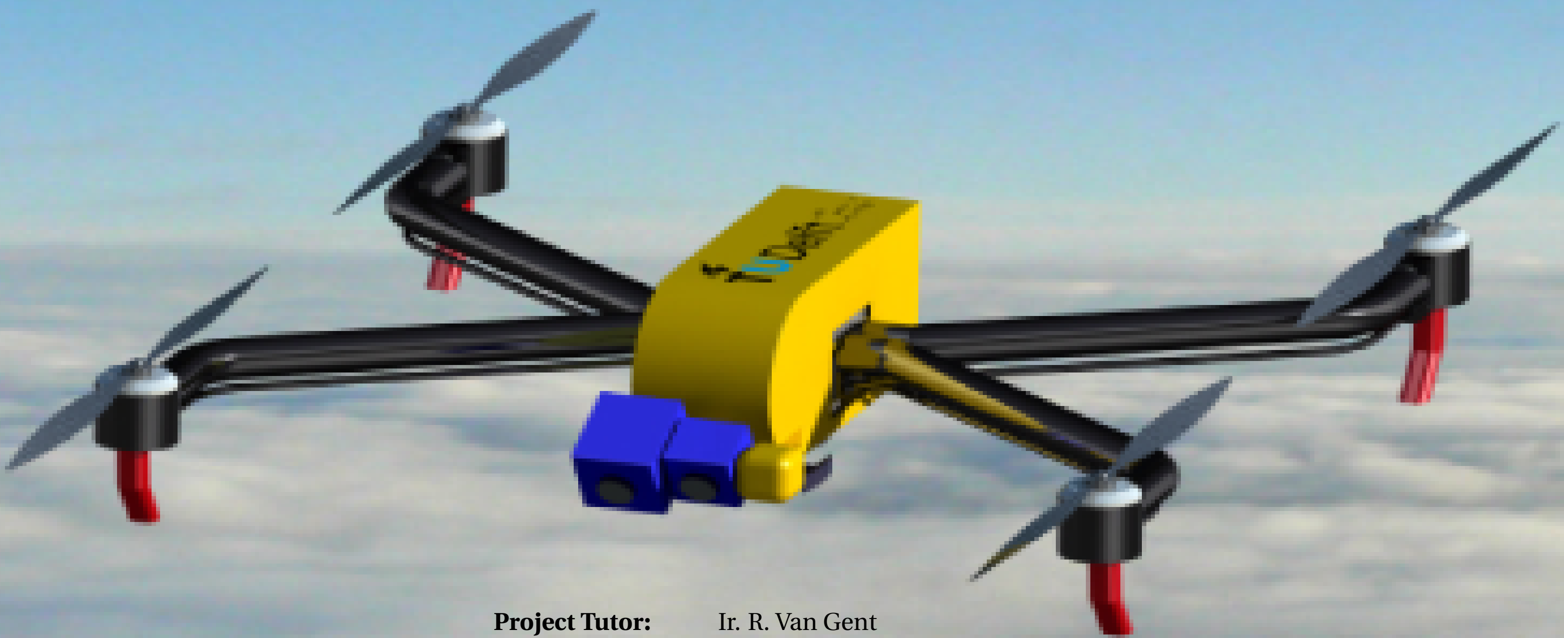
Final Report

by

DSE Group 05
HEMS Reconnaissance Drone



Project Tutor:	Ir. R. Van Gent	
Project coaches:	Dr. J.C. Bijleveld	
	Prof.dr. S.J. Watson	
Group members:	Jilles Andringa	4662822
	Tijmen Brinkhof	4460502
	Roeland Desmet	4278135
	Paco Frantzen	4606418
	Xavier Goby	4488822
	Ruben Goetstouwers	4645669
	Mariano Ramirez	4682254
	Aung Thu tun	4650395
	Raphael Ummels	4669304
	Joost Waaijer	4591356
Date:	May 20, 2020	
Version:	Draft	

TU Delft
Delft University of Technology

Contents

Nomenclature

Abbreviations		
COG	Center of gravity	
DSE	Design Synthesis Exercise	
EASA	European Union Aviation Safety Association	
EGNOS	European Geostationary Navigation Overlay Service	
FHX	Highest hourly average wind speed	
GIS	Geographic Information System	
GNSS	Global Navigation Satellite System	
GPS	Global Positioning System	
HCM	HEMS Crew Member	
HEMS	Helicopter Emergency Medical Services	
HITS	Highway-in-the-sky	
HUD	Heads Up Display	
ICP	Iterative closest point	
IFR	Instrument Flight Rules	
ILS	Instrument Landing System	
IMU	Inertial measurment unit	
IR camera	Infra red camera	
KNMI	Royal Netherlands Meteorological Institute	
PID	Proportional Integral Derivative	
RGB camera	Visible light camera	
RPM	Rotations per minute	
RTK	Real Time Kinematic	
SAR	Search and Rescue	
TRA	Technology Readiness Assessment	
TRL	Technology Readiness Level	
UAV	Unmanned Aerial Vehicle	
WBS	Work Breakdown Structure	
WFD	Work Flow Diagram	
Variables		
β_i	Inclination Angle	deg
Δ	deflection	m
ϕ	Pitch angle	rad
ψ	Yaw angle	rad
θ	Roll angle	rad
AA_{bb}	Acceleration in the body-fixed reference frame	m/s^2
AA_{be}	Acceleration in the flat earth reference frame	m/s^2
C	Cost Coefficient	-
C_T	Thrust coefficient	-
D	Diameter	m
E	E-modulus of a material	Pa
f	Fuel usage of helicopter	kg/s
F_b	Forces in the body-fixed coordinate	N
F_{D_x}	Drag forces on the body-fixed coordinate in Xb direction	N
F_{D_y}	Drag forces on the body-fixed coordinate in Yb direction	N
F_{D_z}	Drag forces on the body-fixed coordinate in Zb direction	N
F_{g_x}	Gravity forces on the body-fixed coordinate in Xb direction	N
F_{g_y}	Gravity forces on the body-fixed coordinate in Yb direction	N
F_{g_z}	Gravity forces on the body-fixed coordinate in Zb direction	N

G	Shear modulus	Pa
g	Gravitational Acceleration	m/s^2
I	Moment of inertia/2nd moment of area	m^4
J	Polar moment of inertia	m^4
L_x	Length of section x	m
m	Mass	kg
M_x	Torque in x axis	Nm
M_y	Torque in y axis	Nm
M_z	Torque in z axis	Nm
P	Probability	-
S_v/S_h	Vertical/Horizontal length measure	m
t	Time	s
T_i	Thrust provided by motor i	N
u_b	Velocity in the body-fixed coordinate in Xb direction	m/s
V	Speed of helicopter	kts
V_b	Velocity of the drone in the body-fixed coordinate	m/s
v_b	Velocity in the body-fixed coordinate in Yb direction	m/s
$V_{gust_{x-c}}$	Gust velocity on the body-fixed coordinate in Xb direction	m/s
V_{gust_x}	Gust velocity on the earth reference frame in Xe direction	m/s
$V_{gust_{y-c}}$	Gust velocity on the body-fixed coordinate in Yb direction	m/s
V_{gust_y}	Gust velocity on the earth reference frame in Ye direction	m/s
$V_{gust_{z-c}}$	Gust velocity on the body-fixed coordinate in Zb direction	m/s
V_{gust_z}	Gust velocity on the earth reference frame in Ze direction	m/s
w_i/w_e	internal/external virtual work	J
w_b	Velocity in the body-fixed coordinate in Zb direction	m/s
X_e	Position in the flat earth reference frame in x direction	m
Y_e	Position in the flat earth reference frame in y direction	m
Z_e	Earth Surface Normal Axis	-
Z_e	Position in the flat earth reference frame in z direction	m

Executive Overview

Previous Work

This report is the final one during this DSE (Design synthesis exercise) project, and three reports documenting the project planning, baseline, and mid-term phases came before it. During the project planning phase the team organized itself by assigning technical and organizational roles, and project logic diagram (such as a work-flow diagram and Gantt chart) were made to document the planning of the project in detail. During the baseline phase, the given requirements were analyzed and thoroughly extended, and then high-level conceptual design candidates were generated while keeping these requirements in mind.

In the mid-term phase, immediately before this one, the conceptual design candidates were put through a trade-off to determine the optimal choice to be developed further. The best candidate was found to be a quadcopter concept, since it could fulfil the performance requirements on par or better than the other concepts, while also being the simplest. The chosen sensing system for the drone uses a millimeter wave radar for obstacle detection through fog, and mainly relying on the concept of 3D 'optical flow' for navigation: the three-dimensional data gathered from the millimeter wave radar is stitched together, and then by determining the transformation matrix of the overlapping part of two scans, the change in position and orientation of the drone can be determined. Since a GNSS (Global Navigation Satellite System) reciever is relatively cheap and lightweight, the sensing system still includes one anyway to also aid in navigation. Finally, it is also important to note that towards the end of the mid-term phase, after analysis and discussion with the customer and a HEMS pilot, it was decided to exclude mid-air retrieval (initially given as a user requirement) from the project, since it was deemed too risky for the benefit it provided, especially compared to the relatively low cost (compared to losing the helicopter and crew) of potentially losing the drone if it cannot be recovered from the ground.

Market Analysis

Previous market analysis already pointed out the products market need, potential customers, volume and a Strength/Weakness/Opportunity/Threat (SWOT) analysis was performed. The most important conclusion to this was that the product will be designed for the main customer, the Helicopter emergency services(HEMS), however other helicopter operators could also be interested by design derivations of the drone. The current expected market volume is around 360 units initially.

The main objective for the current market analysis is to find requirements or obstacles that certain design decisions would cause. In the scope of this project the driving factor in the cost of the complete service and product is the certification cost. Introducing major changes to the design/layout of the helicopter would cause the helicopter to need re-certification. This involves real life flight testing and structural integrity testing. It could be easily concluded therefore that major changes to the helicopter to fit the drone would be undesired and to be avoided during design as much as possible. However interviews with helicopter pilots and stakeholders has revealed that there is a strong preference for a well integrated data presentation system by means of a Head Up Display(HUD). Since this would be a significant change to the operating procedures of the pilot this would require a large amount of development testing, and certification cost would also be significant, as the HUD would have to be thoroughly tested by the European Union Aviation Safety Agency(EASA). The estimation of the certification with EASA alone is estimated at a value of one million EUR. The alternative to the HUD would be a tablet/monitor that would simply attach/detach to the helicopter. The estimated total cost of testing and certification of the tablet is estimated at around 100 000 EUR.

There are also certification costs that are considered unavoidable. These are also estimated in the market analysis as follows. The certification required to allow one individual to control the drone is estimated at a price of 3500 EUR. The certification cost of the release mechanism is estimated at a value of around 70 000 EUR. However this does not include intensive testing and designing as the release mechanism needs to be proven to not endanger the helicopter in any circumstance.

User and System Requirements

To present the compliance with expectations from the user and stakeholders, as well as the project group, initial user and system requirements are presented. This is done After some progress in the system design, resulting in a clearer picture of what exactly should be expected from the system. Therefore, some requirements have either been canceled or have been altered. Two main changes in the user requirements are the following:

After some initial sizing was performed and an estimate of the payload weight was found, it was concluded that the drone dimensions requirement **HD-USR-OPS-01** was constraining the design to an unacceptable extend. Hence, after discussion with the user, the allowed drone dimensions were slightly increased.

During the midterm phase, it was discovered that the user required mid air retrieval of the drone system **HD-USR-OPS-01** is unfeasible. Again, after discussion with the user whomst provided the user requirements, it was decided that the requirement on mid air retrieval is omitted.

Functional Analysis

In order to perform its mission of assisting a HEMS operation in low visibility conditions, the drone needs to perform a set of functions in a certain order. In the functional analysis, these functions are determined by splitting the drone's mission into its separate phases. During each of these phases, it is determined what the drone needs to be able to do in order to fulfill its mission while adhering to the previously set requirements, creating new functional requirements in the process. The mission phases discussed are the flight preparation, deployment, scanning and performing landing. Apart from mission phases, the manufacturing, end of life, and emergency phases are also discussed.

In the manufacturing and end of life phases, a focus is put on efficiency and sustainability. As the drone market is growing ever larger, there are numerous off the shelf parts and sub assemblies readily available to be used in the HEMS Reconnaissance Drone. As many off the shelf parts will be used as possible, increasing reliability while reducing design complexity and cost. As not everything can be bought off the shelf, a supply of raw materials is also needed. When all the parts and materials are acquired, the drone is assembles. The goal of the drone manufacturing phase is to make use of as many recyclable parts and materials as possible. Here the end of life comes into play. When the drone is deemed to be at its end of life, it is disassembled into its individual components. These components are tested for mission readiness. If a part is deemed mission ready, it can be reused in the manufacturing of a new drone or be used as a spare part. Then, all the components that are not reusable but are recyclable will be brought to the relevant recycling facility. The rest of the drone is discarded. The ultimate goal is to produce no waste that is not either reusable or recyclable.

When the pilot decides that he or she might have to use the drone during a mission based on the forecasted weather conditions, the flight preparation phase starts. In this phase, the drone is retrieved from storage and booted up to standby mode. A series of checks is performed to ensure the drone is mission ready. If not, a backup drone is retrieved which is subjected to the same set of checks. When the drone is deemed mission ready, it is attached to the helicopter.

In flight, when the pilot decides the use of the drone is necessary, the drone is prepared for release. In this deployment phase, the HEMS Crew Member takes the role of drone operator. He or she will activate the drone control systems and ensure the drone is ready for deployment. When a safe altitude and flight velocity is reached, the drone release mechanism is activated and the drone is dropped. After a small free fall to create distance from the helicopter, the flight control systems kick in and stabilize the drone.

When the drone is stabilized and reaches a stable hover, the sensor system is activated and the drone starts to collect data. The collected sensor and visual data is processed and sent to the helicopter to provide the pilot with information about the landing environment. To give a complete picture of the environment, the flight scanning path is initiated, where the drone will fly an automatically determined path to get a complete scan of the environment.

If the pilot decides to land, the drone will land at the landing site and act as a landing assist for the helicopter, guiding it to perform a safe landing. When landed, the medical crew can assist the patient while the pilot can retrieve the drone to be transported back to base. If for any reason (i.e. an aborted landing) the pilot is not able to retrieve the drone, a member of the on sight ground personnel, such as the police, will retrieve the drone. The drone will then later be transported back to base by an alternative transportation method.

Finally, as not everything will always go according to plan, an analysis was performed on emergency functions. These functions include a manual override, collision detection, communication loss procedures and other mitigations to ensure the safety of the drone, HEMS crew, and bystanders.

Technical Risk Assessment

Technical risk assessment is used to identify risks during development. Ranking these risks clarifies which events need mitigation measures to prevent and reduce the consequential effects of these risk events. This mitigation should reduce or nullify adverse effects on technical performance, schedule or cost requirements. This work is a continuation of the work done for the baseline and midterm report. Some adjustments were made due to new insights and information. The newly identified risks are: "The drone gets blown away at the landing site.", "Lithium-Polymer battery overheat/fire.", "Drone not clearing the helicopter on deployment." and " chosen off the shelf component is no longer available.". The risk assessment matrix shows the likelihood and severity of the possible risk events before and after mitigation measures have been taken. The matrix is color-coded by the expected impact, where green means less problematic risk events for the project while red means problematic risk events. The constructed matrices for the risk before and after mitigation are shown in 1.

Unmitigated Risk Map

		Severity				
		1	2	3	4	5
Likelihood	1					O7
	2	O12		O8,D6	O3,O4,O10,D2,D3	O1, O14
	3	O6,O9	O11	D1,D4		
	4		D5	O5, O15	O2	
	5	O13				

Mitigated Risk Map

		Severity				
		1	2	3	4	5
Likelihood	1				D2,D3	O1,O7
	2	O3,O12	O10,O11,D6	O8,D1,D4, O14, O15	O4	
	3	O6,O9,O13	D5	O5		
	4	O2				
	5					

Figure 1: Risk map before and after mitigation.

Resource Allocation and Budgets

The mass cost and power budgets are summarized in Table 1. The pod has a high contingency, due to the preliminary status of its components. The detailing of the design should reduce the unknowns and cause a steep drop in its needed contingency margin. Planned contingencies are 0.1-0.05 at the end of the detailed design stage and 0.05 during assembly and testing.

Table 1: Budget Breakdown for Mass, Cost and Power of the Drone and its Pod

System	Preliminary system components at final report	Budgets		
		Unit mass [kg]	Unit cost [€]	Unit power [W]
Drone	**Total:**	**3.8**	**€7,434**	**369**
	With contingency of 0.1-0.15 for subsystems	4.4	€8,287	422
Pod	**Total:**	**10.1**	**€519.36**	**173**
	Contingency of 1	20.2	€1,038.72	346

The drone's current mass is estimated at 3.8 kg. With the contingency margins applied, it will rise to 4.4 kg. The hardware cost for the drone is currently 7,434 euros. This is estimated to rise to €8,287 if the margin is applied. The power budget for the drone at this stage is 369 W. Of this estimate 313 W or 86 percent is reserved for the propulsion. With the contingencies applied this power budget rises to 422 W. The pod's current mass, cost and power are 10.1 kg, €519 and 173 W respectively. These are fairly rough estimates that double due to the contingency margins to 20.2kg, €1,039 and 346 W respectively.

Propulsion System

The propulsion system design was kickstarted using the initial statistical mass estimation performed in the budgets section. The possibility of designing a propeller from scratch was explored, but after trying an analytical BEMT model where the induced velocities would not converge this idea was abandoned in favour of using off the shelf components. Designing propellers from scratch would require a large investment, and off the shelf propellers would be much less of a technical risk durability and performance wise.

The main factors which drive the propeller design are the propulsive efficiency, the maximum thrust to weight ratio, and the propeller diameter. A drone propeller manufacturers' database is used to find approximate relationships between the propeller geometry and the efficiency and deliverable thrust. For this application, where the most efficient level near static thrust is required for the majority of the mission, a bigger propeller diameter would be better, along with a pitch that is as low as possible. The propellers are also limited to 2 blades per propeller, and a spacing of 1/4 of the total propeller diameter for better performance.

The stabilization maneuver when dropping from the helicopter will require a high thrust to weight ratio (3>). This is not achievable using 9 inch propellers, even using overpowered motors, which were the only non foldable propellers that would fit in the 500x500x250mm size requirement. Foldable propellers fit up to 15.5 inches in diameter, if the size requirement is increased to 535x535x250mm. These would allow for higher efficiency and higher achievable thrust. The propellers should fold out through centrifugal force automatically, but if this does not work then a spring loaded mechanism could be designed to assure fold out upon release.

4 combinations of off the shelf propellers, motors, and batteries are made and compared to each other on performance in thrust to weight ratio, motor mass for control and stability, efficiency, cost, and total propulsion system mass. Additionally, they have to be water and dust proof. The batteries are chosen as a result of the voltage, current, and energy requirements of the propeller and motor combination. A similar methodology is used for the ESC, with the ESC being the recommended model from the same brand as the final motor and propeller choices, to ensure that they will work together seamlessly.

The final components are the KDEDirect KDE3510XF-475, KDEDirect KDE-CF155-DP, and the Turnigy Graphene Professional 8000mAh 6S 15 C LiPo Pack, for the motors, propellers, and battery respectively. The ESC that followed from this was the KDEXF-UAS55. This was the best performing package that also fulfilled all of the requirements in the previously mentioned criteria, with enough room to spare for if the system would unexpectedly become heavier than the current mass of 3.8 kg.

The batteries are Lithium-Polymer batteries. The requirements state that the batteries should be Lithium-Ion, but the C-rates achievable by Lithium-Ion batteries are not sufficient for the drone to be able to operate. Moreover, Lithium-Ion batteries are supposedly safer, but the regulatory agencies do not seem to make any clear distinction between both types on safety. Both types prove to be a significant incident risk, so a large amount of resources will be required to certify the batteries for use when attached to the helicopter. This is unavoidable, as other means of energy storage would fundamentally change the design, and this likely makes it impossible in its current form.

Aerodynamics

This section is slightly different to the other subsystem design sections, since there isn't really an 'aerodynamics subsystem,' and since the drone is a multirotor, there is no wing to design. The propellers could be designed down to the airfoil, but for this project it was decided off-the-shelf components will be used for simplicity and cost, so this is not applicable here. Nonetheless, while it might not be as important for design in this case, estimating the drag is still necessary to be able to analyze the performance of the drone, since the drag force will influence what velocities the drone can achieve and thus also the range. To do this, the complex aerodynamics of the rotors were much more relevant than the aerodynamics related to estimating the drone's parasitic drag coefficient.

For smaller multirotor aircraft, it was found that the parasitic drag (due to non-lifting surfaces, proportional to the square of velocity) which tends to be dominant for larger rotorcraft such as helicopters due to their size and speed, is often negligible, especially when flying under 10 m/s. The dominant drag components actually tend to be the drag due to blade flapping, and the induced drag due to the blades' rigidity. These two components can both be modelled as being bi-linear with the thrust and velocity, and thus are frequently lumped together by using a lumped drag coefficient. Other, usually lower, drag components such as translational and profile drag can similarly be lumped with these two as well.

Thus, to model the drag force itself, two possibilities were considered which were found in literature. The first simply tried to model the total drag as being just parasitic drag, since it was all proportional to the square of the velocity, and also proposed an approximate function for the drag coefficient as a function of the pitch angle. In this case, the coefficient was likely being overestimated since it had to implicitly include the effect of the other drag components which don't actually scale quadratically with velocity, resulting in a likely overestimate of the drag force, especially at higher velocities. The second method involved modelling the first order components as proportional to thrust and velocity with a lumped coefficient, while neglecting the parasitic drag.

Structural design and release mechanism

The structure of the drone and the release mechanisms main purpose is to protect all components of the drone against the loads and other damaging phenomena such as water or dust. Analysis and trade-offs has been performed on the layout of the structure, the optimal materials and required thicknesses of the critical load bearing parts of the structure. It has to be noted however, that not every component of the structure has been fully analyzed against the loads that it might endure, for this detailed analysis still has to be performed in later stages of the design. However with the current analysis an accurate estimation of the structural weight can be found. The aspects of the design that are analysed for this design phase are: The arms that connect the propellers to the main body, the main body and its packaging, the release mechanism location on the helicopter and its workings and dimensions and the landing gear configuration. To determine the selection of the material of the drone's structure, the trade-off criteria define which includes strength to density ratio, corrosion resistance, and recyclability. Then the weight is defined for each criterion but it has a different weight for a different part of the drone. For the frame and arm of the drone, the strength to density ratio is prioritized which leads to carbon fiber reinforced polymer. As for the body shell of the drone, the weighting is equally spread for all the criteria. This resultant in carbon fiber reinforced polymer again but the cost of material and manufacturing for this part is a lot higher than the thermoplastic polystyrene or nylons. Therefore the material for the body shell will be polystyrene.

