and fragility. This leaves the Thermocouple and RTD sensors. The RTD sensor is chosen because of its high accuracy and the price falls within the budget of the UAV.

Different RTD sensors that were suitable for air temperature measurements are compared to each other. Eventually a RTD PT100 sensor (Platinum resistance thermometer, 100 $[\Omega]$ resistance at $[°C]$) of model FST600-203 from First rate is chosen because of its good price compared to its really high accuracy of $\pm 0.1\% FS$. The accuracy is given in Full scale This comes down to $\pm$ 0.125 $[°C]$

Table 2.9: Wind and temperature sensor spec sheet

Criteria	**TriSonica Mini**
Size [mm]	91 x 91 x 52
Weight [g]	50
Power [mW]	0.35
Supply Voltage (DC) [V]	5 $\sim$ 36
Price [€]	1450
Signal output	RS-232
Operation temperature [°C]	-40 $\sim$ +80
Wind speed	
Range [m/s]	0 $\sim$ 50
Accuracy [m/s]	0 $\sim$ 10: $\pm$0.1 11 $\sim$ 30: $\pm$1.0 31 $\sim$ 50: $\pm$ 2.0
Resolution [m/s]	0.01
Wind direction	
Operation range out of horizontal plane [°]	$\pm$15
Operation range in horizontal plane [°]	0 $\sim$ 359
Resolution [°]	1.
Accuracy [°]	$\pm$ 1

Criteria	**PT100 FST600-202**
Size [mm]	172. x 22. x 22.
Weight [g]	100
Supply Voltage (DC) [V]	9 $\sim$ 30
Price [€]	26
Signal output [mA]	4 $\sim$ 20
Storage temperature [°C]	-40 $\sim$ +125
Measuring Range [°C]	-40 $\sim$ +85
Accuracy (FS)	0.1%

2.2.6. Sensor integration

In this section the integration of the sensors with the UAV will be explained further. This will be a mechanical, as well as an electrical integration.

The anemometer is placed on top of the UAV, above the location of the payload department. That is about $40[cm]$ away from the nose. This location is chosen to ensure a correct weight distribution. The payload department is placed on the center of gravity and therefore the weight distribution will not be disturbed if something is placed there. The anemometer is placed on the top of the UAV instead of underneath to ensure safe landing without damaging the sensor. Moreover, the anemometer is placed on top of a small pole with a height of $6[cm]$. This is to ensure that there is no boundary layer interference with the sensor measurements and to ensure that wind flow is not blocked by the pitched up nose of the aircraft. If the UAV flies at the maximum pitch angle of 8 $[°]$ during cruise, the height of the volume of air that is blocked by the nose of the aircraft will be about $5.6[cm]$, this is visualized in Figure 2.6. If the UAV pitches up higher than 8 $[°]$ due to sudden wind gusts, there will be a temporary gap in measurements. However, since the measurements are not required to be taken continuously, this gap is acceptable.

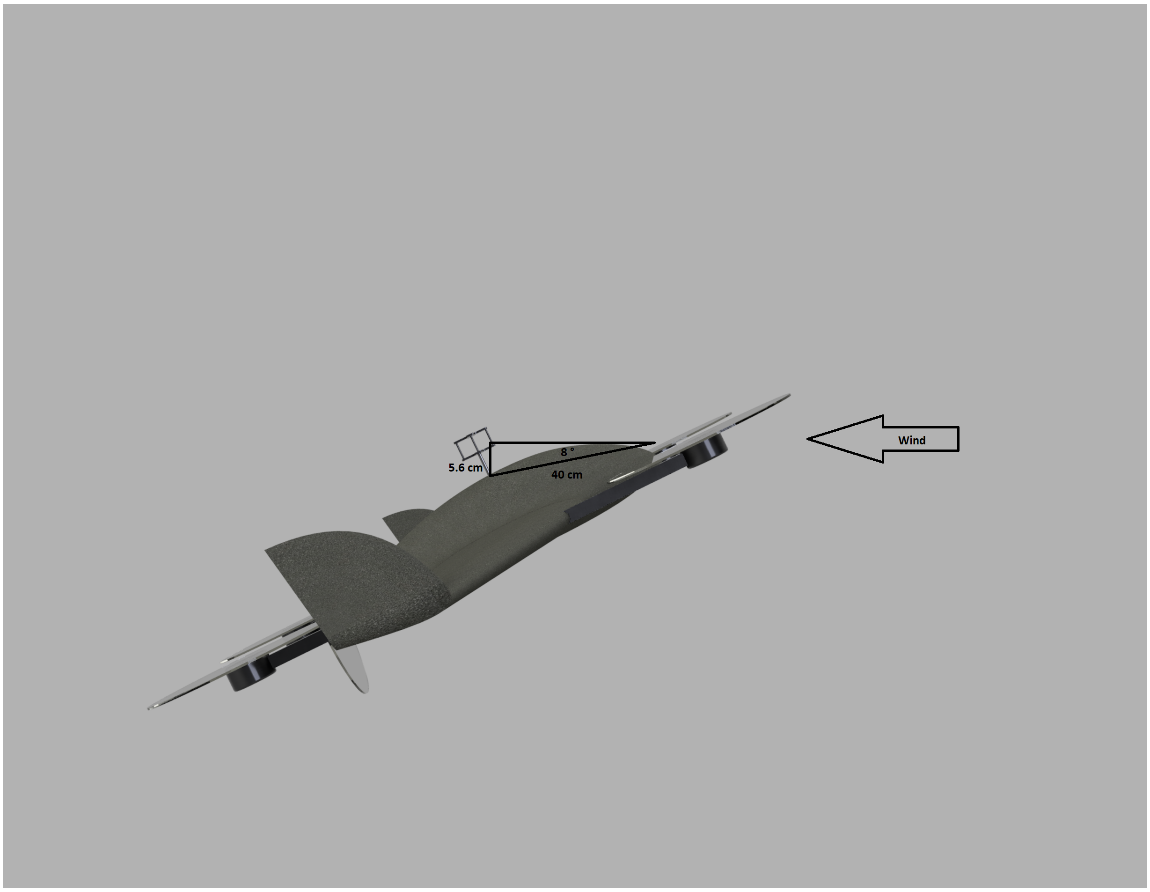


Figure 2.6: The nose of the UAV blocking horizontal wind when pitching up

To ensure the boundary layer thickness does indeed stay below $6[cm]$, a calculation on its thickness is performed. In order to do so, a simplifying assumption was made; to reduce the complete UAV to a thin plate. This assumption was made because of the inability to model the UAV in a Computational Fluid Dynamics (CFD) program. This was not possible, because no complete Computer Aided Design (CAD) file was available and no details were given on airfoil type of size. However, this assumption still holds as a good first estimate according to [11]. In future development of this project, these data will be gathered and a CFD will be performed to ensure the right height of the anemometer. For now the flat plate assumption is used to get an idea of what the thickness of the boundary layer could be. It was found that a turbulent boundary layer results in the largest thickness. In Equation 2.11 the formula for boundary layer thickness is shown for a turbulent flow along a flat plate, retrieved from [11].

$$\delta(x) \approx 0.37 \frac{x}{\mathrm{Re}_x^{1/5}} \tag{2.11}$$

Where x is the location along the flat plate, in this case the location where the sensor is placed. Resulting in x being equal to 0.4 $[m]$. The symbol Re_x stands for the Reynolds number. This number was found to be between 150000 and 400000 for a VTOL UAV with a 5 to 8 $[kg]$ take off weight, according to [12]. This fits the DeltaQuad perfectly, having a take-off weight off 6.2 $[kg]$. For the sake of this calculation the smallest Reynolds number in the given range is used, the 150000, because this will result in the largest thickness. Using this number ensures that the thickness is not

underestimated with this already simplifying assumption. Using these number it was found that the boundary layer for a flat plate in turbulent flow would be 1.36 $[cm]$. This gives us some confidence in the fact that a mount of 6 $[cm]$ would ensure no interference of the boundary takes place. Lastly the sensor will be placed at an angle of 5 $[°]$ downwards, because the UAV should fly at a pitch angle between 3 and 8 $[°]$, according to Vertical Technologies [13]. As mentioned before, the 2 to 3 $[°]$ that the UAV could pitch up or down is taken care of by the 15 $[°]$ vertical measurement capability of the Trisonica Mini.
For the temperature placement a similar reasoning as for the anemometer can be used. First of all the displacement of the gravity point due to extra payload should be limited so this gives two options: on top of the UAV or at the bottom of the UAV. When the sensor is placed at the bottom of the UAV there is not much available space without hitting the sensor during landing. In addition, it would also not be possible to put the sensor outside of the boundary layer if placed at the bottom of the UAV. Taking the past three reasons into account, a logical place to put the sensor is on top of the anemometer. An advantage is that no additional pole is needed to get the temperature sensor out of the boundary layer and use the existing pole for the anemometer. The temperature sensor will also be placed at a 5 $[°]$ angle relative to the chord line of the UAV. Since this pt100 sensor is normally not used for open air UAV mounted wind temperature measurements, an extensive calibration is needed to validate the setup.

To protect the temperature sensor from heating up due to radiation coming from the sun, a radiation shield will be implemented[14]. This shield will be formed out of an aluminium thin plate shaped as a half hollow tube This plate will be painted white on top to reflect light coming from the sun and prevent heating up the plate itself. The bottom of the plate will be painted black to absorb radiation coming from below reflected by the sea.

In terms of electrical integration, the sensors will be connected to the board computer of the UAV which processes the analog data. Furthermore, this data will be send to a master command centre from the UAV. Here the data is processed completely and send to shore to be made available for the client. More detailed information on this can be found in Section 4.2.1 and Section 4.2.4. A BEC, Battery Elimination Circuit converts the battery power to 12 V which is then delivered directly to the sensors. This is explained further in Section 4.2.3.

2.2.7. Payload mass budget

The original maximum payload of the UAV equals 1.2 $[kg]$, however due to the use of a bigger and more heavier battery, the mass available for sensor implementation equals 400 $[g]$, as can be seen in **SR.mass.19.SUB.2**. The masses of all the components that are part of the payload are specified in Table 2.10. As discussed in the previous section, the mount on which the anemometer will be installed has a height of 6 $[cm]$. In addition, it is assumed to have a diameter of 2 $[cm]$, a thickness of 2 $[mm]$ and is assumed to be made out of aluminium. This amounts to a total weight of 100 $[g]$. The mass of the BEC (Battery Elimination Circuit, (voltage converter)) is based on the Blue Sky Mini BEC from SpeedDrones, which has a mass of only 1.6 $[g]$. The mass of additional mounting and wiring is based on engineering sense and has to be validated in the future. As can be seen in Table 2.10, the payload is within the mass budget and therefore meets requirement **SR.mass.19.SUB.2**.

Table 2.10: Mass budget of payload

Component	Mass (gram)
Anemometer	50
Temperature sensor	100
Mount	100
Additional mounting (screws, additive, mounting plate)	50
Wiring	50
BEC	5
Total	**365**

2.3. Swarm design

The swarm element of the design concerns itself with the approach to which the UAVs attempt to measure the wind speed and temperature across the wind farm. From Figure 2.1, it can be seen that UAV flight characteristics and charging parameters act as input to swarm design, and from it can be expected the number of ground stations required, their positions, required communication range as well as the number of drones. Finally, the achievable measurement performance, that is for both the temperature and wind the spatial and temporal measurement resolutions, is an outcome of the swarm department's design process.

2.3.1. Flight path problem definition

From a high level the route planning problem is simply a route inspection problem, with the goal to visit all nodes, that have been separated by a defined spatial resolution, as fast as possible as to limit the temporal resolution. To give an idea of the wind farm as a set of nodes, Figure 2.7 gives a general idea, where the node separation would be equal to the spatial resolution.

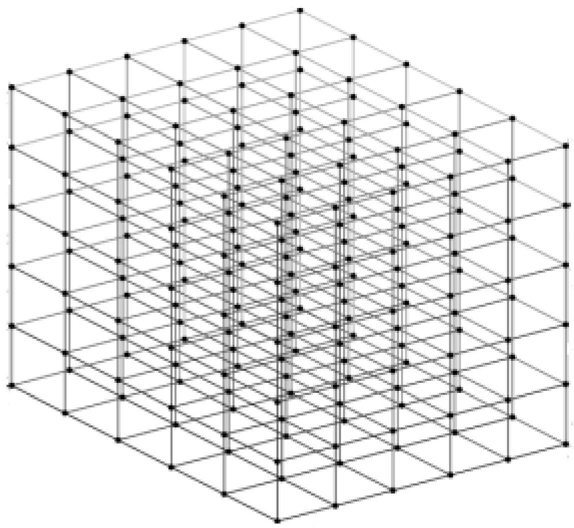


Figure 2.7: General 3D points grid

As an initial exercise, it is useful to outline what a solution needs to be able to do. There are two core functions the solution must provide: full coverage of measurement points and obstacle avoidance, which can be further deconstructed into the avoidance of static and dynamic obstacles. Graph inspection is a heavily researched and written on topic, therefore there already exists many solutions to this category of problem that can be used. However, in this section it will be explained the problems faced with directly implementing these route inspection algorithms and the alternative methods that are further investigated.

2.3.2. Graph exploration

As explained in Section 2.3.1, the problem at hand boils down to a route inspection problem. As a first attempt to solve this, the k-Chinese Postman algorithm (k-CP) is investigated due to its use in [15]. The goal of the k-CP is to visit every node in a graph and finish at the starting node. The implementation can be seen in Figure 2.8.

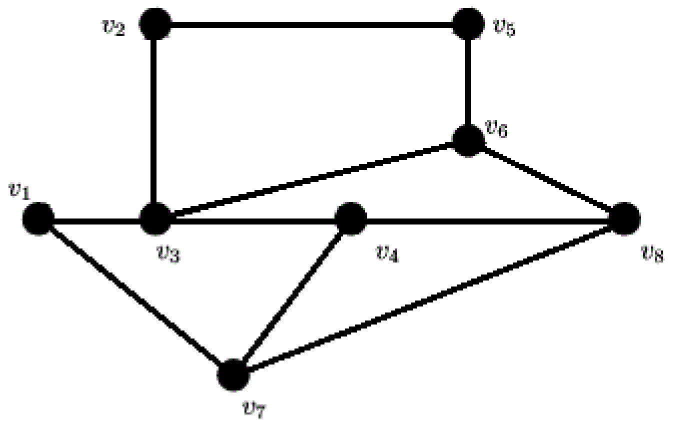


Figure 2.8: Simple implementation of the Chinese Postman algorithm - more connections have been used than necessary to exaggerate the potential inefficiency in the case of drone swarms

This paper [15] explores the use of the k-CP for efficient path planning of many autonomous vehicles, which lines up very well with the problem at hand. However the one issue with this is that there is no constraint on this algorithm to prevent the visit of the same nodes multiple times. While in application having a drone visit the same point is not a massive issue, it does introduce inefficiency, especially for a grid with dimensions 10x10x1 $[km]$. Another constraint for this system that is not useful in this application is the need for the UAV to return to home. It is for these reasons that other algorithms need to be investigated.

From communication with dr. ir. Salua Hamaza, it was noted that the more general form of the k-CP, the Travelling Salesperson algorithm (TSP) would be better suited as in this form the 'salesperson' cannot visit the same node twice.
However. before moving forward with this solution, it must be compared back to the functional requirements the solution must meet:

- Measurement point coverage - TSP by definition can provide coverage of the wind farm
- Static obstacle avoidance - This can be incorporated as a constraint and/or extension to the algorithm
- Dynamic obstacle avoidance - Cannot be implemented directly in the algorithm, would require a separate solution to meet this requirement

In this analysis, one issue presents itself: TSP would not be able to handle dynamic obstacles moving in and out of the path of a UAV. While this may not be a large problem, as indeed another program can be written for that purpose, another problem that comes as a result of abstracting the problem statement is the infeasibility of the generated paths. It has not yet been considered whether or not the tracks that the algorithm will produce are to be flyable or not.

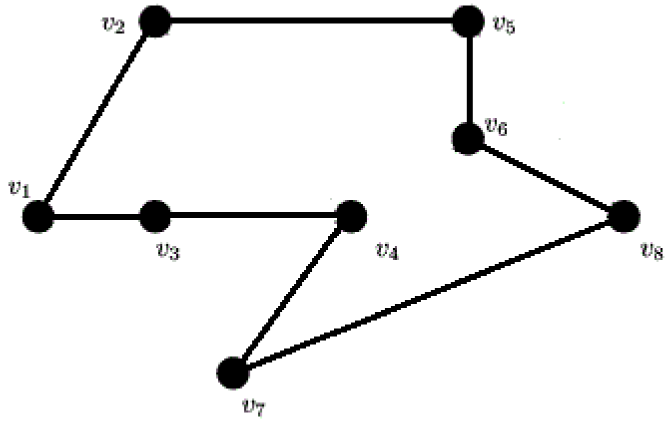


Figure 2.9: Simple implementation of the Travelling Salesperson algorithm

So from these two problems it is decided to continue investigating more options, this time with a focus on generating flyable tracks from the model.

2.3.3. Fixed path

Where the graph exploration method seemed promising, it could not provide flyable flight paths and therefore no practical results. Working as fast as possible to something that would give useful results, i.e. the Minimum Viable Product (MVP), a different, less complex approach was taken.

Approaching the problem with more of a focus on creating flyable tracks, it is decided to design a preset 'master' track, essentially what one UAV would fly if it were the only UAV in the system. The design for this master track is decided to be a zig-zag pattern. This is chosen in an effort to minimize complexity and limit the percentage of flight spent in turn.

Then for each flight altitude, one by one, a drone takes-off and flies to the next available measurable point along the master track. The moment it is determined that the spent endurance of the UAV plus the travel time to the nearest ground station is above 95% of the UAVs total endurance, the UAV will then fly to that ground station and land. This process allows an organised method to create reliable and flyable routes that reduce the complexity induced risk of the system that comes naturally with a system with many UAVs (see **R.B.7**). The program can then be iterated until all points along the master track have been marked as measured, from this simulation a set of flyable segments is found.

Before more detail is added to the explanation it would be useful to define the inputs and outputs of this program, this is seen in Figure 2.10.

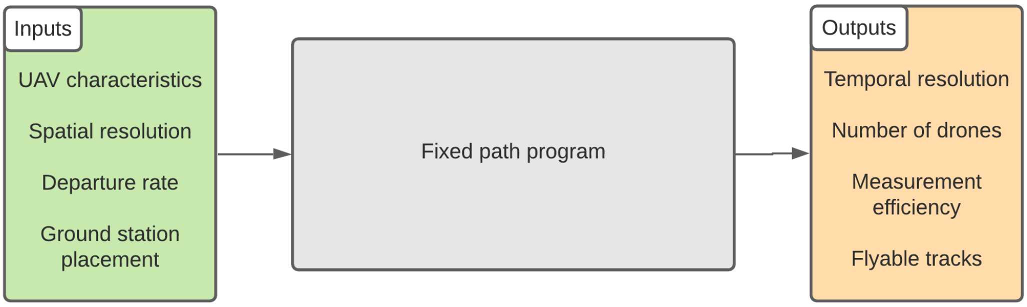


Figure 2.10: Inputs and outputs of fixed path program

Where UAV characteristics is an umbrella term used to describe all performance characteristics use in the program that are derived directly from the UAV, this includes: max turn rate, max climb rate, VTOL speed, cruise speed and endurance at cruise. Spatial resolution is fairly self-explanatory as this value defines the node separation of the grid on which the program is run. The departure rate is explained in greater detail below, what is important to note is that increasing it, increases drone number and in turn reduces temporal resolution, it can be quickly summarised as a tuning factor. Finally ground station placement is simply the location of all ground stations in the wind farm.

On the other side of things, temporal resolution is the time needed for one cycle of measurements. The number of drones is as it sounds. Measurement efficiency is a very useful metric for determining how well the UAVs battery is being used, it is calculated with Equation 2.12.

$$\text{Measurement efficiency} = \frac{\text{Time spent measuring defined measurement points}}{\text{Total flight time}} \tag{2.12}$$

Then lastly, flyable tracks is simply the routes for each UAV.

To give an idea of how the temporal resolution can be found: if the UAV were found to have an endurance of 20 minutes, and from that it is found with this method that 100 segments of the master tracks are needed (this would suggest one drone could fly the entire wind farm in 2000 minutes), then the temporal resolution for the system can be found very simply by calculating the maximum flight time of all the segments. It is found experimentally that implementing a usable endurance of 95% of the maximum endurance will surprisingly lead to an average flight time of 95% of that maximum endurance. Then the maximum can be expected to be in that final 5%. Therefore, if the UAVs have an endurance of x minutes, then a temporal resolution can be fairly accurately estimated to be equal to x minutes as well. However, this does not limit the temporal resolution to be always greater than the UAV endurance, as at this point another input can be defined, the departure rate. If the departure rate is set to 2, then 2 UAVs would set out along the same segment within the endurance window, which put simply means that there always, on average, 2 drones flying along a segment at once. It is important to specify the average as this departure rate does not necessarily have to be an integer.

The importance of this departure rate cannot be understated, as this is the center of the iteration to meet the power and cost requirements. From calculations on the power budget, a maximum number of drones is set, therefore to obtain the best performance, the challenge is to set the departure rate to the factor that will use the maximum number of drones, this is important as with more drones there can be a lower temporal resolution. Departure rate and temporal resolution are directly inversely proportional. Spatial resolution is an input to this program and initializes the grid to the right spatial resolution. Obviously having greater spacing between measurable points reduces the need flight distance which in turn will also reduce the temporal resolution.

Once this is put together for all altitudes, a 3D route plan can be plotted and is shown from two different perspectives in Figure 2.11 and Figure 2.12.

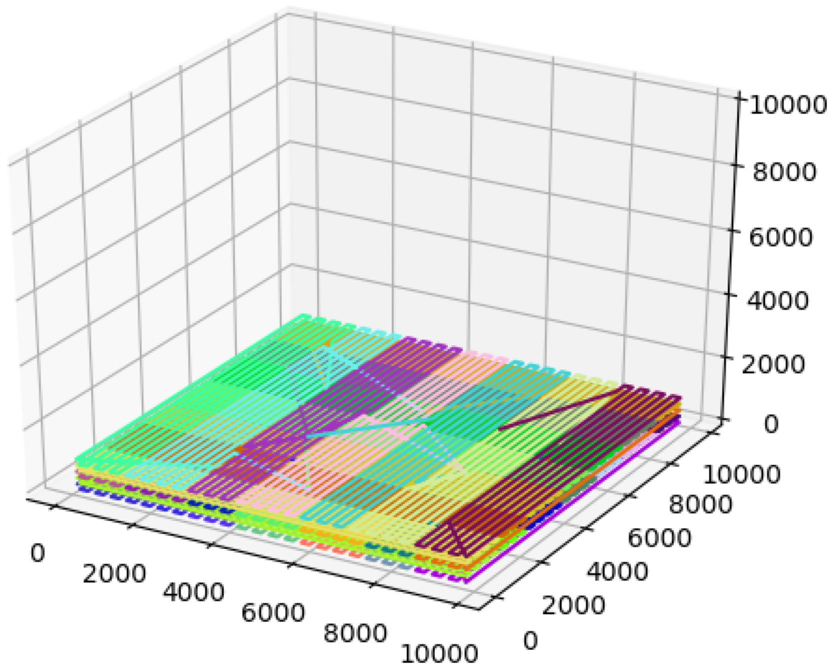


Figure 2.11: 3D view of all flight segments - each color represents one flight track

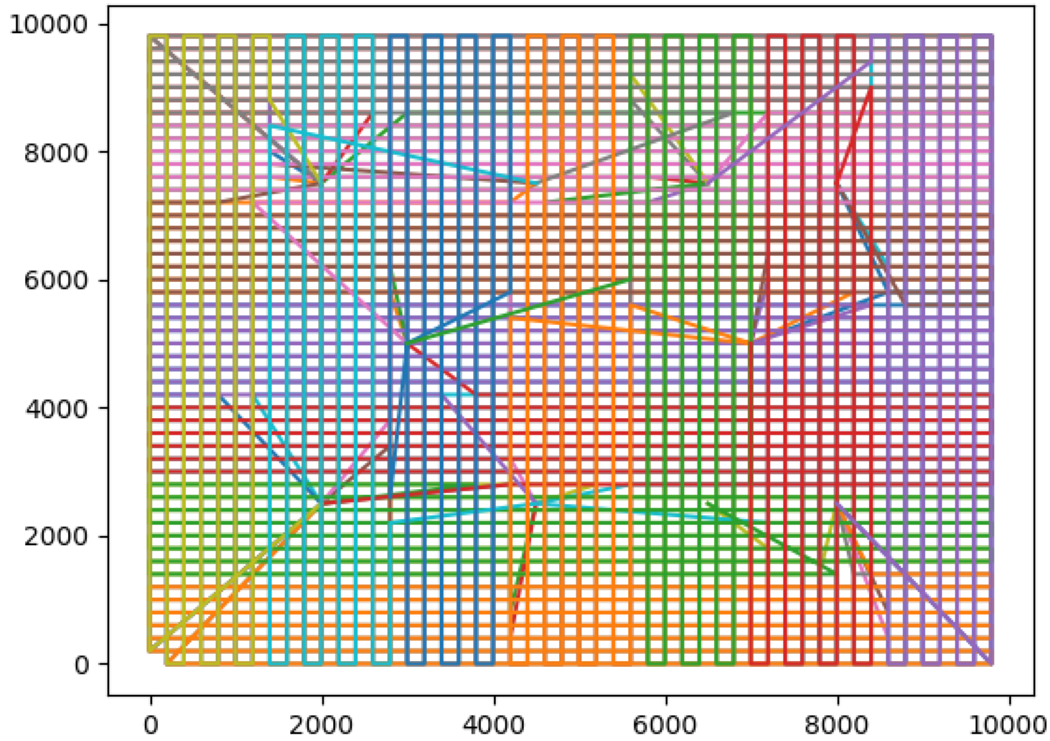


Figure 2.12: Top view of calculated flight segments - shows well the ground station placement

With that implemented it is now possible to look to optimize the number of ground stations. This can be done by iterating this route creation for different ground station configurations and inspecting the resulting measurement efficiency. However, this was not investigated in detail due to the number of ground stations being decided by the ground station department from the power budget.

While this approach improves on the implementation of the route inspection algorithms in terms of creating flyable segments, it must still be compared back to the functional requirements the solution must meet:

- Measurement point coverage - This is made possible by defining a master track upfront, which is then divided between UAVs
- Static obstacle avoidance - Similar to TSP and k-CP, this can be included in the program or added on as an extension through another solution
- Dynamic obstacle avoidance - Again this is not possible with this approach

From this evaluation, the same conclusion as the route inspection algorithms is come to, with one important distinction: the tracks created are flyable. This is enforced by constraints in the program that ensure no behaviour exceeds the input UAV characteristics. With cruise speed combined with the distance between sequential nodes, the endurance for each piece of the flight segment can be found and added to the running flight time to ensure that the total UAV endurance is never exceeded. Climb rate also effects which possible ground stations the UAVs can come from, for example if the first measurement point in a segment lies directly on top of a ground station, the UAV assigned to that segment will not come from that ground station as the point lies within the no-fly cone. This cone is the volume above the cone bounded by the max climb angle of the UAV.

Therefore, from these two approaches already analyzed it is decided to investigate dynamic obstacle avoidance that can be used to extend the functionality of the point-to-point route planning.

2.3.4. Collision avoidance

To ensure the safe autonomous functionality of the UAV units inside the wind farm environment, a collision avoidance system needs to be present. Such a system is composed of multiple obstacle avoidance techniques that may adjust a given flight path such that detectable object-to-object collision is fully avoided. In this subsection, dynamic obstacle avoidance techniques and algorithms are explored in detail. At the end of this section, a diagram showcasing the communication between other swarm department algorithms will be provided.

To begin with, the requirements outline best the way to design forward the obstacle avoidance system. The requirements to be designed for when talking about collision avoidance are **SR.SAFE.8** up until **SR.SAFE.13**. Looking at these requirements, it can be said that the collision avoidance system should be able to detect a number of distinct obstacles. Based on this number of distinct obstacles, an importance ranking matrix can also be considered, as some of these dynamic obstructions for the UAV units are more important and a collision would result in a critical mission failure. This is also further reflected in a risk analysis. Table 2.11 presents the obstacle-importance weight matrix and specific boundary. From the given table, it can be seen that the presence of human beings increase the boundary required significantly. This is of course needed, as a collision with such an obstacle could result in a fatal accident.

An assumption is also made on receiving sensitive information on obstacles. In order to have an efficient and accurate obstacle avoidance system, the need of obstacle position and orientation is required at all times. Thus, several mock APIs are considered throughout the development of this system. These APIs, can also be considered later as micro-services, fetching and relaying information from subsystem to subsystem, for example, master control centre to drone or drone to drone and so on. However, most importantly, the use of APIs comes in most handy for obstacle avoidance, where the telemetry data on wind turbines, naval objects, aircraft, etc. is most relevant.

Given the categories of obstacles listed in Table 2.11, these can be modelled as simple primitive spheres, which come in handy when calculating alternative routes to circumvent these impediments. It's worth mentioning here that birds or other unpredictable obstacles cannot be accounted for and cannot be avoided as the UAV units are not equipped with any obstacle sensing sensors. The obstacles accounted for are the ones that can be predicted with a continuous flow of information on position, orientation, speed, etc.

Table 2.11: Obstacle ranking and avoidance radius

	Obstacle importance ranking [-]	Obstacle minimum avoidance radius [m]
Human beings	10	100
Ships	4	30
Aircraft	8	100
Wind turbines	7	50
Other drones	3	20

The combined detection of and navigation around dynamic and static obstacles can be accomplished in many ways[16]. This depends on the information about the environment available before and during the mission as well as on the nature of the mission itself. Hence, an effort was made to investigate collision avoidance algorithms in both 2D and 3D space. The algorithms that have been thoroughly looked into are the two most utilized path planning, in the context of 3D UAV path planning, algorithms [17] [18]. Specifically A* and Rapidly–Exploring Random Tree (RRT).

The difference between these two is that one roots from Dijkstra's algorithm, which is graph based approach while RRT is based on probabilistic roadmap method.

Essentially an advancement of Dijkstra's algorithm, A* evaluates a function to determine the cost of neighbouring nodes. As a main distinction, A* tries to look for a better path by using a heuristic function which gives priority to nodes that are supposed to be better than others while Dijkstra's just explore all possible paths[19]. The evaluation function for A* is the sum of the actual cost from node x_{init} to a node n ($g(n)$) and the airline cost from node n to the goal point of n ($h(n)$). As $g(n)$ and $h(n)$ cannot be determined exactly, both costs are approximated. This is shown in Equation 2.13.

$$f(n) = g(n) + h(n) \tag{2.13}$$

To better understand this process, Figure 2.13 shows the first two iterations of the A* algorithm. As it can be seen, the goal is to minimise $f(n)$ at the cost of $g(n)$ in brown lines and $h(n)$ shown as the pink vector. the obstacles restrict the use of certain nodes as shown by the blue boundary.

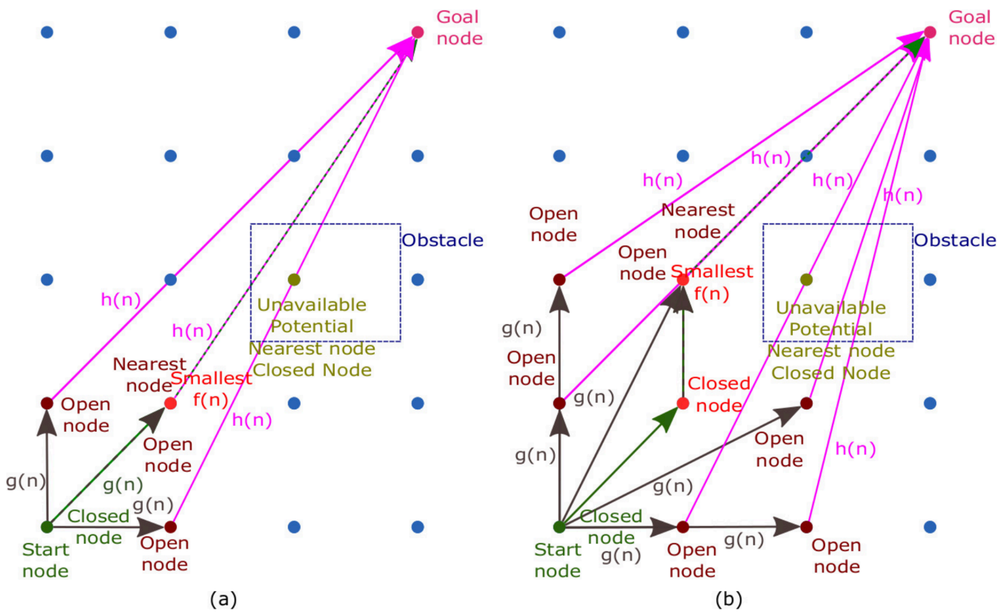


Figure 2.13: A* process with (a) first iteration and (b) second iteration[17]

On the other hand, the Rapidly–Exploring Random Tree (RRT) constructs a unidirectional trajectory by randomly planting so called seeds, which can be referred to as nodes. Thus, by randomly selecting and interconnecting obstacle–free nodes, one of the tree branches may reach the end goal node in a number of iteration. Figure 2.14 describes the working principles of the RRT process.

From a performance review between these two algorithms, it is shown that A* generates shorter paths in less time, even after a smoothing process, compared to RRT. Although A* stands out in speed and performance in general, RRT proves to be more adequate in evenly distributed and focused 3D are exploration applications[17]. Moreover, RRT can perform much better than A* if randomly selected nodes are in view of obstacle shape, position and dynamics[20].

With the obstacle avoidance algorithm selected, one can further improve this system by optimally selecting the nodes where this algorithm could be applied. While continuously calculating the op-

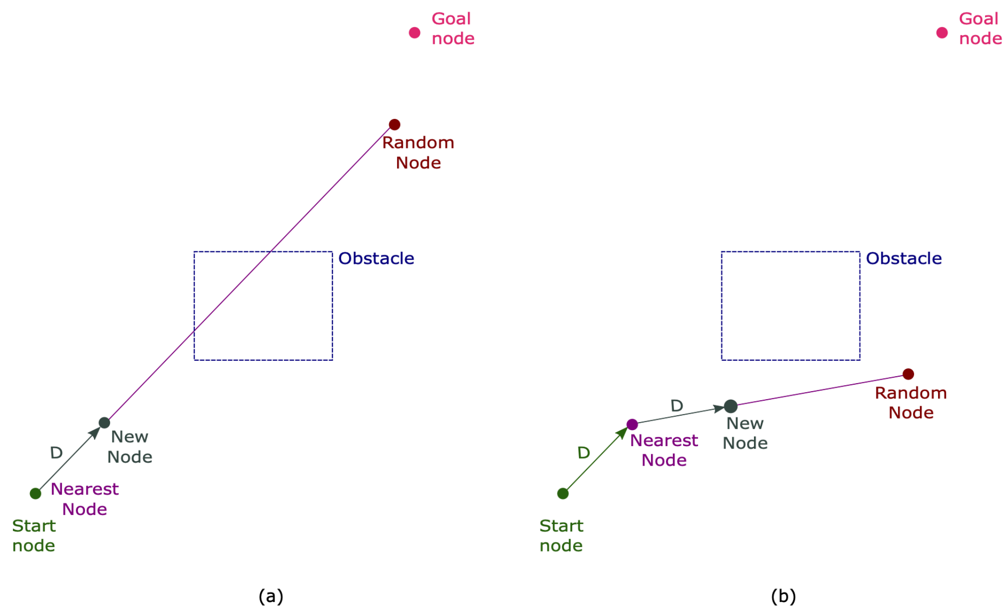


Figure 2.14: RRT process with (a) first iteration and (b) second iteration[17]

timal route using RRTs sounds like a good idea, scaling up to thousands of distinct obstacles is prone to increase the computational time quite significantly. Hence, a second measure was taken to find interest points where to apply this path planning adjustment algorithm. This additional filtering consists of looping over the assigned zigzag path of a flying drone by considering the point in polygon problem. One way to solve this problem is to use a ray casting algorithm, with an extensive use in computer graphics, it's the optimal choice to find intersections between objects. The best way to approach this is to continuously search for intersections between current measurement waypoint and next goal measurement waypoint. As each obstacle can be considered as a sphere with a certain radius from Table 2.11, the intersection problem becomes a very inexpensive calculation. Figure 2.15 showcases all the edge cases, where t_0 and t_1 represent the two solutions by solving a quadratic equation. The solutions to these equations are then filtered to remove outliers, for example intersections that lie outside the airspace, or intersect with another UAV path.

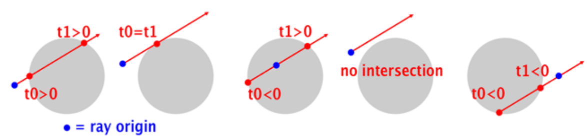


Figure 2.15: Ray-sphere intersection edge cases [21]

By combining the ray-sphere intersection algorithm together with Rapidly Exploring Random Trees (RRT) one can optimize the computational time very significantly by only running the RRT between interest nodes. Those being the entrance and exit nodes of the ray-sphere intersection. This proves to reduce computational time of RRT when considering a large number of obstacles. Figure 2.16 and Figure 2.17 showcase actual simulations for the obstacle avoidance system.

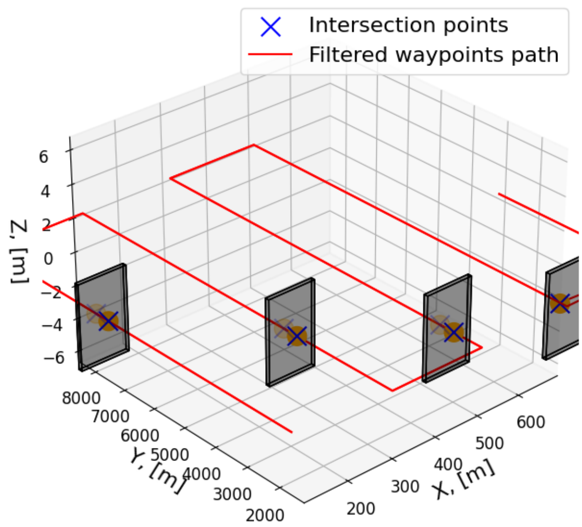


Figure 2.16: Ray-sphere intersection edge cases

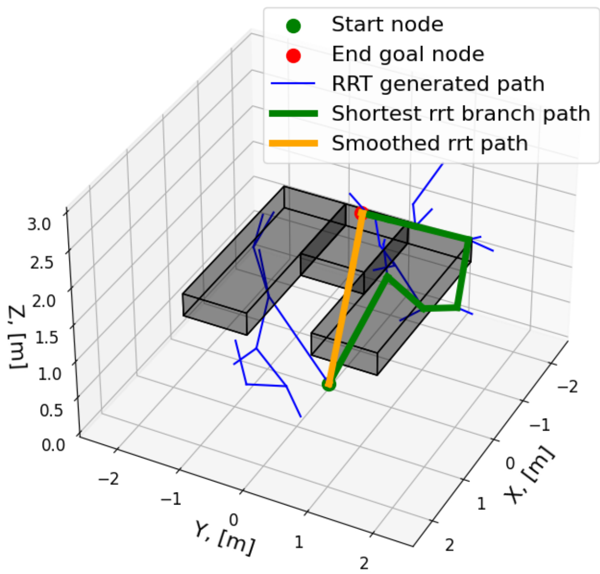


Figure 2.17: Rapidly exploring random tree in 3D between two intersection points

2.3.5. Agent based modelling

In order to explore alternatives to the fixed zig-zag flight pattern, different modelling methods were investigated. Where as explained in previous subsections, the graph based modelling approach was deemed too complex, a agent based evolutionary modelling approach was deemed worthy of investigation. Although time resources were limited, it was estimated that modelling the UAVs as separate moving agents in a three dimensional space would be achievable. Defining inputs to how the UAVs moved in this space and evaluating the quality of these movements would result into flight paths and their respective measurement performance. These flight paths could then eventually be optimized for measurement performance by tweaking the inputs in a evolution based manner. This section now discusses how this model was worked out with the use of the programming language Python.