Control & Stability

The function of the control & stability subsystem is to keep the drone stable during flight, while ensuring controllability. As a drone in itself is not inherently stable, a constant stream of corrections is needed. This is provided by the flight control system. The flight control system is on a constant feedback loop, where it is continuously updated on the drones orientation and position by the on board sensors. The flight controller compares the states provided by the sensors with the reference states set by the user or the autonomous flight system. The error between these states is fed into a PID (Proportional Integral Derivative) controller, where the error is translated to a motor command. This motor command is then executed, affecting the physical state of the drone. This is measured by the sensors and fed back to the flight controller.

This specific control system is designed for two main purposes, recovery after deployment from a helicopter, and regular flight. These two purposes both require a specifically tuned flight controller, fast reaction and high gain settings for the deployment mode, and a smoother, lower gain setting for the regular flight mode. For this, two specifically tuned flight controllers have been implemented into the control system. It is able to recover from a tumbling free fall into a stable hover, where-after the regular flight mode takes over to navigate to a set coordinate while withstanding wind gusts.

Sensors and Communication

The function of the Sensors and Communication subsystem is to provide data of the topography of the planned helicopter landing site to the helicopter operators. Furthermore, all other means of obtaining data on the drone and its surroundings are performed by the Sensors and Communication subsystem.

In order to allow for safe operation of the drone system, the following components are located on the drone: rgb and infrared camera, Inertial Measurement Unit, Flight controller, and a GNSS receiver. The data from these components will be used in order to provide corresponding control for the drone.

The radar sensors on the drone will rotate continuously and map the topography of the landing site surroundings. This data will be processed by an on board computer, by converting the newly obtained radar data to a point cloud format. Subsequently The new point cloud data is appended to the existing point cloud, consisting of all preceding radar measurements. After processing, the radar data along with video camera feed and drone status data, will be sent to the helicopter using a duplex 2.4GHz direct data link, capable of transmitting and receiving data with a bit rate up to 10 megabit per second. Using this link, the system operators can with a little delay view the camera feeds, drone status data and the processed radar data.

The system operators can then view the data trough displays. The drone operator will view the drone status and camera feeds, whereas the helicopter pilot will be presented the topography data of the landing site surroundings, oriented corresponding to the helicopter orientation and position.

Simulation Modelling

Simulation modeling is performed in order to create a virtual prototype of both the drone and operating environment so as to be able make predictions about the performance of such a drone when operating in a real life scenario. In this research paper, the primary tools which are made use of for the creation of a simulation model are (1) the Unreal Engine 4 game development software, (2) the Python programming language and (3) the AirSim Python library developed by Microsoft. More specifically, the simulation model created is most heavily employed in the development of the sensor & electronics subsystem. In fact, this is the very means by which the performance of the drones on-board perception sensors are studied for a low-visibility environment. In addition to this usage of it for the development of the sensor and electronics subsystem, the simulation model is also employed as the sole means by which the study of the drone's task of navigating and scanning of the airspace, as defined by user requirement HD-USR-PERF-01.

Sensitivity analysis

As the design process progressed, numbers, parameters, and requirements inevitably varied, and they would continue to vary in the design beyond this stage as well. Many of the estimated parameters have associated contingencies up to 10% still at this stage. Thus, it is useful to analyze how the design reacts to these changes, how sensitive it is to particular aspects, and this is done through the sensitivity analysis.

Thus, several parameters coming from other subsystems, requirements, as well as parameters coming from manufacturers were varies to see their effect on the design. For the parameters coming from other subsystems, the main driver to the design is the sensing subsystem since this is the payload, thus the required payload mass and payload power consumption were both chosen as parameters to vary. Similarly, the performance of the drone is also closely related to the motor and propeller parameters. The power consumption and thrust generation of the motor and propeller combination were thus varied by varying the thrust and torque coefficients which were derived from the manufacturer test data. Moreover, the battery parameters as given by the manufacturer were also varied. Finally, some of the driving requirements were varied: the maximum mission time, the range the drone needs to cover (derived from the volume it needs to scan), and the maximum drone dimensions.

Note that the parameters were always varied so that they would have the 'negative' effect on the design, since the positive one is not necessarily interesting to analyze (e.g. the maximum dimensions were decreased, the range to be covered was increased). For every case, variations which could be realistic (considering the contingencies or uncertainties, for example) were used. In general, it was found that the design is robust enough that for these variations the drone could still meet the relevant requirements. Most of the time a variation of 20-30% was necessary to make the design unfeasible. The drone was more specifically sensitive to the payload mass, as would be expected: an increase of about 10% already pushes the design to be only marginally feasible. Apart from that, the design is also particularly sensitive to the requirement on the maximum dimensions. If this decreases enough so that the propeller diameter has to be decreased, it can also make the design unfeasible; reducing the propellers to 13 in. propellers is still marginally feasible, but lower than that is not possible.

Operations and Logistics

For the operations and logistics the multiple phases of the missions are further elaborated from an operational point of view. Extra care is taken in providing guidelines for handling the drone in emergency situations that can be triggered by different modes of failure of the system. These emergencies are then categorised in land immediately, land as soon as possible, and land as soon as practical just as the emergency protocols of the helicopter itself. Also the scanning path is further elaborated upon in operations. It was chosen to scan using an initial bigger perimeter scan for power poles and subsequently cable. After this, the drone will perform a lower altitude scan of the landing area after which the pilot can decide whether to land, scan further, or abort the mission. The pilot not landing creates the logistical problem of getting the drone back to the airbase. In order to solve this problem, it is decided to let the first responders take the drone to a pick up point which can be either a police station or hospital. After this someone from the airbase can recover the drone. In order to cover the downtime of the system caused by this retrieval it will be strongly advised to have multiple drones ready to go at the in case a second sortie is required right after the previous one. Furthermore manufacturing and other logistical aspects are further elaborated upon.

Sustainability Analysis

Sustainability has been a troubling subject for this project. This is because of the conflict of interest between saving a life the best way currently available and conserving resources so as not to burden the planet, today and in the future. The relevant stakeholders in this situation can be divided along the sides of this conflict. However, these groups overlap as the people of today have both an interest in saving the lives of themselves today, but also in retaining a livable situation in the future, for themselves and the people they care about that will exist and live in this future, that is shaped by the actions of today. Thus the question of sustainability of this possibly lifesaving project wanders into the realms of philosophy and morality.

At the start of the project this conflict was realized and mitigated by delegating the decision making to the relevant policymakers. As the decision should be based on factual information, this information was gathered during this project. At the project planning phase a tool for sustainable design and a metric for measuring the sustainability were examined. The waste management hierarchy is a tool that ranks waste options for sustainability and provides suggestions for alternatives. The life cycle assessment is a metric to asses the sustainability of a product from its creation to its disposal.[4] During the exploration of design options sustainability was used as an argument to prune some options from the design option tree, mostly in combination with the user requirement HD-USR-SYS-SUST-01 on sustainability that dictates the drone shall be able to perform a 1000 sorties.[2]

After multiple meetings with the client, it became clear that sustainability would be a low priority trade-off item for the design. As the concept choice did not have a clear winner, sustainability was, amongst others, used as an additional consideration. Sustainability justifies not using a concept involving multiple drones, as the extra material and energy used during manufacturing, and the extra waste at the end of life, would make this concept more unsustainable than the other concepts considered. Another item discussed with the client was dropping the mid flight retrieval requirement. To solidify this change, some comparisons were made. First it was assessed what the effect of waiting for the drone to scout would be on CO2 emission over a year. There would be a 6 percent increase in CO2 emission if the drone was used on misty days. This is based on 8000 flights over a year and 85 misty days a year. [1] This 6 percent increase would be unfavorable for the drone. But one can question the validity of this comparison, as the drone can enable flights that can't happen in low visibility conditions without it. Therefore a second comparison was made between the current situation where a landing gets aborted and the new situation where the helicopter waits for the drone to scout. Conclusion of this comparison was that the drone could reduce CO2 emissions if 26 percent or more of landings get aborted on misty days. The third comparison ties into the dropped requirement on mid flight retrieval. It compares the CO2 emitted during manufacturing and the CO2 emitted during the helicopter's waiting time during drone retrieval. This resulted in 5 minutes of waiting time, if the drone is lost every mission. However the drone is not lost every mission increasing the favor towards not doing mid air retrieval. Furthermore the topic waste management of current drones was explored. It was concluded that current end of life strategies are bad, and could be better. Some parts are recycled, but a lot is either burned or send to the landfill. [3]

A life cycle assessment was performed on the drone and its pod. Though some inaccuracies are present due to the modelling options available in CES EduPack and the preliminary nature of the drone pod components, some clear trends emerge from the life cycle assessment. Figure 2 shows that the material creation is the phase that matters most. This is in part due to the inclusion of manufacturing in material creation for selected electronic components. Transport is low because of the efficiency of ocean freight for transporting lots of small, lightweight goods at the same time. Prior to the use of the drone, its battery gets charged using the local electricity grid. The energy mix of this grid determines the effect on sustainability. Disposal show the energy used during the different waste management options used for the components. Comparing this to the potential energy saved during the next products material phase, the benefits of these waste management techniques for sustainability are evident. This is shown as the end of life potential. The end of life potential is based on extensive waste management options. If everything was send to the landfill, the end of life potential would be zero.

RAMS Analysis

For the RAMS analysis the reliability, maintainability, availability, and safety of the system. Due to the lack of data it was decided to make a more qualitative analysis. From this, it was found that the design contained a lot of single point failures, meaning that even though the individual components are very reliable, the overall

[1] `https://www.clo.nl/indicatoren/nl0004-meteorologische-gegevens-in--nederland` [Accessed on 18-05-2020]

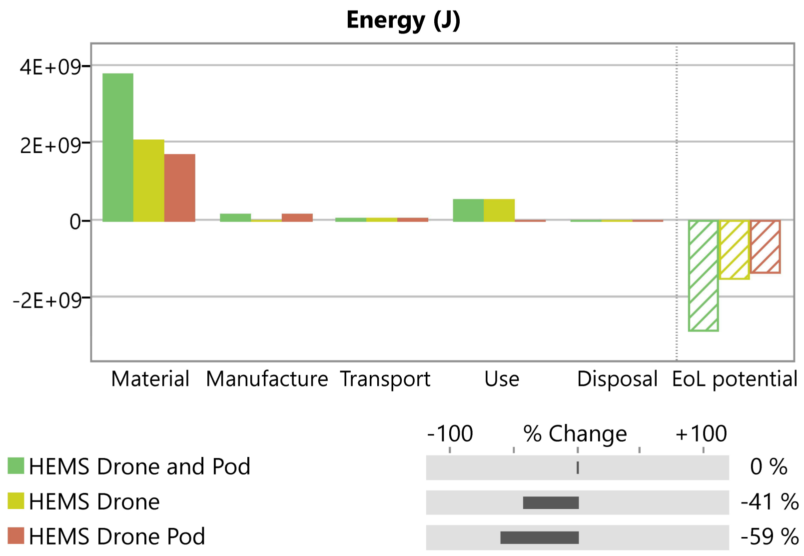


Figure 2: Relative contribution of the drone and its pod during the different life cycle phases.

design was not. Therefore it was decided to put extra redundancies in the design wherever possible. For safety the main points were the possible hazards to both the helicopter itself and bystanders. For these hazards the possible causes and mitigations were identified.

Project outlook

In the project outlook a preliminary plan for the design phases that would be needed after the DSE phase is made. This includes a project Design and Development Logic flow diagram to show the order of the project phases and tasks, a project Design and Development logic Gantt chart to show the time all of the phases would take, and a Cost Breakdown Structure, estimating the total cost of all of the parts of the project.

The further development, testing, and certification of the drone is estimated to take another 1 year and 3 months for a team of 10 engineers, but there is potential for it to take considerably more time. Product support and end of life tasks are also specified, which can be completed by a smaller team when development is complete.

The full project is expected to cost about €8,228,000, for a market size of 360 drones and excluding the price of a HUD. This results in a per drone cost of around €23,000. Adding a HUD to the project would bring the total costs up to €18,641,000. This results in a total system cost per drone including a HUD of approximately €52,000. These prices are all the prices at which the project would break even. They also include a margin safety factor of 30% because of the approximate nature of the cost estimations.

The biggest costs in order are expected to be: the HUD, Off the shelf products, Labour, and Certification.

Conclusion

The aim of the project was to design a drone that is able to aid HEMS operators to land in low visibility conditions. From this and previous reports it can be concluded that the chosen concept is viable, and different subsystems are expected to adhere to the requirements set by the user, which will be verified and validated in the future. although it is recommended that a more elaborate analysis is performed for displaying system and release mechanism. Furthermore, a dedicated planning should be made for certification of the system. The final conclusion thus is that the foundation for such a product is laid down, but it will still take some time before the system will actually be implemented.

1 Preface

This report is the final in a series of four reports by group 05, produced as part of the Design Synthesis Exercise, the concluding project for students of the bachelor program 'Aerospace Engineering' of the Delft University of Technology. In this project a design is developed as a solution for an aerospace related problem.

The report concerns readers interested in the final design of the system designed by group 05, as well as readers interested in the approach taken to arrive at this design.

As group 05, we would like to thank Ir. R. Van Gent, Dr. J.C. Bijleveld and Prof.dr. S.J. Watson, as well as G. Ruijtenberg, for their guidance, contributions and advise during the full length of the project. Furthermore, we would also like to thank Ir. J.A. Melkert and all other instructors, as well as the teaching assistants for the organization of this project and the guidance trough out.

2
Introduction

Bad visibility conditions, for example during instrument meteorological conditions (IMC), can often prevent helicopter emergency medical services (HEMS) from performing their mission, especially when the mission requires landing in unknown and/or remote areas. Considering how drones (also known as UAVs) have evolved in recent years in their performance and sensing capabilities, it seems feasible to imagine that a drone could be designed to be deployed by the helicopter and act as a 'forward observer.' It would scout the unknown landing area and relay the information back to the helicopter, enabling it to land safely even under the marginal visibility conditions.

The benefits of using a drone instead of the helicopter to scout are threefold. First, the sensors that could be installed on the drone are orders of magnitude cheaper than if sensors with the same functionality were to be installed on the helicopter. Second, using the drone to scout ahead instead of the helicopter itself does not put the helicopter and its crew into harm's way. Third, the drone has a much closer vantage point, and can scan the landing site from multiple different angles.

To design a drone system that can fulfil this need, during the baseline phase of this project, the following mission need statement (MNS) and project objective statement (POS) were formulated:
The mission need statement is:

To permit a helicopter emergency medical service pilot to safely perform the approach, landing and take-off in low visibility weather conditions.

The project objective statement is:

Design of a drone that is capable of safely assisting a helicopter emergency medical service pilot in navigation during approach, landing, and take-off in low visibility conditions by ten students in ten weeks.

With these in mind, the design process has been carried out during the last 10 weeks, starting with planning and organization, moving on to the baseline phase to perform requirements analysis and generate preliminary concepts, then performing a trade-off of these concepts during the mid-term phase, and finally performing the detailed conceptual design of the trade-off winner during the final phase. The first three phases were documented in their respective reports, and thus the purpose of this report is to document the detailed conceptual design performed during this final phase.

The report can be split into three main overarching themes, pre-design, design, and post-design. The pre-design chapters are thus chapters 2-7, these are the Previous Work, Market Analysis, User and System Requirements, Functional Analysis, Technical Risk Assessment, and Resource Allocation and Budgets, in order. The results of the work in these chapters influences the design, which is why they have to be included before the design part.

The design chapters then include chapters 8-13: Propulsion system, Aerodynamics, Structural Design and Release Mechanism, Control & Stability, Sensors and Communication, and simulation Modelling, in order. These chapters mostly share a similar layout, with the relevant subsystem requirements and functions from the functional analysis first, following with the design of the subsystem, and ending with verification and validation, when applicable.

Finally, the post-design chapters are chapters 14-20: Requirement Compliance Matrix, Sensitivity Analysis, Operations and Logistics, Sustainability Analysis, RAMS Analysis, Project Outlook, and Conclusion, in order. These chapters are placed after the design chapters since they use results from the design itself.

3
Previous work

This report is the final one in a set of four reports prepared during this ten week project. Since this is intended to be a standalone report, a brief summary of the first two reports is included, as well as a more in-depth summary of the report immediately before this one.

Project planning and baseline phase

The project planning phase involved assigning an organizational and technical role to each team member. The problem that needed to be solved was then analyzed to come up with the mission need statement (MNS) and project objective statement (POS), included in chapter 2 of this report. The tasks needed to complete this project were then planned out through project logic diagrams, including a work flow diagram, work breakdown structure, and Gantt chart. Finally, an organisational risk analysis was performed, and an approach to the project's sustainable development strategy was set out. The reader is referred to [4] for more details.

During the baseline phase of the project, the focus turned to requirement analysis. By analyzing the given requirements, and through a market analysis, technical risk assessment, and functional analysis, more detailed requirements were derived. A requirements discovery tree was also used to increase the completeness of this list. Then, many potential design solutions were explored by building a design options tree to cover as many ideas as possible. This tree was then 'pruned,' eliminating options due to practicality or requirements issues, until only a few options remained. It was also decided around this phase that the design of the sensing system and the the drone platform would be done independently. While not every possible sensing system would be compatible with any drone platform, in general it was found that these two aspects could be designed separately and then integrated, as long as the sensing system weight and power consumption were taken into account in the design stage of the drone platform.

Consequently, four design concepts were generated for the drone platform: a quadcopter concept, a hexacopter concept, a hybrid multirotor fixed-wing concept, and a swarm (or multiple drones) concept. For the sensing system, two design concepts were generated with their main difference being how they employed navigation and position determination: one relied mainly on GNSS (global navigation satellite system), while the other relied mainly on using 3D optical flow techniques. Otherwise, the overall 'sensor package' for both concepts was nearly identical. With these concepts, the project could then move to the mid-term phase where a trade-off would be performed to determine which concept would be designed in more detail during the final phase. For more details on the baseline phase, the reader is referred to [2].

Mid-term phase

As mentioned above, at the end of the baseline phase four high-level conceptual designs were generated for the drone platform, and two concepts were generated for the sensing system. The main goal during the mid-term phase was then to perform a trade-off to select an optimal candidate from these options; the results are summarized below.

Drone platform trade-off

As mentioned previously, four conceptual designs were included in the drone platform trade-off. A brief description of each of these concepts is included below:

- **Quadcopter concept:** The quadcopter (four rotors) is a conventional and very common multirotor configuration. It has advantages over a fixed-wing drone since it can hover and have more maneuverability, at the cost of lower endurance due to a less efficient cruise. Several commercial quadcopters already exist in the range of 3-4 kg which seem to meet most of the mission requirements, indicating this is a very feasible option.
- **Hexacopter concept:** The hexacopter (six rotors) is not very different to the quadcopter concept in its main advantages. Even though it would be heavier than the quadcopter concept, each individual

rotor would still likely need to produce less thrust, meaning it can potentially be more efficient than the quadcopter. However, accomodating six rotors within the limited space of 500 x 500 mm dictated by user requirements is considerably harder than accomodating four rotors. There are also mcuh fewer commercial hexacopters than quadcopters.

- **Hybrid concept:** This concept's main advantage is that it combines aspects of a fixed-wing concept with a multirotor concept, so that it can take-off vertically and hover while still having a more efficient cruise (and thus more endurance) than a pure multirotor because of the wing. At the same time, it cannot hover as efficiently as a pure multirotor since the wing is essentially dead weight when hovering, and the wing also limits its maneuverability. Finally, even though it was decided that detachable wings would be used to avoid limiting the span, storability is still worse for this concept compared to the quad- or hexacopter concepts.
- **Swarm (multiple drones) concept:** The drones making up the swarm would be quadcopters, making this concept naturally quite similar to the (single) quadcopter concept. The advantage of this concept is that instead of a single larger drone, four smaller drones with lower endurance can be used to cover the scanning area in less time. Having multiple drones also adds a level of extra redundancy. Nonetheless, even with smaller drones, storing and fitting four instead of a single one within the limited space is more difficult. Moreover, aggregating data from four different sources, and controlling four different drones, is also more difficult than in the case of a single drone.

To perform the trade-off, first the criteria that the concepts would be judged on had to be decided, as well as their relative weights. After considering several options, it was decided to use the following six criteria: risk, mission duration, wind resistance, flight duration, storability, and cost. Since the drone would be used during HEMS operations, safety is first and foremost, which is why risk was included and why it was also assigned the highest weight of 25%. Similarly, since the mission should be completed as quickly as possible so that help can get to the victim, mission duration was also included and assigned the second highest weight of 20%. Wind resistance, flight duration, and storability were all included since they are relevant to successfully performing the mission, and they were assigned equal weight of 15%. Finally, cost was also included as a criterion since it is still important to try and make the drone as cheap as possible. It was assigned the lowest weight of 10%, however, since the performance, reliability, and safety of the drone are much more important than the cost.

With the criteria defined, it was then possible to give a score to each concept for each criteria. The scores were determined both quantitatively and qualitatively depending on the criterion being considered. The scores range from 1-4, where each category is defined in the following way:

- 4 - **Excellent**, exceeds required performance, colored blue
- 3 - **Good**, meets required performance, colored green
- 2 - **Solvable**, could meet required performance with modifications
- 1 - **Unacceptable**, would require major redesign to even meet required performance

After grading every concept on every criteria, a weighted average using the weights explained before can be calculated to get a final score per concept. The summarized results of this are shown in Table 3.1.

Table 3.1: Drone platform trade-off summary table

	Risk	Mission Duration	Wind Resistance	Flight Duration	Storability	Cost	Weighted Score
Quadcopter	3 - Few risks in mid-level range	3 - High speeds achievable	3 - Good wind resistance	4 - High endurance achievable	4 - Small or foldable design possible	3 - Expensive deployment	3.30
Hexacopter	2 - High risk of attachment failure	3 - High speeds achievable	3 - Slightly bigger resistance than quadcopter	3 - Slightly lower endurance due to 'extra' rotors	4 - Small or foldable design possible	4 - Cheaper unit cost	3.00
Hybrid	1 - Higher risk of helicopter collision than multirotors	4 - Higher cruise speed than multirotors	2 - Wings make resistance worse	4 - Wings allow higher endurance than multirotors	2 - Long wings make storage larger	3 - Expensive deployment	2.55
Multiple	1 - High risks remain after mitigation	4 - Scanning area can be divided up	3 - Same as quad/hexacopter	4 - Same as quadcopter	1 - Same as quad/ hexacopter	2 - Multiple drones increase cost	2.45
Weight	25%	20%	15%	15%	15%	10%	

The results shown above place the quadcopter concept in the best position but with the hexacopter not too far behind, while the hybrid and swarm concepts are definitely at the bottom. Nonetheless, before simply accepting these results and assuming the quadcopter was the best choice, first a technical sensitivity analysis and a trade-off sensitivity analysis were performed. The technical sensitivity analysis, where the variability in each of the criterion scores was analyzed per concept, did not yield different results. In fact, it showed that for most criteria, the worst-case score of the quadcopter was on par with the best-case score of the hexacopter, thus also indicating the quadcopter as the best option. The trade-off sensitivity analysis, where criteria were removed one at a time from the trade-off, and the results recalculated, however, did show slightly different results. When the risk criterion was removed, all the scores became much closer, and more specifically, the difference between the quadcopter and hexacopter became less than 0.1. Thus, this indicated that the only reason the hexacopter was scoring considerably worse was because of the risk (this is also visible in the table scores), and when this was re-evaluated it was deemed that the difference in risk between these concepts was not actually as large as the trade-off might make it seem in the resulting final scores. Thus, it was necessary to look at other aspects to make the final decision.

Among the additional aspects that were examined to make a final decision were: complexity, sustainability, and control & stability. In summary, while the quadcopter and hexacopter did not have large differences in their sustainability, it was determined that the quadcopter was less complex (due to having less rotors) as well as more maneuverable (due to size and likely lower moment of inertia). Moreover, the quadcopter did perform better than the hexacopter when considering the results from the technical sensitivity analysis. Even though these two concepts both scored a 4 (excellent) in storability, the quadcopter can still be considered superior to the hexacopter in this aspect since (for a given payload weight and rotor diameter) it will occupy less space due to having less rotors. Considering all of this, it seemed clear that the quadcopter was a better, simpler choice that would still achieve performance on par or better than the hexacopter, and thus the quadcopter concept was the concept chosen to develop in this final phase.

Note on mid-air retrieval

It is important to note that initially, each concept also had different release and retrieval (from the helicopter) mechanisms. However, it was found that this biased the trade-off negatively since it made some concepts 'appear' better, when actually, in general, the different release and retrieval mechanisms that were being considered could be applied to any of the concepts directly or with relatively small changes. Thus, it was decided to remove the retrieval from the considerations, and change the release (deployment) mechanisms that were being considered so that they were more similar across the concepts. Moreover, after discussion with the customer and a HEMS pilot, it became evident that mid-air retrieval of the drone was potentially too risky, and this should be re-examined to decide whether mid-air retrieval was worth the risk. After a brief cost-benefit and risk analysis was performed, where the cost of losing a HEMS helicopter and the human lives of the crew in it was compared to the cost of the drone, while also considering an estimated probability of a fatal accident during mid-air retrieval, it was indeed determined that mid-air retrieval should not be considered. The requirement stating that the drone should be retrievable in mid-air was then removed from the project. Instead, it was decided that the drone can simply be picked up manually by the pilot after the HEMS helicopter lands, and this was confirmed to be feasible by a HEMS pilot. If the drone is deployed but the helicopter cannot ultimately land, the drone can then land and potentially be picked up by other authorities, since the HEMS pilot also confirmed that some form of ground assistance (such as the police or an ambulance) is virtually always at the emergency scene before the HEMS helicopter assistance arrives. Otherwise, in the worst-case scenario, it is simply preferable to lose the drone than to attempt mid-air retrieval, in accordance with what was found through the cost-benefit and risk analysis.

Sensing trade-off

Multiple different sensors and combinations were considered in the early stages of development. The main competitors were millimeter wave radar, lidar, and IR-cameras. Both lidar and IR-cameras were soon abandoned, condsidering they both operate in, or close to, the visible range of the electromagnetic spectrum. This means they will provide little to no additional information compared to plain eyesight in low-visibility condition caused by, for example, fog. Therefore, the final choice fell on a array of Texas Instruments AWR2243 millimeter wave radars.

Another point of discussion was the way of navigation. Due to the maturity of the technology, GNSS was deemed a viable option. Disadvantages are the reliance on a strong enough signal and the level of accuracy without the addition of RTK. Due to this, a concept based on three-dimensional "optical flow" was deemed more suitable. This concept relies on the stitching together of the three-dimensional data gathered from the millimeter wave radar. By determining the transformation matrix of the overlapping part of two scans, the change in position and orientation of the drone can be determined. Radio beacons will be used to determine the position of the helicopter relative to the drone.

4
Market Analysis

In this chapter some research and considerations are described that are relevant regarding the target price of the final product. To obtain a price however, first it is required to define the market need as well as a list of potential customers. Then a market volume can be found. Afterwards an estimation is made for certification costs. This is done in advance of the design process because there are significant cost differences between certain design choices. Also there are some regulations that apply to the market that the product has to be certified for, this will be discussed in section 4.6. Lastly an analysis will be performed that identifies strengths,weaknesses,opportunities and threats of the final product. Note that this market analysis will be mostly restrict to Europe, mostly because it is convenient due to the location of the team, but also because, in general, the sources that were investigated were European (e.g. the Dutch HEMS pilot that was contacted, the Danish HEMS operators data).

4.1. Market need

As population and per capita expenditure in healthcare grow, the demand for air ambulance services also grows. In the Netherlands, over 8000 Helicopter Emergency Medical Service (HEMS) flights per year are performed by 8 helicopters, and over 200 000 flights in all of Europe. Moreover, according to EHAC (European HEMS & Air Ambulance Committee), there are over 360 HEMS helicopter bases in all of Europe[24].

Providing these services requires a skilled pilot that can find an appropriate landing spot as close to the emergency as possible and perform this landing safely. Urban environments pose the difficulty of having more obstacles but being more well mapped, while remote areas pose the difficulty of being less mapped even if they might have less obstacles. While the instrumentation (e.g. GNSS) is used for navigation and landing, a lot is done visually, under VFR (visual flight rules) regulations, meaning the pilot can simply maintain a safe separation to obstacles and use the horizon and terrain as visual references to do this. Flying under VFR, however, implies that the pilot cannot fly through clouds, for example. In those cases (or in any case where visibility deteriorates) the pilot must either switch to IFR (instrument flight rules) to continue flying or otherwise divert or abort the mission (different countries and institutions specify minima related to visibility and cloud ceiling which determine whether an aircraft is allowed to fly VFR). Flying IFR requires specific equipment and certification, and the pilot must also have the required training to fly IFR. While the possibility to fly IFR means that more missions can be completed (and less missions aborted, potentially saving money) and more lives can be saved, HEMS operators in the UK still preferentially complete their missions under VFR if conditions allow [1].

Even though IFR enables performing missions in worse visibility conditions compared to VFR, it still has limitations. Especially when considering missions that require landing in an unknown or not well mapped area, finding a safe landing spot and performing the approach can be very challenging when flying in bad visibility conditions, even under IFR. Marginal visibility conditions can thus cause a mission to be aborted if the pilot determines landing cannot be performed safely. Thus, as also mentioned in the project's mission need statement (MNS), this drone system would aid the pilot during landing and approach in bad visibility conditions, so that more missions can be completed, and more lives can potentially be saved. Apart from making usually impossible landings possible, the drone could also help in making landings and approaches that the pilot would choose to perform regardless of the drone system potentially safer.

Unfortunately, detailed data about HEMS missions in the Netherlands and how often these are affected by bad visibility conditions was not available. Nonetheless, interviews with a current HEMS pilot in the Netherlands confirmed that this is indeed an issue. The Danish air ambulance services were also consulted, and while they did not have data related specifically to bad visibility they did have data on aborted and cancelled missions due to general bad weather conditions, which still serves as an indication of how often this issue

[1] `https://www.airmedandrescue.com/latest/long-read/flying-aircraft-under-ifr-and-vfr` [Accessed on 29=06-2020]

occurs. This data is shown in Table 4.1 for the years 2015-2019. Note that the data for the years 2015-2018 is based on 3 HEMS helicopters, while for 2019 it is based on 4, and that 'aborted' missions refers to missions that were started and had to be aborted, while 'cancelled' refers to missions that were not started at all.

Table 4.1: Data on Danish HEMS missions

Year	Number of missions	Aborted missions	Cancelled missions
2015	2647	62	234
2016	3488	53	291
2017	3641	67	368
2018	4013	71	433
2019	4230	81	476

As the data in the table shows, missions being aborted does not happen very often, about 2 % of the time. However, mission cancellations are more common, happening about 10 % of the time. As noted before, this abortions and cancellations also potentially include other limiting weather conditions which do not involve bad visibility (e.g. icing conditions), so the amount of missions affected specifically by bad visibility conditions is also less than shown here.

4.2. List of all potential customers

The list of potential customers will be put into order from highest to lowest potential market volume.

1. **HEMS operators (ANWB MAA in the Netherlands):** The most important market and the main target the drone is designed for, are the HEMS operators. Within this group the drone will first be introduced to the Dutch market, with afterwards an expansion into the European and possibly even the global market.In order to achieve this expansion the global regulations regarding aviation should be taken into account.
2. **Search and Rescue:** This sector sometimes has to find victims in tough weather conditions. The drone could be helpful in these situations to find a landing spot in bad conditions. But most importantly locate the victim first as it is probably not as clear where the victim is compared to HEMS operations.
3. **Military helicopter operators:** Although the military is a difficult to assess in market volume it is still a large market and therefore it is left in this list. The biggest problem this market might have is the retrieval, military operations do not favour leaving technology behind. In case of an aborted landing this would be a problem.
4. **Aviation police:** The aviation police owns helicopters and therefore could potentially have interest.
5. **Oil rigs:** Another possible customer can be the transporters to and from oil rigs. These might also have to operate in bad visibility conditions and might thus be interested in the drone. Even though it is quite a specific target, there are quite some flights conducted annually so it might very well be worth it to further explore the possibilities. The certification cost of the drone could be the largest issue to serve this customer.

4.3. Market Volume

For the market volume estimation there will only be focus on the European HEMS operators. Within Europe all regulations and certification is valid so that is why the potential market volume is restricted to this area. As earlier research already pointed out there are 360 HEMS operation bases in Europe[24]. Every base would need at least two drones. It is assumed that in an average market scenario half of the operation bases are interested in the product. That would leave the company with a market volume of 360 units. For other potential customers it is hard to predict their interest. Further development of the product could spark their interest if the results are positive. This would also require a marketing strategy to reach them.

4.4. Stakeholder identification

As stated above, for the scope of this project, the focus will be on the HEMS operators as main customer or target market. Knowing this, stakeholders were identified, for which important requirements were derived in section 5.2. the relevant stakeholders were identified as:

- HEMS personnel (pilot and drone operator)
- The patient
- Bystanders (including people living close to the landing site)
- Manufacturers
- The government and airworthiness authorities
- HEMS operators such as ANWB Medical Air Assistance (or potentially foreign European operators)

4.5. Drone cost

The drone cost will include the cost of the drone and the release mechanism cost. The price of the drone itself was already estimated at a value of 15K EUR. This price would fall in the higher end of the current drone market but that is acceptable because this drone is designed for a smaller market volume and specific application that does not yet exist. The price of the release mechanism is a difficult one to estimate at this time because this would be a very unconvential product in the market and therefore a lot more design and testing has to be put in before it would not only be certified but also entrusted by the user. It is already known that this release mechanism needs to be manufactured with demanding tolerance and well-proven reliability. Therefore the price is left as a range which equals 5K-10K EUR.

4.6. Certification costs

Certification of the drone is essential in order to introduce the product to the market. In order to operate a drone at a distance larger than 120 meters from the ground in the European Union, a dedicated authorisation procedure must be performed[2].

After talking to the HEMS pilot it is clear that there is a strong need for more integrated and dedicated equipment that the pilot can rely on. This means that the price of the drone will go up more than originally estimated. For the market analysis, an estimation is required for certification cost and how far the customer is willing to go in cost versus integration of the system. One of the large cost dependant considerations would be in cabin detachable tablet against a head up display (HUD). Also it can be said with great certainty from the HEMS helicopter pilot interviews that the drone will not be stored in the cabin, but rather in an external attachment, meaning that this will be a certification case as well.

Drone controlling license

An RPA-L license that is required to fly a drone of this weight bracket would cost around 3500 EUR (excl. tax) per co-pilot/nurse that is trained to operate the drone. [3]. There might be a need for more training than this, considering that the drone could be near the helicopter in parts of the mission. However training hours for drones should not be a large expense in comparison to other costs.

Data presentation

The data that the drone will produce and present to the (co-)pilot will preferably be done through an Head Up Display(HUD). This would give the pilot easy access to the information without losing communication or other cues during flight. However a solution like this would be very expensive to certify. The alternative would be a tablet that is simply attached and detached that will present the information from the drone to the (co-)pilot. This would be a lot cheaper to certify as it is not integrated within the helicopter equipment as radically as the HUD. Currently the decision between these 2 concepts is not yet made. It is possible however to report an estimation on the certification cost of the HUD. Looking at similar competitor HUD's the following can be found "Helicopter pilots have conducted 200 to 300 hours of flight testing so far in the above helicopters and an FAA Sikorsky S-76 and on Universal's own helicopters." [4] Flight testing for 300 hours would bring the following cost. Therefore this would easily cost a million EUR to certify. The tablet might not even cost 100 000 EUR, as it is more common to have similar devices in the cabin already. A more exact estimation of this will be presented in the cost breakdown in Chapter 20.

Release mechanism

Obtaining an estimate for the cost of certification of the helicopter attachment is complicated as it depends heavily on EASA. Using EASA's charging fees for similar operations it was estimated that the cost of certification of the release mechanism attached to the bottom of the helicopter would be somewhere around 66K EUR. The reasoning for this is that a convential uninstalled attachment would cost around 29 400 EUR. [5] and it is assumed that it is necessary to test the system with and without the drone in the helicopter. Therefore the certification cost is doubled. In addition to this there is also cost associated with the flight hours of the helicopter that will be used for testing. It is estimated that the total amount of flying time would be around 4 hours for this. Using a estimation of 1500 EUR/hr [6] for flying the EC135 Eurocopter helicopter this would sum up to a total of 6000 EUR.

[2] https://www.easa.europa.eu/sites/default/files/dfu/Easy_Access_Rules_for_Unmanned_Aircraft_Systems.pdf as mentioned in article 12. [Accessed on 11-06-2020]
[3] https://www.droneflightcompany.com/nl/opleidingen/certificering/rpa-l/ [Accessed on 29-06-2020]
[4] https://www.ainonline.com/aviation-news/business-aviation/2020-03-18/head-wearable-display-obtains-first-certification [Accessed on 29-06-2020]
[5] https://eur-lex.europa.eu/legal-content/NL/TXT/PDF/?uri=CELEX:32019R2153&from=EN [Accessed on 19-06-2020]
[6] https://www.aircraftcostcalculator.com/AircraftOperatingCosts/457/Airbus-Eurocopter+EC+135+T1 [Accessed on 19-06-2020]

4.7. SWOT Analysis

In this section, the Strength/Weakness/Opportunity/Threat (SWOT) analysis is presented. It summarizes important points that need to be taken into account for the design of the drone.

Earlier suspicion of strengths and weaknesses were confirmed for this market analysis. As stated in[2]: "Most of the strengths of the product are based on the niche it is trying to fill, but this uniqueness is also a weakness." The strength of this product would be its unique and detailed mapping of possible landing sites almost everywhere. However this, to some extent, pioneering is very expensive. This is not true for some components such as the sensors for example which are composed of off the shelf products.

A fact is also that this is a student project and that is both a strength and a weakness, as the team is lacks design experience, but can rely on the university's support. This support consists, for example, of contact with experts on different aspects of the design and the user as well, like a HEMS pilot. The drone market is rapidly developing. If the product were to make it to the market, its characteristics could be copied and improved on by other players in a short time. However the competition would have to go through the same certification process and that offers a time window to stay ahead in the technical market. Furthermore this drone platform can be converted to fulfill other missions.

The primary customer, Dutch HEMS organisation, have low demand, however generally, it is willing to pay large amounts of money for technology aimed at saving lives and protect the lives of the helicopter crew. Although great attention must be given to the risk that is a drone flying near the helicopter. Regulations are not too specific on a product like this one.

It is expected that this product is feasible by modification of regulations for this specific mission. These strong regulations will likely result in a high certification cost.[1] A derivation of this drone for the military market might offer up a lot of market volume however there might be problems selling this product to the civilian market and military market simultaneously. In Table **??** the most important considerations regarding the SWOT aspects are listed.You may notice that having no similar product on the market is marked as a weakness. This is because regulations are not adapted to this kind of product, meaning that to certify this product a lot of adjustment to the avionic regulations have to be implemented. This will add to the certification costs. Additionally there are already existing solutions to the problem that this product is trying to solve, in the form of helicopter attached sensors. A very significant strength is however, that these solutions are a lot more expensive, such as the Falcon Eye [7] of $500,000 whereas our product is currently estimated at a price of 60,000 EUR(more detail can be found in section 20.3).

Table 4.2: The SWOT analysis, partly from [2] but updated for the current design phase

Strengths:	**Weaknesses:**
Product: · Able to map environment independent of humidity. · Deployable from a helicopter. · No extra risk for helicopter during landing zone exploration. · Potentially less training than competing solutions. · Loss of a drone is favorable to loss of a HEMS helicopter. · Much cheaper than helicopter attached sensors. **Company**: · Network of connections, due to TU Delft link.	**Product**: · No similar product on the market. · Training required for usage might increase cost and effort involved with purchase. **Company**: · Very limited resources available (both time-wise and financially). · Little engineering experience in the company.
Opportunities:	**Threats:**
Product: · Derivatives of this drone platform, with other sensors. · Other enhanced visibility missions, enabled by this product. **Market**: · Different use cases, with the same drone · Generally, customers are willing to pay large amounts of money for technology aimed at saving lives. **Trends**: · Investment and development of drone technology and subsystem. · Openness of the general public to new drone technology.	**Product**: · Solutions that have the same purpose are in development. · Helicopter attached sensors. · Possible increase in risk for helicopter when using the product. · Costly product certification. **Market**: · Low demand in the primary customer area. · Protectionist regulations for the military market. · Strong safety regulations set by the airworthiness authority. **Company**: · Costly regulatory approval for a design organisation · Sensitive information regarding bystanders might be mapped during the mission. E.g. backyards or other privately owned land might be mapped unintentionally.

[7] https://www.aopa.org/news-and-media/all-news/2019/june/pilot/falconeye-flying#:~:text=The%20FalconEye%20is%20the%20first,infrared%20views%20on%20the%20HUD. [Accessed on 29-06-2020]

5
User and System Requirements

The user and system requirements were first established in the baseline phase and listed in the baseline report [2]. The user requirements ultimately dictate the constraints within which the system must be designed, so they are of principal importance to the design phase of the project. The system requirements are the requirements which could not be attributed to a single subsystem.They are often taken into account in the design of multiple of the subsystems. The system requirements are listed here. Specific subsystem requirements are listed in their respective subsystem chapters. The stakeholder requirements take into account other parties affected by the system.

The reasoning for the creation of the user and system requirements that are not new has been established in the baseline report. If any of the requirements are new, or if they have been changed from their initial definition the origin of the requirement and the reasoning for the change will be mentioned along with the requirement.

5.1. User Requirements

These requirements were established directly from the constraints provided by the user in the project guide [48]. Changes in the user requirements were only made if they were absolutely necessary, and always with the agreement of the customer.

- **HD-USR-PERF-01:** The drone shall be able to sense a cylindrical volume with a radius of at minimum 200 m and a height of at minimum 100 m vertically.
- **HD-USR-PERF-02:** The drone shall be able to perform the scan at a distance of at least 2000m from the HEMS helicopter.
  Added 'at least'.
- **HD-USR-PERF-03:** The drone shall be able to perform the entire mission within 10 minutes.
- **HD-USR-SENS-01:** The sensors shall not be negatively impacted by high humidity or fog air conditions.
  Changed from the original requirement of 'The sensors shall be operable in conditions with less than <tbd>' Because radar sensors are generally not impacted by the normal level of visibility at all, instead being impacted more by the fog and moisture in the air under low visibility conditions, the requirement was changed to reflect that consideration.
- **HD-USR-SAFE-01:** The drone's deployment shall not endanger the safety of the HEMS helicopter.
- **HD-USR-SAFE-02:** The drone's recovery after the operation shall not endanger the safety of the HEMS helicopter.
- **HD-USR-SYS-01:** The drone shall weigh a maximum of 10 kg.
- **HD-USR-SYS-02:** The drone's dimensions shall be at most 535x535x250 mm.
  Changed from 500x500x250 to be able to fit the 15.5 inch foldable propellers, following the reasoning provided in subsection 9.3.1. This change was agreeable considering the current placement of the drone on the helicopter.
- **HD-USR-SYS-SUST-01:** The drone shall be able to perform 1000 sorties.
- **HD-USR-SYS-SUST-02:**: The drone's energy shall be provided by Lithium Ion batteries.
- **HD-USR-SYS-SUST-03:**: The drone shall be zero-emission during its mission.
  Added 'during its mission' to avoid confusion on whether it would also be zero emission in for instance production of its components or generating the electricity to charge the batteries (which it is not).
- ~~**HD-USR-OPS-01:**~~ The drone shall be recoverable mid-flight.
  Removed as a result of the risk benefit analysis performed during the midterm phase [3].

- **HD-USR-OPS-02:** The system's proper operation shall not be prevented by helicopter downwash.
- **HD-USR-SYS-CST-01:** The system shall not exceed the cost of 60 k euros. *Customer emphasised that such a system would likely be bought at any price up until an arbitrary limit of 100 k euros, but similar on helicopter systems have a price tag of about 60 k euros, so to compete the maximum price will be set to that (from <tbd> in the baseline).*

5.2. Stakeholder Requirements

The stakeholders for the HEMS Reconnaissance drone were identified as:

- HEMS personnel (pilot and drone operator)
- The patient
- Bystanders (including people living close to the landing site)
- Manufacturers
- The government and airworthiness authorities
- ANWB Medical Air Assistance (or potentially foreign operators)

in chapter 4. To make sure stakeholder needs were also met by the system separate stakeholder requirements were formulated in the language of the stakeholders.

- **HD-STKH-01**: The drone shall make it possible for the helicopter to safely reach the patient.
- **HD-STKH-02**: The drone shall comply with government regulations.
- **HD-STKH-03**: The drone shall not put any bystanders at unacceptable risk of significant harm.
Changed by adding 'unacceptable' to better reflect what is realistically possible. At the end of the day, the mere presence of the system will put the bystanders at extra risk, but if these risks are mitigated to acceptable levels, as explained in chapter 7, this requirement will be fulfilled. Unacceptable risk is defined as the risk event being located in the darker orange sections of the mitigated risk map. (bottom right of the yellow diagonal) in Figure 13.3.
- ~~**HD-STKH-04**~~: The operation of the drone shall not take more than <TBD> percent of the operator's time during a mission.
Requirement has been removed as a result of conversations with the HEMS pilot, who mentioned that the co-pilot/nurse (the projected pilot of the system) essentially has very few other tasks to perform in flight. So, making sure the co-pilot/nurse is not overwhelmed by operation of this system along with their other tasks is no longer a primary concern.
- **HD-STKH-05**: The navigation data provided by the drone shall be presented in a three dimensional environment.
Changed the word 'path' to 'data' to align with the preference of the helicopter pilot, and to better represent the functioning of the drone. The drone will not calculate the path for the helicopter, but the drone will provide as much 3D area information as possible to the pilot so the pilot can decide on a good approach path. This keeps the helicopter pilot in charge of the decision making.