Modelling the UAVs is fairly simple. Any UAV has a certain three dimensional position, a flight speed, a heading and a climb angle. The UAV furthermore has flight characteristics: maximum climb angle, maximum descent angle, maximum cruise speed and maximum turn rate. Finally, the UAV has a certain mass, drag coefficient and battery capacity.

With this UAV model, the flying of the UAV can be simulated by defining 'stick inputs' to the UAV. For example, every five seconds time interval, the UAV could either turn left, turn right, cruise, climb or descent. Then, the new position of the UAV can be calculated after which a new stick input can be given. Posing certain constraints on which stick input is possible at any time, the flying of the UAVs can be logged as actual flyable flight paths. An overview of these stick input constraints is given in Table 2.12. A flight path therefore is modelled as a set of stick inputs for a certain UAV taking off from a certain ground station, i.e. starting at a certain position. In order to decide which stick input is being given to the UAV at a certain moment in time, each input has a certain likelihood based on the UAVs position and heading. The process of then creating a flight path based on the stick input likelihoods is represented in Figure 2.18.

Table 2.12: Stick input constraints for UAV

Condition	Constraint	Explanation
UAV altitude above 1000m	Cannot climb	Flying higher than 1000m is inefficient
UAV altitude below 10 m	Cannot descend	Negative altitudes are not allowed.
Battery capacity left <energy required to fly home	Align with homing vector	UAV should land before battery is empty.
UAV in vicinity of object	Take avoiding measures	This was not yet implemented.

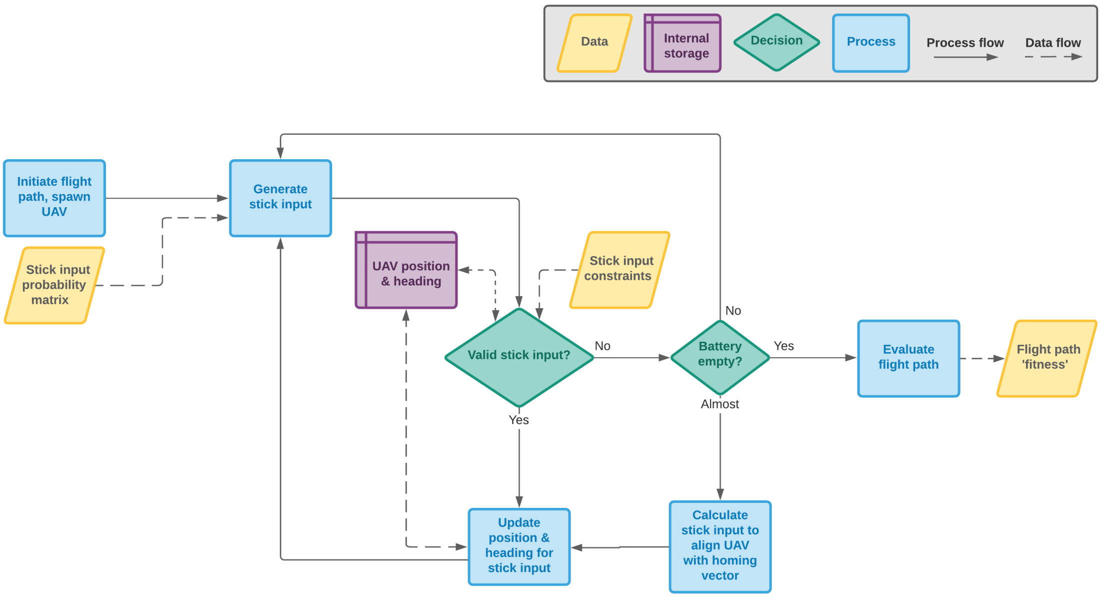


Figure 2.18: Agent based flight path generation method

This framework of being able to model a UAV flight path based on inputs now enables the optimization of the flight path problem, except for the fact that first an evaluation method for any set of flight paths has to be established, a so called 'fitness function'. Difficulty here lies to make the fitness function as least computationally expensive as possible, whilst still being a good estimator for measurement quality. This is achieved with a predefined a set of measurement points, spaced out evenly in intervals of 200 $[m]$ which change their state to 'measured' if a UAV passes within a certain threshold distance. The passing distance to the point is then called the measurement accuracy. With this, any flight path's fitness is then evaluated with two metrics: the number of (newly) measured points and the average measurement accuracy. This is shown in Figure 2.19, where two (rather poor) flight paths are evaluated. The lines represent the flight paths, where the dots are the measured points per flight path.

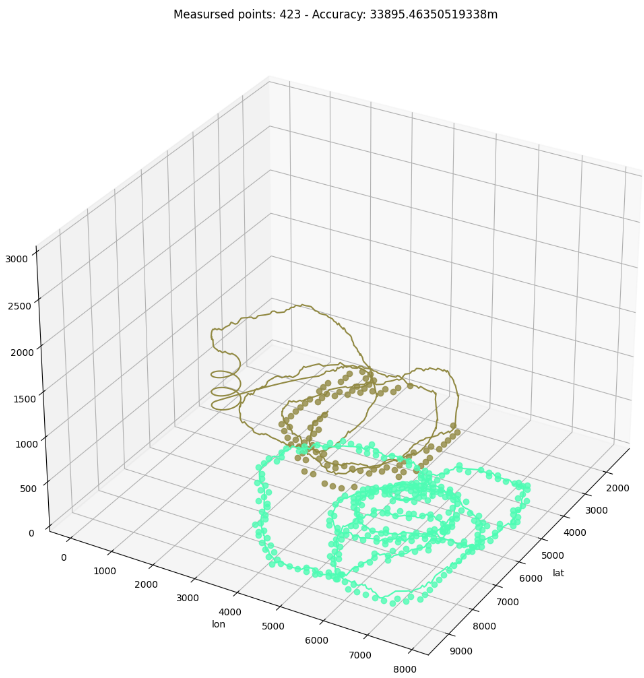


Figure 2.19: Two flight paths being evaluated

With the fitness function defined, the flight paths can now be optimized with alteration of the stick input likelihoods. This was done using an evolutionary approach, where for each generation, the likelihoods for stick inputs for each flight path are randomly mutated after which the set of stick inputs resulting in the fittest flight paths can form the basis for a new generation. Figure 2.20 shows this process in more detail: every epoch starts with a certain population, from which random mutations & permutations would result into n different strains, which would then mutate further for m generations, where finally the winning set would pose the basis for the new epoch.

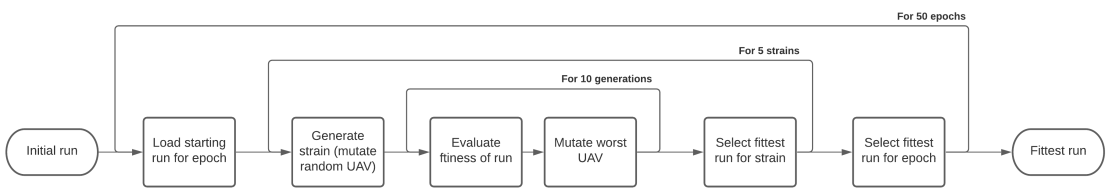
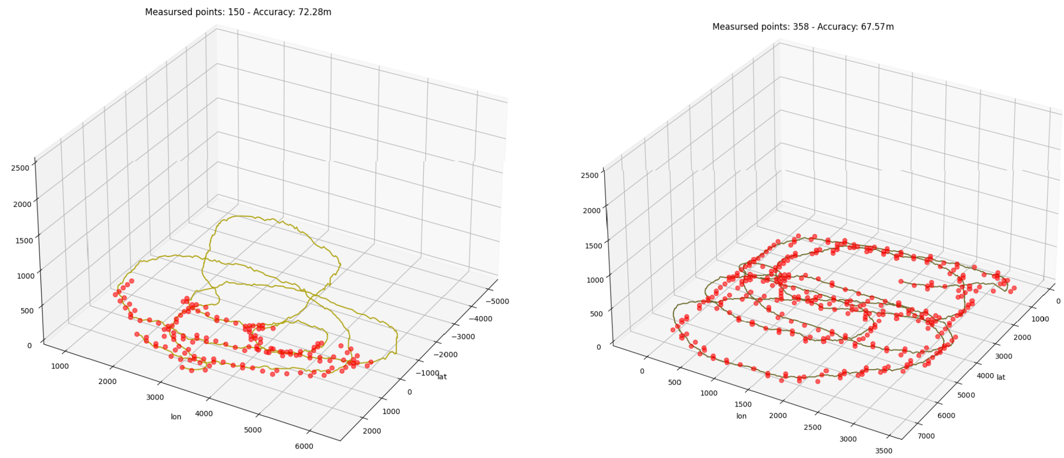


Figure 2.20: Evolution algorithm method

Following this method, some preliminary but promising results could be obtained. Figure 2.21a shows a first epoch UAV with obvious poor performance. The UAV is flying out of the measurement volume[2] (note the negative latitudes) and the number of measured points is low with a value of 150. In contrary, Figure 2.21b shows a later epoch UAV which stays within the measurement volume and has a significantly higher number (358) of measured points.

[2] As defined per baseline report: "the volume of which the system is required to take wind and temperature measurements" [3]



(a) Early epoch **(b)** Late epoch

Figure 2.21: Flight path performance for different epochs

However, the model is not yet iterated enough to produce better flight path performance than the zig-zag pattern previously discussed. The UAV flight paths failed to converge to a single solution and eventually, later epochs produce worse results than earlier epochs. Even when trying to tackle this problem by decreasing the mutation rate, no better results are obtained. Due to limited time and resources available, the decision was made not to continue improving this agent based evolutionary model.

The results of the model do open a discussion. As can be seen in Figure 2.21b, the more organized and less random flight path yields better measurement performance. This hints at the conclusion that the previously discussed zig-zag pattern is quite efficient. Also, one starts to question whether even better results could be obtained if this model would be improved. This will be the topic of section Chapter 7.

2.3.6. Statement of final choices

With the different approaches discussed in this section, a conclusion must be made on which approach is to be continued with. Although the graph exploration would yield promising optimized paths, path flyability is difficult to take into account as well as object avoidance. To obtain the first flyable flight paths, a predefined zig-zag pattern approach was explored, which would pose our MVP (minimum viable product). Finally, to check if the zig-zag pattern could be improved upon, a agent based evolutionary modelling approach was constructed. This method could also eliminate the need for an additional algorithm for object avoidance.

As discussed previously, the evolutionary-based optimisation algorithm provided promising but preliminary results: it did not outperform the zig-zag pattern. This resulted in the fact that the modelling approach with the best flyable flight paths was the zig-zag pattern. Therefore, for the remainder of the design process, the zig-zag pattern was used with additional object avoidance algorithms for both static and dynamic object avoidance.

This choice also allowed for fast design, which would help the inter-department iteration process as discussed in Section 2.1. With certain UAV flight characteristics and number of ground stations as inputs, the number of UAVs required to obtain a certain measurement performance could be quickly determined. This would then lead to a final system cost and power consumption for a certain measurement performance. The different iteration results will be discussed in Chapter 3.

2.3.7. Tool verification

The ultimate goal of verification is to ensure correct functionality of the UAV unit navigation throughout the entire wind farm and handling of unexpected situations. A variety of methods can be used to achieve this goal, each focusing on eliminating a distinct possible source of error that has been introduced through implementation of the path planning system. The first method can be visually inspecting the code. Moreover, there is a distinction to be made between between possible sources of error. The first two errors pertain to human factors while the last two are more fundamental to how computers work in general.

Bugs can be simple programming errors that appear due to a variety of human mistakes. For example misspelling variable names or accidental calling of wrong variables. In the scope of the development of the path planning system, bugs are considered to be programming mistakes that do not involve conceptual understanding but instead involve missing quality checking or edge case testing.

The next error has to do with conceptual implementation, where the author of the code might not have the proper fundamental understanding of the feature to be implemented. It goes without saying that this will lead to discrepancies within the final result of the system.

Discretization errors appear to due representing conversion from continuous function domains to discrete set of values. Finally, floating point arithmetic errors due to the fact that computers can only model numbers with certain accuracy. An error is introduced that is equal to the precision of the computer or machine epsilon.

The following methods will be used to scrutinize the program and identify as many of the above errors as possible.

- Visually checking code: this method checks implementation of swarm system by visually inspecting line by line to build an understanding of what the programming logic is. This method, in theory could identify all issues if the reader is skilled enough to understand the code and implement fixes. Although this method seems to be ideal in the verification and validation spectrum, in practice, it's incredibly hard and time-costly for someone to grasp the complexity of the path planning and obstacle avoidance algorithm.
- Running the code is another ideal and quick verification technique which never gets overlooked. However, this method only checks functionality to a certain extent as it does not confirm consistency and stability, thus not confirming convergence.
- Last but not least, comparison with another independent solution or analytically checking the results deems to be another viable options. By comparing the output of one implementation with another, for example the A* with RRT, it offers the possibility to reliably to verify complex arithmetic.

Moreover, analytical checking will be used throughout unit testing as it's a quick and easy solution to check functionality on a subsystem level. This is done by running for functionality or analytical results and checking results visually or by hand.

For the verification of path adjustment and obstacle avoidance one can also compare it with the alternative A* independent variant. Similar in performance to RRT, the final result should differ only slightly. However, a more thorough simulation should be done to check whether the current obstacle avoidance system can meet the requirements for all edge cases. If it can't, alternative emergency measures can be taken.

The following Table 2.13 describes the unit tests written for the verification of the path generation, obstacle avoidance and integration between these two within the swarm department.

Table 2.13: Unit tests per category for communication, obstacle avoidance, and zigzag generation

ID	Performed unit test	Expected outcome	Actual Outcome
UT-INT-1	Test for master command centre failure procedures (path generation or object collision system failure)	Await connection retrial while hovering, else land on the closest ground station or on water	all UAVs hover for a minute, then land on the closest ground station or on water
UT-INT-2	Test for failure of ground station communication	Land on available stations or land on water	Crash into water in cases where endurance is out
UT-COL-1	Test for a large number of obstacles	Computational time remains under 1 second	With 1000 obstacles, total computational time remains under 0.3 seconds, given ray casting fast performance
UT-COL-2	Test for complete obstruction between start and goal	UAV loiters for one minute, checks alternative route, lands on closest ground station	UAV goes out of specified airspace, corrected
UT-COL-3	Doubling latency in new updates from obstacles API	Lower UAV speed based on latency and radio resposne	UAV speed lowered when a latency of 1s is reached
UT-COL-4	Test for no solution found or non blocking behaviour	Running out the number of iterations should increase RRT step size	Step size is squared twice until a solution is found, when no solution was found drone started hovering
UT-COL-5	Manual calculation from endurance left at distinct points throughout the mission	Average absolute error less than 2%	An average absolute error of 1% was found between calculated endurance and actual endurance
UT-ZIG-1	Test for assigned path length between all UAV units	Each UAV shall be assigned a path that costs more than necessary transit endurance cost	During testing, some UAVs have been assigned paths with less endurance cost than transit cost
UT-ZIG-2	Manual testing for correct outputs	Correct number of UAVs, number of waypoint, paths, and correct temporal and spatial resolution	All correct
UT-ZIG-3	Minimising target temporal and spatial resolution	Temporal and spatial resolution should cap at a maximum given the power requirement	Maximum number of UAVs caps at 59

From the described verification approaches and unit tests, the verification of the drone swarm tools can be summarized by comparing back to the relevant verification requirements set in the midterm report Table 2.14:

verif.tool.I.2 - Visual inspection/comparison of each formula between the written and programmed case.

verif.tool.T.2 - Unit test (in Pytest) is to be written for each formula implemented in the script to compare the output between hand calculations and the code for seven nominal cases.

verif.tool.A.3 - Set all inputs to zero and analyze whether the output would respond as expected based on the written formula, repeat for a large input($\approx$ 10E10 times larger than nominal input)

verif.tool.A.4 - Ouputs of methods for a range of inputs will be plotted

verif.tool.T.3 - Use cases will be implemented in Pytest to achieve minimum 75% coverage

Table 2.14: Table showing the results of the verification on the python script used for the UAV iterations process

ID	Obstacle avoidance tool	Communication tool	Zigzag generation tool
verif.tool.I.2	✓	✓	✓
verif.tool.T.2	✓	✓	✓
verif.tool.A.3	✓	✓	✓
verif.tool.A.4	✓	✓	✓
verif.tool.T.3	✓	✓	✓

2.4. Ground facilities design

The ground department is responsible for any elements in the design that is crucial to the operation on the ground. This includes take-off, landing, parking, battery charging, and communication. The ground stations need to be designed to incorporate all these elements. This makes the ground department a very important part of the operation.

From Figure 2.1, it was already shown that there are several inputs and outputs connecting the ground department to other departments. The inputs that are needed in this department are mainly the UAV characteristics, the number of UAVs and the data size. Then the main output to the swarm department is the number of stations for take-off and landing.

2.4.1. Design options considered

A big challenge in designing the ground station layout is that it needs to be compatible with offshore wind farm. With no land available in the wind farm, there needs to be a substitution for the structure to be built on. There are many options for the ground station layout design that can fulfill this requirement and perform the functions necessary for the operation. A few layout that was considered during the design of the ground station includes:

1. Barge - Barges can used as a structure to build the ground station on. They can be easily moved around in the wind farm if there was ever a need to. To prevent it from drifting away they will have anchors that hold it in place. The problem with this option is the supply of power to the ground station. Having a cable that supplies it with power from the wind turbine is an option which will be expensive and is susceptible to damage since the barge is not able to completely hold its position at sea. While having the barge produce electricity locally will be an inefficient solution.
2. Floating structure - A relatively small-scale semi-submersible platform, anchored to the seabed. With this design consideration, the necessary infrastructure for communications, housing, and charging of the UAVs could be accommodated in one location; this also facilitates more efficient maintenance and inspection procedures. Furthermore, the wind turbines are not exposed to risks such as fires due to charging of the batteries for the UAVs. Another beneficial aspect of this design is that the platform can be scaled up vertically, allowing for more UAVs to be housed if the wind farms are also expanded. The disadvantages of this design are a few; preliminary calculations show that this design would be quite costly, and linking cabling for power supply or communication to this facility will also contribute to this and require a long time. Furthermore, due to the high cost, there should only be one big platform in the wind farm. Since the position and number of stations the UAV can take-off and land influence the time it takes to go to the starting position in the flight path, having this parameter fixed means the flight path optimization will be more limited. In addition to that, in the event of an emergency, the entire system would be at risk, and would need to be replaced if, for example, a fire would occur.
3. Landing on nacelle - Instead of having a structure at sea to build the ground station on, another option is to place the ground station on top of the wind turbine nacelle. This option make use of the already existing structure to build the ground station on so there will be no extra cost and difficulties for a separate floating structure. Another advantage of this option is having the power supply be easily accessible since there is no need for an underwater cable. The feasibility of placing a ground station on top of the nacelle was looked into. After a consultation with experts, the area available to be used was estimated to be 30% of the nacelle surface. This is enough for this option to be feasible.

2.4.2. Ground station overview

The ground station design chosen was based on the 'Landing on nacelle' consideration. The main reason is to reduce cost of building a separate structure in the sea. Subsequently, the remaining aspects of the ground station design had to be made, while considering that:

- The design must house all the UAVs under inoperable conditions, or during downtime.
- The design must facilitate the continuous charging of all the UAV batteries.
- The design must ensure the safety of the system and of the wind turbine.

With the aforementioned considerations in mind, and the constraint of only being able to utlize 30% of the nacelle surface, the ground station can be summarized as follows:

- 1 Master command centre: This is where the measurement data is process and stored, other data pertaining to the UAVs and ground stations are processed and sent back, and where the wind farm weather status is updated.
- 4 Battery charging stations: This is where the battery swapping system, which will be elaborated on, is housed. The spare batteries are also stored here. This station is equipped with a fire protection system and a dehumidifier to ensure that the high moisture levels in the offshore conditions do not damage the batteries. A moving roof is also part of this station, and is deployed when the weather conditions allow.
- 16 UAV housing stations: The UAVs are grounded here in the event of bad weather or operational downtime. This is also where the data about the location of the UAVs is received. A moving roof is also part of this station.

Every subsystem in the ground station is equipped with an antenna, computer, and transceiver. An elaboration on the communication links between these parts of the ground station system can be found in Figure 4.10. The total initial cost of the ground facilities would come out to be 310,340 euros and the cost per year for ground facilities would be 353,376 euros. This includes the cost of the batteries of 220 euros each. A more detailed cost breakdown is shown in Section 6.1. The ground facilities characteristics are shown in Table 2.15.

Table 2.15: Ground facilities characteristics

Ground Facilities Characteristics	Values	Units
numbers of UAVs per UAV station	5	-
numbers of batteries per battery station	183	-
station size	10 x 3	m^2
battery charging time	6.6	hrs
battery swapping time	5	min
battery station cost	29,300	€
UAV station cost	1,900	€

2.4.3. Batteries

With the continuous nature of the operation, the battery of the UAV can be expected to degrade quite quickly over time. It was recommended by the manufacturer that the UAV battery maximum capacity should not degrade below 70% to maintain the performance of the UAV. The degradation of the battery can be estimated from the cycle count. One battery cycle is equivalent to charging and discharging the battery completely. Every 75 battery cycle the battery maximum capacity can be estimated to degrade by 10%. With the operation using around 2.9 battery cycles per day, the time it takes for the battery to degrade below 70% can be calculated. This will determine how many batteries are needed per 6 months of operation before a new batch of batteries are brought in to replace the old batch, this is calculated to be 9.4 batteries per UAV, leading to 731 batteries per 6 months.

The type of battery used in the UAV is lithium polymer. There were two types of battery (lithium polymer and lithium ion) that was investigated for use in the UAV. Lithium polymer was chosen mainly due to its improved safety over lithium ion. Other factors were slower aging and lighter weight.

2.4.4. Battery charging and UAV stations

After the calculation of how many batteries the system would need for continuous operation, it was concluded that the batteries would need to be charged at a considerably fast rate in order to prevent any delays. However, charging batteries at this rate would significantly increase the risk of malfunctions or battery fires. Hence, a battery swapping system was designed to ensure that UAVs can be quickly replaced with charged batteries, and that the charging operations would be carried out as per the manufacturer's recommended guidelines to ensure safety. This battery swapping mechanism consists of a rotating disk, where the UAV first lands in order to be centered. The UAV needs to be centered as a robotic arm will subsequently replace the battery, which is summarized by Figure 2.22. The batteries are stored and charged on a shelf of battery sockets inside the battery station.

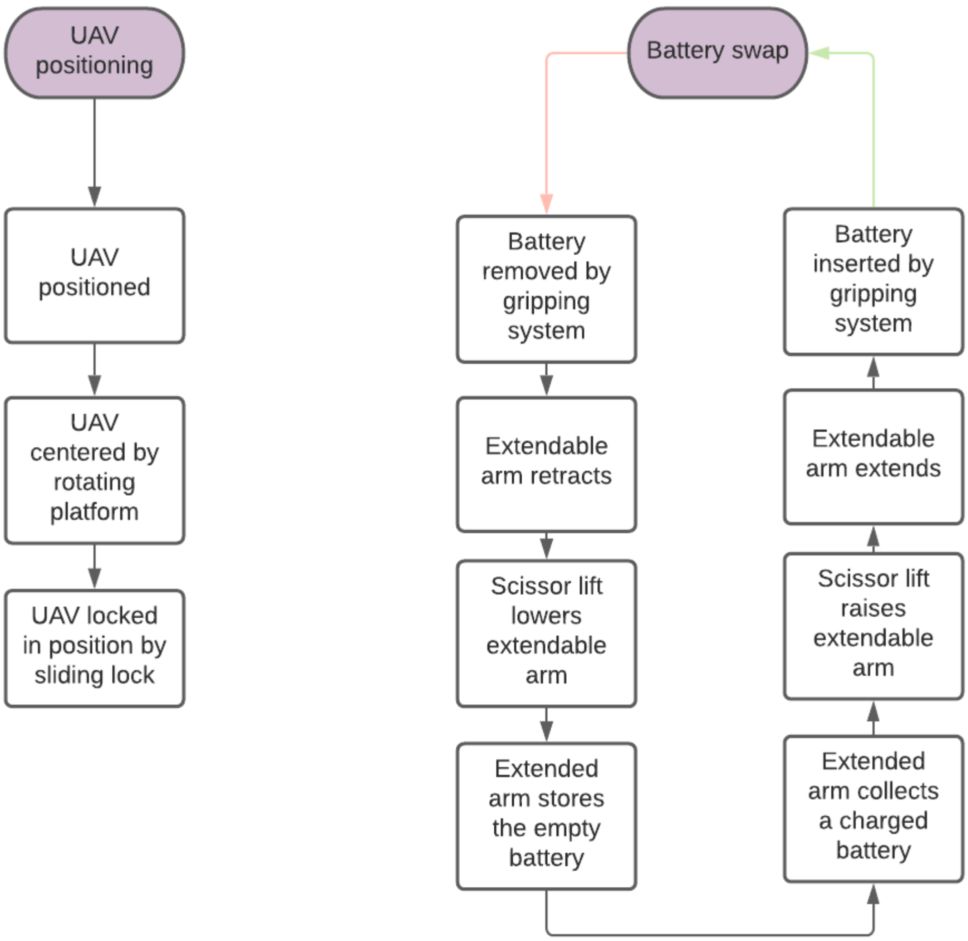


Figure 2.22: Battery swapping system flowchart

Although safely charging batteries would reduce the risk of a fire, it does not eliminate it. Hence, it was decided that the battery swapping station would be housed independently from the UAVs. The housing will be made of fire-retardant corrugated steel, and would include an automatic fire extinguishing (class D) system. It is necessary to have a temperature and humidity control system for the battery swapping housing facilities. This is because while the temperatures in the North sea year-round would be within the safe range for battery storage, the temperature range for battery charging is much more limited. Temperature control is needed to optimize battery charging and minimize battery degradation [22]. A visualization of the two types of housing stations are represented by Figure 4.1 and Figure 4.2.

The UAVs are also stored in a fire-retardant housing with fire extinguisher equipped inside, similar to the battery swapping station, to prevent the spread of fire to the wind turbine.

The ground station design is limited by the size of the housing. As mentioned earlier, the area on the wind turbine nacelle that can be utilized is 30%. For an average wind turbine for an off-shore wind farm, the surface area on top of wind turbine nacelle is 20 x 6 square meters. This information was provided by a senior wind turbine engineer at Underwriters Laboratories, David Coffey. This means 36 square meters of area can used to place the ground station. To give adequate access area for maintenance, the housing was designed to be 10 x 3 square meters. One UAV storage would be able to house five UAVs. From this limitation there would need to be 16 UAV station in total to be able to house all the UAVs.

Additionally there would be four battery stations. This number was chosen based on how long and how often the UAVs require a battery swap. The battery swap is estimated to take five minutes per UAV and they require a battery swap every 99 minutes (the endurance of the UAV). For continuous operation, it was determined that at least three UAVs need to have their battery swap at a time. For redundancy the decision to have four battery stations was chosen, this will give more flexibility in case there is a delay or a malfunction in one of the battery stations.

2.4.5. Communication

The ground station has one master communication station which communicates the information to all the UAVs and housing stations. This decision was made due to the lack of cell service off shore, making communication between UAVs more difficult. This master communication station is integrated into the off shore substation of the wind farm. Having all the data communicated to the master station means the communication link needs to be sufficient to ensure no loss of data. First the amount of data needed to be transferred was computed from the type of sensors and data from the UAVs and ground stations, this can be seen in Table 2.16.

The combined data rate from the UAVs and ground stations is 1,799,932 bps. This can be used to choose the ground antennas with specifications that can handle the data rate. A link budget was performed to ensure a sufficient communication signal is established, shown in Table 2.17. The requirement for the power to noise ratio was 20 dB, which was met by choosing an antenna with 15 dB gain operating at 2.4 GHz as shown in Table 2.17

Table 2.16: Data rate of sensors from UAV and ground station

Type of Sensors	Bit Size (bit)	Frequency (Hz)	Data rate (bps)
UAV			
wind velocity	320	10	3200
wind temperature	64	10	640
gps	2176	10	21760
battery voltage	32	10	320
motor voltage	32	10	320
motor health (temperature)	32	10	320
range	32	10	320
speed	32	10	320
acceleration	32	10	320
IMU	258	10	2580
total per UAV			30100
total UAV			1,775,900
Ground Station			
number of UAVS parked	8	1	8
status (faulty or functioning)	8	1	8
battery levels	5824	1	5824
number of batteries	8	1	8
temperature (inside)	32	1	32
humidity (inside)	32	1	32
wind speed	32	1	32
temperature (outside)	32	1	32
level of precipitation	32	1	32
total per station			6008
total ground station			24,032

Table 2.17: Simplified link budget

Type	Values	Units
Frequency	2.4	GHz
Wavelength	8	m
Bandwidth	20	MHz
Data Rate b/s	1,799,932	bps
Transmitter Gain	15	dB
Receiver Gain	11	dB
Power to Noise Ratio	136	-
Power to Noise Ratio	21.32	dB

2.4.6. Power Consumption

The total power consumption can be determined by calculating the average UAV power consumption using values from Section 2.2.3 and the average ground station power consumption. This is shown in Table 2.18. The operational time for the UAV usage is computed from the wind speed data in Figure 6.4, where it is assumed that the UAV only operates in Region II (see Section 6.2.1). This gives the operational time for the UAV of 72.3%. The temperature control operational time is taken from the temperature data of the North Sea [23]. The temperature control have to keep the temperature above zero degrees Celsius, this gives the operational time of around 1%.

The energy consumption per year is then calculated from the power usage and the weighted operational time as percentage, and then average out to get the yearly average power consumption. This is optimized to be 16.8 kW, to fit within the power budget.

Table 2.18: system power consumption

Energy consumption			
Components	**Power [W]**	**Operational time %**	**Power [kWh/year]**
Antenna	50	100.00%	438
Control station	250	100.00%	2190
Battery swapping station	1800	72.30%	11400.264
UAV usage	19529	72.30%	123686.5309
Temperature control	2000	1.00%	175.2
Humidity control	1120	100.00%	9811.2
UAV	14119.467		123686.5309
Ground Station	2741.4		24014.664
Total System Power	16860.867		147701.1949

2.4.7. Tool verification

The calculations in this chapter are done in a spreadsheet. Allowing for the inputs to be changed easily. Following the Midterm report [1], an outline of tool verification will assist in verifying the calculations made. The tools relevant for this chapter are:

verif.tool.I.1 - Visual inspection/comparison of each formula between the written and Excel case

verif.tool.A.1 - Set all inputs to zero and analyze whether the output would respond as expected based on the written formula, repeat for a large input (≈10E10 times larger than nominal input)

verif.tool.A.2 - Derive relations from specific inputs to the output (linear, cubic etc.), then through manipulation of input values, it can be checked if these relations are retained in the Excel sheet

verif.tool.T.1 - Seven input variations shall be calculated by hand and compared to the output from the Excel sheet

Table 2.19: Table showing the results of the verification on Excel used for the ground station iterations process

ID	Power tool
verif.tool.I.1	✓
verif.tool.A.1	✓
verif.tool.A.2	✓
verif.tool.T.1	✓

3
Finalizing the system configuration

Following the design process discussed in Chapter 2, different system configurations resulted. This chapter serves to determine what configuration is to be continued with. Section 3.1 presents the different configuration options and compares them to each other and the project budgets. A sensitivity analysis is then performed in Section 3.2 to determine how sensitive the system is to the so called snowball effect, which can then be used in Section 3.3 to decide which system is to be continued with. Next, the system is verified by checking its compliance to requirements in Section 3.4. To conclude this chapter, the final configuration is validated in Section 3.5.

3.1. Comparing the configuration options

Following the iterative process, it quickly became evident that the estimations for the system budgets and delivered performance provided in the midterm report [1] were not fitting anymore. The provided power budget was too optimistic as well as the expected measurement temporal resolution. Following this conclusion, it was decided to execute three iteration cycles for the design: one where the system adhered to the system power budget from the baseline report [3], one where the system stayed within the cost estimate provided in the midterm report and finally one where both cost and power budgets were discarded such that the system would provide the same measurement performance as promised in the midterm report. Table 3.1 shows the system characteristics for the three iteration cycles, comparing them to the initial project budgets in the leftmost column and the midterm budgets in the second column. The colors of the cells show how each option compares to the project budget or the midterm estimates.

Table 3.1: Iteration cycle results compared with project budgets and midterm estimates

	Project budget [3]	**Midterm estimates** [1]	**Option 1** (initial power budget)	**Option 2** (midterm cost budget)	**Option 3** (midterm performance)
No. of drones (operational)	n/a	69	59	69	119
No. of ground systems	n/a	6	4	5	8
Total cost $[M€]$	€46M	€21.8M	€18.4M	€21.6M	€37.2M
Average power $[kW]$	17 kW	17.1 kW	16.9 kW	19.9 kW	33.7 kW
Spatial measurement resolution $[m]$	n/a	250 m	300 m	300 m	250 m
Temporal measurement resolution $[min]$	n/a	14 min	41 min	29 min	14 min

In Table 3.1, a few things stand out. For instance, one can see that for Option 3, to obtain the same measurement performance as initially expected, the number of UAVs is nearly twice as high. Note also the difference in temporal resolution for the midterm estimate and Option 1.

Both these differences can be explained by the same cause: the higher system power consumption than expected. This higher power consumption results in the UAVs having to fly slower to experience less aerodynamic drag and therefore waste less energy. This does however come at the cost of the lower temporal resolution and the higher number of operational UAVs than expected. Table 3.2 shows the difference in some (sub)system parameters between what was initially assumed in the midterm report and what resulted from the design process in Chapter 2.

Table 3.2: Final (sub)system characteristics compared to midterm estimate

Parameter	**Midterm estimate**	**Final estimate**	**Remarks**
UAV cruise speed [m/s]	27.8	16.0	UAV flies slower for higher efficiency.
UAV endurance [min]	30	99	Greater endurance due to lower flight speed.
No. of UAVs (total)	207	77	Battery swapping reduces no. of UAVs required.
UAV cost [€]	850	12150	Durable UAV significantly more expensive than estimated.
UAV lifetime	800 hours	2 years	UAV more durable than estimated.

To conclude the discussion in this section, Table 3.1 shows different options for the system layout, cost, power consumption and obtained measurement performance. The table shows therefore that the system is highly scalable. Section 3.2 analyzes this scalability further. Selecting the final configuration will be the topic of Section 3.3.

3.2. Sensitivity of system configurations

With the system configuration options explained in Section 3.1, the question arises on how sensitive to perturbations the design options are. For example, what is the effect of a changing UAV climb angle on overall system performance? Does the so called 'snowball effect' come into play, yielding possible high budget overruns? The purpose of this section is to analyze that sensitivity of system performance.

The sensitivity analysis is split up into three parts. First, sensitivity to uncertainty in UAV flight characteristics is analyzed. Secondly, sensitivity to ground system characteristics is checked. Lastly, the system's sensitivity to changing swarm parameters is given. In order to provide a fair comparison between the different sensitivities, the following sections use Option 1 from Table 3.1 as a basis.

3.2.1. Sensitivity to UAV flight characteristics

UAV cruise speed

Figure 3.1 shows the systems temporal resolution if the UAV cruise speed were to change. Note how the line looks very rough, this is due to the ground station positioning being optimised for a cruise speed of 16 $[m/s]$. As can be seen form Figure 3.1 the faster the drone flies the lower the temporal resolution becomes for a fixed spatial resolution and a fixed number of drones. The values for option 1 in Table 3.1 were taken for this graph.

This in turn would indicate that for the ideal system, the drones would fly as fast as possible. However this graph does not take into account the effect on the increased power consumption of the drone due to the increase in energy required to keep the drone at those speeds. With the help of Figure 3.2 it is clear to see that this power consumption quickly increases as cruise speed increases, this in turn reduces the endurance of the drone and the advantage gained from flying at faster speeds. Rather the opposite is shown and in fact flying at the lowest speed or the optimised endurance air speed would be the best for the temporal resolution as this reduced the required power for the drone allowing for more drones to be used for a given system, thus increasing temporal resolution. However, with how the drone is designed and the aerodynamics characteristics of the drone do not allow the drone to fly at its optimum endurance speed as it hits its stall speed before reaching the optimised speed. This thus indicates that the design team has to choose the most appropriate cruising speed for the drone depending on the deployment of the system.

In terms of sensitivity of the system characteristics to uncertainty in cruise speed, Figure 3.1 shows that the temporal resolution is volatile, but this volatility can be mitigated by optimizing the ground station positions for the different cruise speed configurations. The systems power consumption is also sensitive to UAV cruise speed, shown by the exponential curve in Figure 3.2.

However, based on the discussion in Section 3.1, it seems likely that any contingency in UAV cruise speed can be partially mitigated for in a later stage by adjusting the number of UAVs. For instance, if the UAV were for any reason required to fly faster, it would result in a higher system power consumption but also better temporal resolution. Decreasing the number of drones would mitigate this power consumption increase but come at the cost of also neutralizing the better temporal resolution. The reader is reminded that the current balance between UAV cruise speed and number of UAVs is optimized to provide the best temporal resolution for the lowest power consumption. Section 3.2.3 goes into more detail of the effect on changing UAV numbers on system characteristics.

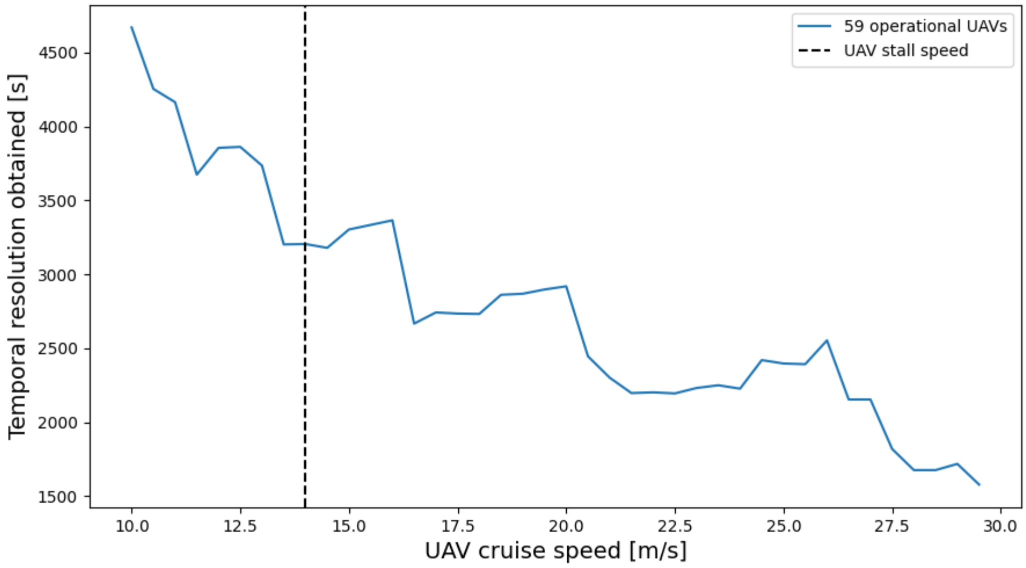


Figure 3.1: System temporal resolution for changing UAV cruise speed

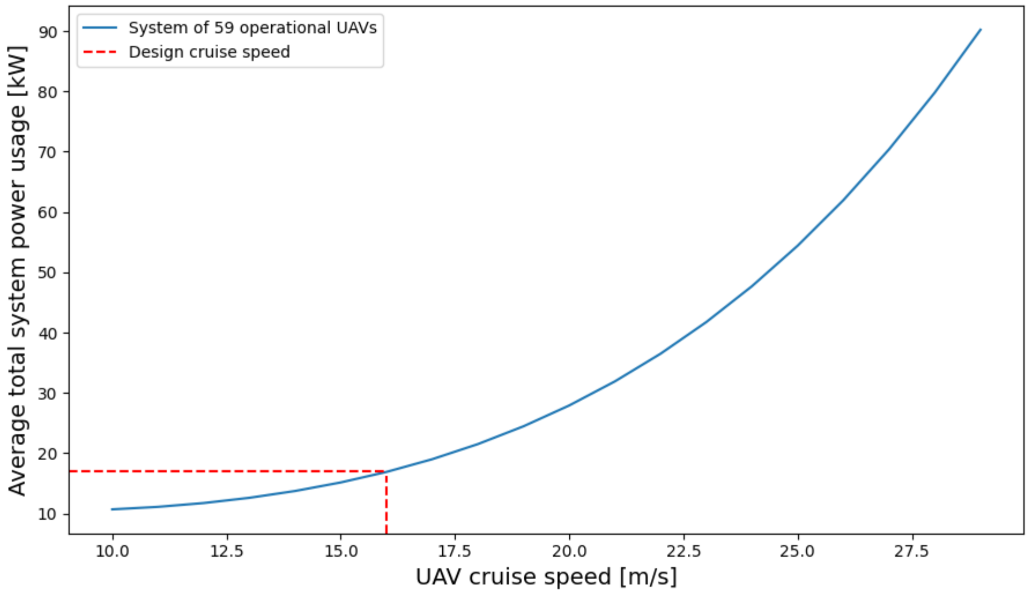


Figure 3.2: system power consumption for changing UAV cruise speed

UAV Power
Another large uncertainty is the UAV power consumption, with Figure 3.3 showing how the temporal resolution reacts to a change in the UAV power consumption. The red line represents the current method of determining the UAV power consumption using a maximum power approach. The green line represents a more average power approach where Figure 3.3 was used to calculate average UAV power consumption. The average power approach is seen as the more accurate measurement as it takes into account the flight time of the two flight modes. The kinks in the blue line are due to the number of UAVs changing with each kink representing a gain or loss of a UAV. The kinks get

larger as the power increases this is due to the impact of loosing a UAV at 20 UAVs has a much larger effect on the temporal resolution than loosing a drone at 70 UAVs.