5.3. System Requirements

System requirements are requirements that influence the design of the entire system or multiple subsystems at the same time.The baseline requirement list was needlessly detailed in some aspects, so the requirements that were not taken into account in the current design, that were too specific for this phase of the project, or that were otherwise not applicable to the design were removed from the requirement list. Removed requirements are crossed out and a reasoning will be given for their removal.

- **HD-SYS-01**: The drone shall be able to safely land autonomously if the communication link with the helicopter fails.
- **HD-SYS-02**: The drone shall have a mechanical case protection of IP56.
- ~~**HD-SYS-03**~~: The drone shall be able to perform a rendez-vous within <tbd> minutes.
Since the midterm excluded the retrieval functionality from the design, this requirement was no longer necessary.
- **HD-SYS-04**: The drone shall have a maximum operational ISA altitude of at least 3000 m.

- **HD-SYS-05**: The drone shall be identifiable as belonging to emergency medical services.
- **HD-SYS-06:** The system shall be able to operate within an environment temperature range of -40 to 35 degrees celsius ISA.
- **HD-SYS-CST-01**: The operations costs shall be less than 5 k euros per year.
- **HD-SYS-CST-02 to HD-SYS-CST-07**: Requirements related to specific costs of the system.
  These requirements are all related to very specific costs in the system, which at this stage cannot be estimated yet. The <tbd>s of these requirements therefore have not been filled in yet, as no analysis has been performed to figure out what acceptable <tbd>s are yet. They are to be examined further starting in the later design phases after the DSE.
- **HD-SYS-RISK-01**: The electrical equipment in the drone shall be off-the-shelf.
- **HD-SYS-RISK-02**: The electrical systems used to control the drone shall be off-the-shelf
- **HD-SYS-RISK-03**: The off-the-shelf equipment used in the drone shall have a TRL of at least 7.
- **~~HD-SYS-SAFE-01~~**: The drone shall not surpass a maximum velocity of 15 m/s during operations.
  This requirement is canceled since it is too ambiguous and compliance cannot be verified.
- **~~HD-SYS-SAFE-02~~**: The drone shall alarm the surroundings when it has crashed.
  Requirement and the corresponding functionality is unnecessary for the product to be employed correctly and safely.
- **HD-SYS-SAFE-03**: The motor shall stop rotating if the drone has crashed.
- **HD-SYS-SAFE-04**: The drone system shall not interfere with the safe functioning of the helicopter.
- **HD-SYS-SAFE-05**: There shall be a backup release mechanism to assure that the drone can be separated from the helicopter in case the primary release mechanism fails.
- **~~HD-SYS-SUST-01~~**: The used materials shall have a net-zero impact on the environment.
  This requirement was too strict to be complied with for the design of the drone. To create a product for a complex and important task like this the materials will often have to have an impact on the environment, out of necessity. Take for instance carbon fibre being used in the drone structure. The aim is still, of course, to minimize the impact the design does have on the environment as discussed in chapter 18. The requirement was made without putting too much thought into it, and in a stage where it was not clear yet how inflexible drone design is when looking at sustainability.
- **~~HD-SYS-SUST-02~~**: The materials shall not be toxic.
  Just like for HD-SYS-SUST-01, this requirement cannot realistically be adhered to. The requirement was made without putting too much thought into it in a stage when it was not clear that this was the case.
- **HD-SYS-SUST-03**: At least 80% of materials used shall be recyclable.
- **HD-SYS-SUST-04:** The maximum produced noise shall be less than <tbd> dB.
  Noise might become a factor in later design, but for this phase of the project it has not been taken into account at all. The argument could also be made that this product is used for emergency circumstances, and that the noise generated by it (if not totally excessive) is of lesser importance. The <tbd> cannot be filled in yet, so it is not accounted for in the compliance matrix.
- **HD-SYS-REG-01**: The drone shall comply with EASA UAS regulations, where applicable for the mission.
- **HD-SYS-REG-02**: Integration of the system to an operational helicopter shall not invalidate the CS-27 certification of the helicopter.
- **HD-SYS-REG-03**: Integration of the system to a helicopter shall make the helicopter certified for instrument flight according to IFR.
- **HD-SYS-REG-04**: Control inputs from the operator shall override autonomous controls.
- **HD-MISC-01:** The drone's batteries shall be able to be tested without disassembly.
- **HD-MISC-02:** The drone's collected data shall be deleted after each sortie.
- **HD-MISC-03:** The drone shall be able to be carried by one person.
- **~~HD-MISC-05:~~** The production time of the system shall be less than <tbd> hours.
  The manufacturing process design will be done in the post-DSE parts of the project, as described in chapter 20. It was therefore removed for this phase of the project.
- **HD-MISC-06:** The controls and display of the drone shall not limit the use of the helicopter avionics.
- **HD-MISC-07:** Any added controls and display shall be able to easily be removed from the avionics dashboard.

- ~~**HD-MISC-08:**~~ The development of the system shall be performed within 10 weeks.
This requirement is not really realistic for the full design of the drone. It was removed as it was an unnecessary requirement.

Operations

- **HD-OPS-01:** The drone shall be released with the minimal altitude of <tbd> m.
This requirement is dependent on the height needed for the drone to stabilize itself after deployment. As this height cannot be accurately determined, this requirement can not be completed at the current design phase.
- ~~**HD-OPS-02:**~~ The drone shall maintain a minimum distance of <tbd> m from the helicopter right after deployment.
This requirement is not relevant anymore as the developed deployment method does not allow the drone to be near the helicopter after deployment.
- ~~**HD-OPS-03:**~~ The drone battery shall be exchangeable within <tbd> minutes.
This operation is later decided to be part of the between sortie maintenance, on which a time requirement is already set.
- **HD-OPS-04:** The drone's maintenance between sorties by a trained employee shall take no more than the minimum refueling time of the HEMS helicopter.
in order to be ready for a new call, without being delayed by using the drone system, the maintenance between sorties shall be done during the mandatory refueling of the HEMS helicopter.
- **HD-OPS-05:** The drone shall be operable by one person.
- **HD-OPS-06:** The time it takes to perform preflight inspection of the system shall be less than 30 minutes.
30 minutes is the time that HEMS operators inspect the helicopter and are not allowed to fly yet. This is also the moment the drone maintenance cycle is planned.
- ~~**HD-OPS-07:**~~ User training shall last at most <tbd> hours.
Training is an essential activity in order to reduce risk during operation, therefore the training time shall be as long as needed in order to assure safe operation of the system. This results in no upper bound set on the training time.
- **HD-OPS-08:** All critical components of the system shall be accessible for inspection.
- **HD-OPS-09:** The boot up time of the system shall be less than 2 minutes.
This requirements flows from the functional analysis, wherein it is stated that the drone will boot up before the helicopter will take off. Generally the helicopter will take off around 2 minutes after a call.
- ~~**HD-OPS-10:**~~ The refresh rate of the displayed data shall be <tbd> Hz.
This requirements became less relevant as during the design phase, it was chosen to continuously update the displayed data, making the sensor sample rates and computing power the limiting factor.

6
Functional Analysis

6.1. Functional Flow

To perform its mission, the drone must perform a set of functions in a certain order. This chronological order is described in the functional flow diagram, see Figure 6.1. This section will describe the functions during various phases of the drone's life and mission.

6.1.1. Manufacturing

Before the drone can perform its mission, it needs to be manufactured. Firstly, as for any product, materials and parts need to be acquired. These were divided into three categories, raw materials, pre-made parts and pre-made sub-assemblies.

As there are numerous off-the-shelf drone components readily available, not everything has to be created from scratch. Parts such as motors, camera's, sensors, ESC's, etc. can be acquired from existing manufacturers, decreasing manufacturing cost and time significantly. To uphold to the set sustainability requirements, a reusability cycle is introduced. When drones reach their end of life, some parts can be removed and reused in a new drone, decreasing the waste.

As not everything can be acquired from off-the-shelf products, there is also a need for raw materials. Again, looking at sustainability, mostly recyclable materials are to be used in manufacturing. Also, together with the reusability cycle, a recyclability cycle will also be introduced. Recyclable material from decommissioned drones will be introduced back into the manufacturing process, reducing waste even more.

6.1.2. Flight Preparation

When the drone is required to fly a mission, it is taken out of storage and booted up to standby. During this procedure it will automatically perform a systems check, indicating if it detects any abnormality in its systems. After this, a hardware check is performed on the exterior of the drone and its main critical flight systems. If necessary, the ESC and IMU are calibrated. If no faults are found that could lead to a critical failure, the drone is attached to the helicopter and is then deemed mission ready. If there are faults found and the drone is not deemed mission ready, a backup drone is used, which will undergo the same procedure of booting up and checking.

6.1.3. Deployment

When approaching the landing site, the pilot decides if the use of the drone is necessary. If not, the pilot follows the normal landing procedure and the drone remains attached to the helicopter. If the pilot decides to use the drone system, the HEMS Crew Member (HCM) activates the drone control system and makes the drone ready to drop. If it is safe to drop, the release mechanism is activated and the drone is dropped from the helicopter.

The following set of actions happens in quick succession to each other. Firstly, the drone determines its status i.e. altitude, location, orientation and direction. Then, to unfold the propeller blades, the rotors briefly spin up. Lastly, when a safe distance from the helicopter is reached, the flight control system kicks in and stabilizes the drone attitude and altitude until a stable hover is reached. After this set of actions, the RGB camera feed is initialized and the HCM, now the drone pilot, has the ability to take control of the drone. Either manually or automatically, the drone flies to the scanning site to start its scanning procedure.

6.1.4. Scanning

When arrived at the scanning site, the scanning sensor system is initialized and the scanning flight path is initiated. While flying the calculated flight pattern, on board computer continuously collects data from the sensor systems. The sensor data is processed into a 3D representative view of the environment while the visual camera feed is processed to give a better visual reference by "de-misting" the image. The data, together with the drone status and location, is then sent to the helicopter. When the scanning path is complete, it is deemed sufficient or insufficient by the pilot, which may lead to a secondary area scan.

6.1.5. Performing Landing

If the pilot decides to land, the drone will fly ahead to the landing site and land at a safe distance. When landed, the drone will activate its landing assist systems, assisting the helicopter in landing comparable to an Instrument Landing System (ILS), found at most landing sites. After the helicopter has landed and HEMS crew is able to perform its medical purpose, the drone is retrieved by the pilot or another member of the on sight personnel. It is then stored on the helicopter and brought back to base.

If the pilot decides to abort the landing, the drone can not be brought back to base by the helicopter. In this case a member of the on sight personnel, e.g. police or ambulance, will locate and retrieve the drone, whereafter the drone will be transported back to base.

6.1.6. End of Life

When it is determined that the drone is not mission capable anymore, it has reached its end of life. To uphold the sustainability standards, the drone will not simply be discarded. First, the drone will be fully disassembled into its individual components. These components will be evaluated, as when the drone has reached its life, does not mean that every component has reached its end of life. Components that are still mission capable will be stored to use as spare parts or be directly implemented into a new drone.

When all components have been evaluated and all reusable components have been filtered, a recyclability evaluation is done. Components and materials that are recyclable are separated and transported to the relevant recycling facilities.

The remaining components and materials are neither reusable or recyclable. These will have to be discarded into landfill. The use of these materials are be kept to a minimum in the drone design and only to be used if there is no sustainable alternative. The ultimate goal is to have no components or materials that can not be reused or recycled.

6.1.7. Emergency

As there is always the probability of something going wrong, the drone has also been designed with emergency situations in mind. The emergency functions are implemented to mitigate the risk of a catastrophic failure, which could lead to damage or injury. The main emergency function to ensure the safety of the drone, crew, and bystanders, is the manual override function. The manual override can be activated at any time during the flight whenever the drone operator sees fit, removing the authority of the autonomous control system. The manual override function can also be activated automatically if the system detects a scenario where it is unable to control the drone autonomously in a safe manner.

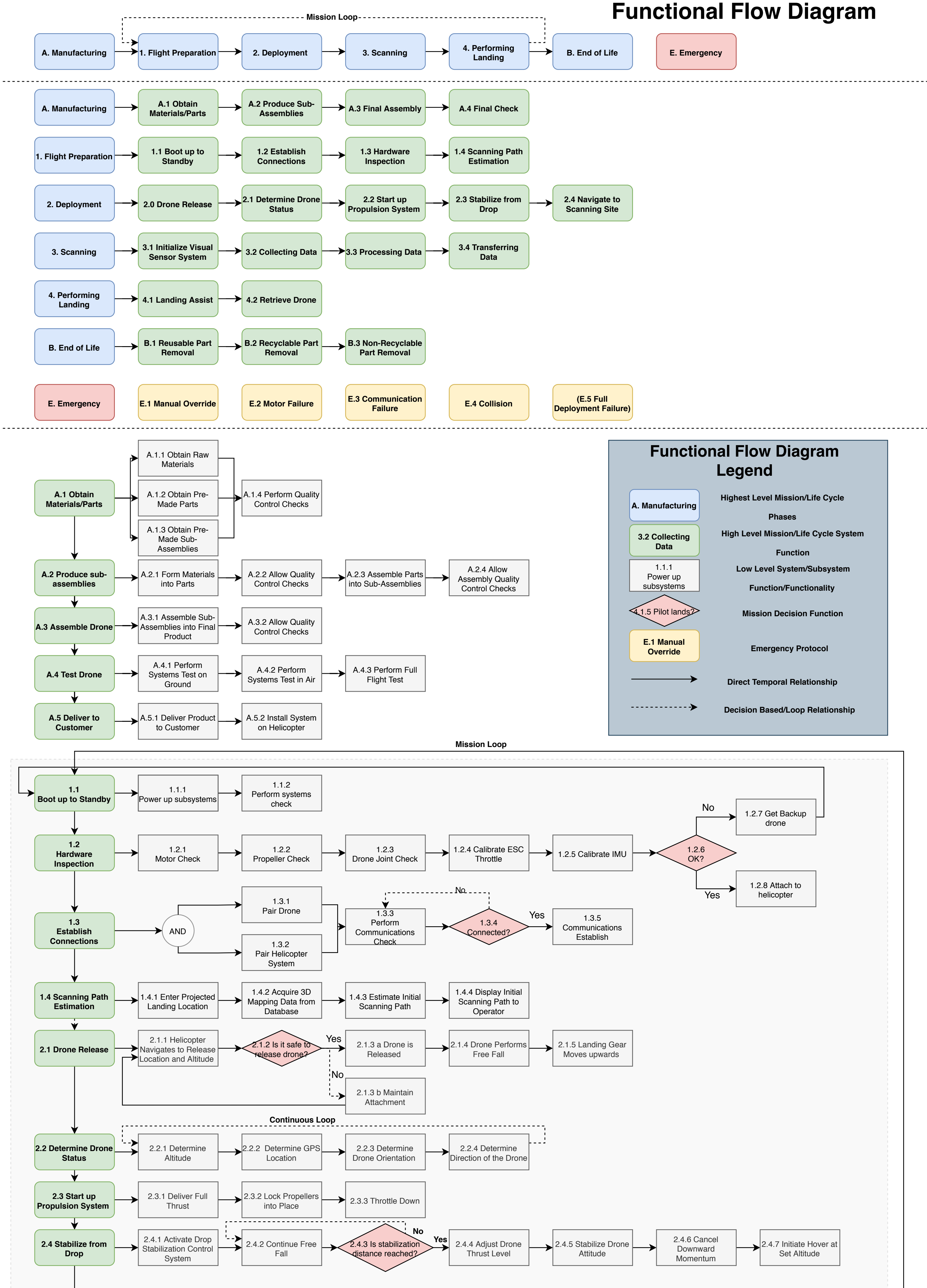
Furthermore, the most critical emergency situations are also evaluated. In case of a propulsion failure, the drone will first attempt to reboot the propulsion system and restabilize itself. If this works the drone will then attempt to land in case the failure may repeat. If this does not work, an emergency parachute will be deployed ensure the drone is not damaged and more importantly, nobody gets injured. The same procedure is applied if the drone deployment failure occurs, where the essential flight systems do not start up after dropping. Then, the drone has until the intended flight altitude to restart.

If a collision occurs and is detected by the IMU, the rotors turn off to mitigate the risk of damage and/or injury. If the drone is above a certain altitude the emergency parachute is deployed. Lastly, if a communication failure occurs, the drone will go into a hover state and attempt to reconnect for a set time (can be set by operator). If connection does not get reestablished, the drone will attempt to land autonomously.

6.2. Functional Breakdown Structure

Next to a functional flow diagram (Figure 6.1), also a functional breakdown structure was made. In this breakdown, the functions performed by the drone are once again shown and adds an extra layer of detail to certain functions. The functional breakdown structure can be seen in Figure 6.3.