As the line is a stair case shape this indicates that there is some lee way in the UAV power, allowing the UAV power to fluctuate a little whilst still holding the same number of drones and thus the same temporal resolution.

$$P = \frac{U \cdot C \cdot (EN - t_{VTOL}) \cdot 3600 + 2 \cdot W \cdot 30 \cdot t_{VTOL}}{EN^2} \tag{3.1}$$

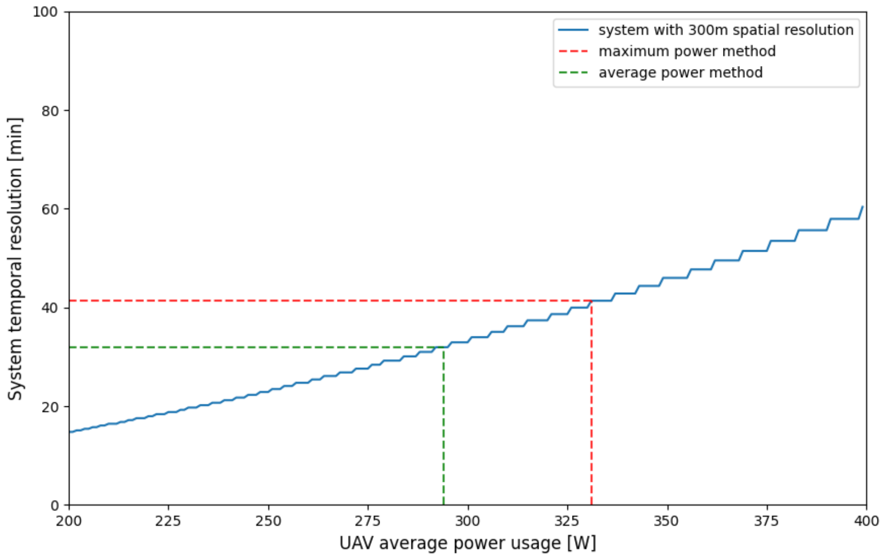


Figure 3.3: Graph showing how UAV power influences the system temporal resolution

Looking at Figure 3.3 it is clear that the lower the UAV power is, the better the temporal resolution. Assuming that the average power calculated in Equation 3.1 is more accurate, the temporal resolution drops to 32 minutes. This is a decrease of $22[\%]$ from the original temporal resolution.

3.2.2. Sensitivity to ground system parameters

First, the battery swapping time for each individual UAV effects the overall cost of the system, it is a useful measure as it allows the team to investigate what would happen if the battery was not swapped, but instead used fast charging technology or charged the UAV batteries normally. This is of course overlooking other aspects to have swap-able batteries such as difference in life span of the battery and the drone.

Figure 3.4 clearly shows that there is a benefit from decreasing the battery swapping time to as low as possible, this makes sense as the longer the battery swapping time, the more UAVs are needed to replace the one charging, meaning the cost of the whole system goes up. This is done to continuously provide full coverage of the wind farm and prevents dips in performance every time a drone has to swap one of its batteries. At the same time however, the figure also shows how the cost increase is relatively minimal. At no point would any uncertainty in swapping time lead to system cost budget overrun, as that budget is €47M (see Table 3.2).

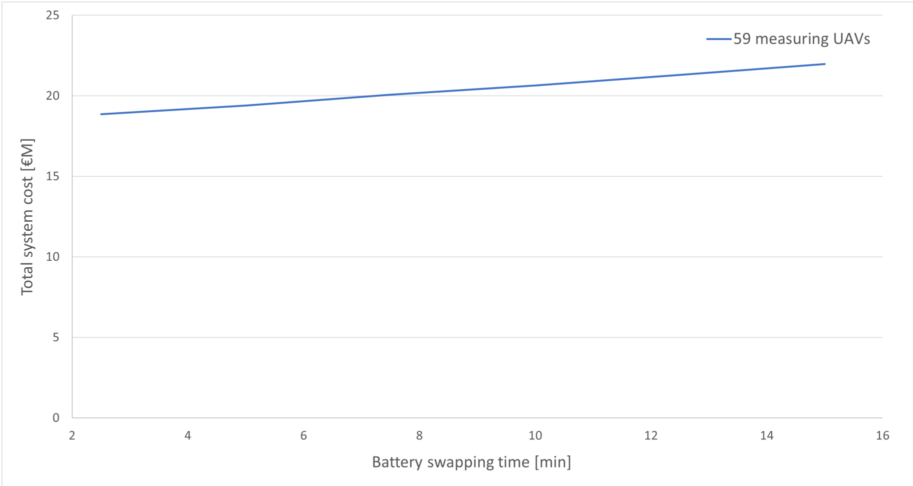


Figure 3.4: Graph showing the increase in total system cost with increasing battery swapping time

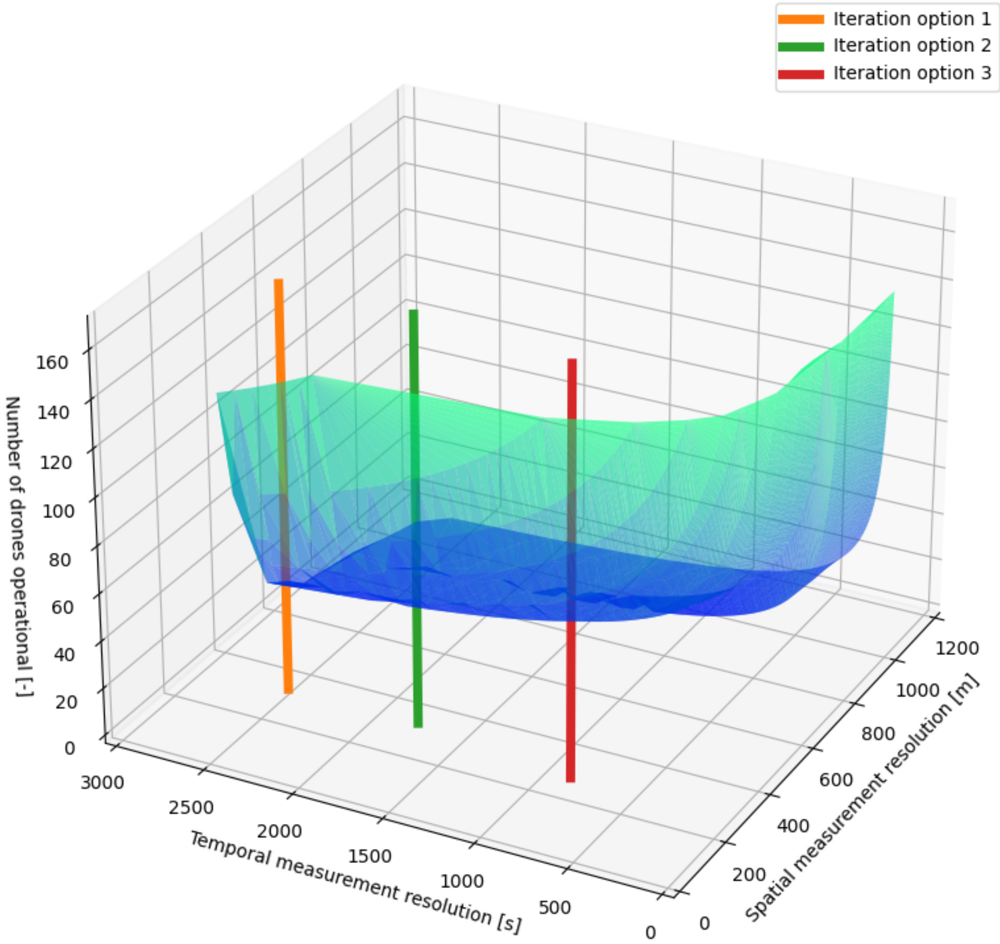
3.2.3. Sensitivity to swarm parameters

This subsection is designed to look into and analyse how sensitive the swarm parameters are to a change of inputs. To analyze the effects on the performance of the system from a change in the number of drones for a given area, Figure 3.5 is generated. Explaining Figure 3.5, it is clear to see its surface represented in 3D space, with the base representing both the spatial and temporal resolution, and the vertical axis representing the number of drones, also indicated by the axis titles. The three coloured bars represent the three different iteration options laid out in the 3D space, these options are more clearly seen in Table 3.1.

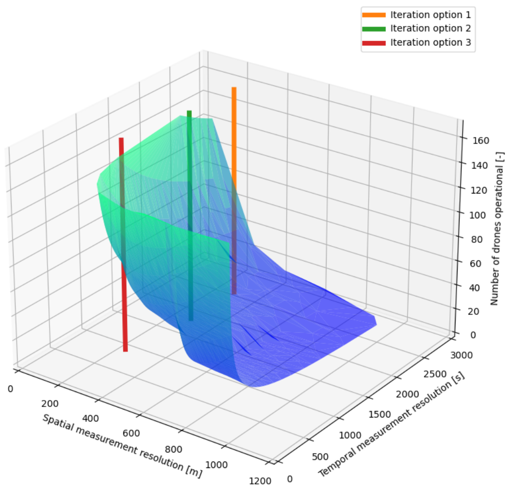
Looking at the 3D plot its clear to see that as the number of drones increases so does the spatial and temporal resolution of the system, keeping in mind that this is for both wind and temperature measurements. Its also very clear to see that the original requirements for spatial and temporal resolution for the wind speed measurements were not attainable. As for both the spatial and temporal resolutions when they tend to zero the number of drones required tends to infinity, meaning that the original requirements would of required an unfeasible number of drones. However, as the surface has a smooth and continuous shape with no gaps or discontinuities, it shows that the system is highly scalable to achieve the required measurement resolution. This is a considerable positive for the system, showing that it is both versatile and robust. As for example several drone failures will not cause the system to fail, but rather just lower the performance.

That being said, it must be noted that the number of UAVs required increases rapidly at some point. This implies that if very accurate or very fast measurements are required, the number of UAVs and with that the system cost and power consumption will escalate.

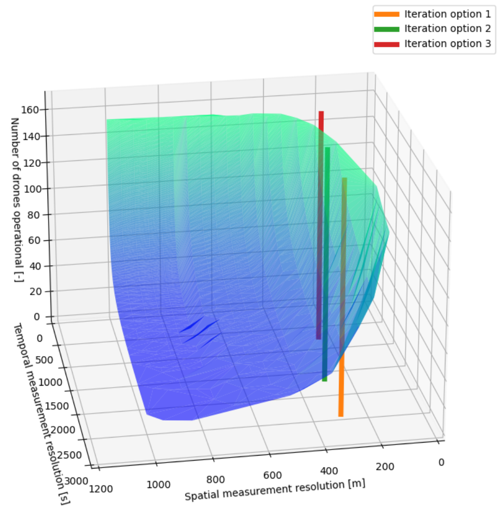
The steep slopes in the region of the iteration options also imply something else. It shows that some contingencies can greatly influence the measurement performance of the system. For example, if the battery degradation is greater than expected, that would result in less drones taking measurements after a certain period of time. Due to the steeper slopes, this would have a relatively large impact on the system's measurement performance. Therefore, the final measurement performance of the system is still quite uncertain as some parameters influencing the actual number of drones taking measurements are uncertain.



(a) Standard view



(b) Rotated view 1



(c) Rotated view 2

Figure 3.5: Swarm temporal resolution vs. spacial resolution vs. required no. of operational drones

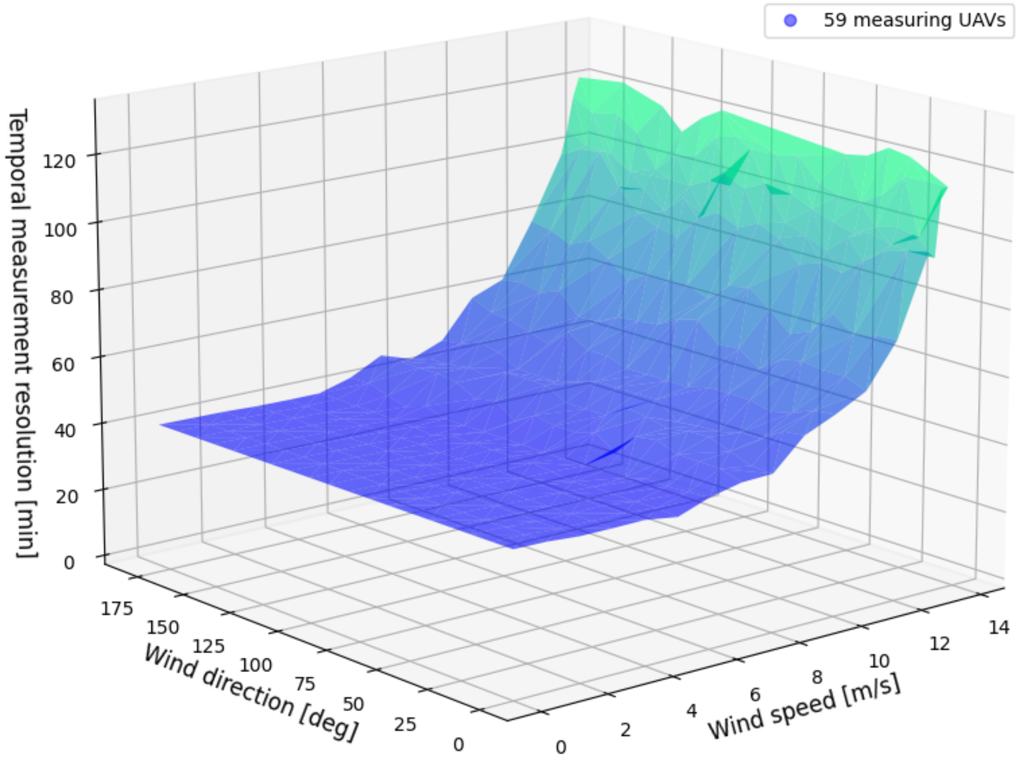


Figure 3.6: Effect of wind speed and direction in temporal measurement resolution

3.2.4. Sensitivity to wind

An important metric to investigate is the swarm's sensitivity to the wind blowing in the wind farm. As discussed in Section 2.2, the UAV has a wind resistance of 14 $[m/s]$. However, although the system will be operational during the required wind speeds, this does not necessarily mean that the system behaves as wished. What happens to the system's power consumption or temporal resolution for different wind speeds is the question at hand.

To answer this question, first the response strategy to the wind blowing in the farm must be determined. There is a choice to be made: either the system can decide to compensate for the wind by having the UAVs fly faster or the system can decide to not compensate for the UAV.

Compensating for the wind would entail having the UAVs fly at such airspeed such that the ground speed stays the same as if there would be no wind. The previously shown Figure 3.2 shows that the system power consumption would be heavily affected for increasing UAV airspeeds. Therefore, compensating for the wind would result in a higher system power consumption.

Not compensating for the wind would result in the UAVs flying at a slower ground speed as they need to adjust their heading to stay on the predefined path while keeping a constant airspeed. Figure 3.6 shows what this would mean for the system's temporal resolution. It shows that the wind speed has a significant greater effect on the system performance than the wind direction. This is explained by the zig-zag flight pattern, where the UAVs basically fly in every direction just as much, such that the wind speed influences the swarm more or less equally for different wind directions. The effect of wind speed shows that near the system's limit of flyable wind speeds of 14 $[m/s]$, the measurement temporal resolution is with 124 $[min]$ a factor 3.0 higher than if there would be no wind (where the temporal resolution would be 41 $[min]$.

Conclusion
Sensitivity analysis shows that in response to wind speed, system control should either allow higher power usage or accept worsened temporal resolution. Based on discussion on swarm characteristics, the worsened temporal resolution can also be compensated by accepting a worse spatial resolution. Depending on what would lead to most Region II control performance increase (this will be topic of Section 6.2), these different metrics have to be balanced.

The sensitivity analysis poses an extra contingency to the expected measurement performances to the options provided in Table 3.2. This depends on the average wind speed expected for the reference wind farm. Assuming the Weibull parameters used for the reference wind farm (this will be discussed in Section 6.2, the expected wind speed during Region II control is 8.76 m/s. Calculating the system measurement performance for this wind speed if no power increase was allowed, this would result in temporal measurement resolution of 47.9 minutes or an increase of 17% on average during Region II control.

However the effect of wind is not the only change to make to the temporal resolution, the change in power also has an effect as described in Section 3.2.1. Taking this 22% decrease into account, the new temporal resolution is 37.4 minutes (2242 $[s]$).

3.3. Selecting the final system configuration

The sensitivity analysis in Section 3.2 enables the selection of the best system configuration option presented in Section 3.1. Deciding which configuration is best fitting for the reference wind farm is necessary in order to verify system compliance to requirements as well as to quantify other metrics like marketability and sustainability in later stages of this report.

To perform this selection, the magnitude of any potential snowball effect must be estimated. Based on the discussion in Section 3.2, the system power consumption and measurement performance are the most susceptible to contingencies. For example, the system power consumption increases exponentially if the UAVs were to fly at different cruise speeds while the systems measurement performance also changes rapidly if the number of UAVs actively taking measurements somehow gets affected. This leads to the conclusion that in terms of system measurement performance and power consumption, the system is sensitive to any snowball effect and therefore that care must be taken to not overrun project budgets. The system cost however is less likely to escalate.

This conclusions hints at which option from Table 3.2 should be picked for the continuation of this report: it hints at picking the option were there is the most room for scaling up the system. Option 1 is the only option that stays within the project power budget and therefore this option is selected as best-fitting to the reference wind farm.

Although Option 1 is actually already at the power limit, such that one can argue that there is no room for scaling up, further findings show that for any wind farm the most optimal system configuration also depends on specific wind farm parameters. This will be the topic of Chapter 6. This reinforces the conclusion that the final system configuration is scalable and prone to change. But for the remainder of this report, Option 1 from Table 3.2 is used. That is, a system consisting of 59 operative UAVs in combination with four ground stations, costing €18.4 million in total and consuming 16.9 $[kW]$ electrical power on average. The provided measurement performance will likely be 300 $[m]$ spatial resolution and 41 minutes temporal resolution for the reference wind farm. In total 78 UAVs will be used, so 19 spare UAVs are available. Of the 59 drones, 3 to 4 drones will have their battery replaced or they will be in transit, while the others take measurements. Three of the four battery stations will be in use and one station is considered to be redundant. Another 16 UAV stations are implemented for the UAVs to shelter in case of bad weather, maintenance or long periods of low wind speeds. A summary of the system characteristics can be found in Table 3.3.

Table 3.3: Summary of UAV and system characteristics - values calculated for a 100 $[km^2]$ wind farm

UAV	DeltaQuad Pro
Wind sensor	Trisonica mini (from Anemoment)
Temperature sensor	FST600-202 4-20mA PT100 (from Hunan FirstRate)
Lifetime system cost	18.4M€
System power draw	16.9 $[kW]$
Spatial resolution	300 $[m]$
Temporal resolution	2242 $[s]$ (37.4 minutes)
UAV cruise speed	16 $[m/s]$
UAV charging time	5 minutes
UAV endurance in cruise	99 minutes
UAV area	2.115 $[m^2]$
No. of operational UAV	59
No. of total UAV	78
No. of charging stations	4
No. of UAV storage stations	16
No. of UAV in a storage	5
Batteries per UAV	9.4
Batteries stored per station	183
Batteries needed per 6 months	731
Battery swapping time	5 minutes
Battery charging time	6.6 hours
Battery capacity	33 $[Ah]$
UAV climb angle	10 [°]
UAV descent angle	10 [°]
UAV climb rate	2.2 $[m/s]$
UAV descent rate	2.2 $[m/s]$
UAV VTOL climb rate	1.5 $[m/s]$
UAV VTOL decent rate	0.6 $[m/s]$

3.4. System configuration verification

As outlined in the guideline for system verification outline in the Midterm report, [1], system verification comes from the evaluation of requirement compliance, as well as the approach to determine compliance. In the Midterm report, the approaches were divided into testing, analysis, demonstration and inspection. Subsequently, this section's aim is to analyze the requirements made in previous reports and evaluate whether they have been met or not. The section is thus layed out, firstly the general list of requirements are given with the indication of weather they have been met or not, as well how this is approached. This then leads into the explanation for any changes in the requirements or why some requirements have not been met. Lastly the section going into discarded requirements and why they have been discarded.

3.4.1. Requirements

With the requirements being made before the start of subsystem design and the finalization of the design many requirements have to be reworded or new ones added to properly constrain the design. Thus with Table 3.4, Table 3.5, Table 3.6, Table 3.7 and Table 3.8, a list of the updated requirements of the project are given. With Table 3.4 showing the mission requirements of the project, Table 3.5 and Table 3.6 shows the system requirements, Table 3.7 and Table 3.8 shows some of the newly added subsystem requirements. Each table has been colour coded to provide an overview on which of the requirements has been met and which have not, with the colour range going from green to yellow to red. With each of the colours representing: the project surpasses the requirements, the project just meets the requirements and the project does not meet the requirement, respectively. In the column named 'confirmation of requirement met', it is explained how or why the requirements are met. In the column next to that, the verification methods are specified. The requirements will either be verified through inspection, analysis, testing or demonstration. Whenever a plus sign (+) is shown behind the verification method, this verification will be done at a later stage.

Table 3.4: Table showing the mission requirements

Identifier	Requirement	Confirmation of requirement met	Verification & Validation Methods
Performance			
MR.perf.1	The system shall measure wind speed in a $100[km^2]$ area.	Incorporated into the swarm algorithm, Section 2.3.	Demonstration+
MR.perf.2	The system shall measure temperature in a $100[km^2]$ area.	Incorporated into the swarm algorithm, Section 2.3.	Demonstration+
MR.perf.3	The system shall measure wind speed to an altitude of $1[km]$.	Incorporated into the swarm algorithm, Section 2.3.	Demonstration+
MR.perf.4	The system shall measure temperature to an altitude of $1[km]$.	Incorporated into the swarm algorithm, Section 2.3.	Demonstration+
MR.perf.5	The system shall provide a spatial resolution of no lower than 1000 m for wind speed measurements.	Horizontal spatial resolution is $300[m]$.	Analysis
MR.perf.6	The system shall have a spatial resolution of $1[km]$ for temperature measurements.	Horizontal spatial resolution is $300[m]$.	Analysis
MR.perf.7	The system shall provide a spatial resolution for temperature measurements in blocks of: $10[m], 50[m], 100[m], 150[m], 250[m], 500[m], 750[m]$ in the vertical direction.	Incorporated into the swarm algorithm and is equal to requirement, Section 2.3.	Analysis
MR.perf.8	The system shall have a temporal resolution of no more than $1[hour]$ for wind speed.	Temporal resolution is $41.4[minutes]$.	Analysis
MR.perf.9	The system shall have a temporal resolution of no more than $1[hour]$ for temperature.	Temporal resolution is $41.4[minutes]$.	Analysis
Adaptability			
MR.adap.10	The system shall be adaptable to be applied on different existing wind farms.	As the ground stations can be put in any location, currently on the nacelles to lower initial installation costs, the system canbe deployed anywhere	Analysis
MR.adap.11	The system shall be applicable to both offshore and onshore wind farms.	The system also meets the onshore budget of €21.8 million, considering a LCOE of $65[€/MWh]$.	Analysis
MR.adap.12	The system shall be scalable to the size of the wind farm.	The number of UAVs/ground stations can be varied to allow for a scalable system	Analysis
MR.adap.13	The system shall be applied to fixed, horizontal axis turbines.	This was used as a consideration in the design of the ground station and swarm operations. In the future different kind of wind turbines can be included.	Analysis
MR.adap.15	The system shall have an IP rating of 54.	The current drone is estimated to have an IP44 rating. This will ensure the drone to be able to fly through precipitation, but the ingress of dust is not avoided completely. This is explained further in further explanations of requirements item 4.	Testing
MR.adap.16	The system shall be able to operate in region 2 of a wind farm.	The UAV is capable of flying upto a wind speed of $14[m/s]$, this is above the average rated wind speed for modern wind turbines, $11.7[m/s]$ Table 2.2	Testing (wind tunnel)
MR.adap.17	The system shall be able to operate in a salt water environment.	Outside of the IP-rating preventing this, the outside materials of the ground station and UAV are resistant to salt water corrosion.	Testing

Table 3.5: Table showing the system requirements

Identifier	Requirement	Confirmation of requirement met	Verification & Validation Methods
Reliability			
SR.rel.1	The system shall have a downtime no longer than 5% of the operation time in region 2 of the windfarm.	The drone is able to fly in the full region two based on a wind resistance of $14[m/s]$. With the improved IP rating due to coating explained in Section 2.2.2 it is able to fly in rainy conditions as well, however it can not withstand heavy rain, meaning it can not meet the $5[\%]$ in the Netherlands. This is further explained in item 3.	Analysis
SR.rel.2	The system shall be fully operative within $1[hour]$ after operational stop complete wind farm.	This is estimated to be $50[minuets]$, based on a maximum $7[minutes]$ travel time from ground station to measurement point at a height of $1[km]$ and a time of $40[minutes]$ to get most of the drones charged.	Demonstration
SR.rel.3	The system shall operate continuously for $25[years]$.	The budget for the system was given for a 25 year life span which also included regular maintenance to sustain the 25 year lifespan of the system.	Analysis
Autonomy			
SR.auto.3	The system shall operate completely autonomously, except when maintenance is required.	There is no human input into the swarm algorithm, meaning that the swarm runs fully autonomously. Maintenance is performed by humans.	Testing
Maintenance			
SR.maint.4	The system shall operate under minimal maintenance, once every 6 months.	This is incorporated in the number of backup drones, number of batteries and in the lifetime of the drone components.	Analysis (Testing+)
SR.maint.5	The system shall survive temperatures between -30 and $40[°C]$.	The UAV can survive -20 to $45[°C]$, with the ground station being heated for a $-20[°C]$ situation.	Testing
SR.maint.6	The system shall survive a category 2 storm.	The ground station is designed to be weather resistant, meaning it can withstand wind gusts up to $162[km/h]$, heavy downpours and lightning strikes	Analysis
Safety			
SR.safe.8	Each drone shall keep a distance of at least $50[m]$ from wild life.	There is no current wild life or specifically bird detection system incorporated. This is something to be considered in the future.	Analysis (Demonstration+)
SR.safe.9	Each drone shall keep a distance of at least $100[m]$ from a turbine under maintenance.	This is incorporated into the obstacle avoidance algorithm, Section 2.3.4.	Analysis (Demonstration+)
SR.safe.10	Each drone shall keep a distance of at least $50[m]$ from an operational turbine.	This is incorporated into the obstacle avoidance algorithm, Section 2.3.4.	Analysis (Demonstration+)
SR.safe.11	Each drone shall keep a distance of at least $50[m]$ from an identified moving vessel on water.	This is incorporated into the obstacle avoidance algorithm, Section 2.3.4.	Analysis (Demonstration+)
SR.safe.12	Each drone shall keep a distance of at least $20[m]$ from another drone.	This is incorporated into the obstacle avoidance algorithm, Section 2.3.4.	Analysis (Demonstration+)
SR.safe.13	Each drone shall keep a distance of at least $50[m]$ from aircraft or helicopters.	This is incorporated into the obstacle avoidance algorithm, Section 2.3.4.	Analysis (Demonstration+)

Table 3.6: Table showing the system requirements

Identifier	Requirement	Confirmation of requirement met	Verification & Validation Methods
Legal			
SR.legal.8	The system shall adhere to the MSFD (Marine Strategy Framework Directive) for offshore wind farms.	The systems adheres to the MSFD guidelines, this is proven in item 4	Inspection
Sustainability			
SR.sust.10	The UAV shall not produce any CO2 emissions during operation.	The UAV is completely electric and does not use carbon based fuel meaning it does not release CO2.	Demonstrate
SR.sust.11	The batteries shall be fullly recyclable.	Batteries are not fully recyclable yet, but if this is achieved the sustainability would increase a huge amount for the whole project.	
SR.sust.13	The system shall be delivered with a manual for troubleshooting and easy maintenance.	There is already a user manual for the UAV from the manufacturer, [4].	Inspection
SR.sust.14	All components of the system shall be replaceable.	The UAV is already capable of having its parts replaced due to the recommendations on maintenance from the manufacturer. The larger components of the ground station can also be replaced.	Demonstration
SR.sust.15	At a distance of $1[km]$ the system shall not produce more than $45[dB]$ of noise.	5 drones taking off and landing at the same time create a noise of $41.9[dB]$ at a $1[km]$ distance.	Testing
SR.sust.16	The system shall not provide any emissions to water through heavy metals or organic pollutants.	This should never happen due to the several counter measures set in place to make sure a drone does not run out of batteries, meaning that for a drone to fall into water it must have had a catastrophic failure. If this happens measure are set in place explained in Section 5.2.4	Testing
SR.sust.17	The system shall abide by the regulations for the use of substances classified as hazardous to health and/or the environment according to Council Directive 67/548/EEC of 27 June 1967.	The project will adhere to the regulations, with guidelines being developed before the manufacture and sale of the first system to ensure the safety of both the client as well as the maintenance and manufacturing. This is further explained in item 4	Inspection
Power			
SR.pwr.18	The system shall not consume more power than $0.01[\%]$ of the wind farm*.	The system uses $16.9[kW]$, with $0.01[\%]$ of wind farm power being equal to $17[kW]$ for the reference wind farm.	Analysis
Cost			
SR.cost.20	The system shall not increase the levelised cost of the wind farm by $1[\%]$	The actual cost of the system is calculated to be €18,407,324.73 with a budget of €47 million, for the reference wind farm.	Analysis
Size			
SR.size.21	The rotor of the drone shall not have a diameter larger than $1[m]$.	The rotor diameter for the propellers is estimated to be about $0.30[m]$. Based on pictures and sizes given of the structure by Vertical Technologies.	Inspection
SR.size.22	The planform area of the drone shall have a maximum area of $5[m^2]$	The drone only takes an area of $2.115[m^2]$ of space.	Inspection

Table 3.7: Table showing the subsystem requirements

Identifier	**Requirement**	**Confirmation of requirement met**	**Verification & Validation Methods**
Reliability			
SR.rel.1.SUB.1	The maintenance of the each drone shall take maximum $3[\%]$ of its lifetime.	This would allocate 20 days of maintenance for each drone every 2 years, resulting in a week of maintenance per maintenance cycle.	Analysis(testing+)
SR.rel.1.SUB.2	The charging of each drone shall take at max $75[\%]$ of its lifetime.	Due to the battery swapping system the charging time for each drone is only $5[\%]$ of its lifetime.	Testing
SR.rel.1.SUB.3	The swarm shall have a minimum number of 10 backup drones for a drone lifetime of 2 years	The current system has 15 drones as backup.	Inspection
SR.rel.2.SUB.1	The drone shall have an end of life procedure.	The system is designed with an end of life procedure as well as having an allocated budget. This procedure is described in Section 7.2	Inspection
Autonomy			
SR.auto.3.SUB.1	The drone shall be stable in all feasible flight conditions.	This is assumed to be true, because the drone is bought off the shelf.	Analysis (Testing+)
SR.auto.3.SUB.2	The drone shall be able to respond to its own telemetry data.	This is assumed to be true, because the drone is bought off the shelf.	Analysis (Testing+)
SR.auto.3.SUB.3	The drone shall know its own location with an accuracy of at least $1[m]$.	This is possible with a GPS system on-board. In the future better location data could be acquired using LiDARs and SLAM.	Demonstration
SR.auto.3.SUB.4	The drones shall be able to transmit and receive telemetry data.	This is seen in the Figure 4.10, as the drone is capable of both receiving data as well as sending it.	Testing
Sustainability			
SR.sust.10.SUB.1	The system shall use rechargeable, high-performing batteries, safe-to-use along their entire cycle.	The system uses LiPo batteries which are rechargeable, high performance and relatively safe to use.	Inspection
SR.sust.11.SUB.1	The disassembly of the system shall not cost more than 1 million euros.	The budgeted EOL cost of the system is €144,540.	Analysis
SR.sust.10.SUB.2	In maintenance mode, the drone shall retain 50% capacity in the battery.	This is guaranteed by charging the drone, if necessary, before going into maintenance mode in the shelter container. This can be seen in Section 2.4	Demonstration

Table 3.8: Table showing the subsystem requirements

Identifier	Requirement	Confirmation of requirement met	Verification & Validation Methods
Power			
SR.pwr.18. SUB.1	The drone shall have $10[\%]$ of power remaining before charging.	This is incorporated into the swarm algorithm.	Testing
SR.pwr.18.SUB.2	The battery shall be rechargeable for 200 cycles.	The drones batteries are swapped once they reach $70[\%]$ capacity which is estimated to take 225 cycles for LiPo batteries, [4].	Testing
SR.pwr.18.SUB.4	The drone shall have an endurance of $60[minutes]$ with a full battery.	The drone has an endurance of $99[minutes]$ as calculated by the UAV department	Testing
SR.pwr.18.SUB.5	The UAV shall not use more than 330 W of power when flying at 16 m/s.	The UAV uses an average of 294 W when flying at a 16 m/s cruise speed. This includes maneuvres, and take-off and landing.	Demonstration
Mass			
SR.mass.19.SUB.1	The drone shall have a mass no larger than $25[kg]$.	The total mass of the drone is $6.2[kg]$.	Inspection
SR.mass.19.SUB.2	The payload shall have a mass no larger than $400[g]$.	The combined mass of the sensors in $150[g]$, plus any mass required to mount and run the sensors, so the full $400[g]$ is used.	Inspection
SR.mass.19.SUB.3	The support facility shall have a mass no larger than $9.2 \cdot 10^3[kg]$.	The station is based on a shipping container which weighs $2[tons]$, it is estimated that this weight will not increase more than 4 times over.	Inspection
Computing			
SR.comp.22.SUB.1	Signal to noise ratio should be larger than $20[dB]$.	The signal to noise ratio is calculated to be $21[dB]$, more information on this is given in Section 2.4.5	Demonstration
Cost			
SR.cost.20.SUB.1	The base UAV shall cost no more than €10000.	The cost of the UAV is €9,999.	Inspection
SR.cost.20.SUB.2	The measurement sensors, anemometer and temperature sensor should cost no more than €1500.	The cost o the anemometer and temperature sensor combined is €1476.	Inspection
UAV			
SUB.UAV.1	The minimum cruise speed of the UAV shall be $14[m/s]$.	The UAV has a cruise speed of $16[m/s]$.	Demonstration
SUB.UAV.2	The drone shall have a minimum $10[deg/s]$ turn rate.	The drone has a turn rate of $1.1[rads/s]$ which is equivalent to more than $60[deg/s]$	Demonstration
SUB.UAV.3	The drone shall have a swappable battery.	The drone has swappable batteries.	Demonstration
SUB.UAV.4	The drone shall climb at a maximum $10°$ flight path angle	A $10°$ climb angle is a limitation of the UAV given by the manufacturer	Demonstration
SUB.UAV.5	The drone shall descend at a maximum $10°$ flight path angle	A $10°$ descend angle is a limitation of the UAV set upon by the manufacturer	Demonstration
SUB.UAV.6	The measurement accuracy of the anemometer shall be at least $1[m/s]$.	The measurement accuracy of the sensor is $0.1[m/s]$ to $1[m/s]$ depending on the wind speed	Testing
SUB.UAV.7	The measurement accuracy of the temperature sensor shall be at least $1[°C]$.	The measurement accuracy of the sensor is $0.1[\%]$ of the actual temperature, this is more accurate than the required $1[°C]$ accuracy, at any temperature bellow $100[°C]$.	Testing
SUB.UAV.8	Horizontal components of wind direction shall be covered in $360°$.	The wind speed sensor can measure in $360°$ horizontally with a $15°$ in the vertical as well.	Testing
Swarm			
SUB.SWM.1	The drone shall spend $10[\%]$ of its endurance in transit to measurement starting point	This is incorporated into the algorithm, Section 2.3.	Demonstration
SUB.SWM.2	The drone shall spend $10[\%]$ of its endurance in transit from measurement end point	This is incorporated into the algorithm, Section 2.3.	Demonstration

3.4.2. Explanation on the requirements

With each of the requirements having been listed in tables 3.4-3.8, there are some that have been completed or reworded from the previous report [3], the reasoning for this update is elaborated on in item 1. Moreover, the TBD values have been given numbers, in comparison to the previous report. Then there is a section on any new requirements that came out of the subsystem design process, indicated by item 2. The second part of the list refers to the reasoning behind why some of the requirements have not been met, this is seen in item 3. Other further statements or explanation on the requirements can be seen in item 4.

1. **Updated Requirements**

MR.pref.5 - This was changed as the original requirement was deemed as a killer requirement and thus had to be modified. After a discussion with the client it was agreed upon to increase this requirement to $1000[m]$.

MR.pref.8 - This again was deemed as a killer requirement and had to be changed, after a discussion with the client it was agreed upon to change the requirement to have a maximum temporal resolution of $1[hour]$.

MR.pref.9 - This requirement was again changed due to a very similar reason to MR.pref.8 again extending it to $1[hour]$.

MR.adap.16 - This requirement was reworded so that it better fits the needs of the customer, with the client indicating that the region 2 of a wind farm is of the most importance to the system.

MR.adap.17 - This was changed from corrosive to salt water environment, such to exclude any acidic or basic environments. As a highly acidic or basic environment is not the typical environment for a wind farm.

SR.auto.3 - Here the "except for maintenance" was added to allow for the manual maintenance of the drones. As the manual maintenance allows for a drastic reduction in maintenance and R&D cost.

SR.cost.20 - This was again seen as a killer requirements in the midterm report, and thus after a discussion with the client it was agreed upon to increase the LCOE from 0.1 to $1[\%]$.

2. **New Requirements**

SR.size.22 - This is based on the area of the nacelle, which is $36[m^2]$.

SR.comp.22.SUB.1 - A signal to noise ratio (SNR) of 20 dB or larger is recommended for data networks and is important to consider for the communication system.

SR.pwr.18.SUB.5 - This requirement is there to specify a limitation the power demand of the drone of the system.

SR.cost.20.SUB.1 - This requirement is based on the cost budget, as seen in Section 6.1, and is required to make a UAV choice. This cost is purely the UAV without the cost of the battery, spare parts or other add-ons.

SR.cost.20.SUB.2 - This requirement is based on the cost budget, as seen in Section 6.1 and is required for the sensor choice. This includes the cost of both the anemometer and the temperature sensor.

SUB.UAV.1 - This was based on the fact that the drone has to fly at a faster speed than its max wind speed resistance.

SUB.UAV.2 - This was required for the swarm department to allow for a more realistic model of the drone path.

SUB.UAV.3 - This requirement is supplied by the ground station department, a swappable battery is required for a battery swapping system.

SUB.UAV.4 - This was needed as a constraint for the swarm design, to ensure that the drone does not try unfeasible maneuvers.

SUB.UAV.5 - Again this was needed as a constraint for the swarm design, to ensure that the drone does not try unfeasible maneuvers.

SUB.UAV.6 - This was needed to more constrain the measurement sensor, and after discussion with the client the value of $1[m/s]$ for wind speed was determined.

SUB.UAV.7 - This was needed to constrain the temperature sensor more, and after discussion with the client the value of $1[°C]$ for temperature was chosen.

SUB.UAV.8 - This again was a limitation set on the sensors, and again after some discussion with the client a value of $360°$ in the horizontal plain was needed.

SUB.SWM.1 - This requirement was made to ensure that the drone does not spend all its time to fly to the start of the measurement area.

SUB.SWM.2 - This requirement was made to ensure that the drone has enough battery power left to return to the ground station safely.

3. **Unmet Requirements**

MR.adap.15 - With the UAV that has been chosen this requirement is not met. With the coated UAV having an estimated IP rating of IP44. Meaning that the drone is not completely protected against ingress.

SR.sust.11 - Right now a battery is not fully recyclable, meaning that it does not meet the requirement. More information can be seen in Section 5.2.1. This requirement was specifically added, because it is important to focus on the recyclability of the batteries, although as of now this is not possible. Recommendations on how this can be improved upon are given in Section 7.3.1.

SR.safe.8 - The drone is not capable of sensing objects around it, as its obstacle avoidance algorithm purely relies on given information about where obstacles are. Due to wildlife such as birds not sending out their location to the system the system can not detect them and is incapable of avoiding them.

SR.rel.1 - The drone does not meet this requirement because for a wind farm in the Netherlands it was found that the number of extremely wet days would be between 23 and 29 days per year. [24] Extremely wet days are identified as days with a precipitation sum of $10[mm]$ or more. This would result in a downtime due to heavy rain of a maximum of $8[\%]$ of the operational lifetime. The drone is able to operate throughout the complete region 2 in terms of wind speeds, however.

4. **Further explanation of Requirements**

MR.adap.16 - With the requirement stating region 2, with this region changing from wind farm to wind farm. This means that the certain drone and wind farm combinations may not be suitable

MR.adap.17 - The steel housing of the ground station is painted and therefore resistant to salt water corrosion. The EPO foam of the UAV is coated with a thin foil which makes it salt water resistant. The carbon fibre propellers will degrade due to the salt water environment, but since they are replaced every year this is accepted. Besides the effects on the mechanical properties of carbon fibre composites is limited, according to [25]

SR.rel.2 - The $7minutes$ for travel time is based on flying from a $90[m]$ high nacelle to the maximum $1[km]$ measuring height with a climb rate of $2.2[m/s]$. There are 59 drones of which about half would need to charge at four different stations, all taking 5 minutes to charge. Only half need charging, because the UAVs are required to have at least 50 % capacity before they move to the shelter station. With taking into account a degrading in capacity while the UAVs are stationed, about 30 UAV are assumed to require immediate charging after sheltering. This will take a total of 40 $[minutes]$ to charge half of the operational drones. Moreover, the spare UAVs could also be used to decrease the time it takes to be fully operative after an operational stop. This results in a total time of 47 $[minutes]$. This is a simplifying assumption and could also be larger. This is something to be investigated further.

SR.rel.3 - The maintenance of the UAVs are done every 6 months to keep the system operating, with the enough budget to replace and maintain the system for 25 years. The system has several extra UAVs in the system in case of a loss of a drone, these can be used to replace the UAVs that need to be maintained, during their maintenance cycle.

SR.maint.5 - These temperature values are based on weather extremes in the Netherlands. They are based on the coldest and hottest day measured, since 1901. [26] and [27].

SR.maint.6 - This storm category is based on the highest wind gust ever measured in the Netherlands since 1910, being equal to $162[km/h]$, according to [28]. This is equal to a category two storm, as show in [29].

SR.legal.8 - The guidelines in the Marine Strategy Frame-work Directive are designed to protect and support the coastal and ocean environments around EU member nations. The system will have no negative effects to the ocean as there is ideally no interaction between the two.

SR.sust.14 - The UAV is capable of being dismantled for easier transport as well as having easy assess to the individual components of the UAV due to its design, both of these allow the drones parts to be easily replaceable. The ground station can be designed in the same way to allow for replacements of its parts, this is also further discussed in Section 7.2

SR.sust.15 - With drones being at their loudest when they are landing or taking of in their VTOL flight mode, as 5 drones taking of or landing is the most the system is designed to handle this situation was chosen to evaluate the noise level to the surroundings.

SR.sust.17 - The regulations regarding the Council Directive 67/548/EEC of 27 June 1967 refer to the safe and secure operations of the systems as a whole. This included how to deal with hazards materials to the work cloths required.

SR.rel.1.SUB.1 - This is the maintenance time for each of the drones in the system, meaning that each of the drones has a total of 20 days of maintenance over the 2 years. This allows for the drone to be completely rebuilt from replacement parts as well as allowing for the quality assurance and calibration of the drone.

SR.pwr.18.SUB.1 - The $17[kW]$ comes from $0.01[\%]$ power out put of the reference wind farm meaning that for differently sized or equipped wind farms the system may have to be scaled up or down depending on the power available from that wind farm.

3.4.3. Discarded requirements

With the changing of the design of the project it is clear that some of the requirements made at the start of the project are no longer relevant to the project and should be removed. Thus here the reasoning for each of the discarded requirements are given in the list below, with all the discarded requirements given in Table 3.9.

Table 3.9: Table showing all the discarded requirements

Deleted requirements:	
Mass	
SR.mass.19	The system shall not have a mass larger than <tbd>kg.
MR.adap.18	The system shall be able to operate with a visibility up to <tbd>m.
SR.comp.22.SUB.2	The sytstem shall be able to correct <tbd>% of errors in data.
Maintenance	
SR.maint.4.SUB.1	The battery shall have a <tbd>discharge rate.
SR.safe.8	The chance of collision with wild life shall be <tbd>%.
SR.safe.9	The chance of collision with people shall be <tbd>%.
SR.safe.10	The chance of collision with wind turbines shall be <tbd>%.
SR.safe.11	The chance of collision with boats shall be <tbd>%.
SR.safe.12	The chance of collision with other drones shall be <tbd>%>
Legal	
SR.pwr.18.SUB.3	The swarm shall use a maximum of <tbd>% of its endurance (time) for maneuvres which do not contribute directly to data acquisition.
SR.legal.6	The system shall comply with legal regulations.
SR.legal.7	The system shall be able to receive permission to operate from the NAA (National Aviation Authority).
SR.sust.9	The system shall limit the scope 2 CO2 emissions by <tbd>kg.
SR.comp.22	The system shall provide <tbd>computing power for all operations.
MR.adap.14	The system shall be able to operate in different environments.

SR.mass.19 - This requirement has been split up into two separate requirements for the ground station and the UAV, meaning its not necessary.

MR.adpt.18 - As there are no longer any visual sensors on the UAV such as lasers or cameras the visibility of the surroundings no longer impact the UAVs performance.

SR.comp.22.SUB.2 - The system will make errors that have to be corrected for later. Removing allows errors to be made but have to be corrected later on.

SR.maint.4.SUB.1 - The battery discharge rate is highly dependent on the chosen drone and its current flight configuration meaning that this is a bad requirement.

SR.safe.8 - This has been replaced by a different requirement, requiring the drone to keep distance from the object.

SR.safe.9 - This has been replaced by a different requirement, requiring the drone to keep distance $100[m]$ from the people on turbines.

SR.safe.10 - This has been replaced by a different requirement, requiring the drone to keep distance $50[m]$ from the Wind turbine.

SR.safe.11 - This has been replaced by a different requirement, requiring the drone to keep $50[m]$ distance from the boat.

SR.safe.12 - This has been replaced by a different requirement, requiring the drone to keep $50[m]$ distance from the another UAV.

SR.pwr.18.SUB.3 - This has been replaced with more detailed requirements.

SR.legal.6 - This requirement has been removed as it was discussed with the client, and from that discussion it was decided that any legal obstructions would be the responsibility of the client.

SR.legal.7 - The same holds for this requirement as for SR.legal.6.

SR.sust.9 - The requirement did not meet the SMART criteria for requirements, meaning that it was replaced by a more verifiable requirement.

SR.comp.22 - This requirement is very hard to verify and has been removed due to the fact that it can not be calculated at this stage.

MR.adap.14 - This requirement has been seen as too vague and was thus removed and replaced with more precise requirement.

3.5. System configuration validation

Validation of the design on a system and sub system level needs to be completed before the product can be delivered. Due to the lack of available data for a wind measuring drone swarm system, validation on the system level is more limited. If available, a validated simulation program can be used to simulate the operation. It seems however more than likely that test flights on a smaller scale will have to be conducted to gain insights on the working of the system.

Validation on the sub system level can be done more easily. There are several sub systems that can be validated through software, simulations, and testing, testing can in most cases be completed easily and inexpensively. For each department, different validation steps are stated with an elaboration on how they are conducted.

The validation processes can be divided into four different techniques. All these four techniques can be applied on both system and subsystem level but in this validation process the first two techniques are used for system level testing and the latter two are more used for subsystem level validation. A short description of the four validation techniques:

- **End-to-end information system testing** - There is data sent from subsystem through subsystem on a whole system level. This data stream needs to be sanitised checked on a system level to see if the data is processed correctly on all subsystem levels.
- **Operations readiness tests** - A simulation or test where the system in its whole is tested. This is essential to demonstrate the proper link and coherence between all the different subsystems. It is important to see if all the different departments can work and connect well with each other. This should be at first simulated but later on this should also be validated with testing with early prototyping.
- **Mission scenario tests** - The testing or simulation of actual small scale missions is essential to prove that all the different parts of a mission can be combined with each other flawlessly.
- **Stress-testing and simulation** - Simulations or tests in which subsystems in which the more extreme conditions than normal are applied to the the system and see if each subsystem is able to cope with this.

3.5.1. UAV department

The UAV will be built almost entirely out of of the shelf components. For the UAV department a prototype can be made rather easily to validate estimated parameters easily.

- Range - This will be tested by letting the prototype fly under the specified flight parameters for maximal range to validate the maximal range.
- Endurance - the same validation procedure as for the range but now with maximal endurance flight parameters will be used to validate the endurance.
- Final UAV weight - This is validated by measuring the prototype of the UAV with the sensor integrated in the UAV.

- UAV Power consumption - Via a test setup the power consumption of the UAV can be measured during different stages of flight and flying conditions.
- Payload power consumption - See procedure for UAV power consumption.
- Sensor integration - Since the sensor integration is completely custom made, the proper working of the sensors has to be validated by testing the UAV in controlled wind tunnel labs.
- Sensor data - The data the sensor provides needs to be validated to see if its processed good by other subsystems.
- UAV payload integration stress - The standard UAV is already validated by the manufacturer, but the additional structure to implement the sensors needs to be validated during stress tests.
- Extreme flying conditions - The UAV should be tested if it is able to fly under non normal flight conditions such as wind turbine wakes.

3.5.2. Swarm department

For the swarm department, a lot of things that requires validation needs testing. This is because they are mostly related to the use of unvalidated programs and assumptions with no real world data that is relevant to the system.

- Flight planning - a simulation environment needs to be designed or existing software can be used to validate and test the motion and flight planning of the swarm.
- Collision avoidance - The program written for collision avoidance implemented on the UAV needs to be tested to proof it's validity. A simple test using one UAV implemented with the collision avoidance program flying to avoid fixed obstacles is to be carried out.
- Flight path fly-ability - The flight path that is to be implemented on the UAV needs to be tested to validate that the UAV is technically able to fly according to the planned route. A test using one flying UAV is to be carried out.
- Reconnecting ability - The scenario where a UAV gets disconnected or gets diverted off the flight path is to be tested. This will validate the ability for the UAV to return to its flight path and to reconnect with the system. A test using one UAV getting diverted off path is to be tested.
- Temporal resolution - The temporal resolution of the physical system needs to be validated to check for any discrepancy against the calculated temporal resolution. A test using one UAV flying a complete smaller demonstration path is to be tested.
- Position accuracy - The position accuracy of the UAV can be tested by measuring the physical distance and compare with the UAV GNSS distance.
- Turbine collision offset distance - The offset distance can be validated by measuring the physical distance between the UAV and the obstacle while the UAV fly pass it.

3.5.3. Ground department

Different components in the ground system can be tested or measured to ensure its validity during operation.

- Battery swapping system - The swapping time of battery is to be tested. This is to validate that the battery station is able to complete the battery swapping process in time before a new UAV arrives to get the battery change.
- Battery charging time - The charging time of the battery can be measured to validate the system ability to charge the battery on time and have enough full battery for the operation.
- Fire resistance - The fire resistance capability of the housing is to be tested. This can be carried out by placing batteries inside the housing and create a fire inside.

- Temperature and humidity control - The temperature and humidity control system is to be tested to validate its ability to maintain the temperature and humidity inside the housing. This can be done by heating or cooling the housing to a specific temperature then measure the temperature and humidity inside the housing.
- Redirecting UAV - In the event the battery swapping station is malfunctioning, its ability to redirect the UAV to another station is to be tested. This can be done through a simple test.
- Communication - The communication is an important part of ground operations. Its ability to maintain a good communication at all times is to be tested. The testing of signal strength when there is interference is to be done as well as its ability to switch to a back up communication channel when the signal strength is too low.
- Data processing and storage - A test is to be done to validate the system ability to process and store all the data.

4 System visualization

With the final system configuration now defined and all subsystems designed, this chapter serves to explain visually what the system looks like, how it operates, what component the system consists of, how these components work and how these components communicate with each other. First, Section 4.1 provides 3D renders of the system to show what each subsystem looks like. Then, in Section 4.2 different diagrams are presented to provide insights in the aforementioned topics.

4.1. Visualization with renders

With this section the intention is to give a general overview of the entire system with the help of renders made from CAD models designed in Fusion 360. Starting the overview with the two types of ground stations, with the first being the battery swapping ground stations with as the name suggests is there to exchange the used battery in a drone with a fully charged one, this is seen by Figure 4.1. The second is the drone storage ground station and again as the name suggest this is where the drones would come to shelter in non operational conditions such as high winds or severer rain/snow, visualized again by Figure 4.2. Both of these ground stations are placed on top of the wind turbine nacelles this can also bee seen in the renders with Figure 4.3 showing how the ground stations are placed very nicely. If the weather conditions are good the drones will leave the ground stations and start going into the zig zag patterns and start to take wind speed and temperature measurements, this is best illustrated by Figure 4.4. Figure 4.5 shows another angle of the drone flying in and around the system, with Figure 4.6 showing a more detailed and close up shot of the drone.

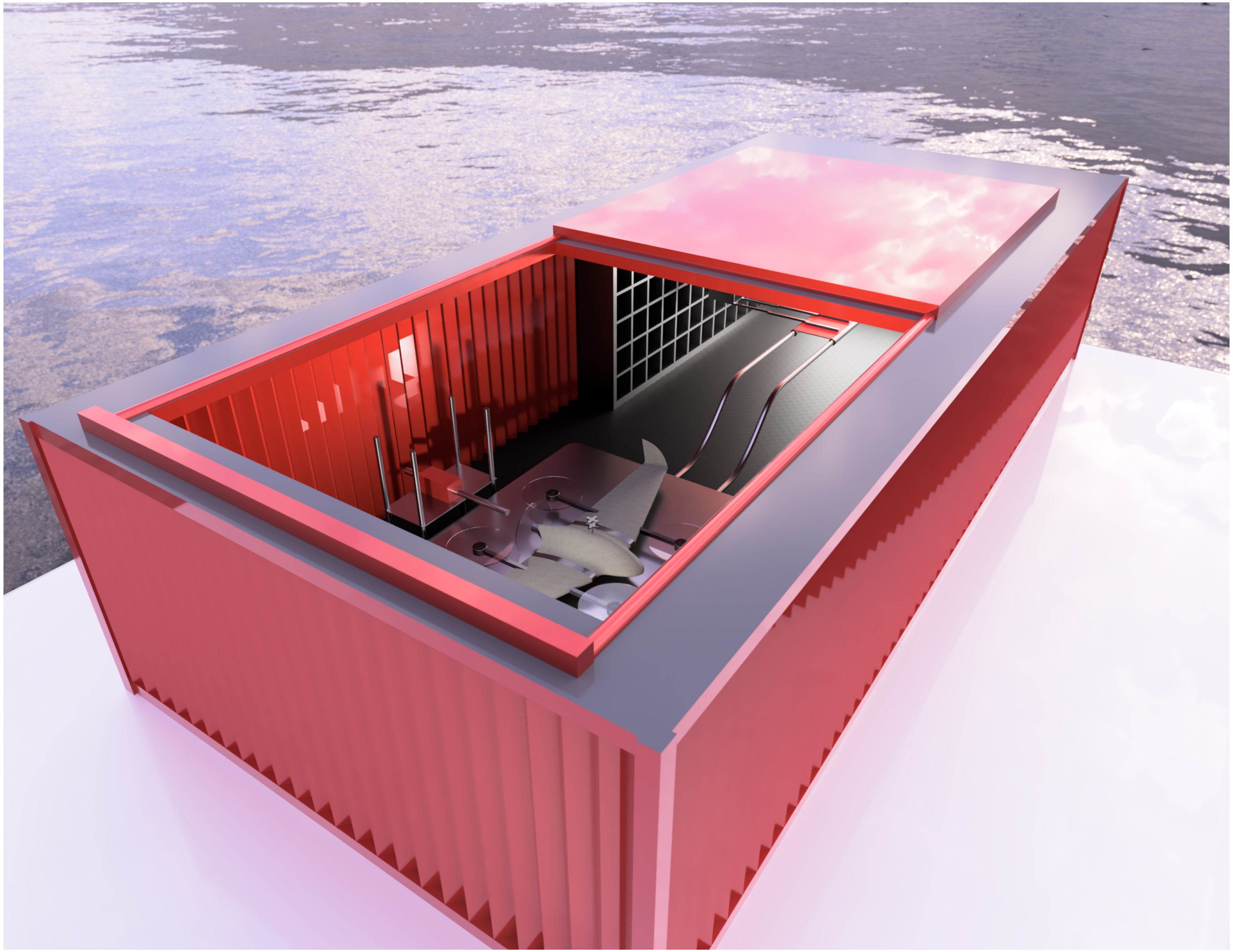


Figure 4.1: Render of the battery swapping ground station

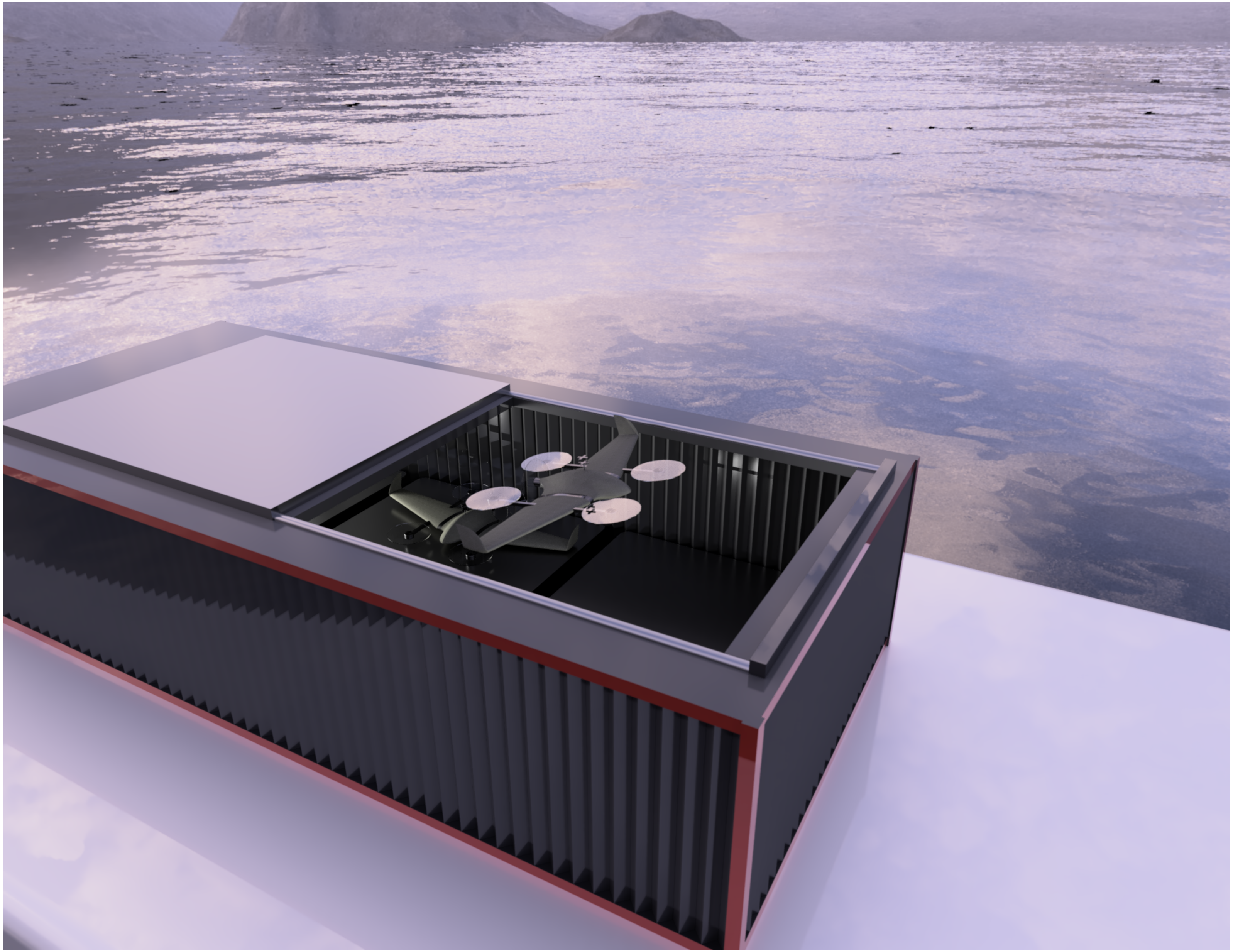


Figure 4.2: Render of the drone storage ground station

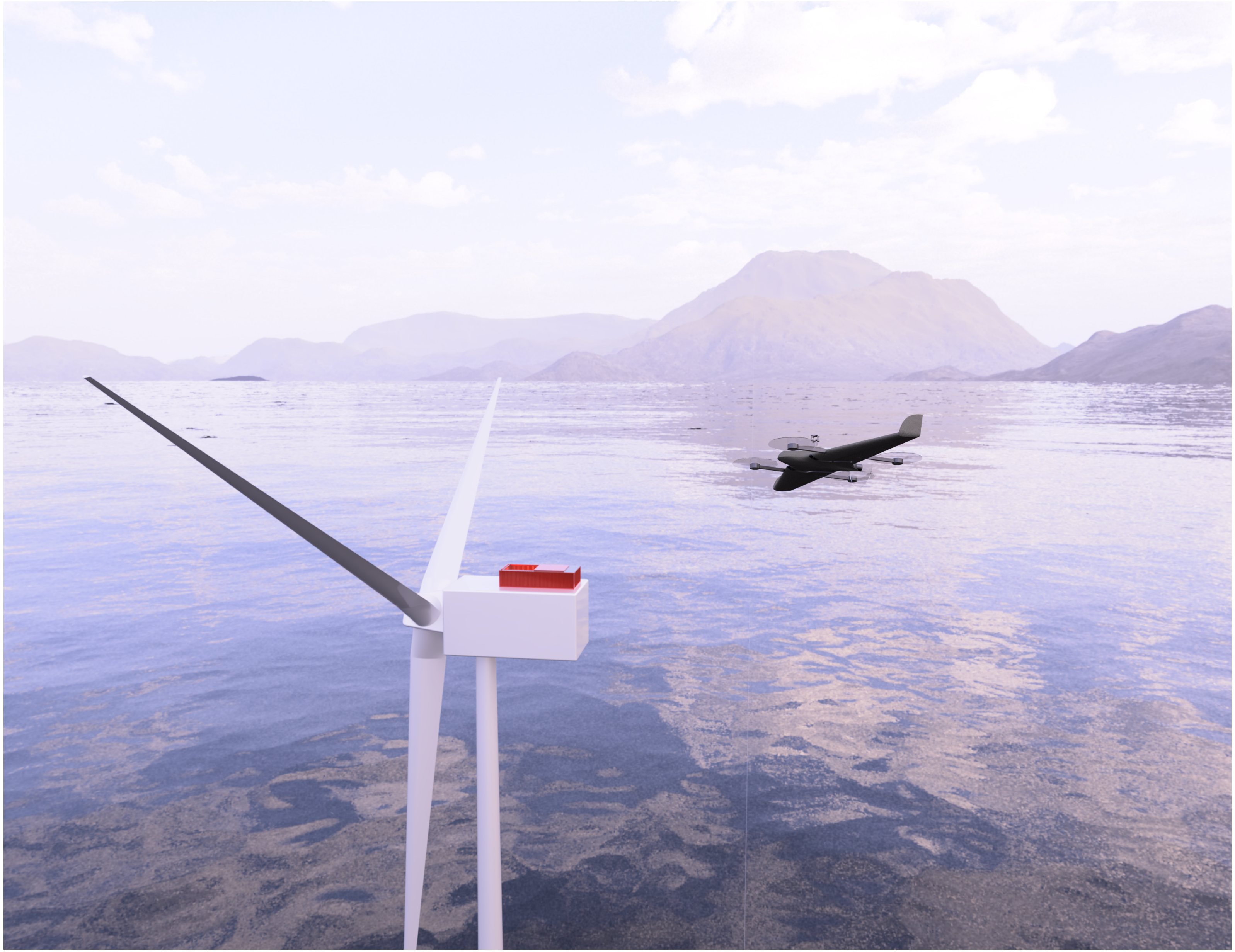


Figure 4.3: Render of the Wide angle view of the system

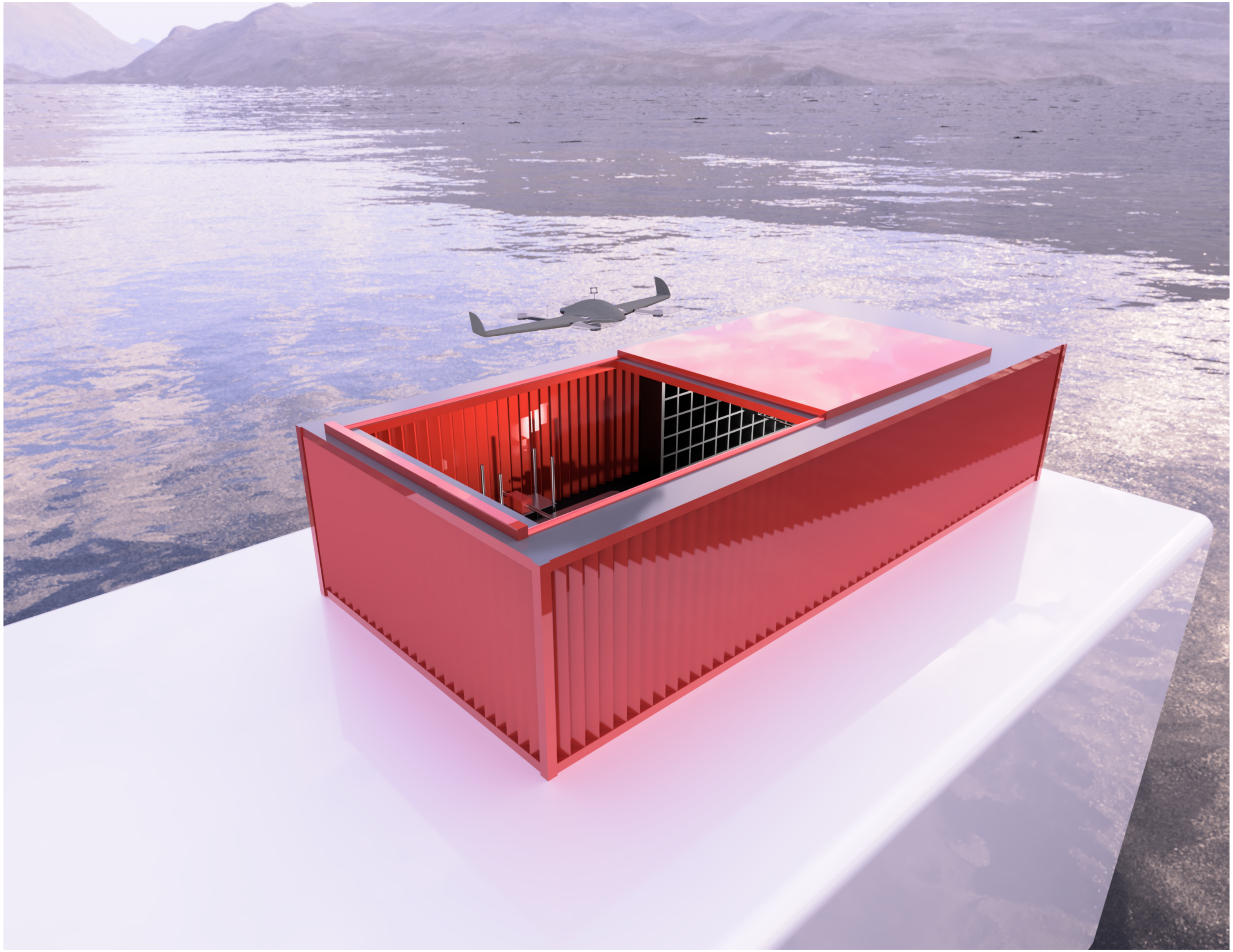


Figure 4.4: Render of drone exciting the ground station

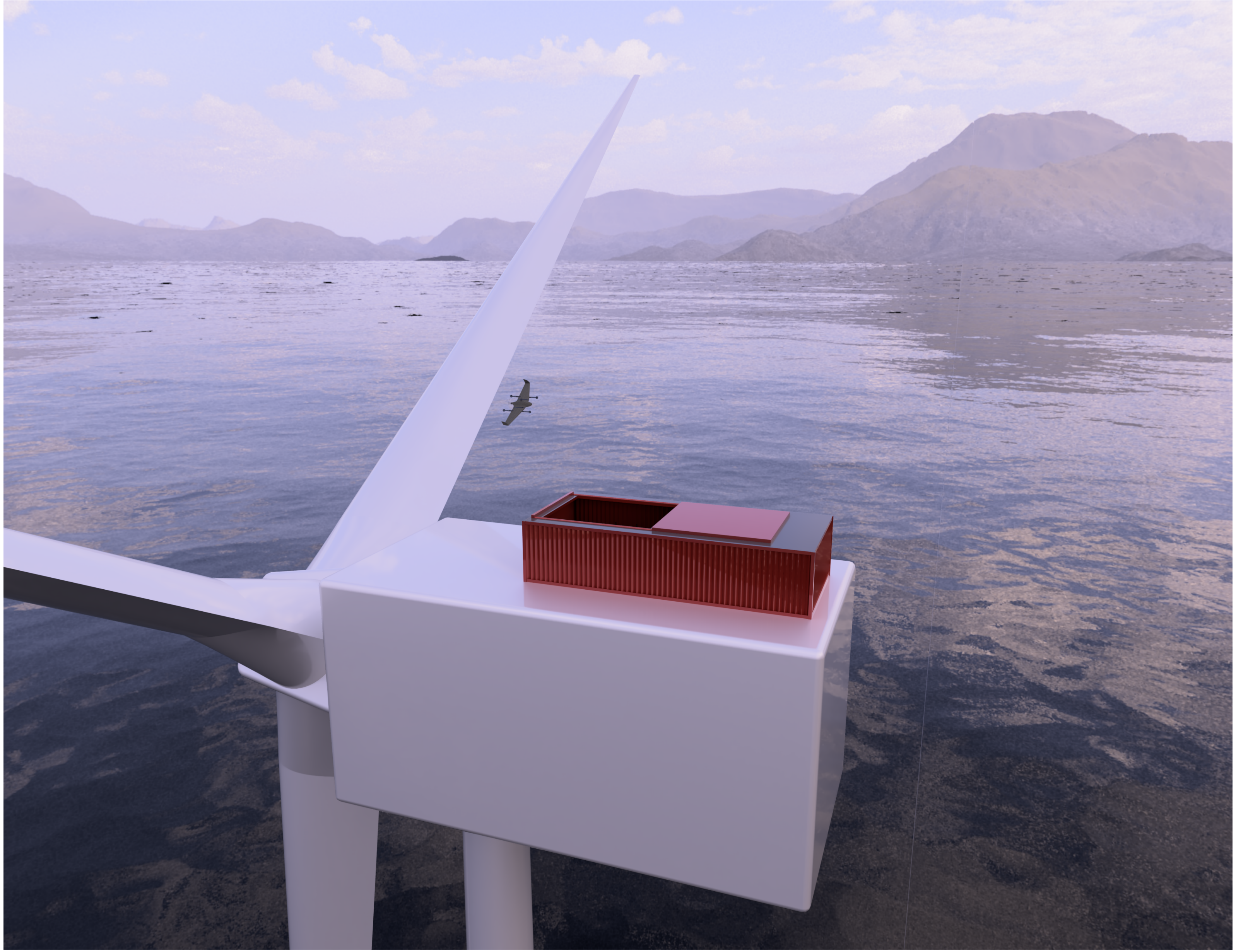


Figure 4.5: Render of the system as a whole

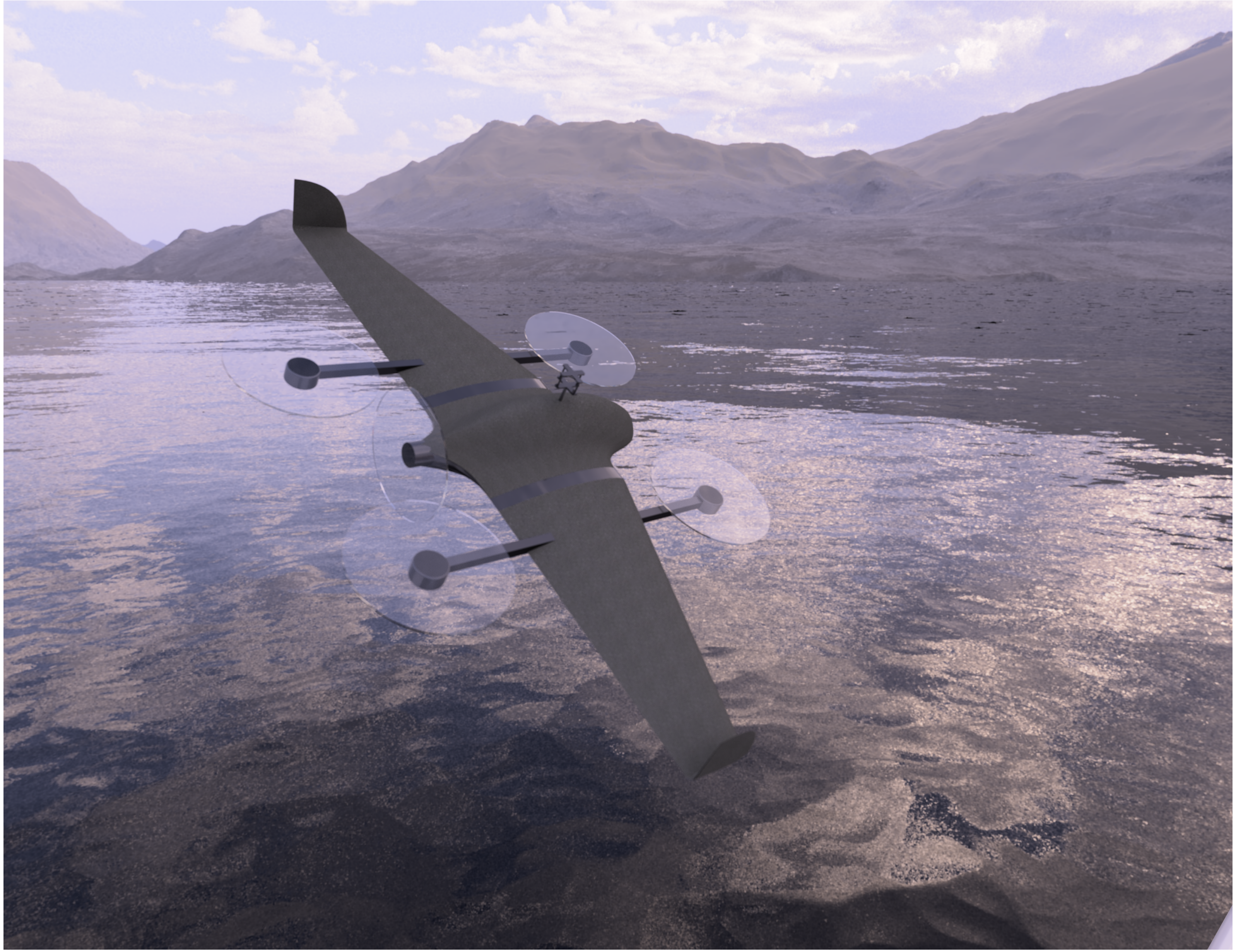


Figure 4.6: Render of the a close up of the drone

4.2. Visualization with diagrams

In this section a number of diagrams will be presented to visualize the working of the system. The components and their relations are shown in different ways and on different levels. Next to that, the data and communication flow between them is presented. Diagrams that will be discussed consist of a hardware diagram, software diagram, electrical diagram, communication diagram, data handling diagram and a functional flow diagram.

4.2.1. Hardware diagram

The hardware diagram illustrates the most important components of the system and the relations between them. The system consists of four main elements: the UAV, the ground station, the master command centre and the shore. All these elements are connected to each other through radio communication and internally there exist a lot of more relations between parts.

Starting with the UAV, it should be clarified that it is bought off the shelf. This means that this element is not designed by the DSE team and the hardware components are copied from supplier data or introduced with engineering sense based on other drones, if supplier data was unavailable. The heart of the UAV is the flight controller and the board computer. The board computer is connected to the transceiver which receives and sends data through the UAV's antenna. This board computer than sends the received data to the flight controller and vice versa. The flight controller processes signals it receives for a certain flight path and will send a signal to the quad drive or fixed wing drive. These are represented by respectively yellow and orange blocks. The quad drive drives the four rotors used in VTOL mode and the fixed wing drive drives the flaps and pusher rotor in fixed wing mode.

This fixed wing mode consist of a left and right flap, used to maneuver, as well as a composite pusher propeller which provides thrust. The flaps are controlled by servos which are in turn controlled by the flight controller. The propellers of both the quad and fixed wing block are powered by motors and these motors are in turn controlled by Electronic Speed Controllers (ESC). These ESCs allow for control and adjustment of the speed of the motors, through the flight controller. The flight controller will give a signal to the ESC, which then changes the voltage supplied to the motor, that in turn changes the speed. The quad drive consists of two clockwise (CW) and two counter clockwise (CCW) propellers made off carbon fibre.

Next to signals from the flight controller, the quad and fixed wing drives also receive power from the battery. The power system consists of a 4S 33Ah Li-Po battery, a power module, which measures voltage and current, and a BEC. BEC stands for Battery Elimination Circuit and is essentially a voltage regulator which converts the provided 14.8V to 5V. This converted voltage is then transferred to the flight controller, which transfers it to the other internal components.

One of these components is the inertial measurement unit, which measures the telemetry of the aircraft. This data is needed to balance the aircraft and to determine its flight path. The Global Positioning System (GPS) also aids in the determination of the flight path by providing the location of the UAV. This is necessary for both obstacle avoidance and for providing the location the measurements are taken at. The GPS determines the location based on data received from Global Navigation Satellite System (GNSS) satellites. The wind measurement sensors are directly connected to the board computer, because they do not contribute to the inner dynamics of the UAV. The analog measurements are converted to digital data and this is signalled to the transceiver, which processes it to be communicated to the master command centre for further processing.

The ground station is, in contrast to the UAV, designed by the DSE team. The reasoning behind the design is explained in Section 2.4. The ground station consists of two different stations; a shelter and a battery charging station. Both are located in different containers, so that when placed next to each other on a nacelle the spread of fire from one station to the other is prevented. When the stations are placed on the same nacelle they will share one antenna and when on separate nacelles the station has its own antenna. With this antenna the ground station communicates to the master command centre and the other way around. The data to be send or received is processed in the station's computer, which will be a minimum standard six-core processor industrial unit computer.