HEMS Reconnaissance Drone Functional Flow Diagram



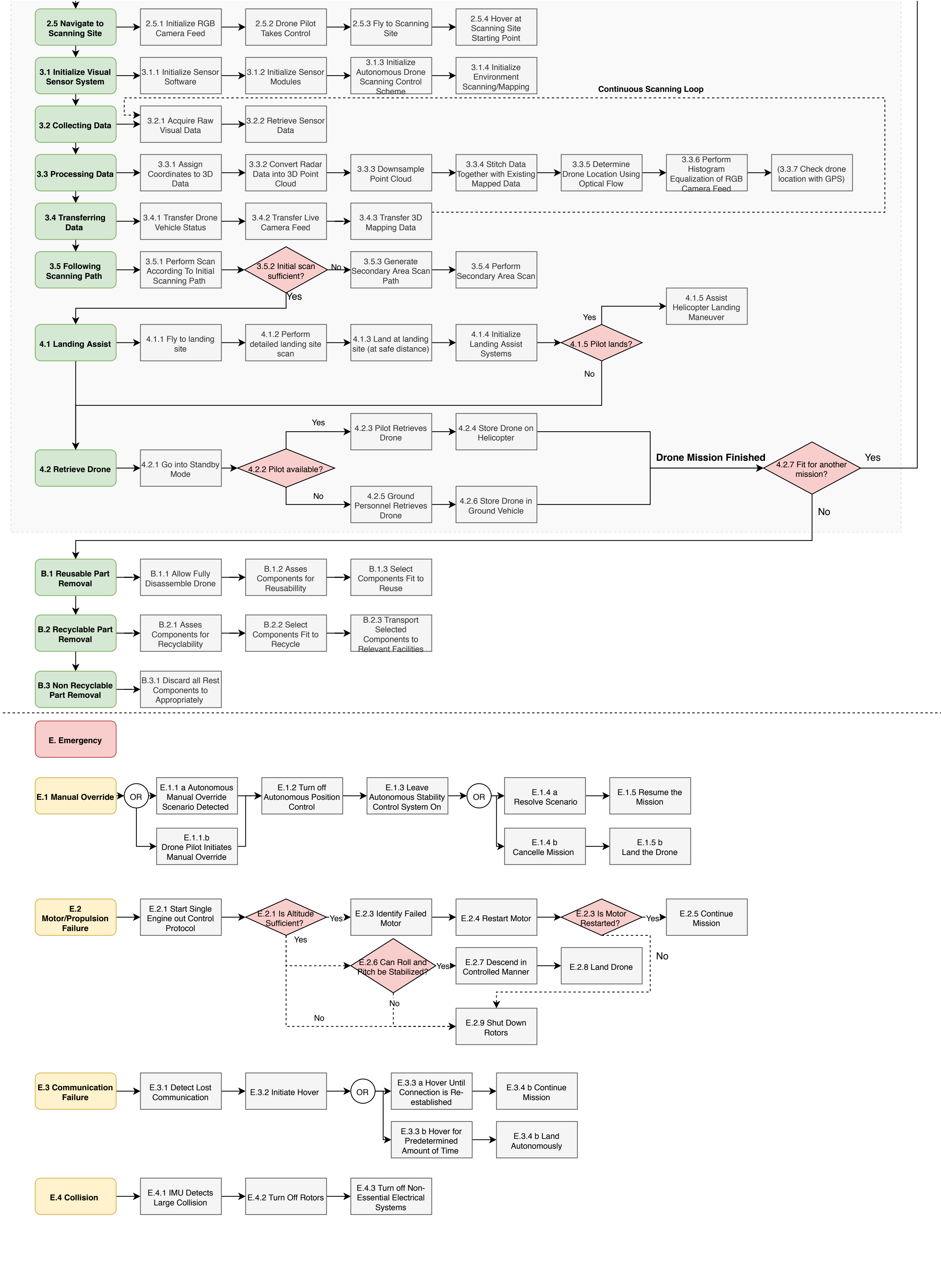


Figure 6.1: Functional Flow Diagram

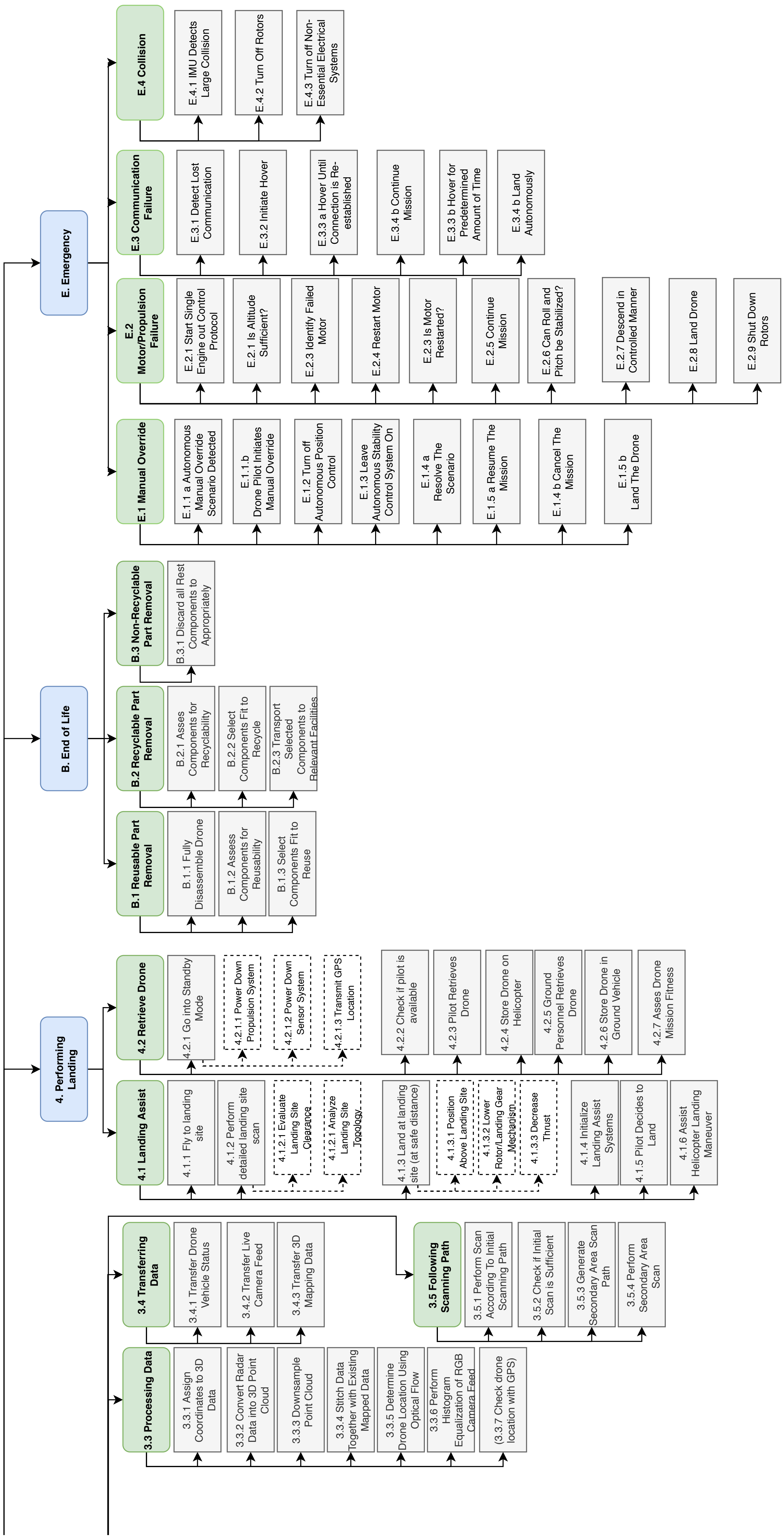


Figure 6.2: Functional Breakdown Structure

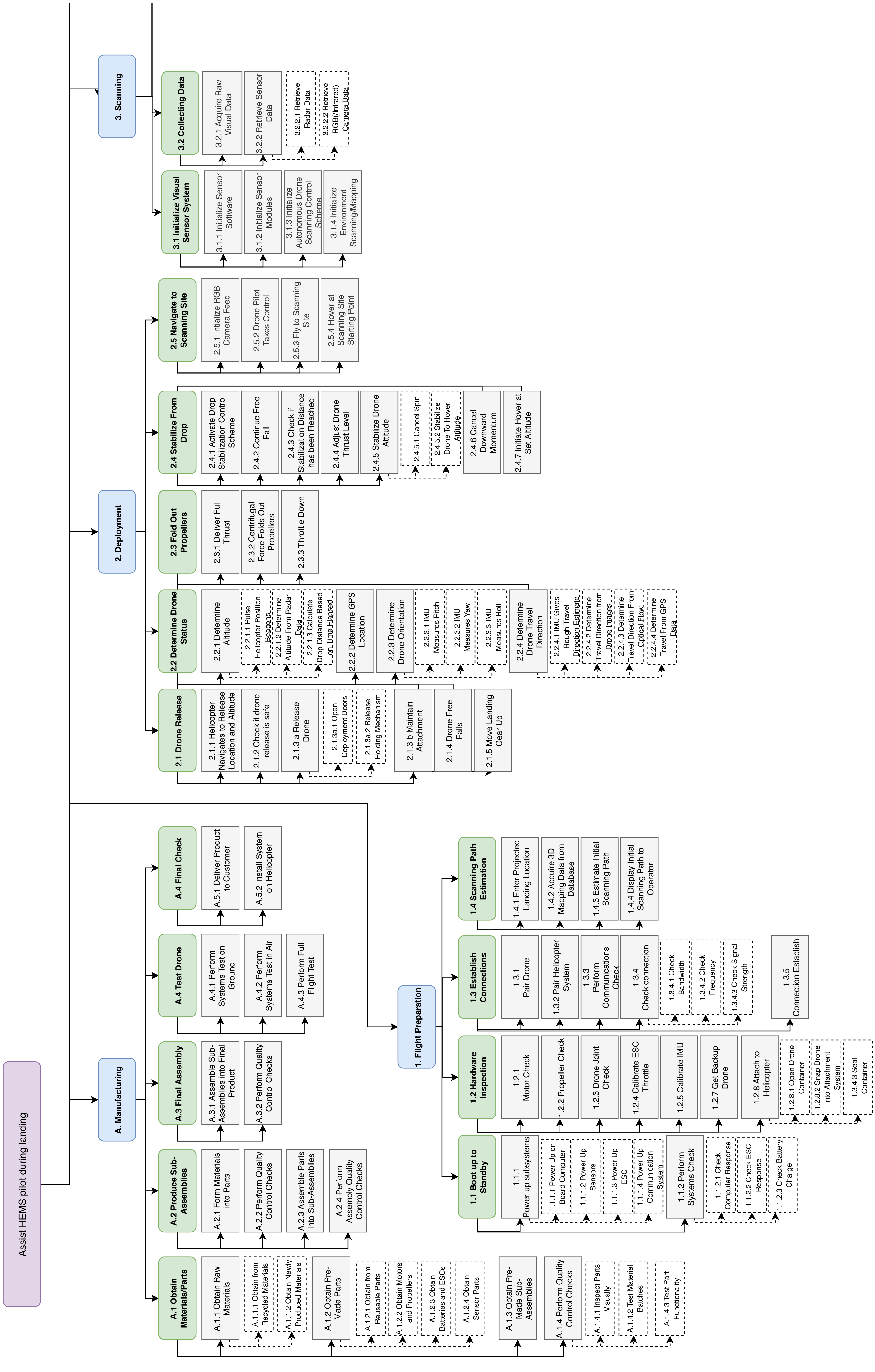


Figure 6.3: Functional Breakdown Structure

7
Technical Risk Assessment

Technical risk assessment is used to identify risks during development. Ranking these risks clarifies which events need mitigation measures to prevent and reduce the consequential effects of these risk events. This mitigation should reduce or nullify adverse effects on technical performance, schedule or cost requirements. This work is a continuation of the work done for the baseline and midterm report. Some adjustments were made due to new insights and information. The assessment scale used to judge the events is defined. Then the risk events, their causes and consequences, and their mitigation is given. Accompanying this is the assessment itself. The technical risk assessment is summarized in the risk maps.

7.1. Defining the assessment scale

Risk is based on the combination of probability and severity. Risk events can occur during operation and during design. The severity of these risk events is assessed on the same 5-point scale. The consequences leading to this severity will differ due to the different nature of operations and design. For severity of consequences, the scale of severity is as follows:

- **5 Loss of Life/Impossible Project Completion:** Death of a human is a realistic possible result of the event occurring. The event causes the project to be impossible to complete.
- **4 Injury of Person/Complete Redesign:** Event is likely to cause injury to personnel or bystanders. Injury of a person takes precedence over any material damage. If an event can cause the death of a person, but is much more likely to only inflict injury, the event is classified as injury of person. The event results in the need for a complete redesign of the product, affecting all subsystems.
- **3 External damage/Major Design Modifications:** External damage is any damage inflicted to the material surroundings or external systems (e.g. the helicopter) which are likely to exceed the cost of the drone system itself. The event leads to major design modifications, impacting an entire subsystem and (at least parts of) an other subsystem.
- **2 Loss of Drone/Cancellation of Mission/Minor Design Modifications:** Any event which would lead to loss of the drone, or which could result in the mission being cancelled. The event leads to minor design modifications, impacting (parts of) one or two subsystems.
- **1 Damage of Drone/Delay of Mission/Negligible Severity:** Any event which would damage the drone or cause a delay in the completion of the mission. The severity of the event is negligible

During operation likelihood mostly depends on frequency of occurring, while risks during design either happen or don't. This explains the double definitions for this scale. For likelihood, the following scale is used:

- **5 Frequently/Almost Certain:** Likely to occur many times or has occurred many times. Almost certain to occur.
- **4 Occasional/Likely:** Likely to occur sometimes or has occurred infrequently. Likely to occur.
- **3 Remote/Reasonable:** Unlikely to occur, but possible or has occurred in the past. Unlikely to occur, but reasonably possible.
- **2 Improbable:** Very unlikely to occur or has never occurred in the past.
- **1 Extremely Improbable:** Almost inconceivable that the event will occur.

7.2. Risk events

The risk events that are assessed in this report were updated based on previous reports.[2][3] They flow from the functional flow diagram, the concept selection, requirements and other analysis. The following table 7.1 contains the risk events and their assessment.

ID	Risk Event	Cause	Consequences	Probability	Severity	Mitigation	Mitigated Probability	Mitigated Severity
Operational Risks								
O1	Attachment failure.	Failure of storage unit operation.	No deployment or unintentional release.	Improbable	Loss of Life	Redundant operating mechanism.	Extremely Improbable	Loss of Life
O2	Communication loss.	Out of range, Communication system Failure, Line of sight.	Inoperatability of drone, drone crash.	Occasional	Injury of Person	Auto landing system.	Occasional	Delay of Mission
O3	Failure of propulsion system.	Loss of a rotor, failure of electronic components, motor unable to start, foldable propellors in wrong state.	Significant decrease in control, stability and thrust.	Improbable	Injury of Person	Possibly add emergency parachute.	Improbable	Damage to drone
O4	Failure of power sources.	Human error, battery failure.	Partial or complete loss of thrust and communication.	Improbable	Injury of Person / loss of drone	N.A.	N.A.	N.A.
O5	Human control error.	Improper handling by drone pilot.	Possible crashing into external objects.	Occasional	External damage	Collision warning.	Remote	External damage
O6	Mechanism failure.	Failure of landing mechanism.	Reduced sensor view angle or absence of landing gears.	Remote	Damage to drone / Delay of mission	N.A.	N.A.	N.A.
O7	Helicopter collision.	Human error, flying near and above helicopter.	Drone damage with possibility of helicopter damage.	Extremely improbable	Loss of life	Drone proximity warning system.	Extremely improbable	Loss of life
O8	Weather.	Challenging weather conditions.	Inaccurate landing of drone and delay of mission.	Improbable	External damage / Delay of mission	N.A.	N.A.	N.A.
O9	Improper maintenance.	Improper maintanance performed on drone.	Reduced controlability in flight or absence of landing gears.	Remote	Damage to drone	N.A.	N.A.	N.A.
O10	Failed deployment recovery.	Failure to stabilize after deployment.	failure to remain in air, causing drone to crash.	Improbable	Injury of Person / loss of drone	Possibly add emergency parachute.	Improbable	Cancelation of mission
O11	Failed drone recovery.	Landing location of drone unknown.	Loss of drone and polluting of environment.	Remote	Loss of drone	Gps system, operator training.	Improbable	Loss of drone
O12	Mapping algorithm fails.	Too much noise in sensor data, lack of terrain features.	Drone loses track of position.	Improbable	Delay of mission	Use GPS as backup.	Improbable	Delay of Mission
O13	Drone gets blown away at the landing site.	Helicopter downwash.	Drone gets damaged or lost.	Frequently	Damage to drone	Land the drone further away or behind a barrier. Operating manual or training.	Remote	Damage to drone
O14	Lithium-Polymer battery overheat/fire.	Inherent dangers of lithium batteries.	In flight fire, damage to drone or the helicopter catching fire completely.	Improbable	Loss of Life	Installing temperature sensors on or near the batteries. Having an emergency release mechanism for the drone (or drone box). Fireproofing the box around the drone.	Improbable	External damage
O15	Drone not clearing helicopter on deployment.	The drone attachment location is at the front of the helicopter. If the drone does not drop far enough away from the helicopter there is a risk that it will hit parts of the helicopter.	Damage to the helicopter and drone.	Occasional	External Damage	Deployment doors naturally guide it away from landing gear. Spring loaded mechanism to give the drone an initial push away from the helicopter. Possibly even an arm to guide the drone away from the helicopter, not dissimilar to the one used for spaceshuttle evacuation.	Improbable	External damage
Design Risks								
D1	Sensor resolution and/or accuracy cannot meet required specification.	No applicable sensor available on the market. Required sensor is too heavy. Needed sensor is too big. Needed sensor is too costly.	Reconsider sensor choice Requirements on performance cannot be met. Requirements on safety cannot be met.	Reasonable	Major design modifications are needed	Abandon '3D optical flow' concept and make use of RTK GNSS for positioning instead.	Improbable	Major design modifications are needed
D2	Navigation of drone in relation to the helicopter is not accurate and/or reliable enough.	Navigation system not available on market. Needed navigation system too heavy or too big or too costly	Alternative Navigation system needed.	Improbable	A complete redesign is needed	Perform extensive research before choice of navigation system.	Negligible	A complete redesign is needed
D3	Drone flight time is too short to execute mission.	Individual subsystems use too much power. Insufficient battery size. Subsystems cannot perform their functions for the required duration of the mission.	Product does not meet user requirements.	Improbable	A complete redesign is needed	Track power budget.	Negligible	A complete redesign is needed
D4	The design of a subsystem prevents the correct functioning of another subsystem.	Lack of communication.	Design does not function as intended.	Reasonable	Major design modifications are needed	Good design practices. System engineer ensures communication. Verification and validation.	Improbable	Major design modifications are needed
D5	A chosen model for design of the system/subsystem does not model the system/subsystem correctly.	Incorrect or lacking information.	Design only works in theory, but not in practice.	Likely	Minor design modifications are needed	Acquire specifications from component manufacturer for better estimation.	Reasonable	Minor design modifications are needed
D6	A chosen off the shelf component is no longer available.	External manufacturer stops producing and stocks of the component run out.	Production of the drone in its current form can not continue.	Reasonable	Minor design modifications are needed	Contact manufacturer to assure availability.	Improbable	Minor design modifications are needed

Figure 7.1: Table of risk events, their causes, consequences and mitigation

A newly discovered risk event flowing from the functional flow diagram was the drone blowing away at the landing site. This would be caused by the downwash of the helicopter during landing. The mitigation for that is easy: landing the drone a bit further away or behind a suitable barrier. This would add a minimal extra training to the drone operator, but reduces likelihood tremendously.

The drone's battery chemistry can pose a fire hazard[1]. Various actions can be taken to reduce this risk. Fireproofing the box should limit the fire to that part. Because fire protection is only a limited time commitment, a temperature sensor on or near the batteries can notify the helicopter crew of a temperature problem. The crew or an automated system could then activate an emergency release mechanism for the drone or even the dronebox.

Even though off the shelf components reduce development time and cost, the dependence on external manufacturers introduces a risk on availability. As the off the shelf components used in this product are currently widely available, and competing components are available too, it is expected to result in only minor design modifications. However if a manufacturer is contacted and maybe even contracted to produce these components, this risk would be mitigated even further.

Three of the risks are not mitigated in the end. These are O4, O6, and O8. O4 can not be mitigated due to the fact that the battery already takes up a very large portion of the size and mass of the drone, meaning that a secondary battery (which would mitigate the risk) would drive the design to an impossible extent. O6 is not mitigated because there will not be enough space in the drone for a secondary mechanism. Also, the mission can still be performed if the mechanism fails, albeit in a slightly less than optimal way. Finally, O8 will not be mitigated because it impossible to influence the weather further than already done in the design by making for instance the motors water resistant.

7.3. Risk Assessment Matrix

The risk assessment matrix shows the likelihood and severity of the possible risk events before and after mitigation measures have been taken. The matrix is color-coded by the expected impact, where green means less problematic risk events for the project while red means problematic risk events. The constructed matrices for the risk before and after mitigation are shown in 13.3.

Unmitigated Risk Map						
		Severity				
		1	2	3	4	5
Likelihood	1					O7
	2	O12		O8,D6	O3,O4,O10,D2,D3	O1, O14
	3	O6,O9	O11	D1,D4		
	4		D5	O5, O15	O2	
	5	O13				

Mitigated Risk Map						
		Severity				
		1	2	3	4	5
Likelihood	1				D2,D3	O1,O7
	2	O3,O12	O10,O11,D6	O8,D1,D4, O14, O15	O4	
	3	O6,O9,O13	D5	O5		
	4	O2				
	5					

Figure 7.2: Risk map before and after mitigation.

[1] https://www.faa.gov/hazmat/resources/lithium_batteries/media/NTSB_safety_recs_to_prevent_cargo_fires.pdf [Accessed on 18-06-2020]

8
Resource Allocation and Budgets

This section shows the difference between the initial mass estimation of 3.5 kg and the most recent iteration of the budgets, based on the subsystems results. The components that determine these budgets are explained in the subsystem chapters that follow later in this report.

8.1. Initial Mass Estimation

To kickstart the development of the subsystems, mainly the Control and Stability and the Power and Propulsion subsystems, a good first step was to try to estimate the expected total weight of the drone as a function of the payload. This was done using a statistical regression of drones that are available on the market. The results for this are listed in Table 8.1. The yellow cells are for drone models whose battery weight were not listed. Instead, the battery weights for these drones were approximated by fitting an off the shelf LiPo battery to the other specifications that were listed for those drones.

Table 8.1: Drones on the market that were used for the statistical regression, and their maximum take off weight (MTOW), battery weight (W_{batt}), and maximum payload weight, along with the fractions of these weights compared tot the MTOW.

Drone	MTOW [kg]	Wbatt [kg]	Max Payload [kg]	Wbatt/MTOW	Pay/MTOW
DJI Inspire 2 [1]	4,25	1,03	0,81	0,24	0,19
DJI Phantom 4 Pro V2.0 [2]	1,38	0,47	-	0,34	-
Skydio [3]	0,78	0,28	-	0,36	-
FreeFly Alta X [4]	34,86	4,58	15,90	0,13	0,46
Matrice 300 RTK [5]	9,00	2,70	2,70	0,30	0,30
DraganFly Commander [6]	3,75	1,23	1,00	0,33	0,27
Matrice 200 series [7]	6,14	1,77	1,45	0,29	0,24
AirRobot AR100-B [8]	1,25	0,38	0,25	0,30	0,20
AirRobot AR180 [9]	6,90	1,65	1,50	0,24	0,22
AerialTronics Altura Zenith ATX8 [10]	9,65	2,63	3,00	0,27	0,31
Aeronavics SkyJib [11]	16,00	3,15	5,00	0,20	0,31
VulcanUAV Mini 8 [12]	8,00	1,75	1,80	0,22	0,23
Thea 130 [13]	25,00	4,45	10,55	0,18	0,42
Walkera Voyager 5 [14]	5,50	1,61	1,49	0,29	0,27

Graphing the results from Table 8.1 in Figure 8.1 led to the linear regression formula in Equation 8.1. The expected payload (sensors and gimbal) mass post midterm phase was about 0.9 kg. As per Table 8.2 the first estimate for the drone mass would then be about 3.8 kg. With a contingency of 15% at this stage that puts the expected range of the drone mass will likely end up in at 3.23 to 4.37 kg. Mistakenly, the value used to calculate the initial mass of 3.5 kg that was used in the initial estimations of most subsystems, was based on the average payload to MTOW ratio, found from the final column in Table 8.2. As this initial estimate was not

[1] https://www.dji.com/nl/inspire-2/info#specs [Accessed on 21-06-20
[2] https://www.dji.com/nl/phantom-4-pro-v2/specs [Accessed on 21-06-20
[3] https://www.skydio.com/ [Accessed on 21-06-20
[4] https://freeflysystems.com/alta-x/specs [Accessed on 21-06-20
[5] https://www.dji.com/nl/matrice-300/specs [Accessed on 21-06-20
[6] https://www.holmans.com/wp-content/uploads/2018/04/Dragonflyer-Commander.pdf [Accessed on 21-06-20
[7] https://www.dji.com/nl/matrice-200-series-v2/info#specs [Accessed on 21-06-20
[8] https://www.airrobot.de/en-gb/ar100-b [Accessed on 21-06-20
[9] https://www.airrobot.de/en-gb/ar180 [Accessed on 21-06-20
[10] https://www.aerialtronics.com/downloads/EN-Specsheet_aerialtronics-AlturaZenith_ATX8_16.06.2017.pdf [Accessed on 21-06-20
[11] https://aeronavics.com/fleet/aeronavics-skyjib/#skyjib-specifications [Accessed on 21-06-20
[12] http://vulcanuav.com/aircraft/ [Accessed on 21-06-20
[13] https://www.foxtechfpv.com/thea-130-agriculture-spraying-drone.html [Accessed on 21-06-20
[14] https://www.walkera.com/index.php/Goods/canshu/id/66.html [Accessed on 21-06-20

too far off the statistical trend, it did not end up hurting the design in the long run. The mass estimation was continually updated throughout the design, with all subsystems being scalable by the drone mass relatively easily, eventually arriving at the final design of 3.8 kg. The drone mass, m_{drone} used for the initial design iterations was thus 3.5 kg, not 3.8 kg! The statistical regression can still be used to see that the final design of 3.8 kg (with a payload that became 1.0 kg in the end) is reasonable within the statistical trend shown in Figure 8.1, with the payload to MTOW ratio being 0.26.

Table 8.2: Final inputs and outputs for Equation 8.1

Input	Value	Unit
$m_{payload}$	0.9	kg
Output	**Value**	**Unit**
m_{drone}	3.8	kg

$$MTOW = \frac{m_{payload}}{0.0165 m_{payload} + 0.221} \tag{8.1}$$

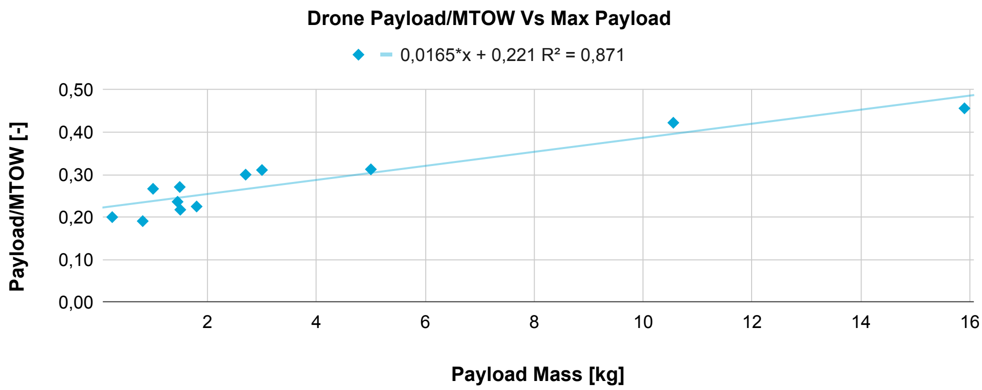


Figure 8.1: Statistical regression of drones comparing payload/MTOW fraction to the actual payload weight.