The computers of both stations are connected to a moving roof system, which contains a servo and motor which control a mechanical arm that opens and closes the roof. The roof will be closed when bad weather occurs and the drones need to be protected. The computer of the ground stations is also connected to a fire alarm system which switches the fire extinguisher on if the smoke detector communicates a detection of smoke to the internal computer. An anemometer is connected to the computer as well to measure the wind speed and direction outside, to prevent a UAV from taking off when the wind wind blows too hard. Lastly both stations have a power supply, which retrieves power from the wind farm grid and contains a converter and voltage regulator to ensure the right voltage is delivered to the other subsystems. The power is delivered to those subsystems through the computer. For the shelter this computer is additionally connected to a photoelectric sensor which counts the number of drones contained in the shelter.

The battery charging station does not contain a photoelectric sensor, but does contain a battery swapping system and an internal environment controller. The environment controller ensures the right temperature and humidity are kept inside of the container in order for the batteries to charge safely. The temperature and humidity sensors send their data to the computer, which determines accordingly if the dehumidifier or the heating or cooling system should be turned on. These are turned off again once the sensors show the environment is safe. The battery swapping system removes the battery from the drone and inserts a new one. It detects the drone using a position sensor and communicates this to the computer, the computer in turn sends a signal to the servos to start swapping the batteries. This is done using an accelerometer and controller. The battery is then put in a charging cell and will be used again when fully charged. The charger is directly connected to the power supply.

The master command centre processes all the data it receives using a bigger computer. It also has an algorithm inside it which calculates the flight path for the UAVs. This is represented by the pink block named software and further detail is given in Section 4.2.2. This computer also receives power from the power supply which it distributes to the transceiver. The power supply retrieves power from the wind farm grid through the substation, at which it is located.

The processed measurement data which the command centre receives from the UAV is saved to an external hard drive. Next to that, the data is send to an antenna on the shore. Here the data is uploaded to a cloud for the customer to access. The computer which is used to upload the data is powered through a conventional power socket.

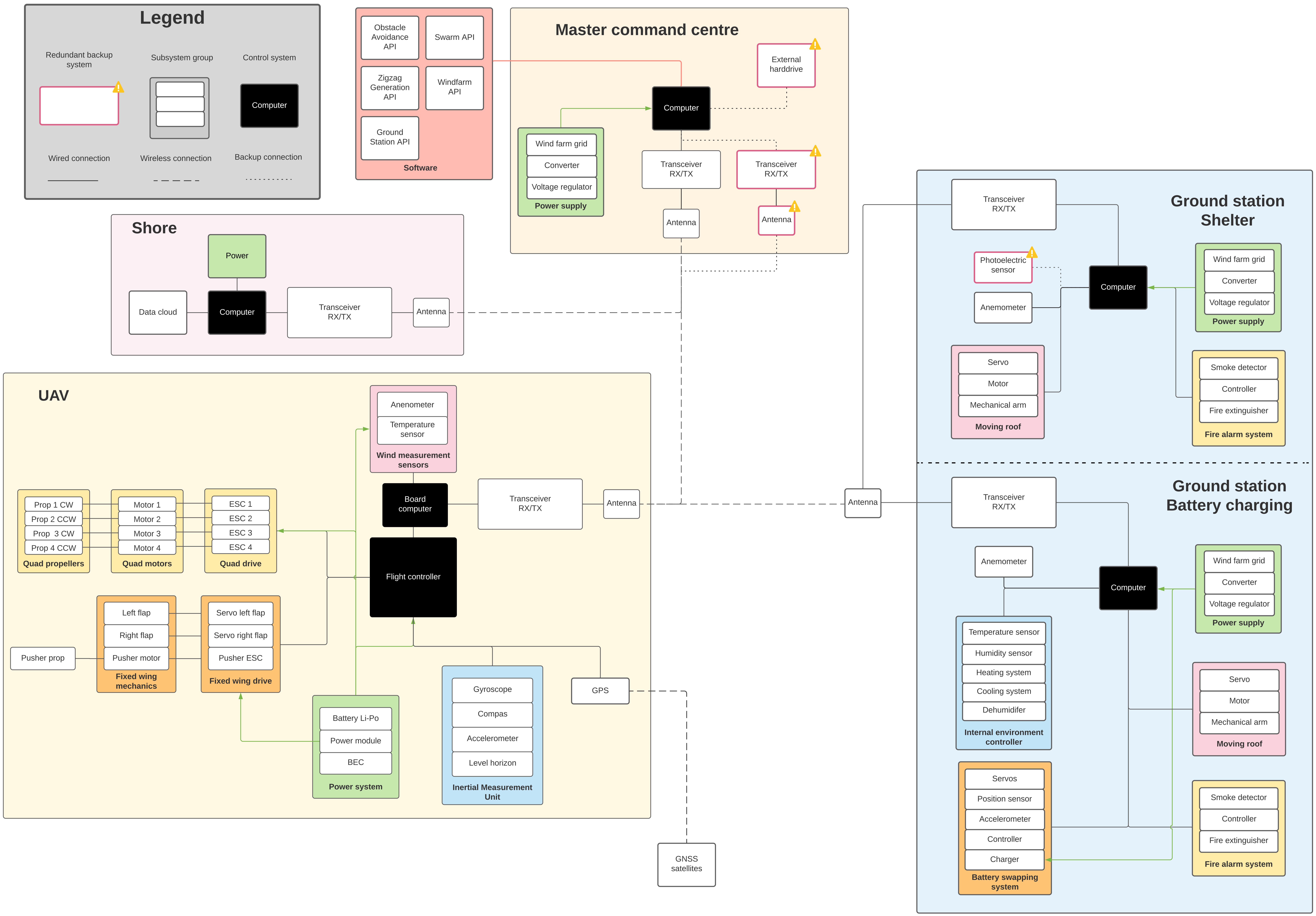


Figure 4.7: Hardware diagram

4.2.2. Software diagram

To better visualise the computation intensive processes of the path planning and interaction with the system, a software diagram is constructed. At a first glance, Figure 4.8 shows the two main components of the swarm behaviour. Looking at the zigzag generation API, the first step happens at the master command center. On the lower left, first, the system is initialised with the starting static variables on wind farm, UAV and ground stations.

Before diving deeper into the schematic, the software is split into micro-services for easier maintainability and reliability. These micro-services work independently in separate virtual containers where are allocated the necessary resources such as memory and computing power. The services are structured into Application programming interfaces (APIs) as follows:

1. **Zigzag API** - generates the master path and assigns waypoints to swarm units
2. **Obstacle Avoidance API** - accepts current unit UAV position, orientation and measurement goal and recalculates route to avoid intersecting with obstacles
3. **Swarm API** - main communication point for updating and receiving data on all UAVs
4. **Ground Station API** - main communication point for updating and receiving data on all ground stations
5. **Wind farm / Dynamic Obstacles API** - used to retrieve data on important obstacles in the wind farm. Returns orientation, speed, location of wind turbines, ships, aircraft, or people that could affect the safety during operation of the product.

For the wind farm, the relevant variables are the AOI (area of interest), described in terms of width and length and turbine initial orientation, radius and height. For the turbines, a continuously running service is also used to fetch relevant data about the orientation of the blades, rotational speed. These are variables later used for obstacle detection. In terms of UAV, the important data are endurance, cruise speed, climb and descent rate and angles. These static variables, taken from the UAV design department, give a sufficiently good approximation on the performance of the drone. Ground stations are also initialised by specifying their location with respect to the wind farm turbines, as they are positioned on the nacelles.

In the same block of zigzag generation, the main loop in the swarm happens at the initialise unit UAV block. Once the master track has been constructed for each altitude as described in Section 2.3, the unit UAV is initialised at the ground station. As the drone takes off, waypoints are being assigned and transmitted to the Swarm API, the communication endpoint for the UAVs. The drone calculates the endurance left and assesses whether it can still make it to another waypoint. While flying to a certain measurement point, the obstacle avoidance API is called continuously with UAV updates on position and orientation, while trying to minimise avoidance endurance cost. Once the measurement point has been reached, the endurance left is calculated and a decision is taken if any more measurements can be taken. If endurance levels become too low, the risk level increases and a decision is made to avoid crashing, thus, the UAV returns to an appropriate ground station and swaps batteries or stays sheltered. It is worth noting that this iterative process is followed by all units in parallel.

On the other hand, it is also worth mentioning that the obstacle avoidance API also takes a big part in the main loop for each unit UAV. This API is called continuously once a measurement point is set. The goal in this API is to take into consideration all dynamic (excluding birds, and other unpredictable objects) and static obstacles, for example, operational wind turbines, ships, airplanes, people, barges and of course, other unit UAVs active in the swarm movement. The inner workings of obstacle avoidance are discussed in Section 2.3, however, the resulted output updates the Swarm API (unit UAV mission status) and the Zigzag API.

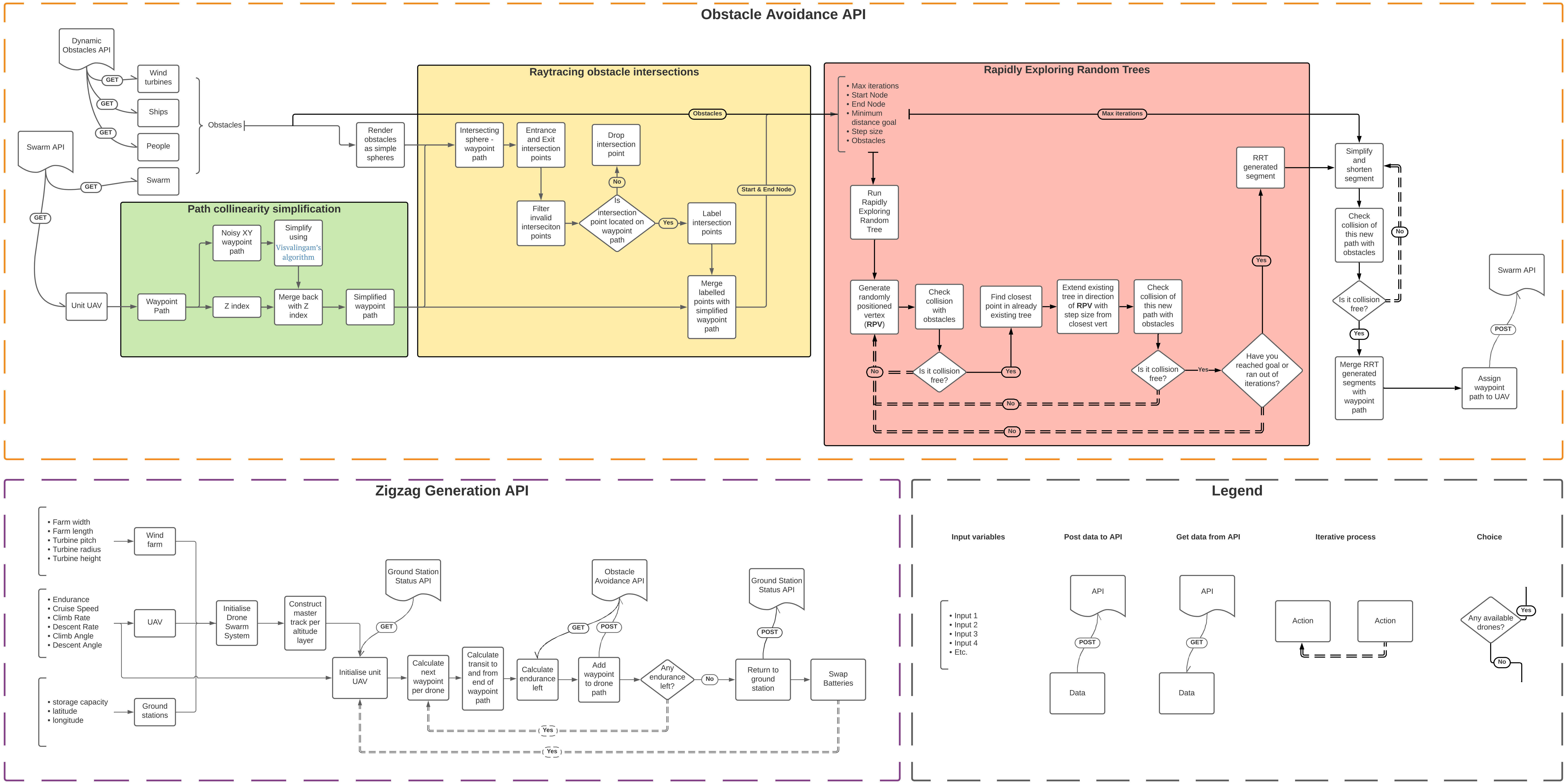


Figure 4.8: Software diagram

4.2.3. Electrical diagram

An electrical diagram is made to give more insights in how all the electrical components are related to each other. Figure 4.9 shows the electrical wiring diagram of the UAV including the sensor payload. This diagram is based on the original electrical diagram of the UAV from Vertical Technologies.[4] It can be seen that it consists out of several groups: Flight controller, power supply, quad drive, fixed wing drive, inertial measurement unit, sensor package , board computer and telemetry unit. The flight controller is the central point of the UAV and distributes the power between all components.

The power supply unit consists out of 4 elements, a battery, a BEC for the Flight controller, a BEC for the sensors and an additional power module. The first element is the battery which is provides a Voltage of 14.8 Volts. The power module is connected both directly and indirectly to all other groups. All the ESCs get direct power from the battery to provide energy for the motors that run on 14.8 Volts. All other components get indirect power via the flight controller. The flight controller and all the other components can not run on this voltage and the voltage from the batteries is first converted into a lower voltage of 5 Volts by the BEC which stands for Battery Elimination Circuit. The second BEC converts the voltage to a 12 Volts to power the sensors. The power module regulates the power supply for the flight controller, and it provides information regarding the battery voltage and current.

Both the fixed wing and quad drive ESCs also get power from the flight controller itself, aside from the power directly from the battery. This is used, respectively to power the ESC's brain and data conversions, the latter to power the actual engines themselves. For the fixed wing drive the flaps directly run from the flight controller and no additional direct power from the batteries is needed to power these.

The inertial measurement unit includes all the sensors for stability such as a gyroscope, compass, accelerometer, and a level horizon sensor. The inertial measurement unit also includes the GPS sensor that can locate the UAV. All sensors are linked to and powered by the flight controller.

The board computer handles all the data that comes from the sensors and is needed for proper communications between the UAV, sensors and ground station. As stated before the sensors run on a higher voltage and are directly powered by the main batteries with a BEC in between to alternate the current. The data however is sent to the board computer, and can be send to the ground station via the telemetry component.

The ground station design is still in an early design phase. In this stage only the general parts that will be used are known but the actual configuration is not known yet. A hardware diagram is useful to get an overview of the different parts in there and this is described in Section 4.2.1. However an electrical diagram can not be made since it is not known yet how all the parts are interrelated with each other on an electrical level.

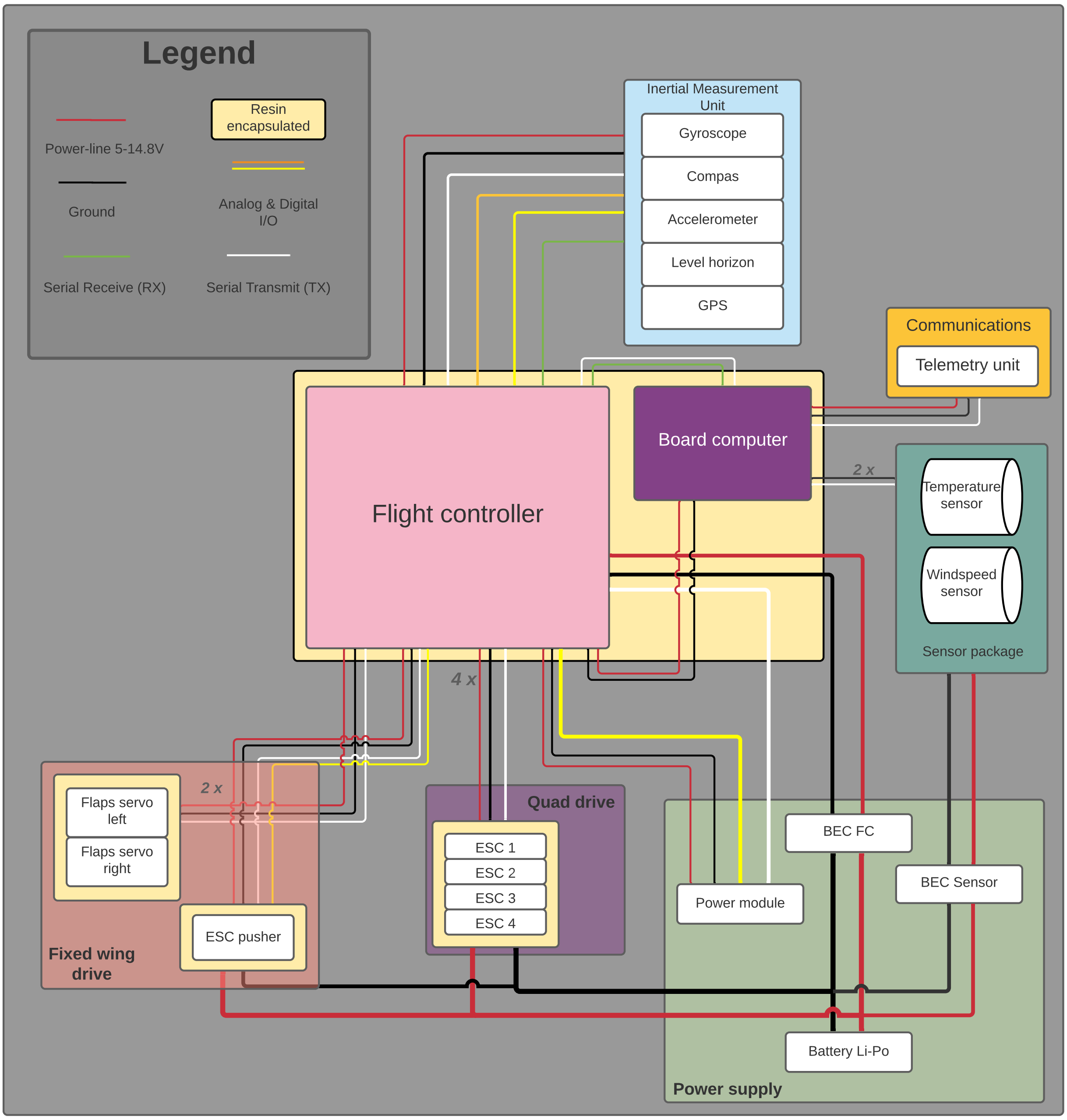


Figure 4.9: Electrical diagram of the Deltaquad in combination with the sensors

4.2.4. Communication flow diagram

In the communication flow diagram shown in Figure 4.10 the communication lines within the system are visualized. Mainly the flow of data between the different computers in the system is shown. There are three important elements in the system that should communicate with each other, namely: the UAV, the master command centre and the ground station. The ground station consists of a battery swapping station and a shelter station. These share one antenna when they are situated on the same nacelle.

In the diagram yellow blocks represent inputs into the computer systems. These inputs consist of data acquired by sensing systems and internal component data. The black blocks in the diagram represent the brains of the complete system; the computers. The white blocks contain other components that are essential for a communication system, such as antennas and transceivers, as well as hard drives, a cloud and internal components in contact with the computers. Lastly, the downlink communication is represented by an uninterrupted line and uplink is represented by a dotted line. Uplink is considered as information send from the master command centre or from internal computers to internal components. Downlink is the considered as the information that is received by these stations. A short explanation of the diagram will be given below.

If one starts reading the diagram at the UAV, it can be seen that it has a lot of inputs going into the flight controller, which is summarised as the telemetry data. This is all the data on the health and operation of the UAV.The IMU input is the Internal Measurement Unit input. This unit contains all data on stability given by the sensors contained in this unit. Next to this telemetry data, the measurement data that stems from the anemometer and temperature sensor have to be communicated. These three data packages are send to the master command centre and processed in the main computer. This will result in a flight path that is send back to the UAV and it will result in processed measurement data that will be send to the shore.

On the shore the data will be uploaded to a cloud for the customer to use. The processed measurement data will also be saved on an external hard drive in case an error occurs in the transmission to the shore. Another line of data that is communicated to the UAV is its location given by the data from GNSS satellites. It should be noted that the transceiver is connected to the board computer, which gathers all the flight path data. The board computer generates a flight command to be further processed in the flight controller, which sends several commands to different components, such as the ESCs.

Lastly, there will be a communication of data and commands to the ground station. The master command centre will send up a signal to communicate whether the drones should shelter because of bad weather and if a drone is coming into the station. The status on the weather of the wind farm is obtained by a small weather station on the substation, where the master command centre is located, and by the weather forecast. This weather data is used by all ground stations to generate a command via its own computer to open or close the roof. Both ground stations have a fire alarm system which is switched on if the internal computer receives an alarm from the smoke detector. Next to that, the battery station also has a battery swapping system which is connected to the internal computer which gives a swapping command and selects the right battery if a drone is located by the battery swap system. Moreover, the temperature and humidity sensors send their measurements to the computer. The computer then sends a command back to the internal environment controller, which then switches on or of the heater, cooler or dehumidifier. The shelter station also has a communication link between its photoelectric sensor and its internal computer, to communicate the number of drones counted by the sensor.

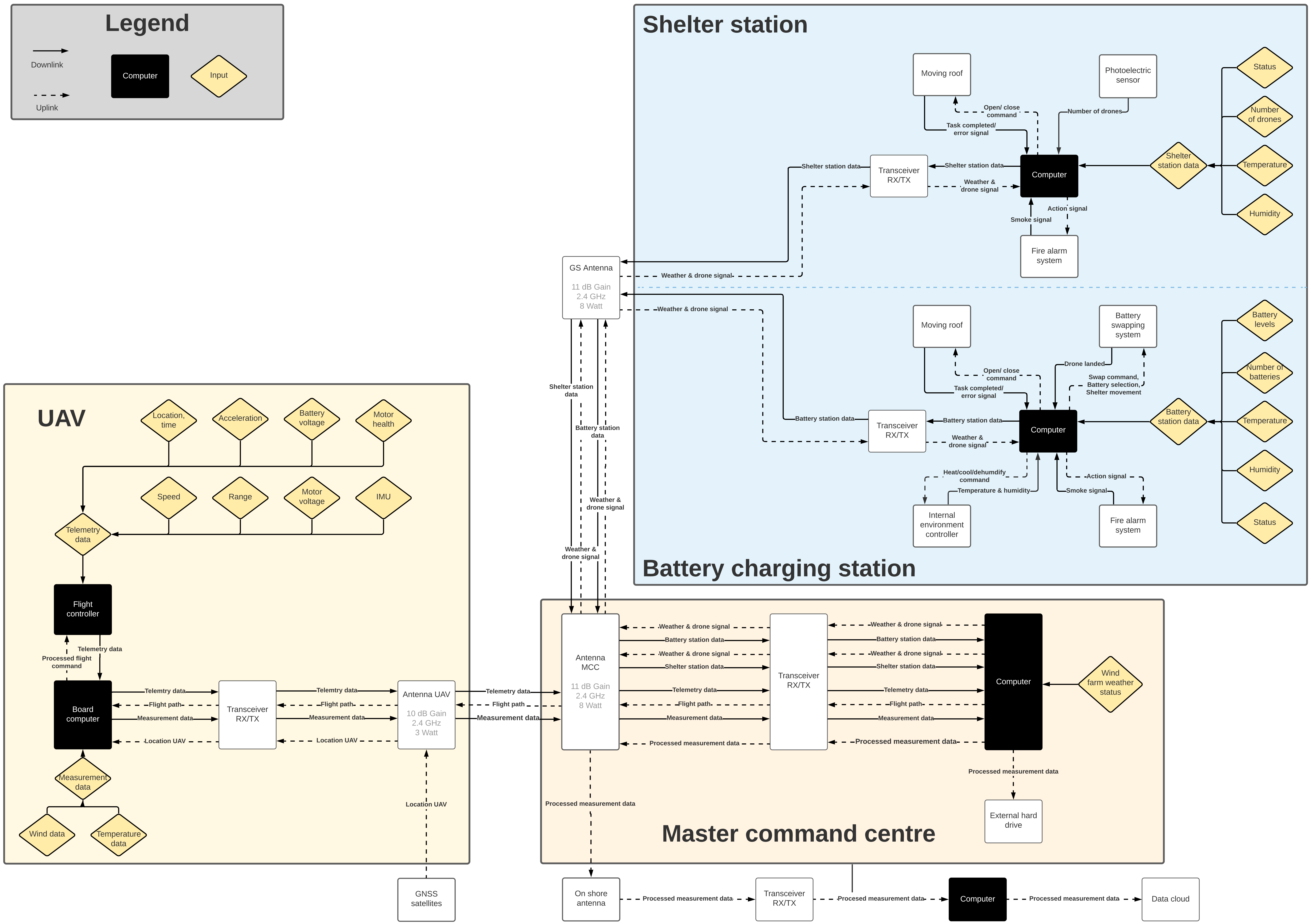


Figure 4.10: Communication flow diagram

4.2.5. Data handling diagram

The data handling diagram illustrates the flow of information between the physical components presented earlier in Section 4.2.1. By indicating the data rates and the physical, wireless links between components one can make sure to have a reliable overview of where bottlenecks could appear or what would happen if one link fails. Thus, in fewer words, ensuring there is not a single point of failure in the data handling system. While the Section 4.2.4 shows what the messages are between various components, Figure 4.11 shows the data rates and links between all physical components. Hence, these two schematics go hand in hand.

To begin with, one can start reading the schematic from the top half, starting with the master command centre. The master command centre talks directly to all ground stations and all UAV units. There is no direct communication between UAV and ground station, but, it can be used as a backup if a certain UAV loses connection to the command centre. The communication is done via radio between all parts of the product. This is represented by the dashed double lines in the middle. The reason for radio over any cellular or ethernet connections are due to the offshore location and lack of possible internet connections. The calculation of the data rate is shown in Section 2.4.5.

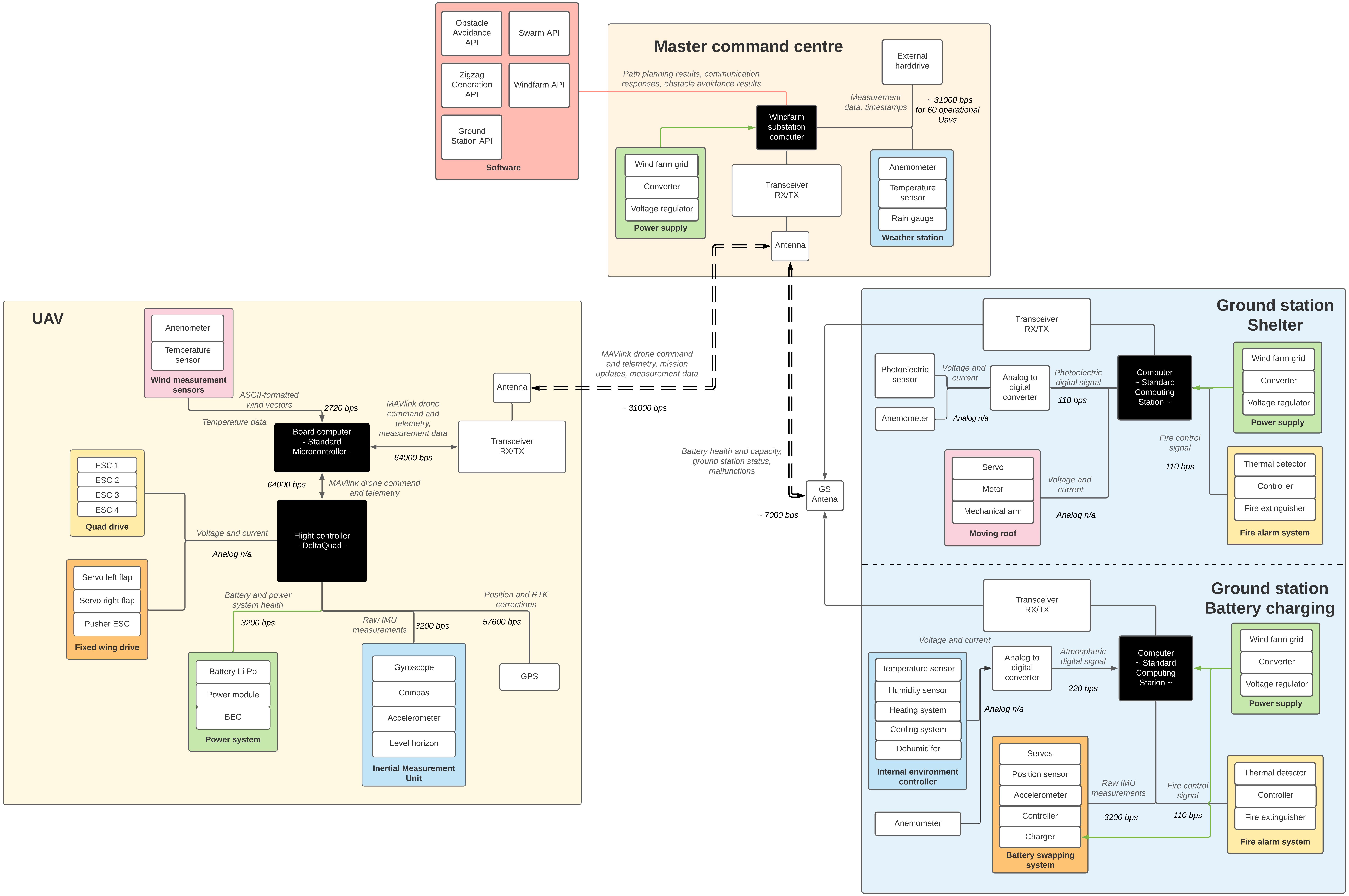


Figure 4.11: Data Handling Diagram

4.2.6. Operations and logistics diagram

The operations and logistics diagram was generated to illustrate the use and support of the system. It provides an overview of the sequence of operations. The rhombus-shaped elements represent decision-based processes, whereas the the rectangle shaped boxes represent processes. For maintenance, the cause of the malfunction will dictate which maintenance facility the system will require. If the issue is rooted in the ground station architecture, then on-site maintenance services will be deployed. Otherwise, the system may be sent to nearby onshore local maintenance facilities. If necessary, it would be sent to a specialized maintenance facility or completely replaced. Deducing the level of severity of the malfunction will be facilitated with the error message processed, and the switching of the subsystem to maintenance mode.

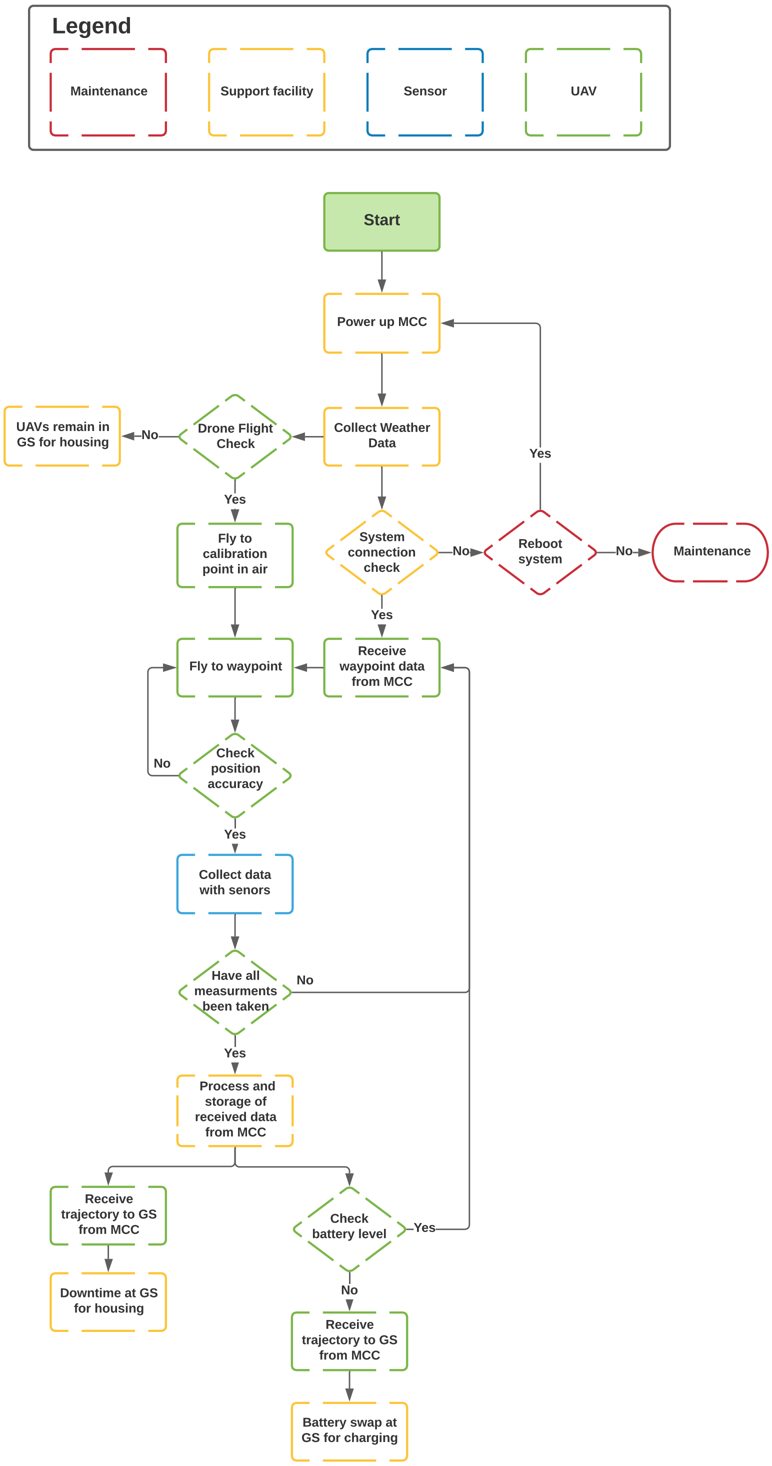


Figure 4.12: Operations and logistic diagram

4.2.7. Functional flow diagram

The functional block and flow diagrams are needed to provide insights on the final design concept. All the functions should be incorporated into the design, by having an extensive diagram detailing all the functions and their logical order.

The functional block and flow diagrams detail all the functions and sub-functions of the project. The block diagram in Figure 4.13 is arranged in a breakdown structure starting with the highest level functions, and branched into sub functions. As the level gets lower, the functions also become more specific. The flow diagram, Figure 4.14, further elaborates the block diagram by arranging the functions in a chronological order.

Moreover, the finalised functional diagrams are more focused on the operational lifetime of the product. With a more comprehensive understanding of the product, compared to the baseline version [3], the functional flow and functional breakdown, are both further extended in the operations phase of the product's lifetime. For example, docking, battery swapping and most importantly path planning tasks are better identified and taken into consideration. This phase is further split into four main steps the product aims to follow in a recursive manner:

1. **Perform flight planning** - phase where the master command centre plans the paths for all UAV units and assesses wind farm and product's overall functionality
2. **Deploy swarm** - phase depicting tasks from take-off until landing of each UAV unit. Route planning is continuously communicated from the first phase.
3. **Monitor swarm** - asses on master ground station quality of the data measured and UAV performance, ship data to client
4. **Perform maintenance** - land on nacelle ground station for either shelter or battery swapping, assess repair time

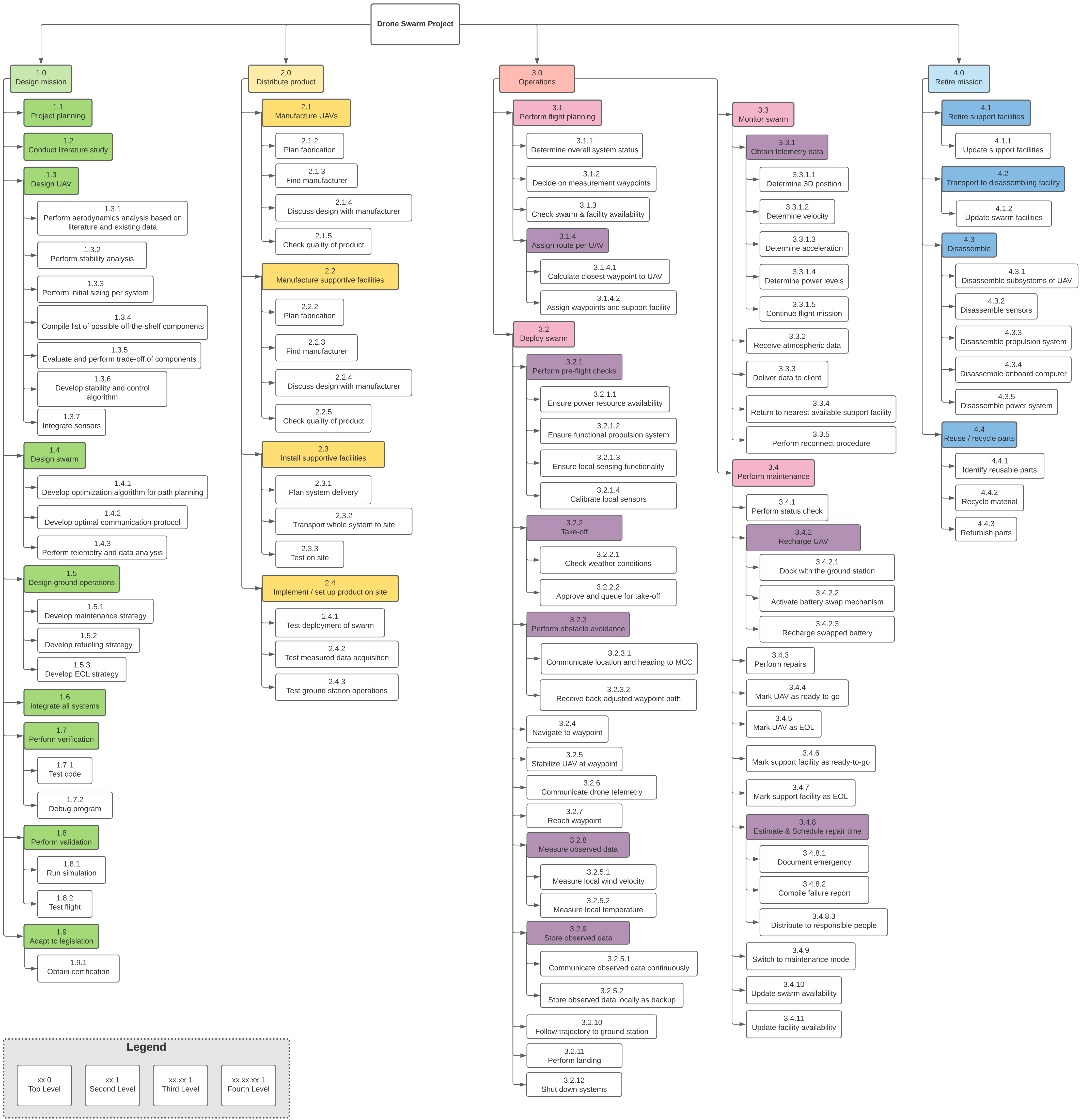


Figure 4.13: Functional Breakdown Diagram

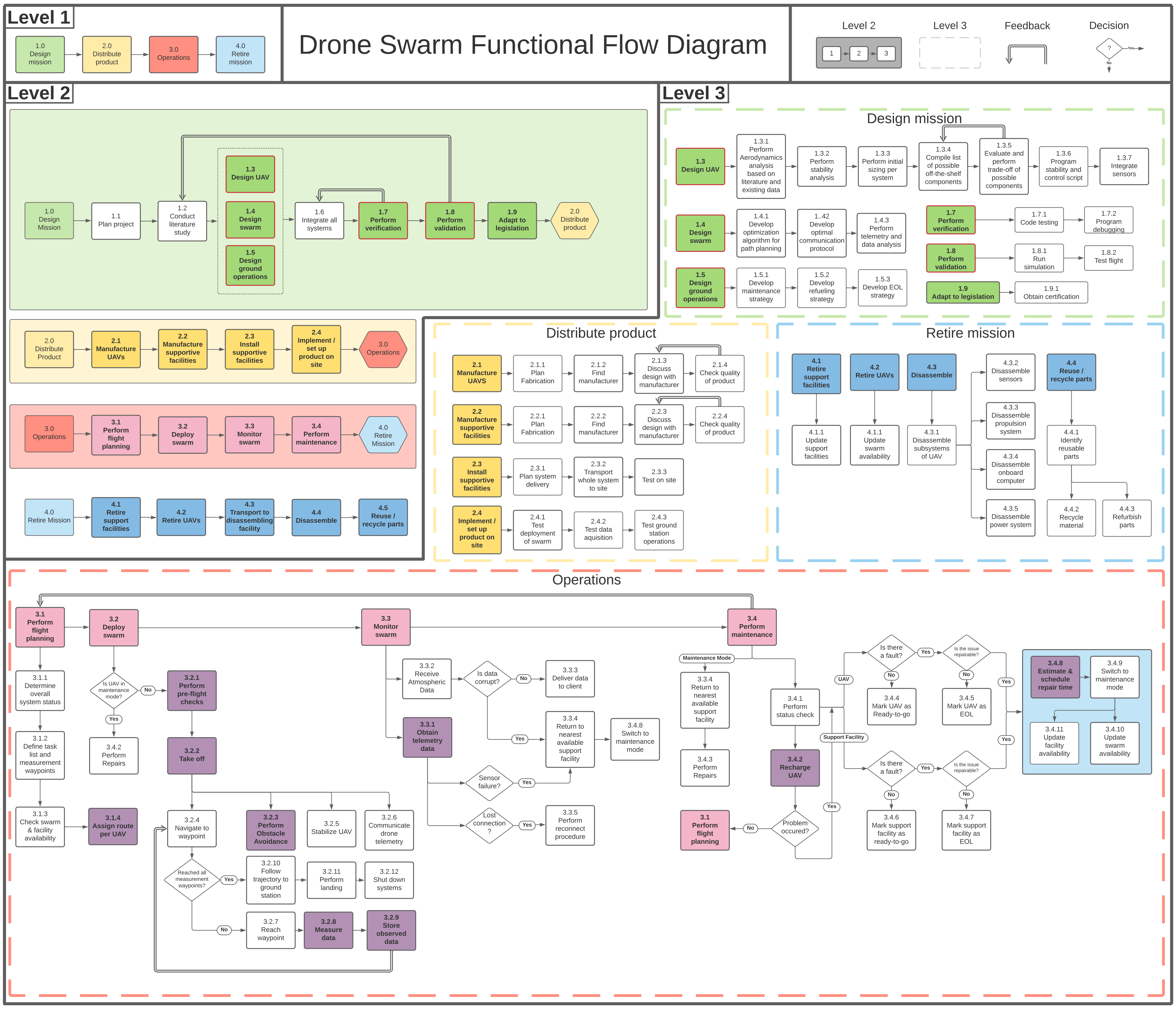


Figure 4.14: Functional Flow Diagram

5

Product technical analysis

Confirming the design through a verification and validation analysis in Chapter 3, and providing diagrams for the more detailed design areas in Chapter 4, the system can be analysed as a whole. This analysis will look to inspect the design on its risk in Section 5.3, its robustness through a RAMS analysis in Section 5.1 and its sustainability through an LCA assessment in Section 5.2. These metrics are the same as used to trade-off between concepts in the midterm report [1] and therefore pose a good set of metrics to evaluate the system.

5.1. RAMS analysis

In this section the RAMS will be discussed. RAMS signifies Reliability, Availability, Maintainability and Safety. These characteristics are also connected to the requirements given in Section 3.4. Reliability of the system can be described as the ability of the system to function without failure; it can be linked to how well risks are mitigated, hence decreasing the probability of the occurrence of these risks or their severity. A decrease in risk levels would increase the probability of continuous function of the system. The risks and mitigation strategies are discussed in section Section 5.3. The reliability of the system is primarily affected by the lifetime of the system and in what weather conditions the system can survive. Availability is dependent on reliability; a system would be more available if it is reliable, i.e. less prone to failure. Availability of the system is influenced by the charging time, the set up time and the wind conditions that the system can withstand. The reliability and availability of the system also directly correlate to the redundancy of the system; in the event of a component failure, for example, a redundant system would mean that this scenario would not compromise the complete functionality of the system. Maintenance cycles also contribute to the reliability and availability of the system, because they ensure that any underlying issues are resolved before the failure becomes critical. It is also a form of quality assurance during the operational phase of the design. Maintainability is dependent on the availability of parts, maintenance time and temperature range. These different factors and their values are expanded upon below. Moreover, a list of safety critical functions, the expected reliability and availability, the redundancies applied and an outline of maintenance activities is given.

5.1.1. Wind speed tolerance

Wind speed is an important criterion to take into account, because wind speeds occurring in and around a wind farm are generally quite a high. In Section 2.2.2 it was found that the UAV is able to operate in the required wind speeds. It meets requirement **MR.adap.16**, becuase the average wind speed in region two is 11.7 $[m/s]$ whilst the UAV has a wind speed resistance of 14 $[m/s]$. Using weather predictions and the real time wind measurements from the UAVs, allowable wind speeds during landing and take-off are taken into account. The DeltaQuad can withstand a wind speed of 9 $[m/s]$ for take off and landing compared to $14[m/s]$ during cruise. The UAV will therefore only take-off and land when the wind speed is lower than or equal to 9 $[m/s]$. Moreover, the drones shall also be able to withstand wind gusts that might be higher than 14 $[m/s]$. A solution for this is if a UAV measures a very high wind speed and consequently loses control, other drones in the neighborhood can act on this. They could, for example, move away from the direction the wind gust is travelling. It should also be noted that UAVs generally have a resistance against wind gusts that is higher than their general wind resistance.

5.1.2. Precipitation

To quantify the resistance against precipitation, that being rain and snow, as well as hail, an IP rating is considered. For this project, a system specified as IP-54 should be operable in both off-shore and onshore environments, which is also reflected in **MR.adap.15**. The system will then be protected from limited dust ingress and water spray from any direction, according to [30]. The UAV by itself, without any alterations, will have a too low IP rating, it is namely estimated at IP-42. However, a protective layer will be applied on top of the outer material of the UAV, as mentioned in Section 2.2.2. This results in a new IP rating of IP-44. The protection for dust ingress is discussed in Section 7.3.

From market research it was concluded that anemometers have a rating of IP-65 or higher and the temperature sensor has an IP-65 rating. Therefore, these sensors will definitely meet the requirement and will be safe to use when the drone is flying. As mentioned in Section 5.3, the quality of the wind measurement data decreases when water droplets enter the anemometer, as they effect the pulse time. This mostly occurs with heavy rain, however. In these circumstances, the UAV would already be sheltered. These errors could either appear as a 180° rotation of the direction of the wind speed or as a large increase in wind speed, reaching up to 40 $[m/s]$, according to [31]. These errors would occur for short periods of time. Generally, according to [32], this can be minimised by analyzing the signals received from the anemometer and deleting the signals with a poor quality.

The ground station is assumed to have a higher IP rating than the required IP54, because it is supposed to function as a protecting shelter for the UAVs. It protects them by keeping rain out with a movable roof and a steel housing. Moreover, it is designed to stay in place and protect the UAVs in the event of a grade 2 storm, complying with requirement **SR.maint.6**. Lastly, the shelter functions as a faraday cage to protect the UAVs from lightning strikes.

5.1.3. Temperature range

For adaptability the temperature range is an important factor to take into account for the design of the system. This is especially important for climates that have a large fluctuation in temperature throughout the year, or climates that are relatively cold or warm. This is connected to requirement **SR.main.5**, specifying a temperature range of -30 to 40 $[°C]$. As the Netherlands is taken as a reference point for the design, the system should be able to as a minimum, survive the temperatures occurring there. The UAV has an operational temperature range of -20 to 45 $[°C]$. The UAV will shelter in this station for outside temperatures below -20 $[°C]$, the shelter is heated to make sure the UAVs survives in colder circumstances.

The battery station is also heated, cooled or dehumidified in order to keep an optimal environment for the batteries and to ensure that they do not become damaged, leak, or burn. This is explained in Section 2.4 and shown in Section 4.2.1.

5.1.4. Collision avoidance

Collision avoidance is an important requirement, which is reflected in requirements: **SR.safe.8**, **SR.safe.9**, **SR.safe.10**, **SR.safe.11**, **SR.safe.12** and **SR.safe.13**. Avoiding collisions is important to avoid human or animal casualties, as well as to avoid expensive damage to property. A detailed description of collision avoidance is given in Section 2.3.4. The risks of collision are described in

Section 5.3.

5.1.5. Set up time

The time it takes to set up the complete system is important for the customer to know in order to know how long it will take for the system to be up and running once its sold. This influences the availability of the system, but is also an important factor for maintainability. If a component needs replacing, this should not take too long and should definitely not cost the system to be non operational for too long.

The time it takes to set up one ground station is estimated to take one working day. In total, to install all ground stations, this would amount to twenty working days. The set up time of a UAV is estimated to take an hour, this includes the assembly of the fuselage, wings, carbon spars and propellers, as well as the calibration of the sensors. For 78 drones, this would amount to ten working days in total. Next to these set up times, time for processing the order, manufacturing and transport should be taken into account. For maintenance a total time of 15 working days per maintenance cycle is allocated, according to **SR.rel.1.SUB.1**. This would allow time to repair or replace all drones, clean and calibrate them and leave five working days for maintenance on ground stations. Not all drones have to be replaced and calibrated every maintenance cycle, however. This leaves more room for unexpected maintenance. A maintenance schedule is shown in Section 5.1.10.

5.1.6. Lifetime

The lifetime is an important parameter for reliability, which is supported by requirement **SR.rel.3**. The longer the lifetime of a component, the more reliable it is. If a component has a longer lifetime, it will also need less replacing, which takes up maintenance time and thus would result in a higher availability. The lifetime of the ground station is estimated to be four years, meaning that it would need full replacement every eight maintenance cycles. The lifetime of a drone is 2 years based on information given by Vertical Technologies. The lifetime of the anemometer is five years. The lifetime of the temperature sensor is not given by the manufacturer, but is assumed to also be five years. This is something to be verified in the future. This five year lifetime of the sensors, means that old sensors from replaced drones will be integrated into the new drones to safe cost and increase sustainability.

5.1.7. Charging time

Charging time is an important requirement, stated as **SR.rel.1.SUB.2** and it influences the availability of the drone. As a battery swapping system is used the drone is only required to be inside of the battery swapping station for five minutes. The batteries themselves take a longer time to charge. The time it takes to charge them is dependent on the current with which they are charge. It is best for the batteries health to charge them with no more than 5 $[A]$, this results in a charge time of 6.6 hours. That is based on the fact that the battery has a 33 $[Ah]$ capacity, that divided by the current gives the charging time. The number of batteries is also based on this charging time, this is further explained in Section 2.4.3. The availability of the drones is increased by a very large amount due to the fact that a battery swapping system is used and the 'charging time' for a drone is reduced to 5 minutes.

5.1.8. List of safety critical functions

The analysis of safety-critical functions facilitate in the general evaluation of the safety of the design. The safety-critical functions can be identified as the functions that significantly influence the overall safety of the system and are critical to it. The safety-critical functions of this design are assumed to be:

1. The battery swapping and charging facility
2. Obstacle avoidance
3. Maintenance and inspection

The hazards of the swapping and charging facility are addressed in section Section 5.3. Although they are mitigated for, the possibility of these risks associated with this system to occur can never be eliminated. Nonetheless, these strategies contribute to the improvement of the safety of the system, and they adhere to the guidelines set, for example: fire extinguishing material specific to the batteries would be used. Obstacle avoidance is critical to the success of the project, as it would define the success of the autonomy of the system. Dynamic obstacle avoidance techniques and algorithms were implemented to manage that, which without, would lead to possible UAV collisions and loss of UAVs as well as data. Maintenance and inspection considers the human-aspect of safety in the system. This has not been addressed in this report as it is something largely out of the control of the design team. Off-shore wind technicians have always accessed the nacelle area for certain activities, and their safety would remain a responsibility for wind farm operators. Hence, it can be assumed that working conditions in Dutch offshore wind farms are safe, and that operators do not permit technicians to work under unfavourable conditions, such as strong winds.

5.1.9. Redundancy

The designed system is a complex system, which comes with a high level of risk. Although a risk mitigation strategy has already been applied, there is no guarantee that the whole system works perfectly throughout its lifetime. Indeed it is very unlikely that this will be the case. To still make the system safe, redundancy is applied. Extra components are added, so that if one component fails, there is a redundant component in place which can take over its function. In this subsection the redundancies applied are stated. If something breaks down and a redundant component is used, the broken down component will be repaired or replaced so that redundancy keeps on being guaranteed.

To begin with there is a redundant battery swapping station. This is determined from the lifetime of a similar battery swapping system of 4 years. This would come in to use if another is damaged by, for example a UAV or storm. It could also occur that one of its functions fail, such as the fire alarm system, the moving roof or the battery swapping system. In case of damaged UAVs, the damaged UAV will shelter and wait for maintenance while a redundant UAV takes its place. The current system stores 15 of such back up UAVs. This is similarly determined by the lifetime of the UAV of 2 years. A different redundancy is applied in the compliance with requirement **SR.pwr.18.SUB.1**, which specifies that the battery should still have 10% of its power before it start charging. This gives space for avoidance manoeuvres or circling before landing the UAV.

One more redundancy is applied in the battery swapping system. Since there is such a large amount of batteries used in the system, a failure of, for example, 10 batteries should not disturb the operations. If a battery fails prematurely, a different, fully charged battery will be used. This is causes the other drones to use their current batteries for a few more cycles, reducing their capacity. However, the fact that so many drones are in use, the overall decrease in capacity can be neglected.

Another redundancy in place is the temperature measurement of the anemometer. If the temperature sensor on the UAV fail, the anemometer can take over the temperature measuring function. The accuracy would, nevertheless, increase to 2 $[°C]$, which exceeds the accuracy requirement. However, this is still preferred to no temperature measurement at all and would in anyway act as a place holder until a back up drone is ready or maintenance is applied. Lastly, redundancy is added at the master command station, which processes the measurement data. Next to sending the data to the shore, the processed measurement data will be stored on an external hard drive. This will make sure the data is still available even if an error occurs in the transmission. Moreover, a redundant antenna is added to ensure there is still a communication line between the master command centre and the drones, ground stations and the client.

5.1.10. Maintenance activities outline

Since this system should be operational for over 25 years, a large amount of maintenance will be required throughout its lifespan. Maintenance should also not take too long to perform, as it influences the availability of the system and would increase cost. This is specified in requirement **SR.rel.1.SUB.1**. This results in an allowed maintenance of 960 hours for four years. The division of those maintenance hours is shown in Table 5.1.

The set up time for the ground station and UAV, as mentioned in Section 5.1.5 is taken as a basis. Every two years the UAV is replaced and the same set up time applies each two years. The same holds for the ground station, except that this is replaced every four years and only the battery swapping stations are replaced. This results in 32 hour maintenance every four years for the ground station.

By the manufacturer of the UAV a scheduled maintenance and replacement of a number of components is set at one year. This will take longer than setting up the UAV, because it needs to be inspected, taken apart and partially replaced. It is estimated this will take double the set up time. Lastly, it is assumed every half year, some drones need to be repaired or replaced because of damage or failure. This is allocated to be 39 hours every 6 months in between a big maintenance or replacement cycle. The specification on the specific maintenance on parts of the UAV is stated in Figure 5.1. Finally, a large amount of hours are left for unscheduled maintenance. The amount of hours this takes cannot be predicted and can vary per maintenance cycle. However, things to be considered in this maintenance cycle are damage of components before they are scheduled for maintenance. For example, a UAV could be struck by a bird and land in the sea, the retrieval of the drone would fall under unscheduled maintenance. The maintenance or replacement of the shelter stations and maintenance without replacement on the ground station also falls under unscheduled maintenance. Every maintenance cycle cleaning, inspection, software updates and if necessary repairs, replacement and calibration are performed.

	Maintenance hours		
Years	**UAV**	**Ground station**	**Unscheduled**
0	78	160	38
0.5	39	0	38
1	156	0	38
1.5	39	0	38
2.0	78	0	38
2.5	39	0	38
3.0	156	0	38
3.5	39	0	38
4.0	78	32	38
Total	624	32	304

Table 5.1: Allocated maintenance hours for the UAV and ground station divided over 6 month periods.

	Custom repair	Basic tuneup	Complete refresh
Software upgrade	✓	✓	✓
Recalibration of sensors	✓	✓	✓
Full inspection and test flight	✓	✓	✓
New propellers		✓	✓
New motors		✓	✓
New speed controllers		✓	✓
New BECs		✓	✓
New servos		✓	✓
New connectors			✓
New board computers			✓
New GPS			✓
New power module			✓
New wiring			✓
Recommended after	Crash or damage	12 months	24 months

Figure 5.1: Scheduled maintenance provided by Vertical Technologies [13]

5.1.11. RAMS conclusion

In conclusion, the analysis of the RAMS characteristics has guided the design team in ensuring the system is reliable, available, maintainable and safe. This is incorporated in all parts of the design process.

The system is reliable, because the lifetime of the separate components has been considered and they will be replaced once the end of life of a component has been reached. This decreases the probability of premature failure. The system is also reliable in the sense that it is able to operate under the required wind speeds, as the UAV has a 14 $[m/s]$ wind resistance while it has to be able to operate in wind speeds of up to 11.7 $[m/s]$ on average. The reliability of the system is also proven by the fact that the system is able to operate under rainy conditions up to 10 $[mm]$. The UAV can be improved by better dust ingress protection and even better reliability under wet conditions. Lastly, the operational temperature range influences the reliability as well. This range is guaranteed by the range of the UAV given as -20 to 45 $[°C]$ and by sheltering in a heated UAV station when the temperature drops below -20 $[°C]$. The availability is also dependent on the reliability of the UAV and is therefore also connected to the characteristics discussed above. Next to those points, charging time has an influence on the UAV's availability. As the charging time is only five minutes because of the battery swapping system, this will not be a problem for availability. Although, the time this takes is still an assumption and can change in further design phases. The set up time of the system also influences availability. This is mainly important for the first time the system is integrated and for when complete parts are replaced. The set up time for one ground station, UAV or battery, is one working day. The time it takes to set up a UAV is assumed to take one hour. Both reliability and availability are also increased by the use of redundancy. One battery station, 19 UAV's, an antenna on the master command station, an external hard drive, a redundancy in charging cycles and the temperature-measuring ability of the anemometer are all included as redundancy in the system. The maintainability of the system is guaranteed by scheduling maintenance hours per system and including hours for unscheduled maintenance. Safety is ensured by analyzing the risks of the system and by realising what the safety critical functions are. These critical functions can be made less critical in future design by paying more attention to these functions in the design. The risk mitigation of collision avoidance is mainly discussed in Section 5.3.

5.2. Sustainability analysis

To facilitate decision-making for a sustainable design, a Life Cycle Assessment (LCA) must be done. The results of an LCA will highlight the significant issues in the design, from which conclusions and recommendations may be made. Furthermore, the LCA will allow for a comparison between the chosen design and existing systems that can be considered as alternatives. The issues in the design are identified through the analysis of the environmental impacts of unit processes that are active throughout its life cycle. A unit process is defined, by the ISO 14040 principles and framework, as the "smallest element considered in the life cycle inventory analysis for which input and output data are quantified". The input data includes materials, energy and resources. The output data includes products, waste to treatment, and emissions. In brief, the design's life cycle will be comprised of all the unit processes that contribute to it. SimaPro was the software used for the LCA, in conjunction with the comprehensive ecoinvent v3 database [33].

Figure 5.2: The LCA framework

5.2.1. Goal and Scope Definition

The goal and scope definition is as follows: An LCA will be carried out to present the environmental impacts of a swarm of UAVs with the purpose of data collection, assuming it will be of use for 25 years, and operational in the offshore territories of the Netherlands. Part of the scope identification is identifying the system with which the UAV swarm design will be compared to. In order to do that, the identification of a functional unit must be done; a functional unit addresses the aspects that are relevant to systems with the same purposes, and will be used to decide which unit processes to include in the inventory analysis phase of the LCA [34]. Unfortunately, a functional unit cannot be made because there are no existing alternatives to the chosen design that can take spatial and temporal measurements to a similar scale in an offshore wind farm. Nonetheless, the system with which the final design will be compared to is the following: A system comprised of a wind LiDAR mounted on every nacelle of a 100 $[km^2]$ offshore wind farm for the collection of wind data. Another aspect of scope definition is the identification of system boundaries. System boundaries simplify the LCA, and provide a clear outline for the planning of data collection in the subsequent phase [35]. In this phase, two more assumptions were made to further simplify the LCA of the design, that is:

- Only the components that were presumed to have a considerable influence on the sustainability of the manufacturing and assembly process were considered.
- The end-of-life phase was not taken into account. Recycling lithium-ion batteries with the current technologies available is an expensive process [36], which would exceed the budget allocated for decommissioning. Hence, it will not be considered at this phase of the design. Furthermore, the disposal of batteries will not be considered entirely, as it would contribute to the continuation of natural resource extraction to reproduce a system like this; for example, to produce one tonne of lithium, $500,000[gallons]$ of water would be required [37]. Manufacturing batteries is the most environmentally-damaging phase of the design, which will be apparent further in this section.

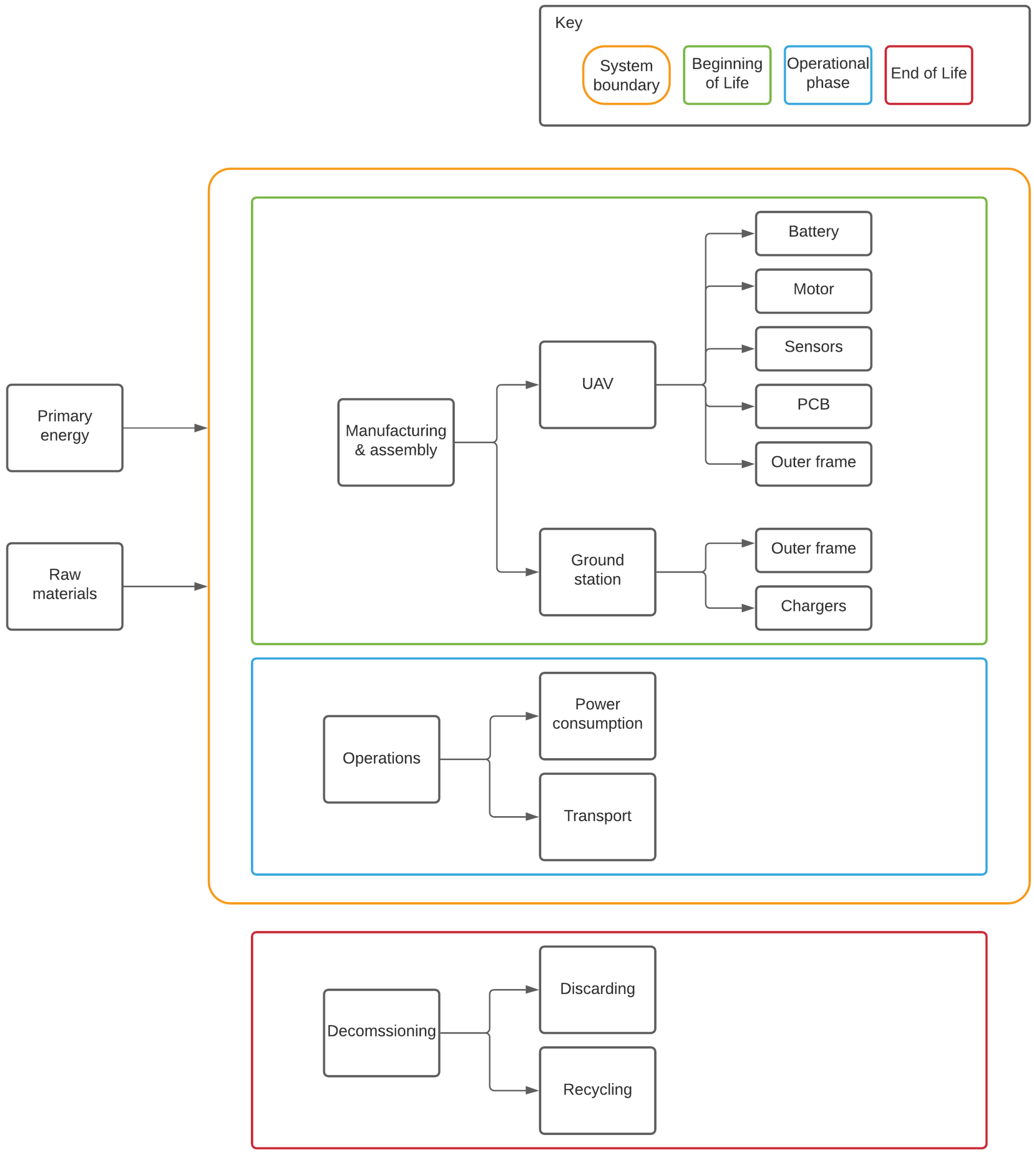


Figure 5.3: System boundary of the LCA

5.2.2. Inventory analysis

The inventory analysis is dictated by the goal and scope definition, and it is the phase in which all the unit processes within the boundaries of the system are collected [38]. Unit processes were chosen from the ecoinvent database in SimaPro. In the beginning-of-life phase, all the components depicted in Figure 5.3 and their sub-components and manufacturing processes were considered. For example, for the outer frame of the UAV, the following inputs were included:

- The material required (EPO foam (Expanded PolyOlefin) and carbon fibre)
- The processes (for example: injection molding)

During data collection, the lifetime of each component was taken into account, and the amount of each component required (in $[kg]$|) for the duration of 25 years was considered. For example, 731 batteries are required at a time, and the lifetime of a battery is 6 months. Hence, for a lifetime of 25 years, knowing the batteries weigh an average of $2.5[kg]$ each [4], $91375[kg]$ of batteries would be required, and the input in SimaPro would be represented as follows:

Output	**Input**	**Amount**	**Unit**	**Quantity**
Battery	Battery cell, Li-ion{GLO}|market for| Cut-off, U	91375	[kg]	Mass

Table 5.2: A unit process input in SimaPro

It is worth mentioning that certain unit processes in the database are not updated, and can be based on outdated data and methodologies. In addition to that, a unit process is usually a compilation of at least 100 flows. Hence, for simplicity, it was assumed that all the data chosen was updated and corresponded to the latest technologies used in the market. Furthermore, the database includes unit processes from various locations around the world; the "global" standard option was mostly chosen, and where not possible, the geographic locations that were relatively similar to the Netherlands was chosen.

5.2.3. Impact assessment and Interpretation

In the impact assessment phase, the information gathered from the previous phase is translated into environmental impact scores. A collection of impact categories can be found by choosing an LCIA method. The LCIA method chosen for this LCA is the ReCiPe model; the ReCiPe model was created by the RIVM and other dutch institutions on behalf of the Dutch Ministry of Infrastructure and the Environment, and hence was considered the most suitable model in correspondence with the scope of the LCA [39]. The environmental indicators in the ReCiPe model are the following: climate change (Human Health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, climate change (Ecosystems), terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agriculturual land occupation, urban land occupation, natural land transformation, metal depletion and fossil depletion. Of the aforementioned indicators, the ones that make a notable contribution to the analysis are the following:

- Climate change (Human Health)
- Human toxicity
- Particulate matter formation
- Climate change (Ecosystems)
- Metal depletion
- Fossil depletion

The remaining indicators have been omitted from Figure 5.4 and Figure 5.6 in order for the reader to have a better overview of them. The results of the impact assessment are represented in Figure 5.4, Figure 5.5, and Figure 5.6. The unit $[kPt]$ is an eco-indicator point; the higher the point, the greater the environmental impact.

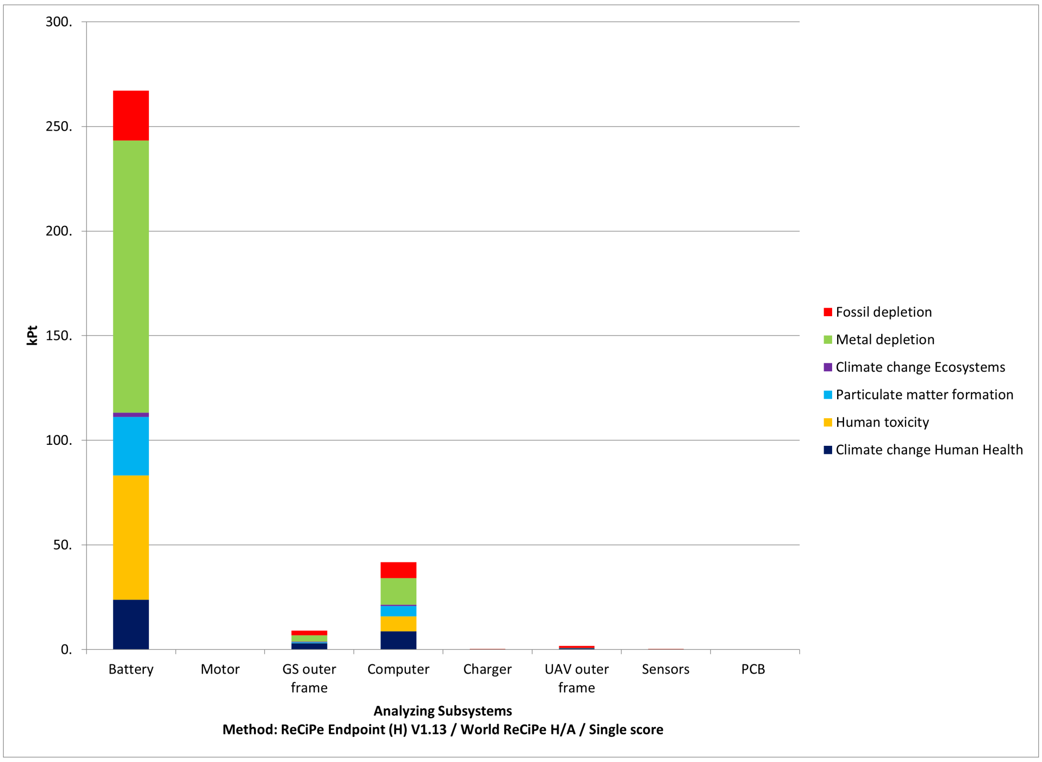


Figure 5.4: Main components of the design translated into impact categories.

From Figure 5.4, it is clear that the batteries are negatively influential and significantly supersede the other components. This is justified due to the short lifetime of the batteries, the number of batteries that would be needed, and the natural resources required to manufacture them.

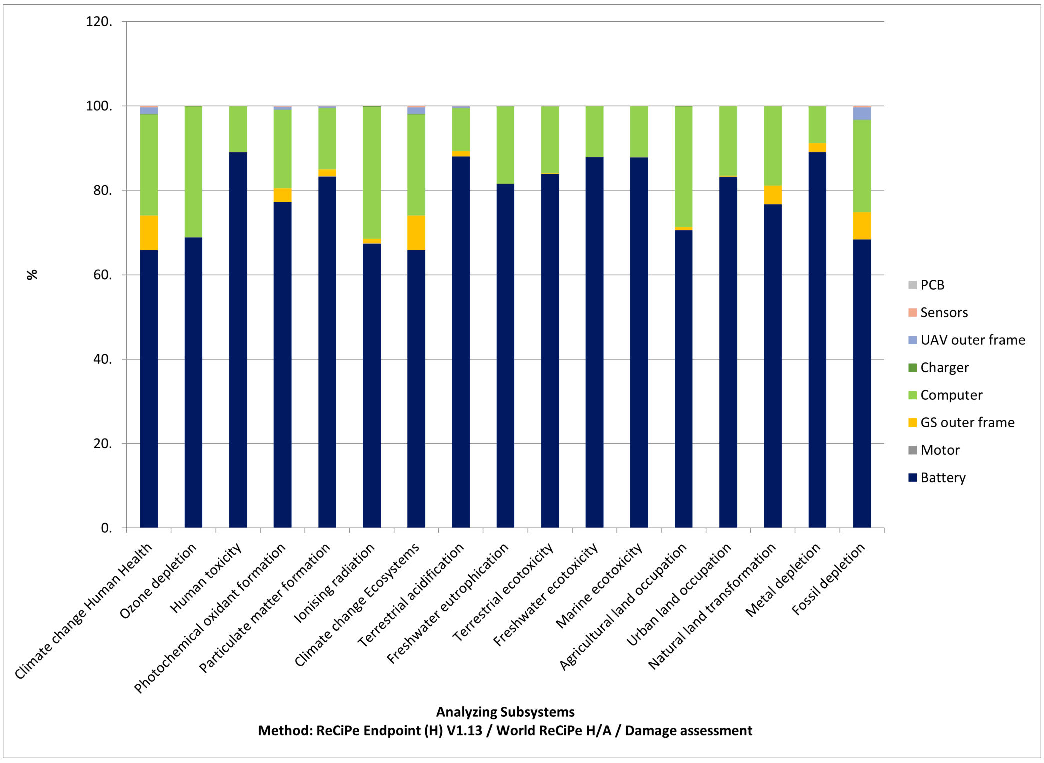


Figure 5.5: Contribution of subsystems to the impact categories.

From Figure 5.5, it can be concluded that the batteries have the greatest negative impact across all the categories in the ReCiPe model. Furthermore, it also shows that the computers required for the ground stations would also have a considerable impact across all the indicators.

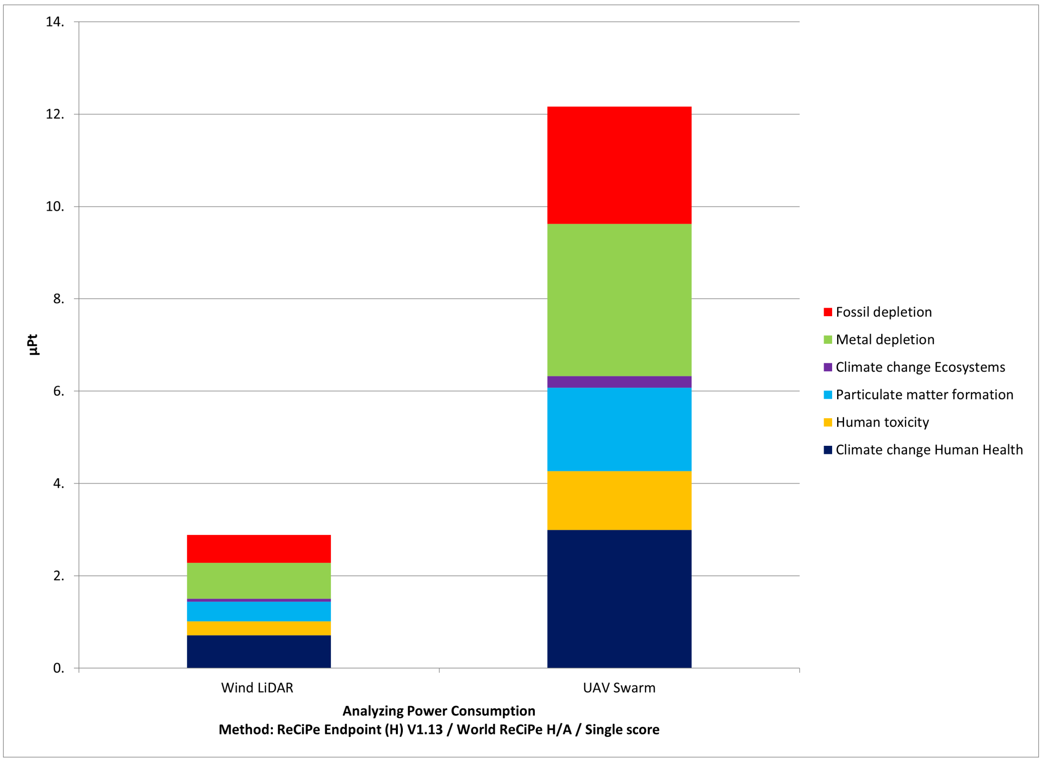


Figure 5.6: Power consumption analysis of the two different design concepts.

By analyzing the second system in the LCA (the wind LiDAR system), it was observed that the phase in which the wind LiDAR system has a more significant negative contribution to the environment is in the operational phase. Nonetheless, the UAV swarm design consumes almost 3 times as much power as the wind LiDAR one. The final interpretation made from the analysis of these figures is that across the phases analyzed within the system boundaries of the LCA, the UAV swarm design is the least sustainable one, mainly due to the number of batteries which would be required, and the power consumption in the operational phase of the system.

5.2.4. Recommendations for a sustainable approach

The results of the LCA give an indication of what to focus on to improve the sustainability of the design. Several suggestions are in order:

- The current batteries chosen could be replaced with more efficient batteries with a longer lifetime.
- Delay the start of the implementation of this design until newer technologies that commercialize the recycling of batteries surface.
- Experiment with the use of replacements for lithium-ion batteries, from the TU Delft batteries lab [40], for example.
- Decrease the number of drones required by using more advanced sensors.
- Commercialize the UAV swarm system by expanding its use cases, subsequently raising more funds and allocating these funds into existing lithium-ion recycling solutions.

The aforementioned suggestions are based on the assumption that resolving the issue with batteries will independently significantly increase the environmental sustainability of the design, and that other suggestions, such as optimizing flight path that would lead to a decrease in operational time, would be relatively negligible compared to the former. These suggestions also assume that the final choice of design will be adhered to, and that no other alternative will be considered. Of course, this is a reasonable idea if the increase in AEP is significantly higher than the ones provided by existing solutions, and if the data required for the research of certain aerodynamic phenomena would be a meaningful contribution to academia; however, if this is not the case, it would be wise to consider alternatives, such as the wind LiDAR, which is a suggestion made on the basis of the LCA results and the environmental impacts analyzed. Other suggestions that have the potential to decrease the negative impact on the environment, that were not derived from the LCA:

- The system can be provided with a manual for troubleshooting and easy maintenance for offshore technicians.
- A retrieval system can be designed for the event a UAV is lost to the water. Possible ideas to explore are the use of fluorescent dye which can be released into the water, and would make visually tracking the UAV easier.
- Recycling the other components of the design, other than battery, to decrease certain impacts such as ”metal depletion” for these components.

5.2.5. Social & Economical Sustainability

Social and economic sustainability are aspects of sustainability that are not deeply explored in the LCA. Economic sustainability refers to ’economic development that does not have a negative impact on ecological or social sustainability’ [41]. A few measures were taken which ensured the profitability of the system. For example, the system costs less than half of the budget allocated to it. However, with current technologies, recycling every component of the system would overshoot the decommissioning budget allocated to that phase of the system. Hence, a suggestion to ensure that the economic sustainability is sustained in the continuation of the project, is to reduce the costs of recycling the system through further research of more efficient technologies.

Social sustainability is the human-aspect of sustainability; this aspect of sustainability was considered by making a marketable design, which would create jobs in the communities local to the wind farms in which this design will be implemented. Furthermore, through a marketable design, the following targets which were set in the baseline report [3], can be met:

- Create job opportunities for the manufacturing, maintenance, operation, and R&D aspects of the system.
- Provide a fair pay for workers throughout the value chain of the design by devising an economically feasible design solution.
- Maintain information transparency with the general public regarding sustainability measures and waste management, if required.

5.3. Technical risk assessment

After investigating the sustainability and the RAMS for the project it is important to map all the possible risks. When all risks are identified, each risk can be categorised by the probability of occurrence and the severity of the consequences it brings with them. Both the probability of occurrence and the severity of a risk are divided into 5 levels, which are specified in Table 5.3 and Table 5.4. These 2 parameters, multiplied with each other form a risk level, which indicates the urge to mitigate a risk. A distinction between different origins of the risks is made — there are risks that apply to the UAV, ground station or form a general risk. The risks are listed in Table 5.5 each identified with an ID, and also corresponding with the score of probability of occurrence, severity level, and risk level.