8.2. Final Hardware Budget Breakdown

The hardware budgets for the drone mass, cost and power for all components are shown in Table 8.3. Contingency at the current stage is 15 percent for most subsystems. As sensors and electronics is at a more developed stage than the others, the contingencies for these are lower. These contingencies follow from the baseline report. [2]

For the drone most components are known selected and final. The few unknowns that will be found in a later design stage are picked up by the small contingency. For the pod, attached to the helicopter containing the drone, the component selection is very preliminary. The budgets for the drone pod are shown in Table 8.4 There are lots of unknowns on material and other requirements and some values had to be estimated based on figures provided, instead of manufacturer specifications. These will be investigated in a later design phase. The biggest unknown is the spring mechanism that aids in pushing the drone out of its box. No information on mass, cost or power was found. Because of this preliminary status, a contingency of 1 was chosen for this system. At final design the unknowns should be reduced significantly. For that reason the contingency drops so steeply.

The drone's current mass is estimated at 3.83 kg. With the contingency margins applied, it will rise to 4.35 kg. The hardware cost for the drone is currently 7,339 euros. This is estimated to rise to €8,178 if the margin is applied. The power budget for the drone at this stage is 364 W. Of this estimate 313 W or 86 percent is reserved for the propulsion. With the contingencies applied this power budget rises to 443 W. The pod's current mass, cost and power are 10.1 kg, €519 and 173 W respectively. These are fairly rough estimates that double due to the contingency margins to 20.2kg, €1,039 and 346 W respectively.

These budgets relate to different subsystems. The power and mass directly influence the propulsion, battery power and structural strength of the airframe and landing gear (See chapter 9 and chapter 11). Through the mass moment of inertia it influences the control system (See chapter 12). Via the center of gravity the stability of the landing gear is influenced (See section 11.7). The cost relates to the market analysis in chapter 4 and the cost breakdown structure in section 20.3. These relations are not one way but rather iterative and reciprocal.

Table 8.3: Budget Breakdown for Drone Mass Cost and Power

		Drone components at final report	Budgets			Contingencies			
Subsystem	**Quantity**	**Component name**	**Unit mass [kg]**	**Unit cost [€]**	**Unit power [W]**	**Final Report**	**Final Design**	**Assembly and Testing**	**Final Product**
Propulsion	4	Motor: KDE3510XF-475	0.2	€82	77	0.15	0.1	0.05	0
	4	Propeller: KDE-CF144-DP	0.0	€104	0				
	4	ESC: KDEXF-UAS55	0.1	€78	2				
		Total for subsystem:	**1.1**	**€1,058**	**313**				
Battery	1	Battery: Turnigy Graphene Professional 8000mAh 6S 15C LiPo Pack w/XT90	1.1	€64	0	0.15	0.1	0.05	0
		Total for subsystem:	**1.1**	**€64**	**0**				
Electronics	1	Flight controller: Pixhawk 4	0.0	€187	3	0.1	0.05	0.05	0
		Total for subsystem:	**0.0**	**€251**	**3**				
Sensors	2	Radar: TI AWR 2243	0.1	€1,000	8	0.1	0.05	0.05	0
	1	RGB Camera: RunCam 5 Orange	0.1	€100	3				
	1	GNSS Receiver: mosaic-X5	0.0	€30	1				
	1	IR Camera: FLIR Vue Pro	0.1	€2,000	3				
	1	Radio Transceiver: Huano HN-550	0.1	€150	12				
	1	Gymbal: X-CAM A10-3H	0.3	€450	5				
	1	Location determination receiver: TBD	0.0	€50	2				
	1	On board computer: Raspberry Pi 4 B 8GB	0.1	€87	5				
	1	Steppermotor for camera control: Johnson Electric UBD20	0.0	€25	0				
	1	Steppermotor controller: Greenwich Instruments GSM 2 Stepper Motor Controller	0.0	€75	0				
	1	Encasing and supporting structure for camera steppermotor	0.0	€15	0				
		Total for subsystem:	**1.0**	**€4,982**	**47**				
Structure	1	Body shell	0.2	€703	0	0.15	0.1	0.05	0
	2	Motor arms	0.2	€141	0				
	4	Landing gear	0.0	€15	0				
	1	Steppermotor: Johnson Electric UBD 2/8	0.1	€35	6				
		Total for subsystem:	**0.6**	**€1,079**	**6**				
Drone		**Total:**	**3.8**	**€7,434**	**369**				
		With 10-15 percent contingency	4.4	€8,287	422				

		Preliminary Pod components at final report	Budgets			Contingencies			
Subsystem	**Quantity**	**Component name**	**Unit mass [kg]**	**Unit cost [€]**	**Unit power [W]**	**Final Report**	**Final Design**	**Assembly and Testing**	**Final Product**
Structure	1	Aluminum plate 1*1m 2mm	5.6	€36	0	1	0.1	0.05	0
	8	Corner profile 25+25*2 500mm	0.1	€20	0				
	4	Corner profile 25*25*2 250mm	0.1	€7	0				
		Total for subsystem:	**7.0**	**€226**	**0**				
Electronics	1	Indicator light	0.1	€2	1	1	0.1	0.05	0
	1	Temperature sensor	0.1	€53	2				
	1	Spring	1.0	€100	50				
	4	Door actuator	0.5	€35	30				
		Total for subsystem:	**3.2**	**€293**	**173**				
Pod		Total:	**10.1**	**€519**	**173**				
		Contingency of 1	20.2	€1,039	346				

Table 8.4: Budget Breakdown for Mass, Cost and Power of the Drone Pod

9
Propulsion System

The propulsion system is a critical subsystem to the functioning of the drone platform. The drone is unusable without proper propulsion, and a large part of the drone's design is related directly to the design of the propulsion system. The propulsion system consists of the propellers, the motors, the electronic speed controllers (ESCs), the propulsion system related wiring, and the battery.

9.1. Functional Analysis

The propulsion system provides the forces and moments to fly the drone. It is foldable to maximize efficiency with its dimensions constrained. As the drone has to stabilize itself after its drop through the helicopter's downwash, it needs a high thrust to weight ratio, which is best achieved through a high efficiency. The batteries of the propulsion system should provide enough electrical power both during the entire mission and at peak consumption. And the propulsion system has to do all this, while being composed of off the shelf components.

9.2. Subsystem Requirements

The requirements that apply to the propulsion and power subsystem are listed in this section. The requirements that have existed since the baseline [2], and that were not altered are not expanded upon with an explanation and an origin. Any requirements that are new or altered will have an explanation.

- **HD-PROP-01**: Shall be able to stay at a maximum RPM for at least 20 seconds.
  Requirement from 'The motor shall be at maximum RPM for no longer than <TBD> minutes' to reflect a requirement that could actually be used in the design. Within the mission there is no conceivable mission section where maximum thrust would be required for more than 20 seconds, with the helicopter drop being the most high thrust part.
- **HD-PROP-02**: The motor shall have a maximum thrust to weight ratio of at least 3.0 in nominal flight conditions.
  Given a value based on general drone design practice[1] *and the value of 3.0 flows from the drone release method calling for the drone to be able to stabilize itself and cancel its downward momentum quickly.*
- ~~**HD-PROP-03**~~: Each propeller shall be able to provide a maximum thrust of <tbd> N in nominal flight conditions.
  Removed because it is essentially already covered by HD-PROP-02.
- **HD-PROP-04**: The propellers shall have a lifetime of at least 170 hours.
  Added 'at least'.
- **HD-PROP-05**: The propulsion subsystem shall have a peak power consumption of 824W in nominal conditions.
- **HD-PROP-06**: The propulsion subsystem shall have an average power consumption of at most 98 W in nominal conditions.
- **HD-PROP-07**: In the event of a single propeller failure the other propellers shall have a summed maximum thrust to weight ratio of at least 1.5.
  Follows from mitigation of risk event O3 and requirement HD-CRST-04. A minimum total thrust to weight ratio of 1.5 would allow for yaw control while still being able to fly level.

[1] https://innov8tivedesigns.com/images/specs/Prop-Chart-Instructions-B.pdf [Accessed on 08-06-2020]

- **HD-PROP-08**: The propulsion system components shall function nominally in a voltage range of 22.8 and 26.1 Volts.
Normal LiPo batteries have a battery voltage range of 3.7 V at 20% charge to 4.2 V at 100% charge. The LiHV batteries needed here operate at a slightly higher voltage of 4.35 V at 100% charge and are assumed to drop down to about 3.8 V at 20% charge. With 6S batteries this would result in the given voltage range.
- **HD-PROP-09**: The motors shall be able to operate betwen a temperature range of -40 to 35 degrees celsius ISA.
- **HD-PROP-10**: The propulsion system shall have a maximum mass of 2.5 kg.

- **HD-PROP-11**: Each propeller shall be separately controllable. *Flows naturally from the control system being based on separately control the propellers*
- **HD-PROP-12**: The propellers shall be foldable to a point where they fit inside the 535x535x250mm size limitation box.
Follows from the analysis performed in the following sections. A non foldable (9 inch at the most) propeller would not be able to provide enough thrust and bigger non foldable propellers would not fit within the size limitations dictated by the user requirement HD-USR-SYS-02
- **HD-PROP-13**: The propellers shall have a minimum spacing between each other of 1/4 propeller diameters.
Follows from the analysis performed in subsection 9.3.1. This propeller spacing ensures that the propellers do not negatively influence each others' ability to generate lift efficiently.
- **HD-PROP-14**: The propellers shall have a maximum diameter of 16 inches.
Limitation from analyzing the available propeller space withing the 500x500x200mm size limitation box, taking into account the minimum propeller spacing of about 1/4 propeller diameter from HD-PROP-13.
- **HD-PROP-15**: An individual motor shall have a maximum mass of 200 grams including wires.
Added as a result of the control system being difficult to tune at motor masses higher than 200 grams.
- **HD-PROP-16**: The propulsion system components shall be at least IP 56 rated.
*Results from **HD-SYS-02**.*
- **HD-PROP-17**: The batteries shall have a minimum continuous C-rate of 5C.
Minimum value is based on the current design value of an 8 Ah battery with a continuous discharge of 20 Amps draining at a C-Rate of 2.4, with an applied safety factor of 2 for future design iterations (and because LiPo and LiHV batteries usually start at 5C).
- **HD-PROP-18**: The batteries shall have a minimum burst C-rate of 25C.
The motors will have to provide maximum RPM for at least 20 seconds, see HD-PROP-01. As burst C-rate is usually only measured for 5 seconds, a safety margin to the calculated necessary C rate is applied. The necessary C rate is 18C This necessary C-rate was based on the current design value of an 8 Ah battery with 4 motors drawing 36A of current at max RPM.
- **HD-PROP-19**: The ESC shall be able to handle a maximum continuous current of at least 36A.
The ESC should be able to handle the maximum current drawn by the motor.
- ~~**HD-PWR-01**~~: The batteries shall be fully rechargeable in <tbd> minutes.
This requirement was cancelled because it does not have relevance during design. This was possible due to the ability to have multiple batteries charging during operations.
- **HD-PWR-02**: The batteries shall provide 6462 mAh of energy. *This depends on the typical power usage. See also chapter 8 for the power budget and subsection 9.3.3 and Equation 9.10 for the equation used*
- **HD-PWR-03:** The batteries shall have a lifetime of 1000 cycles.
- ~~**HD-PWR-06**~~: The battery shall be able to provide up to <TBD> A.
This requirement has been replaced by HD-PROP-17 and HD-PROP-18.
- ~~**HD-PWR-07**~~: The battery shall be at <tbd> V nominal voltage when it is not used.
This requirement was not relevant during this point in the design phase.
- **HD-PWR-08**: The battery shall warn the user when each cell in the battery is lower than 3.7 V.
At 3.7V the cell of a LiPo battery has only 20 percent charge left. The warning notification is for a later design phase.
- **HD-PERF-01**: The drone shall be able to achieve a horizontal airspeed of at least 10 m/s.
Added 'at least'.

- **HD-PERF-02**: The drone shall be able to achieve a vertical airspeed of at least 5 m/s upwards.
  Added 'at least and upwards. Achievable vertical airspeed is not really a limiting factor for the design, but for general use and maneuverability a minimum of 5 m/s is set..
- ~~**HD-PERF-03**~~: The drone shall have an endurance of at least <tbd> minutes.
  Requirement has been removed because the endurance required is determined by the required range and airspeed for the mission, so this requirement was obsolete..
- **HD-PERF-04**: The drone shall have a range of at least 7 km.
  Added 'at least'. The estimations in subsection 17.2.3 put the maximum required range for a scanning mission at about 5.5 km, so the minimum will be set to that plus a buffer of 1.5 km..

9.3. Propulsion System Design

To start the design of the propulsion system the following factors were identified as the most important parameters to consider in the propulsion system design:

- **Overall Specific Thrust (η_{sp}) [36]:** The definition of the overall specific thrust of a propulsion system is given by Equation 9.1
$$\eta_{sp} = \frac{T}{P_E} \tag{9.1}$$
  Where T is the total thrust in grams, and P_E is the electrical power supplied to the motor in Watts. This parameter makes it very easy to compare the propulsive performance of one system compared to another, as the higher the Overall Specific Thrust at a given thrust level, the less power is necessary to maintain that thrust level, reducing the power draw of the system. As will become clear in later sections, the propulsion system uses the most power of any system, so any gain in efficiency will directly decrease the necessary battery size and weight, or an increase in endurance.
- **Maximum Thrust to Weight Ratio T_{max}/W :** The maximum thrust to weight ratio is a good indicator of the maneuverability of the drone, and it is common practice to choose a thrust to weight ratio of at minimum 2.[2]. However, to facilitate the self stabilizing maneuver the drone has to make when being dropped out of the helicopter, the minimum thrust to weight ratio requirement was set to be at least 3 (**HD-PROP-02**). T_{max} is the maximum thrust that can be delivered by a given motor-propeller combination, and W is the weight of the drone in Newtons.
- **Maximum Propeller Diameter (D_{max}):** The propeller diameter is constrained by the maximum allowable drone size and the distance needed between propellers (**HD-PROP-13** and **HD-PROP-14**). As will be come clear later: the bigger D_{prop} the better the overall specific thrust, and the maximum thrust of the propellers with a given motor. Foldable propellers will be considered to increase D_{max}, and as a result increase η_{sp} and T_{max}/W, if necessary.
- **Propulsion System Mass ($m_{propsys}$):** As always, mass is central to the design of any aerospace (sub)system. The mass is constrained by the maximum mass allotted to the system (**HD-PROP-10**), and must be minimized wherever possible, as any reduction of mass will manifest itself in an even larger reduction of the overall drone system mass as a result of the snowball effect. The total propulsion system mass is given by Equation 9.2.
$$m_{propsys} = m_{motors} + m_{props} + m_{ESCs} + m_{battery} \tag{9.2}$$
  Where m_{motors}, m_{props}, m_{ESCs}, and $m_{battery}$ are the combined motor, propeller, ESC, and battery masses respectively. Additionally, m_{motors} was later identified to be of extra importance to the control and handling of the drone. A limit of 200 grams was placed on the mass of a single motor in requirement **HD-PROP-15**.
- **Reliability:** The reliability of the propulsion system is an umbrella term for the following considerations related to fulfilling subsystem requirements:
  - **Durability:** The durability of the propulsion system is given in flight hours, and is a measure of the amount of missions that can be expected to be flown with the given propulsion system components.

[2]`https://innov8tivedesigns.com/images/specs/Prop-Chart-Instructions-B.pdf` [Accessed on 08-06-2020]

- **Environmental Resistance:** As the drone will have to fly (or be landed) in fog or dust , the propulsion system must be as moisture and dust proof as possible. A specific instance where a helicopter kicks up a large amount of dust is a 'brown out' scenario like depicted in Figure 9.1. There is also an equivalent snow 'white out'. The possibility of damage being inflicted to the drones by these events should be minimized as much as possible.
- **Operating Temperature:** The operating temperature window of the drone is dictated by the requirements, and will have to be adhered to by the propulsion system components.

Any factors of lesser importance that were also taken into account during design will be mentioned whenever applicable. Furthermore, the propulsion system should be able to meet all of the requirements stated in section 9.2. This will later be checked in the requirement compliance matrix in chapter 15.

Figure 9.1: Dust 'brown out' of a helicopter. Footage Courtesy of HEMS Pilot G. Ruitenberg

To get an initial estimate of the subsystem parameters some research was done into semi-empirical estimation methods, akin to the first and second order relationships used in preliminary aircraft design [38]. Some preliminary drone sizing methods do exist, but they either required too many unknown values as inputs [21] [36], [13], or were too involved for the purposes of this project [17].

A promising preliminary design method from [20], based on off the shelf drone statistics and physics, was coded in python and its results were explored. However, part of the methodology used was not available or unclear, so reproduction of the validation of the model was impossible. Additionally, it gave some unreliable results, like the predicted hover power being much higher than the power used in forward flight. Finally, the quality of the paper created doubt about its trustworthiness.

Eventually it was decided to pick or design the parts for the propulsion system part by part, using the thrust and efficiency relations mentioned above, with the initially estimated mass of 3,5 kg in chapter 8 as a starting weight at first, which was eventually adjusted to 3.8 kg. The propeller and motor were chosen in conjunction with one another, because of the way performance data is made available, and because the data of the propeller and the motor on their own do not necessarily indicate the performance of a propeller and motor pair. The ESC and battery follow from the chosen propeller and motor pair, with a preliminary battery weight estimation being taken into account when picking the propeller and motor.

9.3.1. Propeller Design/Choice

Propeller design is a complex topic, with most design methodologies like Blade Element Theory (BET), Momentum Theory, and Blade Element Momentum Theory (BEMT). These are all limited by their underlying assumptions, especially at the relatively low Reynolds numbers quadcopters operate at [27]. Moreover, the computational implementation is relatively complex for the purposes of this project and easily falls victim to small unnoticed errors.

A promising BEMT based method where the results of BEMT were reduced to analytical equations for quadrotor propeller designs for ideal hover performance was described in [9]. This was turned into a python script for which a simplified propeller geometry could be used as input to estimate its performance, along with wind and drone velocity. Once the model code was finished it became clear that the induced velocities at the blade could not be non-linearly solved for due to the assumptions made in the analytical derivation process. Any efforts to solve for the induced velocities at the blade resulted in the solver ending up in an alternating pattern between a large negative thrust and a large positive thrust, with the induced velocities never converging to a stable value. The final results of the computations were very sensitive to the input values for the induced velocities, with a small change resulting in a relatively large (30%) change of the resulting thrust, making it dangerous to use a guess as an input for the induced velocities at the blade. In the interest of space the exact implementation of the model is not explained in this document, as it was not used in the final design anyway.

The analytical BEMT model was discarded because of the inaccuracies and uncertainties caused by the unknown induced velocities. Additionally, designing and producing a reliable and efficient propeller from scratch for a relatively small production run would be a disproportionately large investment compared to using a well researched off the shelf product.

Propeller Database

The choice was made to explore off the shelf propeller components for use on the HEMS reconnaissance drone. Few manufacturers supply detailed testing/performance data for their drone propellers. Luckily one of the more popular high performance drone propeller manufacturers, APC, has an extensive database of the predicted performance of all of their drone propellers[3], generated using their own design methodology according to the following quote: [4] *"The performance data are based on vortex theory, using actual propeller geometry. The NASA Transonic Airfoil Analysis Computer Program is used to generate estimates for section lift and drag. As a result, airfoil drag is under-predicted at lower speeds and computed results may not match experimental results for all scenarios."*

As mentioned, the drag performance is overestimated at lower Reynolds numbers. However, as the drag performance is consistently overestimated for (almost) all of their propellers, the database can still be used to make comparisons between propellers of different diameters and pitches within the APC propeller catalogue, and judge overall propeller performance based on diameter and pitch. Furthermore, the University of Illinois has assembled a database of wind tunnel measurements of an assortment of drone propellers [5], including APC propellers, which can be used to eventually apply a knockdown factor to the predicted values and efficiencies of the propellers in the final design, if any APC propellers were to be used. The Illinois University database test setup is described in [15], and the method was validated on the website using another university's data.

Drone propeller geometries are named under a common naming convention of (*Diameter in Inches*)x(*Propeller Pitch in Inches*). That naming scheme is also used here. Table 9.1 displays the data given for a 9x5 propeller at an RPM (Revolutions per Minute) of 3000. The parameters of interest are thrust, and power (PWR). The upward velocity (V_u) is the wind-tunnel velocity perpendicular to the plane of the propeller, or equivalently the speed of the drone were it to fly in upward direction. For the purposes of the HEMS Reconnaissance drone the static thrust data (V_u = 0) will be used to differentiate between propellers. Static thrust data has been tested to be reasonably accurate at forward drone velocities of up to 15 m/s, combined with inclination angles of up to 30 degrees [22]. The drone is expected to operate below or close to those thresholds for the majority of its mission, therefore the most thrust efficient design choice can be based on static thrust data.

Table 9.1: Example Propeller data of 9x5 propeller at given propeller RPM

9x5 Propeller RPM = 3000							
V_u	**J**	**Pe**	**Ct**	**Cp**	**PWR**	**Torque**	**Thrust**
(mph)	**(Adv Ratio)**	-	-	-	**(Hp)**	**(In-Lbf)**	**(Lbf)**
0.0	0.00	0.0000	0.1097	0.0460	0.006	0.124	0.206
0.7	0.03	0.0614	0.1087	0.0465	0.006	0.125	0.204
1.3	0.05	0.1203	0.1075	0.0469	0.006	0.126	0.202
...							

The data is given at discrete RPM levels divisible by 1000. The RPM is interpolated using linear splines to be a function of thrust (T) as in Equation 9.3. Then the required power is interpolated similarly, but as a function of RPM in Equation 9.4. When combining the results of Equation 9.3 and Equation 9.4 into Equation 9.5 and plugging in the required thrust level, T_{req}, the required power, P_{req} can be calculated as a function of any input T_{req}. T_{req} and P_{req} can then be plugged into Equation 9.1 to find the specific thrust at the required thrust level for that specific propeller.

[3]`https://www.apcprop.com/technical-information/file-downloads/` [Accessed on 09-06-2020]
[4]`https://www.apcprop.com/technical-information/performance-data/` [Accessed on 08-06-2020]
[5]`https://m-selig.ae.illinois.edu/props/volume-1/propDB-volume-1.html` [Accessed on 08-06-2020]

$$RPM = f(T) \quad (9.3) \qquad P_{req} = g(RPM) \quad (9.4) \qquad P_{req} = g(f(T_{req})) = h(T_{req}) \quad (9.5)$$

Choosing a Propeller

The T_{req} is seen as the design thrust, the approximate thrust a propeller will have for the majority of the mission while it is in steady forward flight. It is calculated using Equation 9.6. The equation follows from vertical equilibrium of forces in Figure 9.7 (Where $\theta = \beta_i$. m_{drone} is the drone mass, g is the gravitational acceleration, n_{prop} is the number of propellers, and β_i is the drone inclination angle. The propellers will first be ranked based on their thrust efficiency at this design thrust.

Table 9.2: Final Inputs for calculating the design thrust for a single propeller.