Table 5.3: Probability corresponding to probability level, derived from [42]

Probability of occurrence	**Probability range** (PR)
Very high (5)	PR $\geq$ 70
High (4)	50% $\leq$ PR $<$ 70%
Moderate (3)	30% $\leq$ PR $<$ 50%
Low (2)	5% $\leq$ PR $<$ 30%
Very low (1)	PR $<$ 5%

Table 5.4: Severity of consequence and description of mission impact, derived from [42]

Severity of consequence	**Description**
Catastrophic (5)	Mission failure or significant non-achievement of performance
Critical (4)	Mission success is questionable or considerable reduction in technical performance
Moderate (3)	Degradation of one or more secondary missions or some reduction in technical performance
Marginal (2)	Degradation of secondary mission or small reduction in technical performance
Negligible (1)	Inconvenience or non-operational impact

Table 5.5: Risks

Risk ID	Risk Discription	Probability	Severity	Risk Level
General risks				
R.A.1	Radio-frequency interference	2	3	6
R.A.2	Cybersecurity risk	3	4	12
R.A.3	Limited adaptability for wind farms	3	3	9
R.A.4	Strong winds/stormy conditions	4	4	16
R.A.5	Airworthiness legislation does not permit operation	4	5	20
R.A.6	Inefficiently planned flight path	2	2	4
R.A.7	Unresponsive master communication center	2	4	8
R.A.8	Risk of high electronic waste	4	2	8
R.A.9	Data loss due to malfunctioning hardware	3	3	9
R.A.10	Resources for components scarce	2	3	6
R.A.11	UAV crashes at takeoff due to high winds	3	3	9
UAV specific risks				
R.B.1	UAV losing control due to wind turbine wake	3	3	9
R.B.2	Structure cannot withstand loads during its flight	1	3	3
R.B.3	Saltwater corroding UAV components	4	3	12
R.B.4	UAV catches fire	2	3	6
R.B.5	Wind turbine collision	2	4	8
R.B.6	Bird collision	2	2	4
R.B.7	UAV collisions	3	3	9
R.B.8	Short circuit due to moisture	4	4	16
R.B.9	Icing on rotor blades in cold conditions	4	4	16
R.B.10	UAV runs out of battery mid flight	2	2	4
R.B.11	Too many UAVs in maintenance	4	3	12
R.B.12	Sensor malfunctioning	2	3	6
R.B.13	Data gaps due to loss of UAV	3	1	3
R.B.14	Degredation of UAV's body	4	4	16
R.B.15	Incorrect measurement data from Anemometer	3	3	9
Ground station risks				
R.C.1	Lipo fire	5	5	25
R.C.2	Groundstation failure	2	4	8
R.C.3	Nacelle itself catches on fire	1	4	4
R.C.4	Battery switching system fails	2	4	8
R.C.5	Deploying system fails	2	4	8
R.C.6	Animals intrude ground station	2	4	8
R.C.7	Theft	1	4	4
R.C.8	Lightning strike	1	3	3
R.C.9	Weather effect on ground station	3	3	9

Table 5.6: Risk map

Risk Map			**Severity of consequence**				
Legend			1	2	3	4	5
High		5			R.A.8		R.C.1
Medium High		4		R.C.2	R.B.3, R.B.11	R.A.4, R.B.8, R.B.9	R.A.5
Medium High		3	R.B.13		R.A.3, R.A.9, R.A.11, R.B.1, R.B.7, R.B.15, R.C.9	R.A.2, R.B.14	
Medium Low	**Probability of occurrence**	2		R.A.6, R.B.6, R.B.10	R.A.1, R.A.10, R.B.4, R.B.12,	R.A.7, R.B.5, R.C.4, R.C.5, R.C.6	
Low		1			R.B.2, R.C.8	R.C.7	R.C.3

Risks with a higher level form a bigger threat to the success of the mission and therefore need to be mitigated. Approaches to mitigate these are explained in the following subsection Section 5.3.1. This can either be done by lowering the severity of consequence, the probability of occurrence, or a combination of these two. On the other hand, risks with a lower level form a less direct threat, this can come due to a lower probability of a risk occurring, a low severity of consequence, or a combination of these two. These risks do not have to be mitigated instantly, however an eye should be kept open to see if the risk level stay low and does increase over time.

5.3.1. Mitigation strategies

With the risks explained, these have to be mitigated against. In the following list below, the risks are divided per risk levels, going from high, to medium-high, to medium, represented by red, orange and yellow respectively. Risks with a severity level of medium-low or low are not mitigated against as they do not pose a substantial threat to the system. Each item in the list represents a mitigation strategy for a risk, with the risks identification number given as reference to which risk is being mitigated.

- **High level Risk mitigation strategies, red risks -**

R.A.5 - Close contact with regulating parties must be obtained and maintained to discuss new exceptions for the regulations. By starting early with these negotiations, the chance of getting hindered by legislation can be lowered. Nonetheless, the risk officers should maintain high attention to this due to the high level of severity even after mitigation.

R.C.1 - LiPo batteries have a lower thermal stability and when failing can cause fire or in some cases even explosion[43]. The ground station will be fitted with special LiPo protection systems and the charging of the batteries will closely be managed to try and prevent malfunctioning during charging and storage of the batteries. Both this measures decrease the probability and severity of risk.

- **Medium high risk mitigation strategies, orange risks -**

R.A.2 - Extra focus should be laid on cybersecurity to prevent digital attacks that could take control of the UAVs. Security measures such as end to end encryption for communication will be taken into account. During the operation phase of the system, cybersecurity risks should be kept an eye on for new risks and security measures should be updated regularly.

R.A.4 - The ground stations will consist out of a strong metal container that is designed to withstand big storms and protect the UAVs during a storm.

R.A.8 - During the life of the system a lot of batteries will be used and replaced. Although it is not a direct risk to the mission success, sustainability is deemed highly important and a plan for pend of life battery processing is implemented in the design. The used batteries will have to be recycled at a later phase of the system's life and alternative sources for energy storage will be investigated further Section 5.2.4
autorefsubsec: fwuav

R.B.8 - The UAVs inevitably will have to fly through rain. To prevent short-circuits from happening, all electrical components will receive an epoxy resin layer to protect it from moisture, reducing the chance of short-circuits and thus mitigating the risk.

R.B.9 - In-flight icing of a UAV causes safety and performance concerns that can lead to malfunctioning of the drone.[44] In the flight planning of the drone, cold conditions should be taken into account such that risk R.B.9 can be mitigated and the drone will not have to fly in these conditions.

R.B.14 - The UAVs will be coated to prevent degradation. In addition, the UAVs get replaced once in two years. Both these steps highly reduce the chance of this risk of happening.

- **Medium risk mitigation strategies, yellow risks -**

R.A.7 - There will be a backup communication system that can be used when the normal communication system malfunctions.

R.A.9 - The measured data is sent directly to the ground station, if there is still a problem with the data processing inside the UAV itself, there are back up UAVs that can replace a broken unit.

R.A.11 - When the UAVs are taking off they can be overwhelmed by a strong wind compared to the windless conditions inside the ground station itself. Therefor a TriSonica Mini is also implemented at all the ground stations. If the wind speed, this will prevent the launch of a UAV.

R.B.1 - To be able to measure the all the required measurement points, the UAV needs to fly through the wakes of wind turbines. Careful weather monitoring in combination with flight planning, can be used to forecast if the winds are not strong enough can reduce the probability of losing control in the wakes, and mitigating risk R.B.1

R.B.3 - The UAV will be coated with a resin that prevents the circuit from becoming wet and corroding. Next to that the UAV itself is replaced every 2 years. Both these measurements reduce the probability of corrosion.

R.B.5 - By careful flight planning, described in Section 2.3.4, the probability of a collision with a wind turbine or 2 UAVs colliding into each other is decreased. Non-solid and moving objects such as humans and boats can be added to the system when there is extra activity at the wind farm.

R.B.7 - By careful flight planning the probability of a collision with a wind turbine or 2 UAVs colliding into each other is decreased.

R.B.11 - By having an overview about the spare, operational, and broken UAVs, a shortage of UAVs can be spotted early on prevented reducing the probability of this risk occurring.

R.B.15 - Outliers are filtered out and will not be taken into account as accurate data.

R.C.4 - There is one redundant ground station. If the battery switching system fails, the system will still be able to operate with one ground station not operational.

R.C.5 - Same mitigation strategy as R.C.4

R.C.6 - Same mitigation strategy as R.C.4

R.C.9 - The ground station will be fitted with a climate control system including heating and cooling elements. A proper maintained temperature inside the ground stations reduces the probability and risk of the ground stations in cold conditions freezing up or malfunctioning due to other weather conditions which could affect the performance of the whole system.

For all the risks that could be mitigated, a new chance of occurrence and severity of consequence including risk level is given. The new values are plotted in a new mitigated risk map to show the danger of each risk to the system Table 5.7.

Table 5.7: Post-mitigation general risk map

Risk Map			**Severity of consequence**				
Legend			1	2	3	4	5
High		5					
Medium High		4		R.A.8, R.C.2	**R.A.4**		
Medium High		3	R.B.13	**R.B.15**	R.A.3,	**R.C.1**	**R.A.5**
Medium Low	**Probability of occurrence**	2		R.A.6, R.A.7, R.A.9, R.B.6	R.A.1, R.A.10, R.A.11, R.B.1, R.B.3, R.B.4, R.B.7, R.B.11 R.B.12, R.B.14R.C.4, R.C.5, R.C.6, R.C.9, R.C.10	**R.A.2, R.B.8, R.B.9**	
Low		1		**R.B.10**	R.B.2, R.C.8	**R.B.5,R.C.7**	R.C.3

6 Financial viability analysis

This chapter analyzes the compliance of the final system design to the financial budgets set out in the midterm report [1] and verifies the systems financial viability. This is done by first providing an elaborate Cost Breakdown Structure (CBS), then analyzing the wind farm market such that finally, the Return on Investment (ROI) can be estimated for the final product. With this, it becomes clear whether the designed system actually could pose a feasible investment to wind farm operators and therefore dictates whether the system is viable or not.

6.1. Cost Breakdown Structure

To obtain a clear overview of the product cost, a cost breakdown structure is constructed. A cost breakdown structure is a tree like structure detailing all the elements that contributes to the cost of the product, as shown in Figure 6.1.

The cost of the product can be broken down into three main categories: initial cost, operational cost and end of life cost. These are further branched out into sub categories and then elements in each sub category. The initial cost includes the cost of the UAV, ground station, the initial batch of batteries, and the development. The operational cost over the period of 25 years will include maintenance and battery replacement, this is where the majority of the budget goes. The end of life cost is the cost of decommissioning the product.

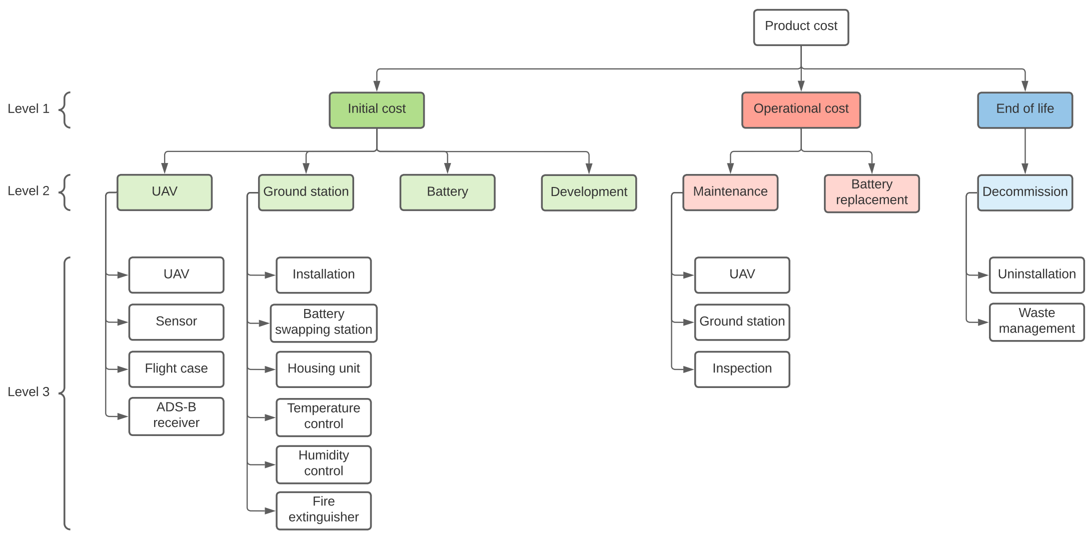


Figure 6.1: Cost breakdown structure

The initial cost for the UAV is a combination of the UAV cost itself and other components needed to be installed. This consists of sensors, flight case and receiver. The selected UAV costs 10000 [€] and with 78 UAV in the system, this brings the total cost of the UAVs to 780000 [€].

The initial cost for ground operation includes the cost of installation, the battery swapping station, the housing container and other components required to keep the batteries stored safely. The development cost includes the testing cost and the salary for eight team members working 8 hours for 10 weeks at an average aerospace engineer salary of 38 [€$/hr$] in The Netherlands.

INITIAL		
UAV	**946,625**	€
UAV cost	780,000	€
Sensor cost	112,375	€
flight case	7,750	€
ADS-B receiver	46,500	€
Ground	**154,040**	€
Total installation cost	44,540	€
Total battery station cost	60,000	€
Housing	23,000	€
Temperature control	4,400	€
Humidity control	3,200	€
Fire extinguisher	18,900	€
Battery	**160,820**	€
Development	**221,600**	€
Total INITIAL	**1,483,085**	€

The total operational cost can be computed from the operational cost per year over the 25 years period. The maintenance of the UAVs are crucial to the operation and will have a significant cost since the UAVs have to fly almost continuously for 6 months. Another significant cost for the operation is the battery replacement, since the batteries need to be replaced often.

OPERATIONAL		
Maintenance	**10,028,077**	€
Inpection	435,659	€
UAV	9,224,918	€
Ground	367,500	€
Battery replacement	**7,880,180**	€
Total OPERATIONAL	**17,908,257**	€

The end of life cost is associated with decommissioning the product. This includes uninstalling and waste management. Waste management is the cost of dismantling, reuse, and recycling components.

EOL

Decommision	**144,540**	€
Uninstallation	44,540	€
Waste management	100,000	€
Total EOL	**144,540**	€

This brings the final total cost of the product to 19,435,882 [€] as shown below. This is a slight increase from the initial estimation made in Chapter 3 due to extra cost arising from having more details added in the design. This should not affect the design or the trade-off in any way since the increase is comparatively small, the product cost is well under budget, and the effect applies equally for all the options.

Initial Cost	1,483,085	€
Operational Cost	17,908,257	€
End of Life Cost	144,540	€
Total Cost	**19,535,882**	€

6.2. Market analysis

It is necessary to explore any possible markets for the final product in order to estimate its attractiveness to customers. This section provides such market analysis, by first determining the product's added benefit to any wind farm, then by comparing the product to existing competitors and finally by determining how big potential markets are, e.g. how often the product could be sold. These results will ultimately be used by Section 6.3 in order to estimate the return on investment.

6.2.1. Calculating wind farm potential performance increase

Wind turbine operations can be categorized into four regions of wind speed: the wind turbine is inoperative during Regions I and IV, extracts maximum wind energy during region II and extracts only its rated power during region III [45]. This is depicted in Figure 6.2, which shows the power delivered by a normally operating wind turbine P_{norm} as a piecewise function of wind speed v. The set of equations corresponding to this graph is given in Equation 6.1. Here, P_{rat}, v_{rat}, v_{in} and v_{out} represent the turbine rated power, turbine rated wind speed, turbine cut in wind speed and turbine cut out wind speed, respectively. Furthermore, K_{opt} is defined in the appendix of [45] and η_{turb} represents the turbine efficiency. Assuming a constant η_{turb} with respect to wind velocity, K becomes constant as well and can then be calculated by Equation 6.2.

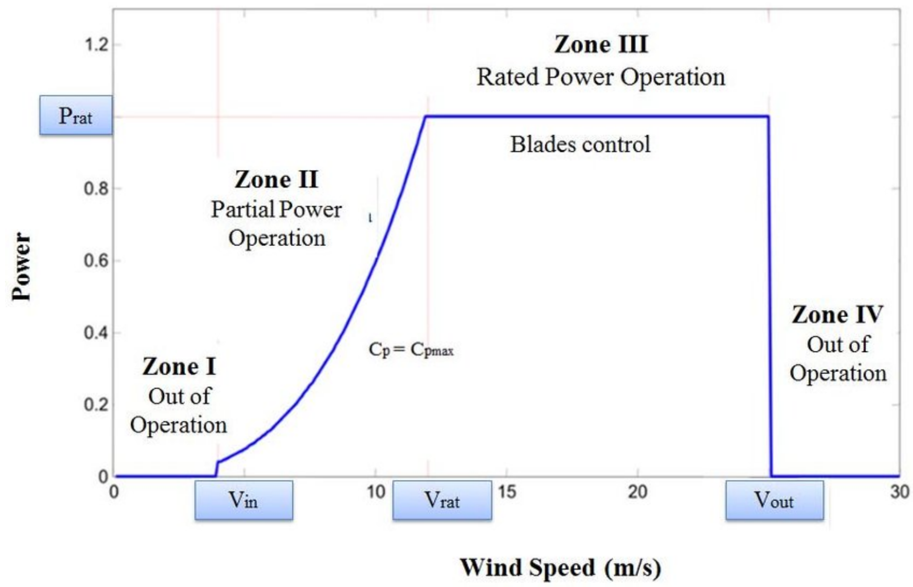


Figure 6.2: Wind turbine control regions [45]

$$P_{norm}(v) = \begin{cases} 0 & v \leq v_{in} \\ K_1 v^3 & v_{in} \leq v \leq v_{rat} \text{ with } K_1 = K_{opt}\eta_{turb} \\ P_{rat} & v_{rat} \leq v \leq v_{out} \\ 0 & v > v_{out} \end{cases} \tag{6.1}$$

$$K = \frac{P_{rat}}{v_{rat}^3} \tag{6.2}$$

The system will only affect wind farm performance when the turbines are operating in Region II control. Otherwise, the farm is either shut off or delivering the maximum rated power. Now, the performance increase that the system will provide during Region II is difficult to predict, but wind farm control can certainly be optimized. For example, [46] shows different optimization models for wind farm control providing gains ranging between 2% to 14%. Although these results are to be taken with a grain of salt, this proves that it is safe to assume that the designed system could increase wind farm performance by 5% during Region II control. With this, any potential farm performance increase can now be quantified.

This assumption changes the second equation of Equation 6.1: the power gets multiplied by 1.05 but also limited as the wind turbine cannot produce more than its rated power. This results in the improved turbine power P_{impr} function given by Equation 6.3. Figure 6.3 shows the power curves for an arbitrary wind turbine with normal control and a turbine with 5% improved Region II control.

$$P_{impr}(v) = \begin{cases} 0 & v \leq v_{in} \\ min(K_2 v^3, P_{rat}) & v_{in} \leq v \leq v_{rat} \text{ with } K_2 = 1.05 \cdot K_{opt}\eta_{turb} \\ P_{rat} & v_{rat} \leq v \leq v_{out} \\ 0 & v > v_{out} \end{cases} \tag{6.3}$$

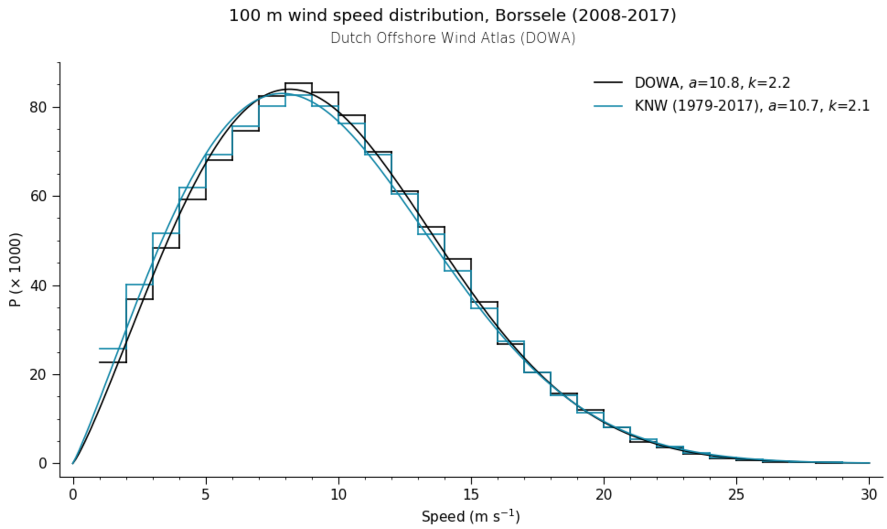


Figure 6.4: Weibull wind distribution parameters for Borssele wind farm area [49]

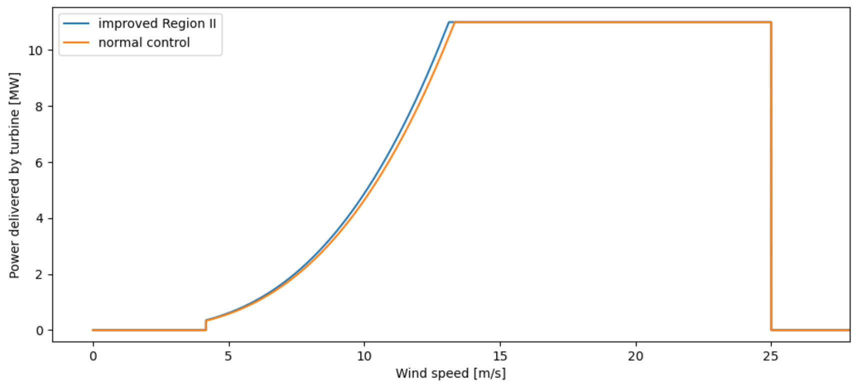


Figure 6.3: Difference in turbine power delivery due to 5% improved Region II control (for an arbitrary wind turbine)

In order to determine how the 5% Region II performance increase influences the average wind turbine performance, it is required to know how often a wind turbine operates in each region. This depends not only on the v_{in}, v_{rat} and v_{out} of the wind turbine, but also on how often wind blows between these wind speed ranges.

How often wind blows within a certain speed range can be estimated using the wind distribution parameters for the location where the wind turbine is placed. A Weibull distribution is typically used to represent the probability distribution of wind velocities for a certain location [47]. The Dutch Offshore Wind Atlas, a project aimed to provide better information on wind resources in the North Sea [48], provides Weibull distribution parameters for different farm locations in the North Sea. For example, Figure 6.4 shows Weibull parameters $a = 10.8$ and $k = 2.2$ for the Borssele wind farm.

With the power function for a wind turbine and with the Weibull distribution of the wind speeds where that wind turbine is located, one can estimate the average power delivered by the wind turbine. This is shown in equation Equation 6.4, where the wind is distributed as $X \sim \mathcal{W}(a, k)$ and

$P_{turb}(v)$ the wind turbine power for wind speed v defined by either Equation 6.1 or Equation 6.3.

$$P_{avg} = \int_0^\infty P_{turb}(v) \cdot P(X = v) dv \tag{6.4}$$

Using Equation 6.4, one can calculate the effect of the Region II performance increase on the average wind farm power generation as set out in Equation 6.5. For example, by using the Weibull parameters from Figure 6.4 and by using the cut-in speed, rated power speed and cut-out speed for the Siemens-Gamesa 8 MW turbines used by the Borssele 1 & 2 wind farms [50] (that is 3.5 $[m/s]$, 13 $[m/s]$ and 25 $[m/s]$ respectively [51]), one can find a performance ratio value $\phi = 1.0251$, meaning an average performance increase of 2.51% for the Borssele 1 & 2 wind farms if the system were to be installed.

$$\phi = \frac{P_{avg,impr}}{P_{avg,norm}} \tag{6.5}$$

The method set out in this subsection now enables the exploration of the possible return on investment for different wind farms if the system were to be installed on these wind farms. This will be the topic of Section 6.3. Next to that, Section 7.3 discusses how further work should investigate whether the 5% assumed performance increase during Region II control is achievable.

6.2.2. Comparison to competitors

In the space of wind farm measurements, there is no alternative drone swarm type system. This makes the system a highly unique product. In this sense it cannot be readily compared in terms of low-level metrics such as e.g. UAV endurance. Therefore, a comparison is to be done, looking at the net service provided back to the customer: the measured data.

It is found that there are two effective approaches in the current market: meteorological masts (a large tower placed inside a wind farm with measuring units placed on top) and LiDAR systems (either placed on the ground or on the nacelle of the turbines).

Meteorological masts provide point measurements, coinciding with the where the sensor is positioned on the mast. These masts cannot move and therefore the spatial resolution they can achieve comes from the density of these towers in the wind farm, this means that if you want a high resolution in space the system will be very expensive with single mast installation costing in the range of €10M [52]. However, the expected use case for these masts are not for full wind farm coverage, but to attain an idea of the meteorological status for the farm as a whole, therefore typically it would be expected to find one meteorological mast per wind farm to monitor operating conditions. The measurement quality can be very good as the sensors are stationary and the quality is limited only by the performance of the sensors used. The benefits of masts are the high real estate allowing for extension to facilitate further sensors for measuring a range of parameters. An example of this is the offshore meteorological mast at IJmuiden [53], where cup anemometers, sonic anemometers and wind vanes have been placed along the mast. This mast measures the wind speed/direction, temperature, pressure, relative humidity and lastly the precipitation continuously. Then from these signals further metrics such as horizontal wind speed (for 0, 120 and 240 $[°]$) and air pressure can be derived. To attain a full profile of the flow, sensors can be attached at a range of heights along the mast [54] [55]. The cost of these sensors, in the scope of this analysis, are negligible in comparison to the installation cost of the mast. Therefore, an estimate for the cost of a fixed mast installation over 25 years can be calculated with an upfront cost of 10M [€] and further yearly cost in the order of 250k [€], this value comes to 16.25M [€] [52].

LiDAR systems are the most popular remote sensing option, in the current market they are either placed at ground level (in the offshore case this requires a buoy), or mounted on the nacelle. From a high level, LiDAR systems have similar positives to meteorological masts in the sense that they have high quality measurements with high output rate, the difference in so far as the performance of the LiDAR, is the ability to measure remote points. With a lifetime of 2 years, and an estimated cost of €1-2M for offshore LiDAR systems, LiDARs quickly become an expensive option [52]. Even in the case of one single floating LiDAR (to mimic the role of a meteorological mast), the lifetime and system cost would produce a ballpark cost of €25M, twice that of the mast. The WindCube® from Leosphere ('industry's best vertical profiling LiDAR suitable for demanding offshore deployments'[56])[57], can provide measurements at a 300m range for 20 simultaneous levels, giving a realistic spatial resolution of 15m vertically, therefore a fine spatial resolution can be obtained in the horizontal plane within a measurable cone. However this system is mounted on a buoy, meaning that for wind farm coverage, temporal resolution would be extraordinarily high. Furthermore, the system provides near continuous measurements with possible sampling rate of 1 $[Hz]$ for raw data or 1-10 minutes for processed data (this is left to the user to decide). WindCube® Nacelle from Leosphere ('WindCube® Nacelle is the industry's most used and trusted nacelle-mounted LiDAR'[56])[58], gives measurements at 50-700m range at 20 levels simultaneously, with raw data output at 1 $[Hz]$ or averaged and processed every 10 minutes (again left to the user to decide).

In principle both work the same way, however the buoy mounted system looks to obtain a vertical profile of the flow, whereas the nacelle-mounted system measures what the face of the wind turbines 'see'.

Both meteorological masts and LiDAR based systems share the common ability to provide high quality data, however, what they both lack is a cost effective way to attain full coverage of a wind farm. From the current systems available it would be infeasible for masts to do given the €10M price tag for a single mast. Regarding the floating LiDARs it is technically possible, however with an infeasible temporal resolution. The gap in the market in this case is fairly clear, there is no product that can provide the atmospheric data for the entirety of a wind farm with an acceptable temporal resolution.

This is exactly what the drone swarm system provides, at the cost of two met masts and one vertical profiling LiDAR, for a lifetime of 25 years.

In the future, the wind energy sector is definitely transitioning from meteorological masts to LiDAR systems (SoDAR is also used, however LiDAR is much more popular), or even a combination of the two [59]. Therefore, the question becomes: is the drone swarm system competitive with remote sensing options going forward?

There is positive outlook for the future, currently the hole in the market is (ironically) coverage. Measurement quality is already high, that's why the buoy mounted LiDAR is a good step towards mobile LiDAR sensors. However, if the entire farm is considered then the temporal resolution is very poor. In the case of a 100 $[km^2]$ wind farm, either LiDARs will have to become cheap enough that they can be placed more densely in the volume or they can measure much further such that you can have solely nacelle mounted and they could sweep the volume for example. With the current state of the technology, drone mounted local sensors give the best wind farm coverage (in the sense they actually can cover the entire wind farm), this is unique selling point: full coverage with a reasonable temporal and a continuous measurement system at a reasonable spatial resolution.

6.2.3. Potential customers

With the method set out in Section 6.2.1, one can calculate the potential performance increase for different wind farms if the system were to be deployed in these wind farms. Table 6.1 shows potential performance gains for some Dutch offshore wind farms for which both turbine and wind data could easily be found online. In this table, the wind farm data follows from the Noordzeeloket [60], the Weibull distribution data follow from the DOWA [48] and the turbine specifications follow from an online wind turbine database [61]. Table 6.1 shows potential wind farm gains ranging from 2.0% to 2.7%, depending on the location of the wind farm and the type of wind turbines. The farms consisting of turbines with a bigger Region II control, that is when v_{in} and v_{rat} are further apart, show more potential performance increase. It must be noted that for the Vattenfall HKZ wind farm, turbine control speeds are not available as they are missing from the turbine specification sheet given in [61]. Therefore, the average speeds of $v_{in} = 4.17[m/s]$, $v_{rat} = 13.3[m/s]$ and $v_{out} = 25[m/s]$ are used.

Table 6.1: Potential performance gain for some Dutch offshore wind farms (based on data from [48], [60] and [61])

Wind farm	turbines	area $[km^2]$	$P_{rat,turb}$ $[MW]$	v_{in} $[m/s]$	v_{rat} $[m/s]$	v_{out} $[m/s]$	Weibull a	Weibull k	$P_{avg,norm}$ $[MW]$	$P_{avg,impr}$ $[MW]$	Potential gain
Borssele 1&2	94	112	8	3.5	13	25	10.8	2.2	336.8	345.4	2.55%
Princess Amalia	60	14	2	4	15	25	10.9	2.2	43.2	44.55	3.12%
Gemini	150	120	4	5	12	25	11.3	2.2	321.2	327.6	1.99%
Vattenfall HKZ	140	214	11	-	-	-	10.7	2.1	656.8	673.6	2.57%

Depending on the cost of the product, there might be a positive Return On Investment if the system were to be installed on any of these wind farms. This will be the topic of Section 6.3. The question that now arises is: are the wind farms depicted in Table 6.1 the only wind farms were the system would cause any performance increase? The answer is not straightforward.

Although Table 6.1 shows potential performance gains for all these wind farms, per wind farm it must be checked whether there is a business case or not. As there are many (>2300 worldwide [62]) offshore wind farms, this analysis of other regions will be left for future work.

Another question that arises is whether onshore wind farms could also experience increased performance due to the system, with the onshore sector currently comprising 89% of the total capacity inside the European Union [63]. Based on the fact that a typical onshore wind turbine has a similar size to the Princess Amalia wind farm turbines in Table 6.1 (2.5 - 3 [MW] [64]), it seems likely that onshore wind farms will also benefit from the system. As the wind onshore is also less constant [65], the Region II performance increase due to the added wind insights might even be higher than that for offshore wind farms. This must however be verified in further project work.

To conclude this section, one can assume that the system could have a positive impact on the performance of most of the many onshore and offshore wind farms but that detailed financial analysis must be carried out per wind farm to size the system. This will be the topic of Section 6.3.

6.2.4. SWOT analysis

Similar to the baseline report [3], this report will now investigate the Strengths, Weaknesses, Opportunities and Threats for the system and its market in which is going to operate, known as a SWOT analysis. The strengths and weaknesses follow from internal factors while the opportunities and threats follow from external factors. The SWOT analysis for the system is shown in Figure 6.5.

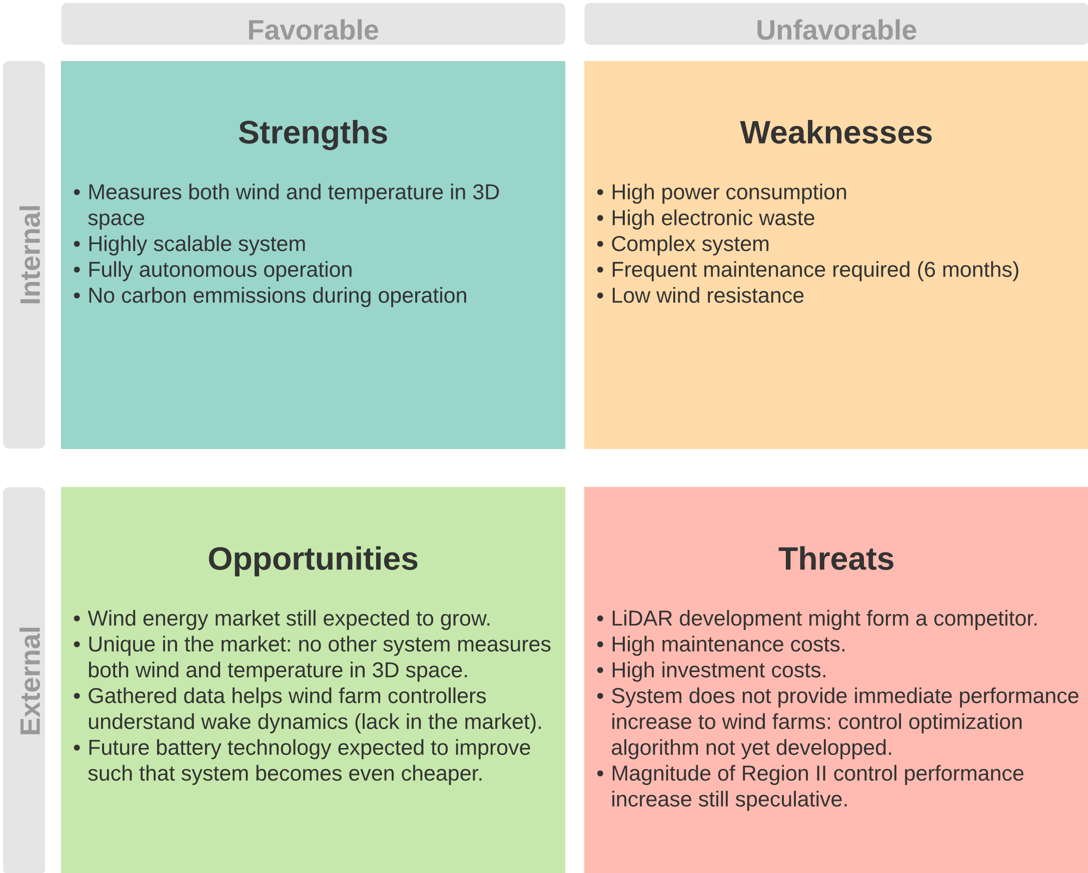


Figure 6.5: SWOT analysis for system

Strengths
The strengths of this system is immediately apparent from Section 6.2.2, where the clear gap in the market is ability to provide full wind farm coverage. This alone provides a unique selling point that can attract customers. Further, the system is highly scalable, if the user desires more frequent measurements at higher spatial resolutions, or even a smaller system to reduce costs, this is easily doable. No system redesign is needed, as UAVs/ground stations can be added/removed as seen fit depending on the circumstance. The systems ability to operate autonomously additionally reduces the need for human interaction, limiting it to every 6 months for maintenance. This reduces complexity of implementing and/or trialling the system. Lastly, from the perspective of sustainability, having no carbon emissions in operation is of great appeal to a sector focused on clean energies and sustainability.

Weaknesses
Throughout design the greatest limiting factor has been the power budget due to the drones requiring high power draw, this is exaggerated in the case of a local sensing design with the high number of required drones. However, with this high power draw comes short battery lives, which in turn leads to high waste production and subsequently frequent maintenance (every 6 months) to, amongst other tasks, bring in new batteries and take away old ones. Another weakness of the system is its complexity, with the high UAV number, additional complexity is introduced for swarm

design (see risk **R.B.7**) and day to day ground station operations. As an extension of this, damaged drones are likely to fall into the sea and create electrical waste (see risk **R.A.8**). Finally, the low wind resistance of the UAV is not ideal given the possible turbulent nature of airflow behind wind turbines, however given the improved efficiency of horizontal flight this is seen as an acceptable consequence of using hybrid drones.

Opportunities
A clear and obvious starting point is the expected growth of the wind energy sector [63], the possible list of customers will only grow and with it potential new challenges and use cases. However, this is not always a problem, as this leads to new functionality allowing high portability to alternate applications. More information on other applications can be found in Section 6.2.5. The inability for wind farm operators to gather the data necessary to understand wake dynamics is problem that this system quite uniquely fills in the sense that this system can measure the conditions behind all turbines in a farm. It is not the case like it is with vertical profiling LiDAR where a multi-million euro system is needed for one turbine, this makes this system highly unique.

Threats
As discussed in Section 6.2.2, LiDAR will develop and become smaller, lighter, cheaper etc. so it is not always going to be the case that there is no similar system that can provide full coverage in a reasonable time-frame. However, this is not to say that the system cannot itself develop and in future incorporate developments in LiDAR technology to remain competitive. Costs are high, with lifetime system costs of just over 20 million euros, the system is not cheap. However, compared to LiDAR and met masts as discussed in Section 6.2.2, for equivalent cost over a 25 year period, it does provide unbeatable coverage. Expected efficiency and performance gains are still speculative and can only be estimated. This area requires more research and investigation, though the argument could be made that this research may accelerated with a highly scalable system such as this to provide real life data.

6.2.5. Alternative applications

In its most basic sense, the drone swarm system is simply a methodical approach to the quick and accurate taking of measurements of an area/volume. If, with this simplified understanding of the product think on potential other applications, a lengthy list can be generated. Quite easily, if the sensors were changed, then the system can be ported to important projects such as:

- Air quality studies - measuring air toxicity around an area of interest
- Agriculture - measure growth rates of crops
- Surveillance - act as an improved form of CCTV

Even remaining in the wind energy space, this system would be very effective acting as a turbine inspection system. Moving over to this application would require again a change in sensor and a new, much simpler, route plan. This application would not even require a new system, this use case could be purely an extension of the current drone swarm system, where one drone may have a different sensor configuration that allows it to go from turbine to turbine, independent of the rest of the system.

6.3. Return on investment

Now that the cost breakdown structure and the market analysis is complete, the potential Return On Investment (ROI) can be estimated were the system deployed on a wind farm. The purpose of this section is to provide the potential ROI for different wind farms in Table 6.2. For convenience, this section continues with the four Dutch offshore wind farms mentioned previously in Table 6.1.

The ROI can be calculated by dividing the expected revenue gain by the total system costs, as shown in Equation 6.6.

$$ROI = \frac{\textit{Expected revenue gain}}{\textit{Total system costs}} \quad (6.6)$$

In this equation, the total revenue gain can be estimated by multiplying the increased wind farm energy yield (minus the system power consumption) with the so called 'sales value'. [66] argues that the expected revenue from wind energy is likely to increase, with predicted sales values of 53 [€$/MWh$] in the year 2025 up to 76 [€$/MWh$] in the year 2035. Taking the average of these two values, that is 64.5 [€$/MWh$], the predicted revenue gain values in Table 6.2 can be calculated.