Input	Value	Unit
m_{drone}	3.8	kg
n_{prop}	4	-
β_i	20	deg
g	9.81	m/s^2
Output	**Value**	**Unit**
T_{req}	9.92	N

$$T_{req} = \frac{m_{drone} \cdot g}{n_{prop} \cdot \cos(\beta_i)} \quad (9.6)$$

Any propellers that are not intended for drone use, that exceed the maximum propeller diameter, or that have to exceed the propeller type specific maximum RPM/Diameter value specified by the manufacturer [6] to achieve T_{req} are filtered out. The propellers that remain are intended for drone use and are capable of achieving T_{req} without danger of structural failure. The propeller thrust efficiency results are plotted in Figure 9.2.

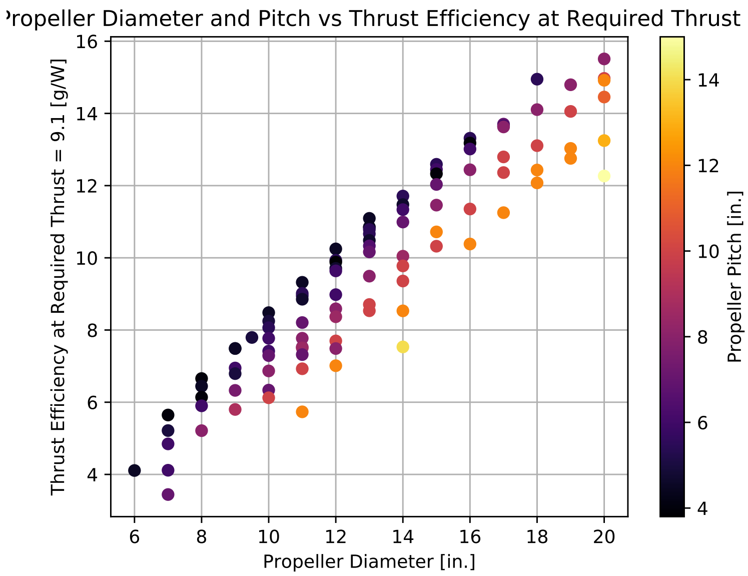


Figure 9.2: Plot of the Thrust Efficiency of the feasible propeller geometries at T_{req} = 9.1 N versus the diameter and the pitch of the propellers.

It becomes clear that the thrust efficiency of propellers is almost directly proportional to the propeller diameter. This is as is expected from the previously explored analytical BEMT model equations. The thrust efficiency decreases when propeller pitch increases. For static thrust efficiency the obvious choice would consequently be the biggest propeller diameter that fits into the propeller design limit (**HD-PROP-14**), combined with the smallest available propeller pitch.

[6] `https://www.apcprop.com/technical-information/rpm-limits/` [Accessed on 09-06-2020]

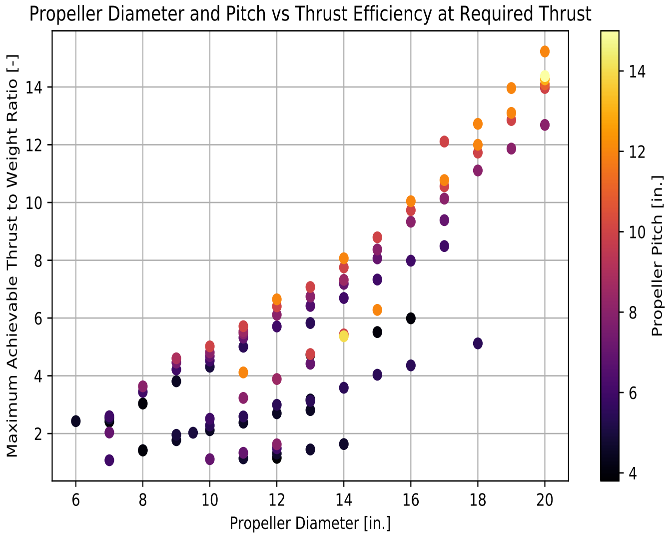


Figure 9.3: Plot of the achievable thrust to weight ratio as a function of propeller diameter and pitch.

The second factor to look at is the maximum thrust to weight ratio performance of the propellers as a function of the propeller geometry. The maximum thrust of the propellers is determined by taking the thrust at the maximum allowable RPM for the propeller model. This is depicted in the graph in Figure 9.3. The maximum thrust to weight ratio is clearly a function of the propeller diameter, with an increase in propeller pitch resulting in an increase in maximum thrust, for the price of a loss in efficiency. Important to note are the 2 distinct black bands present in the diagram. The bottom band values correspond to 'Slow Flyer' propellers, which have a relatively stringent maximum allowable RPM, compared to the non 'Slow Flyer' propellers.

The design rule for an efficient propeller capable of achieving a certain T_{max}/W should thus be to pick the largest propeller diameter possible, combined with the smallest pitch that allows for achieving the required T_{max}/W. The weight increase from a small diameter propeller to a large diameter propeller is negligible when compared to the total drone weight, so that is not a factor. The propeller mass moment of inertia, I_{prop}, does increase noticeably with increasing propeller size, causing a slower response time to control inputs. This difference can be offset by picking a more powerful motor. Actual response time data of motor and propeller combinations are hard to come by (or calculate without knowing the motor geometry exactly) so the snappiness of the control inputs cannot meaningfully be quantified and considered in the design as of now.

Propeller Distance

The propeller size is limited by 2 factors: requirement **HD-USRS-SYS-02** and the distance required between the edges of the propeller disks. While the flow of the propellers is mainly downwards, there is still a horizontal region of turbulence and unwanted flow phenomena that extends outside of the disk diameter. Quadcopter propellers placed too close to one another suffer in their efficiency and lift output, negating the benefit of using a bigger propeller diameter, as shown in [33]. The same paper investigated the optimal distance to avoid rotation effects between propellers as a function of drone weight, propeller diameter, and pitch. The maximum weight and diameter investigated are 3.0 kg and 14 in. respectively. Throughout the whole mass, diameter, and pitch range the rule of thumb seems to be that the propellers are optimally spaced at least 1/4 D_{prop} apart as a worst case scenario. That distance will be used for the design of this drone.

Number of Blades

Drone propeller blades usually come in 2 or 3 blade varieties (or more for the smaller diameter options). Generally, 3 blade propellers are capable of delivering a higher thrust at a given RPM, while 2 blade propellers are more efficient at all thrust levels [46]. For the purposes of this project a 2 blade propeller would thus be the best choice. This is reinforced by the greater availability of 2 blade propellers compared to 3 blade propellers, providing a larger sample size to choose from, and the fact that most foldable propeller varieties are only available for 2 blade propellers.

Maximum Propeller Diameter
The maximum usable propeller diameter for a traditional propeller is about 9 inches with the given dimensional limitations for the drone. As will become clear in the next section, that diameter is too small to expect a reasonable performance from the propulsion system with the initial weight estimation of about 4kg, both in efficiency and in achievable thrust to weight ratio (using the data available from manufacturers.

A remedy for this could be to use foldable propellers, which are available from most propeller manufacturers (excluding APC, whose foldable propellers fold vertically, not horizontally). This would push $D_{propmax}$ up to 15.5 inches, if the maximum size requirement was changed from 500x500x250mm to 535x535x250mm, to accommodate for proper propeller spacing as will be discussed later. This requirement change was agreed upon by the customer. 15.5 inches was chosen instead of 14 or 13 inches, which would have fit in the original requirement, as 13 or 14 inch propeller varieties either were not foldable, did not have performance data, or did have performance data, but could not be be combined with a motor that was not too heavy (to allow for tuning of the control system) or too inefficient in normal flight (requiring an unreasonably large battery).

These propellers would be folded towards the drone body, until deployment, when they would be folded out by centrifugal force supplied by applying maximum thrust with the motor. Currently this exact usecase has not been tested, so it would require testing once a prototype has been assembled. If it turns out that the propellers do not reliably deploy, then the propeller attachment piece could be redesigned with springs to be able to ensure full deployment during the drop.

9.3.2. Motor Design/Choice
The majority of multirotors use brushless DC motors [36]. They provide a higher efficiency and wear less than brushed DC motors, and they are the standard for the majority of drone motors. As a result, a brushless motor will be used. A brushless motor requires a more complex ESC, because the ESC also has to fullfil the role of a commutator.

The pool of motors to choose from came down to which motor manufacturers supplied useful and reliable data of propellers used in conjunction with the motors. The performance of a propeller and motor combination can be hard to predict, so heavy use will have to be made of actual test data to make a reliable and well informed choice. 3 manufacturers for motors fulfilled the performance data requirements for the type of drone system that is being built: Cobra Motors USA (Compatible with APC propellers) [7], KDEDirect [8], and T-Motor [9] There were other manufacturers, like Xoar [10], but their data was for drones outside of the weight and propeller diameter range of this drone.

The drone motors are normally named according to a 4 numbers scheme followed by a KV value (e.g. 2814). The first 2 numbers are the motor width. From going through the motor catalogues to make a selection there was a clear correlation between an increase in motor width and an increase in efficiency, everything else remaining constant. The last 2 letters are motor height.

An increase in motor height usually seems to lead to a bigger rise in achievable thrust (and RPM) than an increase in motor diameter, but also quickly increases the motor mass.

Finally, the KV is a measure of the RPMs a motor can reach as a function of its voltage. The higher the propeller diameter, the lower the KV. A roughly 15 inch propeller seems to perform optimally at a KV of 400 to 700, while a 9 inch propeller performs well at around 1000 KV.

Motor Choice Objectives
For propellers the choice of geometry was dominated by efficiency and maximum thrust delivery. That is also the case here, but there is an additional consideration of mass of the motors. Motors applicable to this usecase range from 120 to 300 grams (and higher) cables included. The motors are relatively heavy compared to the overall weight of the drone and positioned far away from the center of gravity, so they will make up the majority of the mass moment of inertia of the drone. When tuning the control system with a preliminary motor weight of about 250 grams, it was found to be almost impossible to tune for stability, due to the relatively high mass moment of inertia. To allow for controllability and stability, the motor mass must be as low as possible. Losses of efficiency, leading to a higher battery weight, picking a lighter motor results in are acceptable, because the added battery mass will be placed very close to the center of gravity, still improving

[7] `https://www.cobramotorsusa.com/` [Accessed on 12-06-2020]
[8] `https://www.kdedirect.com/` [Accessed on 12-06-2020]
[9] `http://store-en.tmotor.com/` [Accessed on 12-06-2020]
[10] `https://www.xoarintl.com/` [Accessed on 12-06-2020]

the mass moment of inertia of the overall drone.

Additionally, the motor has to operate in high moisture (fog) and high dust (brown-out) environments. Specifically dust and waterproof motors will be looked at to ensure compliance with the durability requirements.

Finally, the total cost and mass of a motor, propeller, and (preliminary) battery combination will be considered to distinguish between the setups if the right choice is unclear, or to make sure the total weight or cost of the chosen option is not substantially higher than weights or costs for the other setups.

In conclusion, the objectives for choosing the motor are to minimize motor weight and to ensure durability, while still achieving a reasonable overall thrust efficiency and while satisfying the thrust to weight ratio requirements necessary for the drone release stabilization. The expected masses and costs the a propeller, motor, and preliminary battery combination will also be analyzed for comparison.

Motor and Propeller Combination Choices

Three viable 15 inch propeller and motor combinations were chosen from the manufacturers' catalogues. More different combinations could be made, but these combinations would provide the best performance in the design objectives listed previously. The propellers and motors are from the same brand because the only performance data supplied is for propellers of the same brand. It was considered safer for the design process to go with reliable performance data, and products that are proven to work together, rather than trying to find the optimal propeller for a given diameter and extrapolating the motor data.

The only possible 9 inch propeller combination which manages to get close to the maximum thrust to weight ratio requirement (and for motor and propeller data combination is available) has also been added to compare the foldable and non foldable propeller options. It should be noted that the chosen motor is meant for RC airplanes, not specifically for multicopters. However, this was the only motor for which data was present that suggested it could supply enough thrust combined with the 9 inch propeller.

Table 9.3: 4 Combinations of propulsion system components made for further comparison of different options. The battery pack choices are preliminary, and only used for comparison purposes.

Combination	Motor	Propeller	Battery
1	T-Motor U5 KV 400 [11]	T-Motor FA15.2x5 [12]	ZIPPY Compact 6200mAh 6s 40c Lipo Pack [13]
2	Cobra C2826 KV 1470 [14]	APC 9x5 [15]	2x ZIPPY Compact 8000mAh 3S1P 30C LiPo Pack [16]
3	KDEDirect KDE3510XF-475 [17]	KDEDirect KDE-CF155-DP [18]	Turnigy Graphene Professional 8000mAh 6S 15C LiPo Pack [19]
4	KDEDirect KDE3520XF-400 [20]	KDEDirect KDE-CF155-DP	ZIPPY Compact 6200mAh 6s 40c Lipo Pack [21]

Battery type

Requirement HD-USR-SYS-SUST-02 states that the drone shall be powered by Lithium-Ion batteries. However, when designing the drone it became clear that most drones use Lithium Polymer batteries, they have a higher mass energy density than Lithium-Ion batteries [22], and it seems that only the Lithium-Polymer battery offerings are capable of providing the C-rates required for the power system to function. Though no source

[11] `http://store-en.tmotor.com/goods.php?id=318` [Accessed on 12-06-20]
[12] `http://store-en.tmotor.com/goods.php?id=390` [Accessed on 12-06-20]
[13] `https://hobbyking.com/en_us/zippy-compact-6200mah-6s-40c-lipo-pack-xt90-1.html?queryID=9a55c348569ac102001b3fae28ae9c05&objectID=71640&indexName=hbk_live_magento_en_us_products` [Accessed on 12-06-20]
[14] `https://www.cobramotorsusa.com/motors-2826-6.html` [Accessed on 15-06-20]
[15] `https://www.apcprop.com/product/9x5/` [Accessed on 15-06-20]
[16] `https://hobbyking.com/en_us/zippy-compact-8000mah-3s1p-30c-lipo-pack-with-xt90.html?queryID=046b7617c89ce9843f70341da08d04e6&objectID=82625&indexName=hbk_live_magento_en_us_products_hbk_price_stock_2_group_0_asc&___store=en_us` [Accessed on 15-06-20]
[17] `https://www.kdedirect.com/collections/uas-multi-rotor-brushless-motors/products/kde3510xf-475` [Accessed on 15-06-2020]
[18] `https://www.kdedirect.com/collections/multi-rotor-propeller-blades/products/kde-cf155-dp` [Accessed on 15-06-2020]
[19] `https://hobbyking.com/en_us/turnigy-graphene-professional-8000mah-6s-15c-lipo-pack-w-xt90.html?queryID=9a55c348569ac102001b3fae28ae9c05&objectID=71562&infdexName=hbk_live_magento_en_us_products` [Accessed on 15-06-2020]
[20] `https://www.kdedirect.com/collections/uas-multi-rotor-brushless-motors/products/kde3520xf-400` [Accessed on 15-06-2020]
[21] `https://hobbyking.com/en_us/zippy-compact-6200mah-6s-40c-lipo-pack-xt90-1.html?queryID=9a55c348569ac102001b3fae28ae9c05&objectID=71640&indexName=hbk_live_magento_en_us_products` [Accessed on 15-06-2020]
[22] `https://www.electronicdesign.com/power-management/article/21806525/` [Accessed on 18-06-2020]

was found to put an exact number on the limitations of C-rates Lithium-Ion batteries, no battery models were found that could safely support the currents required by the motors.

From anecdotal evidence it seemed like Lithium Polymer batteries would be less safe than Lithium-Ion batteries, but the evidence seems to be conflicting on this, with multiple sources stating that Lithium-Polymer batteries are actually safer than Lithium-Ion batteries [23] [24], or safety protocols like those from MIT [25] not mentioning any difference between the handling of Lithium-Polymer and Lithium-Ion batteries, or with National Transportation Safety Board safety recommendations not making any distinction between the two. [26].

This led to the decision to use Lithium-Polymer batteries, based on the C-rate requirement and there being no clear evidence that Lithium-Polymer batteries are less safe than Lithium-Ion batteries in aviation applications. What did, however, also become clear is that both battery types prove to be a relatively significant fire risk for manned aircraft. This is supported by the FAA Battery Incident chart [27], which shows about 268 battery incidents involving Lithium batteries (once again not mentioning exact battery types) since 2006, with most incidents involving fire or excessive heat.

This fire risk was added to the risk analysis in chapter 7, with mitigation methods being: placing a temperature sensor on or near the battery and having an emergency release mechanism in case of fire, and fireproofing the box the drone is kept in. Additionally, the placement of the drone attachment provides a natural buffer against fire spreading from the drone to the helicopter itself.

Significant effort will have to be put into certifying the batteries and fire mitigation system for flight with a crewed helicopter, but as of now it seems like that would be unavoidable no matter which Lithium battery type is chosen.

Motor and Propeller Combination Final Choice

The most important performance values of the chosen motor and propeller combinations are listed in Table 9.4. The red cells are a visual indication of which performance parameters disqualified a given combination compared to the best combination. The full specifications for all of the combinations are listed in Table 9.5.

The full motor, propeller and battery parameter values are listed in‘. The thrust efficiency, power, RPM, and current at the required thrust were calculated by linearly interpolating between manufacturers' measurements given at discrete throttle values (like 25%, 37.5% , etc.). Most other parameters were taken directly from manufacturer specifications. The T_{max}/W was calculated using **??**. The propulsion total mass and cost were calculated using Equation 9.7 Equation 9.8. Where C_{motor}, $C_{propeller}$, and $C_{battery}$ are the respective costs of those components. The preliminary battery choice was made using equations explained in the following paragraph.

$$m_{proptot}(\text{no ESC}) = 4\cdot(m_{motor} + m_{propeller}) + m_{battery} \tag{9.7}$$

$$C_{proptot}(\text{no ESC}) = 4\cdot(C_{motor} + C_{propeller}) + C_{battery} \tag{9.8}$$

Combination 2 demonstrated why using a non foldable propeller almost is not an option. It performed the best on cost and motor mass, but the low efficiency called for large batteries, resulting in a relatively high total propulsion system mass. This combination was the only 9x5 propeller motor combination that could almost get higher than a 2.0 T_{max}/W ratio. Furthermore, the motor was not water and dust proof. Thus, using foldable propellers was almost a necessity.

Combination 1 performed best in the overall efficiency department, resulting in a low battery mass and thus a low overall propulsion system mass. The remaining combinations' costs were very similar. The main problem with this combination would be the achievable T_{max}/W. A T_{max}/W of 2.5 does not fulfill the minimum requirement. A step up in T-Motor's catalogue to the water and dust proof U7 motor would allow for a sufficient T_{max}/W, but would push the motor mass all the way up to 296 grams [28], which would make the drone very hard to tune from a control perspective (**HD-PROP-15**).

[23] https://batteryuniversity.com/learn/archive/is_lithium_ion_the_ideal_battery [Accessed on 18-06-2020]
[24] https://www.electronicdesign.com/power-management/article/21806525/w [Accessed on 18-06-2020]
[25] https://ehs.mit.edu/wp-content/uploads/2019/09/Lithium_Battery_Safety_Guidance.pdf [Accessed on 18-06-2020]
[26] https://www.faa.gov/hazmat/resources/lithium_batteries/media/NTSB_safety_recs_to_prevent_cargo_fires.pdf [Accessed on 18-06-2020]
[27] https://www.faa.gov/hazmat/resources/lithium_batteries/media/Battery_incident_chart.pdf [Accessed on 18-06-2020]
[28] http://store-en.tmotor.com/goods.php?id=835 [Accessed on 15-06-2020]

Combination 4 was originally the final choice for the propulsion system. However, as mentioned before the control and stability requirements did not allow for its motor mass to be this high.

After combination 4 was discarded, all of the manufacturers' products were looked through again, and a motor which would provide nearly equivalent (or better) performance at a lower weight was found and used for combination 3. This combination was capable of exceeding the T_{max}/W requirement, while performing marginally worse on total mass and overall efficiency than combination 1.

Combination 3 and 4 exceed the T_{max}/W requirement with a decent margin, but there is a good reason for that. Between the 2.6 and 3.5 T_{max}/W range for this drone with a final weight of m_{drone} = 3.8 kg, there are no worthwhile alternative to the ones chosen in combinations 3 and 4. Any alternatives would have higher motor masses, worse thrust efficiency or a combination of the two. Furthermore, the extra T_{max}/W margin would allow this combination to be used for an m_{drone} of up to 4.5 kg while still fulfilling **HD-PROP-02**. This would any design iteration that would have to be performed when there is an increase in m_{drone} compared to the current design value, thus making the propulsion design less sensitive to drone mass changes.

Taking all of these considerations into account, the motor and propeller combination that was chosen was combination 3. A final battery and ESC model will be chosen as a result of this motor and propeller combination.

Table 9.4: Performance of the chosen propeller and motor combinations on most important performance criteria.

Parameter	Combination 1	Combination 2	Combination 3	Combination 4
Thrust Efficiency At Required Thrust [g/W]	12.6	7.7	11.2	11.3
Maximum Thrust/Weight Ratio [-]	2.6	2.0	3.7	3.5
Motor Mass (With Cables) [g]	195	171	175	245
Total Mass [g]	1725	1902	1928	1933
Total Cost [$]	789	316	729	761
Environment Proof?	Yes	No	Yes	Yes

9.3.3. Battery and ESC Choice

A battery was added to each propeller motor combination based on off the shelf components. The battery had to fulfill some calculated requirements. These requirements are the S value, C rate and capacity in Ampere hour. The S value is dictated by the motor. Each cell of the LiPo battery has a nominal voltage of 3.7V. The S value is the amount of cells put in series. The cells in series add up the voltage, so $6S = 6 * 3.7V = 22.2V$. The C rate is a metric of how fast the battery can be drained, or how much Ampere it can supply to the electrical system for a continuous time. There is usually also a higher burst (5 seconds) value for C rate. The necessary continuous C rate can be calculate using Equation 9.9. Its unit is usually shown as C but this is equivalent to h^{-1}

$$C_{neces} = \frac{4 \cdot I_{maxthrust}}{BatteryCapacity} \tag{9.9}$$

Battery capacity is calculated using Equation 9.10: the current typically drawn throughout a mission times the time the mission takes. A safety factor is added to this to account for depth of discharge (80 percent), atypical mission conditions and the electrical power for the sensors. The power used by the sensors is less than a sixth of the total power budget. See also chapter 8. This safety factor was chosen as 2 comparable to a double mission.

$$BatteryCapacity = SF \cdot I_{typical} \cdot t_{mission} \tag{9.10}$$

Based on these requirements the lightest off the shelf available battery can be chosen. This provides the other specifications like dimensions needed for the design. The chosen battery is the Turnigy Graphene Professional 8000mAh 6S 15C LiPo Pack.

The ESC has few requirements: it needs to be as light as possible, while being able to handle the voltages and amperes going to the motor. The ESC was therefore chosen based on the motor manufacturer's recommendation. This was the KDEXF-UAS55.