The total system costs are currently estimated for a wind farm size of 100 [km^2] and although they do not necessarily scale linearly, one can get an estimate for system costs per wind farm by multiplying the previously calculated system cost with the area ratio $\frac{A_2}{A_{syst}}$ as shown in Equation 6.7. Here, C_2 and A_2 represent the total system cost and farm area for the wind farm in question, where C_{syst} and A_{syst} are the system costs and farm area of the basis wind farm. System power consumption can be estimated in a similar fashion. Using the results from Section 6.1, that is total system cost of €19.4M and total system power consumption of 17 $[kW]$, the predicted system costs and with that the ROI values can be calculated as shown in Table 6.2.

$$C_2 = C_{syst}\frac{A_2}{A_{syst}} \quad (6.7)$$

Table 6.2: Predicted return on investment for several Dutch offshore wind farms

Wind farm	Area [km^2]	Nominal farm power [MW]	System cost [M€]	System power usage [kW]	Power gain [%]	Revenue gain [M€$/25y$]	ROI
Borssele 1&2	112	336.8	21.728	19.04	2.55	121.2	5.58
Princess Amalia	14	43.20	2.716	2.366	3.12	19.04	7.01
Gemini	120	321.2	23.28	20.28	1.99	90.12	3.87
Vattenfall HKZ	214	656.8	41.516	36.17	2.55	236.8	5.70

Table 6.2 shows ROI values ranging between 3.87 and 7.01. That last value however is only suggestive as the Princess Amalia farm is 7 times smaller than the reference wind farm such that the assumption of linear scaling system cost does not hold anymore. With these ROI values, Table 6.2 proves that potential gains are likely achievable for any offshore wind farm. Especially taking into account the conclusion of Chapter 3, stating that the system is highly scalable, it is safe to say that for any offshore wind farm there is likely a viable system configuration that will provide a positive return on investment. Section 7.3 goes into more detail in what is required to perform a more reliable estimate of the ROI for different wind farms.

7
Project recommendations

Following the completed conceptual design phase of the project, the future of the design will be explored in this chapter. In Section 7.1, the timeline of the subsequent phases is outlined by a Gantt chart and visualized with a design and development logic diagram. In Section 7.2, the manufacturing and assembly are discussed, and a production plan is presented. Lastly, design recommendation for future iterations, for each subsystem, are discussed in Section 7.3.

7.1. Project planning

What type of testing is needed. For example, extensive validation procedures were recommended in chapter 3, but the link to this project planning is missing. Further, the Gantt chart seems to suggest that you would be able to have a working implementation by June 2022, i.e., within 5 months. Do you think this is feasible? This section is here to provide a plan on how the project should be structured into the future. This is done by fist providing the design and development logic diagram which is there to lead the future team through to system integration. This is then reinforced by the time line given in the Gantt chart for the future of the project.

7.1.1. Design and development logic

On a larger scale, this point of the DSE project is the end of the conceptual design phase. If this project were to be continued, the next phase would be the preliminary design, in which the focus will be on the UAV design as that could still be largely improved, followed by the detailed design phase, where all the subsystems will be analyzed in more detail and more extensive algorithms could be implemented in the swarm department, for example. Between these phases, a review would be done to ensure that the design still meets the set requirements, such as the cost budget. The design will then go through the process of acquiring the relevant certification. The production phase is one of the last phases, which is elaborated on in Section 7.2. Testing is the next phase, where components are not only tested individually, but also the synchronization of the subsystems and their coordination will be put to test. If testing proves the system functional, the final phase would be system integration, wherein the design is implemented on an offshore wind farm for operation.

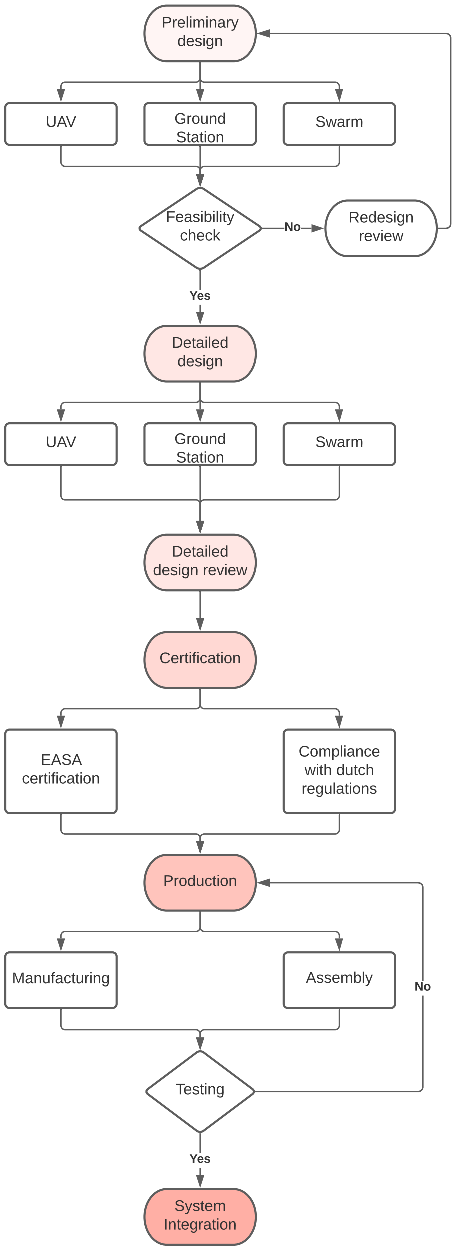


Figure 7.1: Design and development logic diagram

7.1.2. Project Gantt chart

Figure 7.2 gives a rough outline of how the project should be structured in the future. As Figure 7.2 is a gantt chart, the time line in which the future events are to take place is seen very easily. It is worth noting that although the time line spans a couple of months, this is not feasible and was only done so for visualization purposes. Following the time line it is clear that the project picks up right where the current report finishes, going strait into a more detailed preliminary design phase for the chosen design. Then going into a detailed design phase ironing out any of the kinks in the project and fully finishing the product ready for certification. The project then ends with the manufacturing and integration of the product.

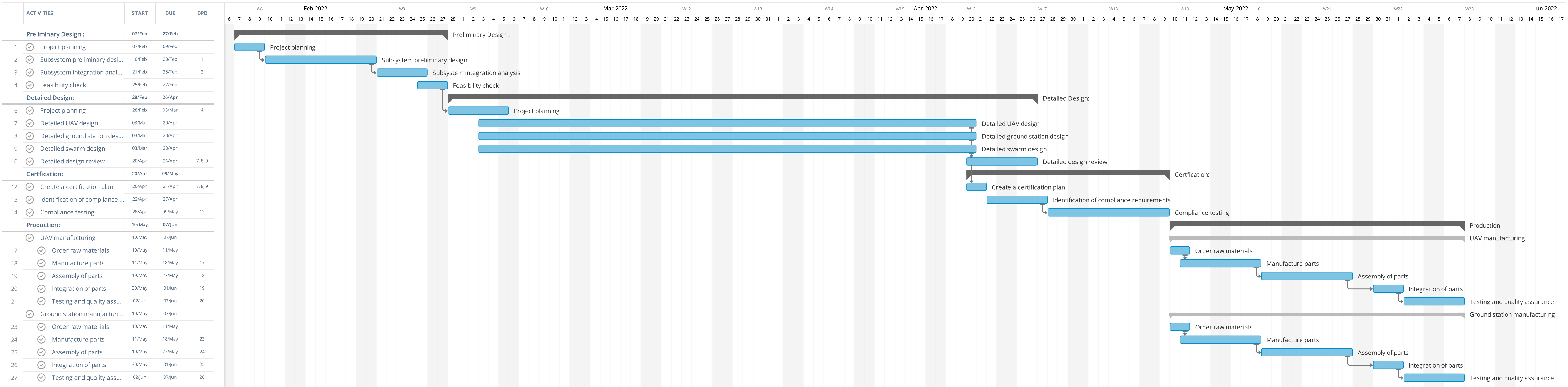


Figure 7.2: Gantt chart representing the timeline of the project continuation

7.2. Product manufacturing

This section describes the manufacturing of the final design for both the UAV and the ground systems. Firstly expanding on the assembly of the project components, then going into the different manufacturing processes and techniques. Finally this is all summarized into a production plan. The goal of the section is to describe the entire manufacturing process in sufficient detail to give a good estimate for the requirements on the manufacturing capabilities.

7.2.1. Reason for assembly

After completing the final design stage of the product, it is important to implement a production plan to determine how the product is to be manufactured. In this case there are two parts to the system that have to be manufactured, these being the UAV itself, and the ground support stations, both of these systems have very different requirements on their manufacturing needs. Thus for ease of manufacturing the two systems are separated into assemblies, there are many benefits to doing this however they all come down to one of these three aspects: increasing production efficiency, ease of production and ease of maintenance. Explaining each one of these aspects, starting with production efficiency, it is clear that breaking up a part into separate assemblies allows for several people to work on the same part at the same time rather than having to wait for the previous work order to finish. Workers are also able to have easy access to components that are otherwise unreachable in the final part. This then leads into the next aspect that being the ease of production, this comes more into effect for the ground system as it is a very large structure and splitting it up into assemblies has a much larger effect on the ease of production than the relatively small and light UAV. Thus splitting the part allows the part to come to the worker and not the worker to the part, meaning that its much easier and hence more efficient to work on the part, this can be chained to produce a manufacturing line, again another method to increase production efficiency.

Having the system operate in the harsh environment of the ocean it is important that the system in well maintainable. Dividing the product into assemblies allows for more easy access to the separate parts of the product allowing maintenance to be done more efficiently and easily on site, rather than having to cut into the final product to conduct maintenance. However there are some down sides to splitting up the product into separate assemblies for manufacturing. The product can not be split at just any location, the location of the assembly joint has to be considered carefully such that it does not disturb the structural integrity of the product. It is quite clear that cutting through a supporting member is not a good idea for structural integrity. This limits the number and location of the assemblies. The other aspect to consider is the type of joint that is required to join two assemblies, as a welded joint would severely hinder the ease of maintenance in the product if it stops access to a compartment, thus the joining mechanism have to be considered carefully as well.

7.2.2. Manufacturing

In this section the main manufacturing processes are explained for the main components of the product. Each of these processes have been chosen for their efficiency in manufacturing as well as their environmental and economic sustainability.

Firstly the ground station, as this is a fire proof box it has to be made of certain materials and using certain joining methods to prevent a fire from spreading from the box to the wind turbine. Checking commercially available fire proof boxes [67], its clear that they have to be made of high strength and high heat resistance steel, in this case 7035 sheet steel. Thus, these sheets can be ordered at the correct thickness and then cut to shape using water jet cutting, with an abrasive added to the water due to the high strength of the steel. The sheets can then be formed into shape using rubber forming or bending depending on the sheets thickness and required shape, rubber forming for thinner more complex shapes and bending for thicker less complex shapes. These sheets are then welded or bolted together to form a strong and cohesive unit capable of preventing the fire from spreading.

To add further structural strength, the box can be strengthened with a frame consisting of large reinforcing beams, these are needed due to the length of the box to prevent sagging. These beams can be ordered and cut to size using mechanical saws, and then welded together to provide the main supporting structure of the ground stations. This can then act as a jig to mount everything else too, as it is an open rigid structure.

The delicate electronics of the battery swapping and battery storage system can be assembled in a clean room to ensure that there is no dust or debris in the delicate electronics. These then have to be placed into electrical boxes both for the safety of the electronics from the harsh environment as well as any personal from interacting with the high voltages and current needed for the battery charging. These should however be easily accessible due to maintenance requirements, as well as the likelihood of failure of the components.

Moving onto the UAV. As the UAV is an off-the-shelf component and is not produced as part of the product, the manufacturing is rather focused on the integration hardware required.

The battery swapping system requires a socket to be installed on the drone to easily accept the swap-able battery, as this does not have to be structurally supporting and instead has to be as light as possible, it is made of plastic using injection moulding as several hundred of these are required. With the assembly of the drone being done with a conventional production using human labor rather than robots due to the complexity of the work. Splitting up the work into different work packages allows for a more efficient manufacturing processes.

The battery packs for each of the drones has to be assembled, the housing can again be made of plastic and produced using injection moulding, using the same mould as the battery socket to save money on the initial investment cost. The separate cells of the battery can be ordered from a manufacturer, however the assembly is done in a specialized battery assembly room due to the safety concerns that come with working with lithium polymer batteries.

The sensors can also be integrated with the UAV, preferably in a clean room due to the sensitivity of the sensors. The sensors will then also go through a verity of tests and calibrations both before and after integration to ensure that they work nominally.

7.2.3. Production plan

The production plan is shown in Figure 7.3, firstly it was split into two separate manufacturing lines one for the drone and the other for the ground station systems. This was done as the two systems are very different in their manufacturing needs, as the drone is simply being modified, where as the ground system has to be constructed from the ground up. Looking at Figure 7.3, it is clear that this is an overall layout of the manufacturing/production process from the raw materials to the end of life of the product. Both the UAV and the ground system follow the same manufacturing principle.

Explaining each step of the production plan in more detail. Firstly the ordering or manufacture of parts, here parts are ordered from a supplier or are produced from materials that have been ordered, indicated by the green or black border respectively, with the drone having much more supplied from the suppliers and the ground station manufacturing the majority of its components. The product then moves into assembly, donated by the yellow border, here different parts are put together to form sub assemblies these can then be further assembled into assemblies. These assemblies are then integrated into the final product or products, indicated by the blue border. To ensure that the product meets the requirements set upon it has to pass qualification, indicated by the purple border, here the product is tested and receives any safety certification that it requires. The product then goes into its operation phase indicated by the orange border, and then finally it goes into its end of life phase indicated by the red boarder where it is either recycled or dismantled, with reusable parts being reused and non reusable parts being scrapped or recycled.

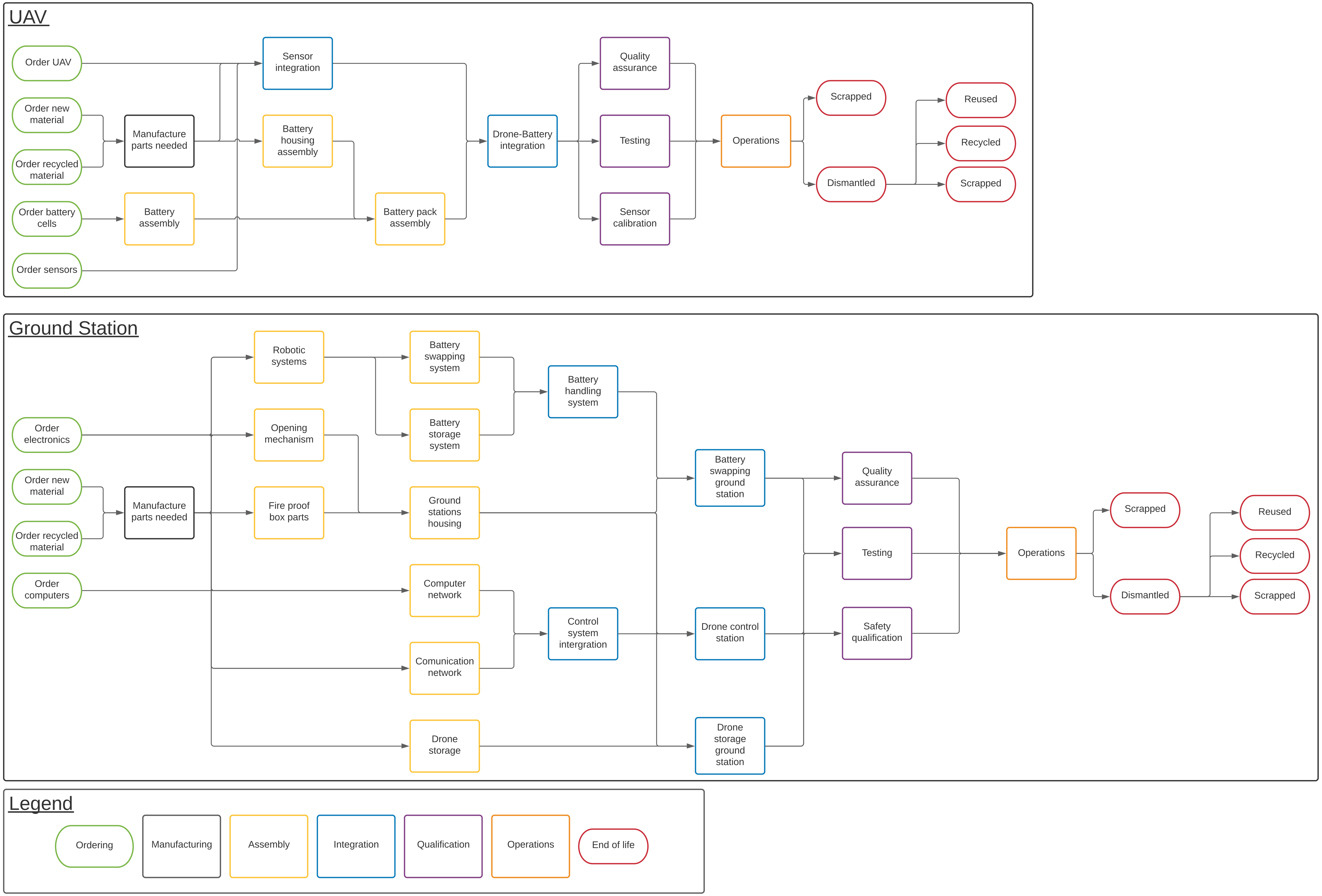


Figure 7.3: Flow chart showing the production steps of the two components of the project

7.3. Further work

During the design of this mission it was aimed to meet the stated requirements to the greatest extent possible. However, a design can always be improved in the future when more resources are allocated or new technology is available. This section presents a technical discussion on the further work recommended for the project divided into subsections for all three departments: UAV, swarm, and ground station design. Each subsection starts off with recommendations for the design if a few extra iterations could be run and can be implemented directly to the system without leading to a completely different system. This is followed by how the current design could be changed when there is a breakthrough in some areas or technology which can contribute to performance characteristics of the current design. Lastly, recommendations for a potential new design are given with expected developments of current technology and breakthroughs in current and new technologies.

7.3.1. UAV design

Starting with improving the current UAV design, extra attention could be focused upon robustness and sustainability. Currently the UAV is rated for an IP rating of 44. During extra iteration rounds there could be an attempt to seal off seams and joints further to certify the UAV for a higher IP rating, resulting in less dust and moist inside of the drone that can affect the electronics inside. At this stage, the materials out of which the drones are made bring limitations with recycling. Since every component in the UAV must be completely replaced after two years, as depicted by Figure 5.1, a big leap forward can be made by making all of these components of the UAV out of recyclable materials such as thermoplastics; this way, the entire system can be recycled when it is no longer operable. Although the manufacturer recommends to replace the whole UAV in two years, more research is needed if this is actually needed. Some parts of the UAV such as the carbon fibre frame might be useable for a longer period of time .Recycling all the components would be preferable over reusing them because recycling ensures that the need to harvest more raw materials for the production of a new system is decreased; as analyzed in the LCA, harvesting precious metals and other raw materials make up a significant portion of the negative impact the system has on sustainability. Lastly, more attention can be paid to the radiation shield of the RTD sensor. Not much information regarding radiation shields for RTD sensors applied to UAVs could be found, so extra resources could be implemented to research the shape and configuration of the shield to reduce extra induced drag and to increase the performance of the shield.

There are some promising developments in technologies that could be useful for improving some characteristics of the UAV design. Starting off with much research into Li-ion battery performance in combination with electric UAVs. For example, by making use of pulse charging in a proper way it can offer increased battery charge, energy efficiencies and increased battery safety [68]. In the current design, a large amount of batteries are needed during the systems operational lifetime and these batteries need to be discharged in a proper way. Room for improvement lays in the recyclability of the batteries that will be used and should be looked into [69]. Li-ion batteries are most certainly not at the end of their era and research is done into improving the energy density while maintaining lifetime and safety [70]. This research is promising for the development of battery lifetime and performance, resulting into a more sustainable design because of the lower number of batteries needed and an increase in endurance due to higher performance of the batteries.

Some technologies are being developed that are promising for fulfilling the current mission statement but require a complete change in UAV design. First is the use of solar powered UAVs, when taking the development of solar efficiency's and energy density is taken into account, solar powered UAVs can overtake non-solar-powered UAVs [71]. Hydrogen fuel cells have a high energy density and research is done into UAV application [72] and can strongly increase range and endurance compared to existing UAVs with conventional Li-ion battery packages[73].

At the begin of this design, measuring the wind speed with LiDAR technology seemed to be an option. Eventually this option was not chosen due to the too high mass of the LiDAR systems. However, with the development of more lightweight LiDAR, this could give the design an advantage in increasing the resolution of the wind speed measuring resolution.

7.3.2. Swarm design

The current obstacle avoidance and navigation system of the swarm department, meets the initial requirements successfully, however, large improvements can be made on the accuracy and speed of both obstacle avoidance and path generation. With the use of additional hardware and better automated decision making logic, unpredictable obstacles can be intercepted and avoided. Moreover, a graph based path planning method should receive further attention and research to optimise the current zigzag flight path procedure.

Graph exploration algorithms

As explained in Section 2.3, the k-Chinese postman (k-CP) and the Travelling salesperson (TSP) algorithms were investigated at the start of the swarm design. TSP was dropped from consideration due to time constraints and non-flyable tracks, however this does not mean that there is no potential in this approach. A different perspective on the use of TSP may be all that is needed. For example, if the process were to be to implement the TSP algorithm for multiple UAVs, to attempt to obtain some improvement over the zig-zag segments, it may be better to ignore the need for flyable tracks. First just get an idea of what the algorithm deems optimal, and then work back and attempt to translate those tracks to flyable ones, it may be found that this provides a quick way to obtain more optimal tracks than those given by the zig-zag program.

Further, k-CP and TSP are not the only graph inspection algorithms, more time can and should be spent investigating further algorithms that may provide better performance in this specific use-case. Building on this, towards the end of the design a paper outlining the implementation of path planning in dynamic scenarios using genetic algorithms to solve the multi-travel salesman problem [74] was found. This could provide extremely relevant information and advice on taking the next step towards a more efficient flight plan.

Further investigation in battery conscious path planning

Battery capacities reduce with each charging cycle, therefore the endurance of a UAV with an older battery will have lower endurance than a UAV with a brand new battery. With this in mind it may be pertinent to investigate the allocation of flight paths to drones based on their battery. For example, it may be more optimal to only allocate paths on the topmost layer to UAVs with newer batteries. This would produce a higher measurement efficiency as more time can be spent in horizontal flight along the measurable points compared to the transit time flying to and from the ground station.

Further research on collision avoidance methods

To begin with, regarding the collision avoidance subsystem, many simplifications have been made. While a lot of effort was put optimizing the speed of RRT by applying domain constraints, improved variants of the same algorithm have not been investigated. Multiple Rapidly-Exploring Random Tree (MRRT) in which an arbitrary number of RRTs are simultaneous expanded with two starting from start and goal, and the rest from predefined points or randomly-selected points[75]. Their aim is to enhance algorithmic performance and expansion issues. This of course, could result in a speedup of the current implementation, if efforts are also made to constrain the domain of exploration.

On the other hand, a lot of other advancements are also present in the field of A* algorithms, such as D*, or sometimes called Dynamic A*. In this algorithm, by making use of linear-interpolation and re-planning of existing nodes, low–cost and smooth paths are generated[76]. Other promising variants include Life Long Planning (LPA*), Differential A*, Generalized Adaptive A*, Anytime Repairing A*. More attention should be dedicated to comparing speed and accuracy wise between these solutions and integrating them within the current system. With the use of external hardware these robust and matured path planning algorithms can be further optimised by adding constraints. If a unit UAV has a certain level of awareness of its surroundings, more constraints can be set for each of these algorithms, therefore simplifying the problem leading to a decrease in complexity and computation time of a single run.

Another point of improvement is the smoothing operation after running the RRT computation. Most likely, the path found by the RRT might not be optimal and usually requires smoothing and shortening. As shown in previous Figure 2.17, the path found in blue is usually not the most direct way to reach the given end goal node. In the current implementation a simple recursive path shortening algorithm is performed, however, more optimised solutions exist, such as the Ramer–Douglas–Peucker (RDP) algorithm[77], which could be looked into. Another point of improvement is increasing the obstacle avoidance for wildlife detection. The UAVs and wildlife can form a risk for eachother when they crash into eachother. In the further there can be looked further into obstacle avoidance with LiDAR or radar technology.

Further development of agent based model

As mentioned in Section 2.3.5, the agent based evolutionary model provided promising but preliminary results. In order to improve the results, different steps can be taken.

Firstly, the fitness function should be made more extensive. Where currently, the fitness function purely looks at the number of measured points for a flight path, a smarter way would be to also implement other parameters. For example, if it passes an already measured point, what is then the added temporal resolution? Does the UAV fly out of the measurement volume? Does the UAV fly towards the part where a lot of points are already measured? Questions like these can be converted into fitness parameters which would speed up the evolution process.

Secondly, more features can be added to the model. A benefit of the model is that it is modular, meaning that complexity can be added later on. For instance, object avoidance is currently not implemented but wind turbine collisions or collisions with other UAVs could be relatively easily modelled such that the resulting flight paths become more safe and practical.

Thirdly, the evolution algorithm itself can be improved. The current method is quite coarse, where flight path improvements relied on pure chance. The mutations often were too coarse or too subtle, often providing epoch results that were worse then previous epochs. This resulted in the flight path performance reaching a plateau with no significant performance increase in later epochs. To tackle this problem, more literature study is recommended in the topic of evolutionary algorithms to enable the improvement of the evolution algorithm.

Finally and perhaps the most important recommendation for improving the model is to simplify the flight path generation. In the current model, flight paths are generated from stick inputs which are in their turn generated from the probabilities of taking a certain stick input. While at first this seemed like a good method to simulate the UAVs flying as long as the battery was not empty, it quickly became evident that using the probability matrix would lead to inconsistent results. The same probability matrix could either lead to good or terrible flight paths. This meant that the evolutionary algorithm often accepted the wrong improvements. The recommendation is to simplify the flight path generation process such that any flight path follows from a set of stick inputs which can then be evaluated consistently. A solution to the variable input set length depending on decisions taken can be by introducing an extra fitness parameter for battery life left.

7.3.3. Ground station design

With the current ground station design, the main recommendation for future design iterations is one that is derived from the UAV design; replacing the current batteries with more efficient batteries will improve the ground station for the following reasons:

- More efficient batteries means a decrease in the total number of batteries, and in turn a decrease in the number of battery swapping ground stations.
- More efficient batteries could potentially mean UAVs with better endurance. This would mean a decrease in the number of UAVs required, and less UAV housing stations would be needed.

The aforementioned recommendation would have a positive contribution to the sustainability, power consumption, and possibly cost as well. In terms of the design, if there would be an increase in resources available to allocate to the ground station, a recommendation would be to incorporate ventilation systems to all the ground stations. Ventilation systems would further reduce the risk of battery fires.

7.3.4. Others

The system itself will not provide any direct performance boost to a wind farm, as it will only provide wind and temperature measurements. A tool must be developed which would convert the measurements into actual improved wind farm control.

The development of this tool would ensure that the system itself would be actually useful. With just the measurements, there would be no incentive for wind farm operators to invest in the system. Furthermore, the development in this tool is necessary for the design of the system itself as well as it would provide better estimations on how much performance increase during Region II control can be realized and with that, the estimated ROI and most optimal system configurations can be determined with less uncertainty.

Furthermore, the effect of the stations (on the nacelle) on the flow around the wind turbine should be assessed; at the moment this was not considered, but the drag generated from the stations could well possibly decrease the efficiency of the wind energy production of the next wind turbine if, for example, the air flow due to this station becomes turbulent. If it is indeed turbulent, the decrease in energy production due to this could be compared to the increase in energy production due to the UAV system. Alternatively, a more aerodynamic station design could be further investigated.

Further work on UAV operation in strong winds

To protect the system during high wind speeds, the UAVs will be housed in the UAV station. However, if winds unexpectedly change, and it is no longer safe for the UAVs to vertically land in the station, it is of utmost importance to provide the UAVs with a safe method to land. Several ideas could be implemented, and they will be discussed now. Firstly, having a ‘shield’ greater in height built around the ground station may allow the UAV to reach the point where it may land vertically due to this protection. However, this suggestion is the least favourable as it would presumably greatly contribute to the drag behind a wind turbine. Another possible recommendation would be having a barge by the wind farm on which the UAVs could land onto a runway instead of vertically, as they would have a greater wind resistance while doing so. Another possibility is decreasing the reference temperature or wind speed that would make the MCC give the UAV the command to return to the station. In order for this recommendation to be effective, the relationship between temperature and wind speed must be further researched. Lastly, in the subsequent phases of the design, designing the UAV in detail could allow for a more wind-resistant design. The exploration of the aforementioned recommendations will be done in the following stages of the design.

8 Conclusion and DSE Wrap-up

The objective of the project as a whole was to design a system that could **measure the atmospheric conditions with full three-dimensional coverage of a wind farm to optimize its operational performance and control**, as per the Mission Need Statement defined at the start of the project [78].

This has been the focus of the team throughout all phases of design; through the project planning where an extensive plan for the project was set out; through the concept discovery phase where, with requirement analysis, functional requirements could be produced further, allowing the production of an extensive design option tree to come to a shortlist of concepts; through the concept exploration phase where this set of possible concepts are further investigated to come to a final choice. In the final design phase, this concept was designed at a subsystem level.
Out of this 10 week process, the local sensing system design was generated, utilizing hybrid UAVs with mounted anemometer and thermometer, supported by nacelle mounted storage and charging containers. A summary of the properties of this solution can be found in Table 8.1.

Coming back to the MNS, the designed system provides the user with the ability to obtain atmospheric measurements in 3-dimensions. The second half of the MNS ”...optimize [the wind farms] operational performance and control.” is also satisfied in that with greater resolution of data, more informed decisions and processes can be made. The extent to which this is true is not so clear cut and requires further testing. However, this is not a problem for the system in question due to its high scalability. For a small test, the system can be reduced to a handful of drones and a couple of ground station units. In the case a user has been using the system and wants a higher temporal resolution, the system can equally be scaled up, this modularity does very well to reduce risk on the end of the operator. For example, if we look to maximize the proposed cost budget for the reference 100 $[km^2]$ wind farm, the cost jumps by 3M [€] and the power draw rises by 3 $[kW]$, this results in a 31% decrease in temporal resolution. While it can be said that for any system, if you increase allowable cost and power, obviously performance will increase; the point to be made is that for this system no redesign is required. The additional resources can map directly to an extended system implementation.

A scalable system is not the only value provided to the customer. This system also gifts the user with the ability to make more informed decisions and further research optimization algorithms. At an early stage of the investigation into wind farm efficiency gains (explained in more detail in Chapter 6), ROI of 4-7 can be estimated, leading to profits in the realm of 55.2M - 128.8M [€] for the reference wind farm of 100 $[km^2]$. With this it is hopeful that this system can improve the profitability of the wind energy sector and in turn assist in the transition towards emerging green energies.

Table 8.1: Summary of UAV and system characteristics - values calculated for a 100 $[km^2]$ wind farm

UAV	DeltaQuad Pro
Wind sensor	Trisonica mini (from Anemoment)
Temperature sensor	FST600-202 4-20mA PT100 (from Hunan FirstRate)
Lifetime system cost	18.4M€
System power draw	16.9 $[kW]$
Spatial resolution	300 $[m]$
Temporal resolution	2242 $[s]$ (37.4 minutes)
UAV cruise speed	16 $[m/s]$
UAV charging time	5 minutes
UAV endurance in cruise	99 minutes
UAV area	2.115 $[m^2]$
No. of operational UAV	59
No. of total UAV	78
No. of charging stations	4
No. of UAV storage stations	16
No. of UAV in a storage	5
Batteries per UAV	9.4
Batteries stored per station	183
Batteries needed per 6 months	731
Battery swapping time	5 minutes
Battery charging time	6.6 hours
Battery capacity	33 $[Ah]$
UAV climb angle	10 [°]
UAV descent angle	10 [°]
UAV climb rate	2.2 $[m/s]$
UAV descent rate	2.2 $[m/s]$
UAV VTOL climb rate	1.5 $[m/s]$
UAV VTOL decent rate	0.6 $[m/s]$

For a more visual description, a render is provided in Figure 8.1. It shows one of the system's UAVs in operation: it is vertically taking off from a battery charging station where it has had its battery replaced. In a short while, it will transition to horizontal flight such that it can go on to take measurements along the flight path defined by the swarm control department. In the meantime, the empty battery removed from the UAV is being charged in the charging station, such that the cycle of drones autonomously taking measurements continues.

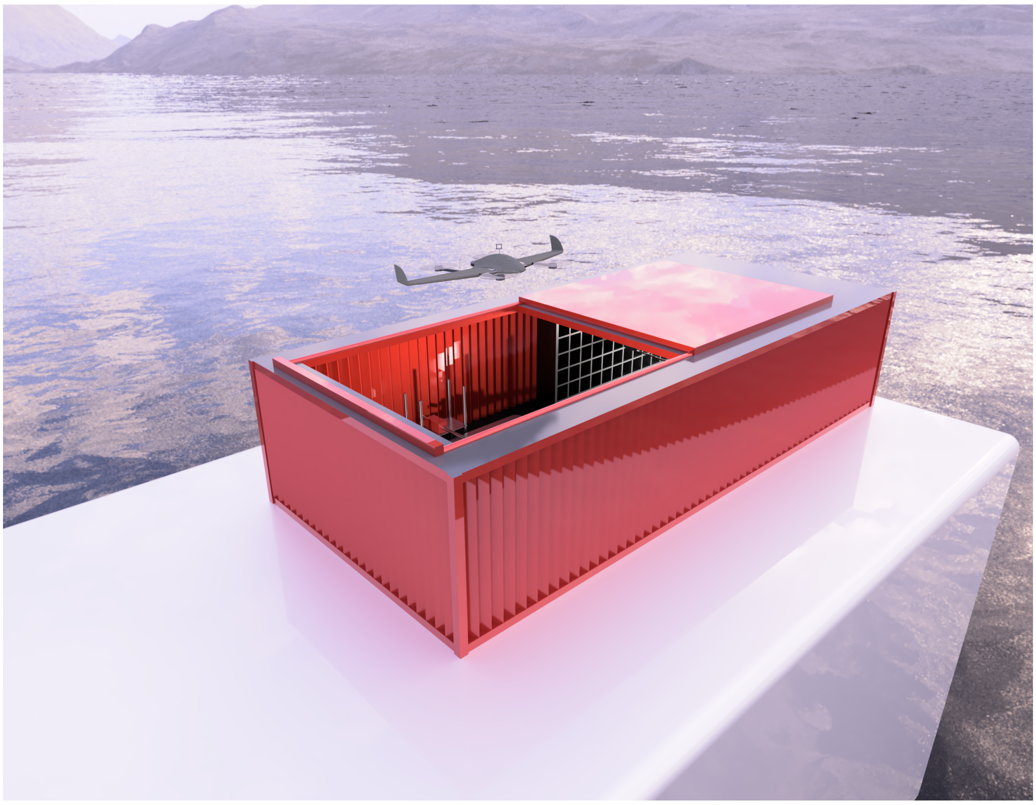


Figure 8.1: Drone swarm system in operation

This concludes the detailed conceptual design phase of the drone swarm system design and subsequently closes the final report in the sequence, capping off the DSE and 10 weeks of work as a team. We would like to take this opportunity to thank our coaches again: dr. ir. Dries Allaerts, dr. ir. Salua Hamaza and dr. ir. Rudolf Saathof for their support over these past 10 weeks, especially the time and effort spent in meetings and the riveting task of reviewing drafts.

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Change log

ID	Location	Change	Date
1	all	Fixed Spelling	21/01/22 - 25/01/22
2	Section 2.1	Extended explanation of 'Ground station department' to explain that there is no communication drone-to-drone	21/01/22
3	Section 2.2	added the UAV,length,wingspan and service ceiling	21/01/22
4	Section 3.2.4	Added system wind speed sensitivity, implemented this also in remainder of report.	21/01/22
5	Section 5.3	Added risk R.A.11 to risk table, risk maps, mitigation strategies	21/01/22
6	Section 5.3	Added risk R.A.11 to risk table, risk maps, mitigation strategies	21/01/22
7	Section 3.2	added reasoning for why reducing the air speed can increase the temporal resolution by adding more drones	21/01/22
8	Chapter 1	Adds further explanation of the final concept (local measuring system)	21/01/22
9	Section 2.2	Added a reasoning to why the drone was bought of the shelf, starting right after the mention of the UAV being Off-the-shelf	
10	Figure 4.10 Figure 4.11	Implemented an anemometer in diagram	21/01/22
11	Section 2.2.5	Changed the Typo from 365 to 360	21/01/22
12	Section 3.4	Changed the Typo from 365 to 360 degrees	21/01.22
13	Table 2.6	Changed the lifetime and material of the FT742 and the Trisonica Mini to the correct sensor	
14	Section 5.3	Changed R.A.8 and added risk map and mitigation strategy for batteries	21/01/22
15	Section 2.4.3	Added the number of batteries per UAV and explanation on battery type chosen	21/01/22
16	Section 2.4.4	Added description on how the batteries are stored and charge, added UAV housing description, added explanation on how the number of stations were chosen, added the number of UAVs stored in each station, and added station size	21/01/22
17	Section 2.2.1	Added requirements to support the categories used in the trade-off	21/01/22
18	Section 2.2.5	Added the requirements corresponding to the chosen categories for the trade off	21/01/22
19	Section 2.2	Added a reasoning for the results of the table being normalised	21/01/22
20	Table 2.3	Added the MTOW to the Table	21/01/22
21	Section 2.4.1	Rephrase and add explanation on why semi-subsermisble platform limits the flight path optimization	21/01/22
22	Section 2.2.5	Added range as a requirement taken into account for the temperature sensor selection	21/01/22
23	Section 2.2.5	Explained that resolution, sensitivity and linearity are all in a way connected to the accuracy requirement	21/01/22
24	Section 2.4.2	Added the ground facilities cost, and a table containing ground facilities characteristics	21/01/22
25	Figure 2.4	Added footnote with reference	25/01/22
26	Section 2.4.6	added a section explaining how the power was calculated for the system	25/01/22
27	item 3	Added an explanation on why requirement is added SR.sust.11 and how we want to meet this requirement in the future	25/01/22
28	Figure 3.3	Added the figure on UAV power and talked how this effects the system	25/01/22
29	Table 3.2	Added units to the UAV endurance	25/01/22
30	Section 2.3	Explained how optimization from ground station configuration could be approached	25/01/22

31	Section 2.3	Clarified reasoning for moving on from graph inspection algorithms	25/01/22
32	Section 3.3	Explained the number of operational drones and the number of ground stations	25/01/22
33	Section 2.2.7	Elaborate on payload mass budget, give definition of BEC, changed weight of wiring	25/01/22
34	Section 5.1.11	Added a conclusion to the RAMS section	25/01/22
35	Table 3.5	Referenced the explanation of requirement SR.rel.1 on downtime due to precipitation	25/01/22
36	Section 5.1.1	Included a more extensive explanation on wind gust survival	25/01/22
37	Table 3.5	Added an explanation to how the spare UAV will be used during the maintenance cycle	25/01/22
38	Section 3.5.2	Added simulation environment for validating flight planner	25/01/22
39	item 2	Explained added requirements: SR.pwr.18.SUB.5, SR.cost.20.SUB.1, SR.cost.20.SUB.2	25/01/22
40	Table 3.8	Added requirements: SR.pwr.18.SUB.5, SR.cost.20.SUB.1, SR.cost.20.SUB.2 to this table, needed to explain trade offs	25/01/22
41	Section 2.4.6	Added a section on power consumption	25/01/22
42	Section 2.2.6	Added note for temperature sensor setup validation	25/01/22
43	item 4	Changed the time it takes to charge the drones after operational stops (requirement SR.rel.1) to a more realistic value	25/01/22
44	item 4	Changed the time it takes to charge the drones after operational stops (requirement SR.rel.1) to a more realistic value	25/01/22
45	Table 3.5	Changed the confirmation of requirement met to a more realistic value for requirement $SR.rel.2$	25/01/22
46	Section 7.3.1	added note for the two year replacement for each UAV	25/01/22
47	Section 6.1	Added testing cost to the cost breakdown	25/01/22
47	Section 5.1.9	Added redundancy explanation	25/01/22
48	Chapter 7	Included provided paper discussing 'Path planning and following using genetic algorithms to solve the multi-travel salesman problem in dynamic scenarios' [74]	25/01/22
49	Chapter 7	Introduced idea to allow battery age to dictate allocation of flight paths	25/01/22
50	Chapter 8	Added more information to focus on the customer demographic for the system	25/01/22
51	Section 2.2.6	Added the fact that the UAV pitches up more than 8 [°] in the occurrence of wind gusts and added Figure 2.6 as an explanation.	25/01/22
52	Chapter 7	Addressed the high wind speed scenario as well as the relationship between wind speed and temperature	25/01/22