9.4. Modelling the Propulsion System

To aid in the sizing, design, and performance analysis of the propulsion system it is useful to model its components. A simplified diagram is shown in Figure 9.4, which shows how the typical multirotor propulsion subsystem can be broken down to a battery, an ESC (electronic speed controller), motor, and propeller [13, 43].

Table 9.5: General specifications of the propeller and motor combinations.

Parameter	Combination 1	Combination 2	Combination 3	Combination 4
Performance at required thrust = 9.92 N				
Efficiency [g/W]	12.6	7.7	11.2	11.3
Power [W]	91.1	115.0	97.9	111.3
RPM	2805.2	8958.0	3958.1	4067.3
Voltage [V]	22.2	11.1	23.1	23.1 (6S)
Current [A]	4.1	10.4	4.2	4.3
Performance At Maximum Thrust				
Maximum Thrust [N]	24.3	18.9	34.5	32.6
Efficiency [g/W]	6.5	4.0	4.3	6.1
Power [W]	381.8	481.2	824.0	548.0
RPM	6500.0	13396.0	7580.0	7580.0
Max Thrust/Weight [g/W]	2.6	2.0	3.7	3.5
Current [A]	17.2	43.4	35.7	21.0
Motor Specifications				
Weight (No Cables) [g]	156	-	120.0	190.0
Weight (With Cables) [g]	195	171.0	175.0	245.0
Voltage [V]	22.2	11.1	23.1	23.1
Dimensions [mm Diameter x mm Length]	42,5*37,5	46,0*35,0	42.2*35	42.2*45
Idle Current@10V [A]	0.3	3.0	0.2	0.3
Internal Resistance [mOhm]	116	18.0	105.0	78.0
Max Continuous Current [A]	30	65.0	30.0	45.0
Shaft Diameter [mm]	5	5.0	4.0	4.0
Cost [$]	126	49.0	93.0	113.0
Battery				
S Value	6.0	3.0	6.0	6.0
Max current [A]	17.2	43.4	35.7	21.0
Typical current [A]	4.6	10.4	4.8	4.6
minimum C rate	11.3	12.6	22.1	13.6
Capacity [Ah]	6.1	13.8	6.5	6.2
weight [g]	655.0	1130.0	1110.0	655.0
Battery + motor weight [g]	1435.0	1814.0	1810.0	1635.0
Price [$]	73.0	107.8	118.2	73.0
Length [mm]	144.0	167.0	165.0	144.0
Height [mm]	44.0	69.0	59.0	44.0
Width [mm]	51.0	24.0	46.0	51.0
Propeller				
Diameter x Pitch [in. x in.]	15.2x5	9x5	15.5x5.3	15.5x5.3
Weight Per Propeller [g]	27.5	22.1	29.4	29.4
Cost per Propeller [$]	49	3.0	59.0	59.0
Total				
Mass	1545	1902.4	1927.6	1752.6
Cost	773.0	315.8	726.0	761.0

The set point is provided by the flight computer, which then essentially regulates the output the ESC will provide to the motor to be able to throttle it. Each of these components can then be modelled with simplified equations, so that several performance parameters can be estimated if the specifications of these components are known. The model and governing equations is largely taken from [43], with some modifications to take into account extra data that is available.

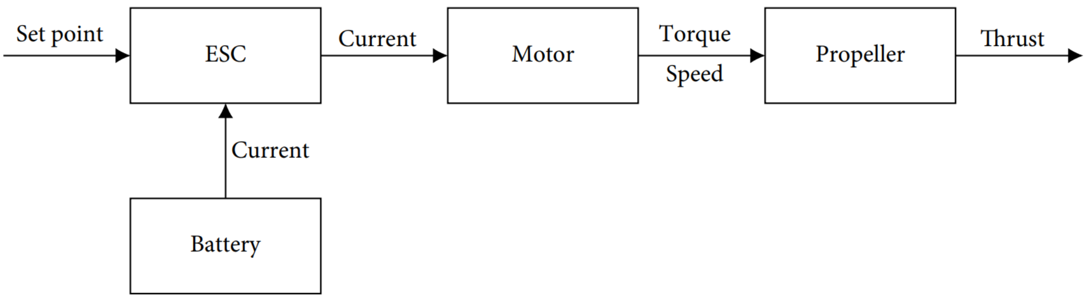


Figure 9.4: Simplified diagram of the propulsion system

9.4.1. Propeller Model

To model the propellers, two quantities are of importance: the thrust and the torque. These can be calculated with the two simplified equations shown below, again taken from [43], and more fundamentally these relations are derived from momentum theory [9].

The static thrust of a propeller is proportional to the square of the angular velocity, 'ω' in Equation 9.11 [43]:

$$T = C_T \rho \omega^2 D_p^4 \tag{9.11}$$

Additionally, the air density, 'ρ', naturally also plays a role, as well as the propeller diameter, 'D_p.' The propeller-specific thrust coefficient C_T then encompasses all other effects which influence the thrust, such as the aerodynamic characteristics of the propeller's airfoil, for example. Note that the literature is not always consistent about the definition of this coefficient, the diameter and air density are sometimes included implicitly in it, for example, to write the equation as simply

$$T = c_T \omega^2$$

. Similarly, instead of writing the equation in terms of the propeller diameter, it is written in terms of the rotor disk area. All the equations are essentially equivalent, but care should be taken to be consistent with how the thrust coefficient is defined.

Similarly, the torque can be defined by Equation 9.12 [43]:

$$M = C_M \rho \omega^2 D_p^5 \tag{9.12}$$

Where C_M is the torque coefficient. Again, care should be taken with the consistency of the coefficient's definition, since it can also sometimes be defined as simply

$$M = c_M \omega^2$$

. Note that the power coefficient C_P, also frequently mentioned when dealing with propellers, is equal to the torque coefficient C_M [9].

These two coefficients are not usually parameters manufacturers provide. Thus, the paper proposes estimations, shown in Equation 9.13 and Equation 9.14, using only the propeller diameter, pitch, and blade number, and several estimated parameters and correction coefficients mostly related to the propeller's aerodynamics to calculate them:

$$C_T = 0.25\pi^3 \lambda \zeta^2 B_p K_0 \frac{\varepsilon \arctan \frac{H_p}{\pi D_p} - \alpha_0}{\pi A + K_0} \tag{9.13}$$

$$C_M = \frac{1}{8A} \pi^2 C_d \zeta^2 \lambda B_p^2 \tag{9.14}$$

Where C_d, the drag coefficient of the propeller must also be estimated with Equation 9.15, also using the propeller parameters and other correction as well as aerodynamic coefficients:

$$C_d = C_{fd} + \frac{\pi A K_0^2}{e} \frac{\left(\varepsilon \arctan \frac{H_p}{\pi D_p} - \alpha_0\right)^2}{(\pi A + K_0)^2} \tag{9.15}$$

The derivation of these equations is beyond the scope of the project, and the reader is referred to Appendix A of [43] for this. Moreover, a short description for the terms used in these equations, as well as their typical range and suggested value from are presented in Table 9.6:

Table 9.6: Description of terms in the propeller thrust and torque coefficient equations

Term	Symbol	Typical Range	Suggested Value
Propeller diameter	D_p	N/A	N/A
Propeller pitch	H_p	N/A	N/A
Propeller blade number	B_p	N/A	N/A
Aspect ratio	A	5 - 8	5
Downwash correction factor	ϵ	0.85 - 0.95	0.85
Blade airfoil area correction factor	λ	0.7 - 0.9	0.75
Correction factor for the propeller average linear speed	ζ	0.4 - 0.7	0.55
Oswald factor	e	0.7 - 0.9	0.83
Zero-lift drag coefficient	C_{fd}	0.015	0.015
Zero-lift angle of attack	α_0	$\frac{-\pi}{36}$ - 0	0
Slope of lift curve	K_0	6.11	6.11

Note that the first three terms don't have a typical range or suggested value since these are simply design choices, or alternatively if an off-the-shelf propeller is chosen these three values are always available from the manufacturer. The suggested values for the coefficients and correction factors are also taken from [43], where the authors refer to literature [35, 47] to justify these. These are also verified by comparing the results using these values with experimental results from APC propellers[29].

Thus, inputting numbers for the propeller diameter, pitch, and blade number, and using these suggested values, the thrust and torque coefficient can be easily calculated. Nonetheless, even if the values are verified, it is stated by the authors of [43] themselves that "...in practice, it is impossible to determine the values of [the parameters shown above] to match all kinds of propellers." When comparing the coefficients derived from manufacturer data and the coefficients using the proposed estimations, they yielded relatively similar results, but it is still nonetheless hard to verify Equation 9.13 and Equation 9.14 for our application and the assumptions these imply, and it is also hard to estimate the degree of uncertainty the resulting coefficients would have for different propellers. Therefore, while these equations and parameter values are still useful to initially explore design options, for design iteration and performance analysis of the chosen design they will not be used. Instead, since only propeller/motor combinations where the manufacturer provided test data were considered for the design (as is evident in subsection 9.3.1 and subsection 9.3.2), these data can be used to derive the coefficients through regressions between thrust and angular velocity, as well as between the torque and angular velocity (since it is known that both are proportional to the square of the angular velocity), eliminating the need to estimate the thrust and torque coefficients with the suggested equations.

9.4.2. Motor model

As mentioned in subsection 9.3.2, brushless DC motors (BLDC) are now commonly used for drone applications. These can be modelled as permanent magnet DC motors using the equivalent circuit shown in Figure 9.5:

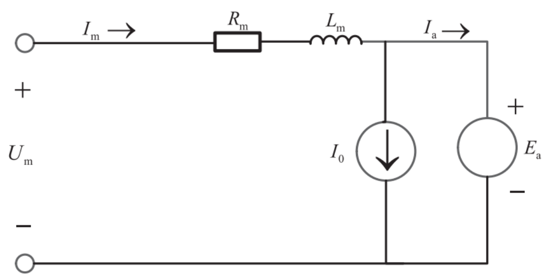


Figure 9.5: Equivalent electrical model for the motor [43]

Where E_a (V) is the back electromotive force of the motor, R_m (Ω) is the armature's resistance, L_m (H) is the armature's inductance, I_0 (A) is the no-load current (current needed to overcome mechanical friction, as

[29] `https://www.apcprop.com/` [Accessed on 16-06-2020]

well as magnetic losses), I_m (A) is the equivalent motor current, U_m (V) is the equivalent motor voltage, and finally $I_a = I_m - I_0$, from Kirchoff's current law. Using this model, it is desired to calculate U_m and I_m using the manufacturer-given motor parameters and the calculated propeller torque for a given flight condition.

BLDC motors for this kind of applications are usually designed to have a very low inductance (<0.2mH), so this can be neglected, and similarly, other transient effects can be neglected [12, 43]. Knowing this, expressions needed for U_m and I_m can now be derived.

From electric machine theory, the electromagnetic torque T_e of the motor is:

$$T_e = K_T \cdot I_m$$

With K_T being the motor torque constant (Nm/A), while the no-load torque T_0 is:

$$T_0 = K_T \cdot I_0$$

[16] This current I_0 is technically not exactly the same as the no-load current mentioned above, but in practice, the difference between them is negligible [43].

Then, the total output torque is simply the electromagnetic torque minus the no-load torque, and this total output torque is also equal to the propeller torque, M, so that:

$$M = T_e - T_0 = K_T(I_m - I_0)$$

Which can finally be rearranged to yield Equation 9.16:

$$I_m = \frac{M}{K_T} + I_0 \tag{9.16}$$

The value of the motor torque constant K_T can be used directly if available from the manufacturer, but when it is not provided it can also be calculated from the no-load velocity constant K_V0, the no-load motor current I_m0 (assumed equal to I_0), and no-load motor voltage U_m0 through Equation 9.17, where the reader is again referred to [43] for the derivation:

$$I_m = \frac{MK_{V0}U_{m0}}{9.55\,(U_{m0} - I_{m0}R_m)} + I_{m0} \tag{9.17}$$

Then, to find an equation for U_m, first, the back-electromotive force is [16]:

$$E_a = K_E \cdot \omega$$

Then from the Figure 9.5, using Kirchoff's voltage law (voltages around a loop must add up to zero) around the outermost loop:

$$U_m = I_m R_m + K_E \omega$$

It can then be shown that, actually, $K_E = K_T$, the motor torque constant mentioned earlier [16]. Note that in [43], a factor of 9.55 is included in the equality, this is only necessary if one of the constants was defined in terms of RPM, since then this factor of 9.55 ($60/2\pi$) will convert to rad/s or vice-versa, thus care should be taken to include it only when applicable. Since ω, the angular velocity in rad/s has been used throughout, the factor is not necessary in these equations. Thus, knowing this, and replacing the previously found expression for I_m in Equation 9.16, the final equation for U_m is shown in Equation 9.18:

$$U_m = R_m(\frac{M}{K_T} + I_0) + K_T\omega \tag{9.18}$$

As stated above, if the torque constant K_T is not directly available, this can be calculated with other provided motor specifications. The derivation for this is again shown in [43]; the final result of replacing this alternative expression for K_T yields Equation 9.19:

$$U_m = R_m\left(\frac{MK_{V0}U_{m0}}{9.55\,(U_{m0} - I_{m0}R_m)} + I_{m0}\right) + \frac{U_{m0} - I_{m0}R_m}{K_{V0}U_{m0}}N \tag{9.19}$$

9.4.3. ESC model

As stated previously, the ESC (electronic speed controller) essentially performs the commutation that the motor requires electronically. It outputs a three-phase alternating signal which is synchronized with the rotation of the motor. For the purposes of modelling the ESC, it is a simple two-port with an input current and voltage I_e and U_e, an internal resistance at its output of R_e, and the output currents I_m and U_m, the equivalent motor current and voltage described previously. This is shown graphically in Figure 9.6:

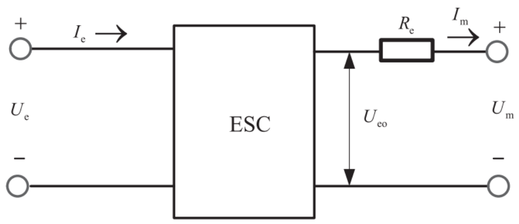


Figure 9.6: Electrical model for the ESC [43]

Where U_{eo}, the equivalent DC voltage, is also labelled.

From this model, similarly to the motor, expressions for I_e and U_e, the input current and voltage, are desired. First, using Kirchhoff's voltage law:

$$U_{eo} = R_e I_m + U_m$$

The duty cycle σ (essentially proportional to the throttle) of the ESC can be written as [43]:

$$\sigma = \frac{U_{eo}}{U_e} \approx \frac{U_{eo}}{U_b}$$

Replacing the expression found above for $U_e o$ leads to the final expression for the duty cycle in Equation 9.20:

$$\sigma = \frac{R_e I_m + U_m}{U_b} \tag{9.20}$$

With the duty cycle σ, from the perspective of power electronics, the ESC can also be seen as DC-DC buck converter, so that the following relation can be written for the ESC input current in

$$I_e = \sigma I_m \tag{9.21}$$

Lastly, to find an expression for U_e, first an expression for I_b, the battery current, is needed. For a quadrotor, there will be four ESCs (one per rotor) connected to the battery, which means that the battery current can be expressed by Equation 9.22:

$$I_b = 4I_e + I_c \tag{9.22}$$

With I_C being the current supplied to the flight controller, usually about 1 A [43]. Then, U_e, the voltage supplied to the ESCs, is simply Equation 9.23:

$$U_e = U_b - I_b R_b \tag{9.23}$$

With I_b, the battery current, described previously, and U_b and R_b, the battery voltage and internal resistance respectively, being known parameters.

9.4.4. Battery model

Finally, for the battery model, using the now known battery current from Equation 9.22, and the parameters of the battery such as its capacity and depth of discharge, the time to discharge can be found, which will effectively be equal to the endurance. For simplicity, the battery voltage is assumed to remain constant, and the capacity is assumed to decrease linearly [43], which means the time to discharge can be expressed by Equation 9.24:

$$T_b = \frac{C_b DoD}{I_b} \cdot \frac{60}{1000} \tag{9.24}$$

Where DoD is the depth of discharge used for the battery (as a decimal), typically this number is between 60-80 %. Note that the factor 60/1000 is included, so the capacity should be inputted in mAh, and the output will be in minutes.

With this last equation, the model is complete and the hovering endurance can be estimated. Additionally, combining this with a drag model also allows estimating the maximum speed and range of the drone.

9.4.5. Hovering endurance estimation

To estimate the hovering endurance, first the required total thrust to hover is equal to the drone weight, so that the thrust per rotor is:

$$T = \frac{W \cdot 9.81}{n_r}$$

Knowing the required thrust per rotor means the required RPM can then be calculated, either using the thrust coefficient derived from manufacturer static thrust data or using Equation 9.13 with the known propeller parameters. In this case, a required RPM (N) of 4040 is calculated. From the known RPM, the required torque can also be calculated, similarly using the torque coefficient derived from data or from Equation 9.14. Next, the motor equivalent voltage U_m and current I_m can be calculated using Equation 9.18 and Equation 9.16 respectively, inputting the calculated RPM and torque, and known motor parameters. Continuing down the chain, with U_m and I_m known, the duty cycle σ and input current I_e of the ESC can be calculated using Equation 9.20 and Equation 9.21. Finally, the battery current I_b can be calculated with Equation 9.22, so that the time to discharge can be calculated using Equation 9.24, which will then be the resulting estimated hovering endurance.

Using the input parameters summarized in Table 9.7, following the process described above (coded in Python) results in a hovering endurance of 14.2 minutes. Note that while the battery capacity is 8000 mAh, for this calculation this capacity was 'penalized' by 500 mAh to account for the power the sensors consume. This capacity of 500 mAh that the sensors 'occupy' can be calculated knowing that the sensors and avionics need about 50 W, the battery voltage is 22.2 V, and the time they'll be operational is about 15 minutes.

Table 9.7: Table summarizing inputs for the model

Parameter	Symbol	Value used
Propeller Parameters		
Diameter [in]	D_p	15.5
Pitch [in]	H_p	5.3
Blade number [-]	B_p	2
Motor Parameters		
No-load velocity constant [RPM/V]	K_{V0}	475
Nominal no-load current [A]	I_{m0}	0.2
Nominal no-load voltage [V]	U_{m0}	10
Motor internal resistance [Ω]	R_m	0.105
Torque constant [Nm/A]	K_T	0.0201
ESC parameters		
Internal resistance	R_e	0.008
Battery parameters		
Capacity [g]	U_b	22.2
Internal resistance [Ω]	R_b	0.003
Voltage [V]	U_b	22.2
Depth of discharge [-]	DoD	0.8
Additional parameters		
Drone mass [kg]	m	3.8
Number of rotors [-]	n_r	4

9.4.6. Maximum speed and range estimation

Estimating the maximum speed and range is relatively similar to the process that was needed to estimate the hovering endurance described above. For simplicity, only steady-state forward flight will be considered for this estimation.

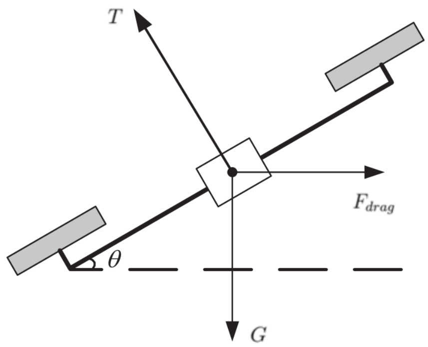


Figure 9.7: Free body diagram of a quadrotor in equilibrium at a pitch angle θ [43]

Then, looking at the free-body diagram in Figure 9.7, for vertical equilibrium, $T \cdot \cos(\theta) = G$ (where $G = m \cdot 9.81$). For horizontal equilibrium, $T\sin(\theta) = F_{drag}$, and thus, combining these two expressions:

$$G \cdot \tan(\theta) = F_{drag}$$

Which then means that if the drag can be modelled as a function of velocity and other known parameters, the expression can be used to solve for the resulting velocity at a given pitch angle θ. The two proposed drag models are explained in section 10.3.

Being able to calculate the velocity at a given pitch angle, all that is left now is calculating the flight time at a given pitch angle. This will actually be the exact same process as described above in subsection 9.4.5, except that now the required thrust per rotor is:

$$T = \frac{m \cdot 9.81}{\cos(\theta) n_r}$$

With the thrust required calculated, the same steps can then be followed to find the required RPM and torque, followed by the currents, voltages, and duty cycle, and finally the time to discharge which will be equal to the flight time.

Then, all that is left is combining the velocity with the flight time (taking care to multiply the flight time by 60 if it is in minutes) to calculate the range at a given pitch angle. By the numerical traversal theorem [43], one can then simply vary the pitch angle θ from zero to a maximum pitch angle, and find the maximum range among the results. The maximum pitch angle is theoretically limited by the thrust, (a pitch of about 70 degrees required a thrust-to-weight ratio of about 3 for equilibrium). In practice, it is limited by other effects. looking at similar drones such as the DJI Inspire 2 or the DJI DJI Matrice 200 V2, their maximum pitch angle is 35-40 degrees [30], and this trend is true for most (non-acrobatic) drones of a similar scale, even though their maximum thrust is likely not the limiting factor. Thus, the maximum pitch angle was set at 35° for these calculations; this maximum pitch angle of the drone would have to be validated at a later design stage, likely through more detailed simulations that include the relevant aerodynamics in detail, or through flight testing. Using the system parameters described above in Table 9.7, the maximum pitch angle set at 35°, and combining this with the drag model that will be explained in chapter 10 yields a maximum range of 10.8 km.

9.5. Verification

9.5.1. Propulsion Component Choice Calculations

A couple of tools were built to be able to quickly evaluate propulsion system combinations on design parameters. Furthermore, a python tool was written to cycle through the APC propeller database. These tools

[30] `https://www.dji.com/nl/inspire-2/info#specs` [Accessed on 19-06-2020]

were verified to make sure they were functioning correctly. Simple data type tests and/or unit tests performed quickly during the coding of the tools are not mentioned here in the interest of space. Other test results are described per tool, along with applicable inputs, expected outputs, and actual outputs wherever applicable.

Database Script
The following tests were some of the bigger tests performed to verify that the database cycling script was working correctly:

- **Required thrust calculation**:
  - **Test goal:** Test if the tool correctly calculates the required thrust according to Equation 9.6.
  - **Input and output**: Listed in Table 9.2.
  - **Expected output**: (Calculated by hand) 10.4 N
  - **Conclusion**: Calculation procedure for required thrust is verified to be exact to the way the model is intended to function. The program does not work for $n_{prop} = 0$, or $\beta_i = 90$ deg, as that will result in division by 0.
- **Identification of Propeller diameter, pitch, and type**:
  - **Test goal**: Check if the program correctly identifies the propeller diameter, pitch and type from the file name.
  - **Input**: List of all filenames. (Example: *875x825W.dat, 12x6EP(F2B)*)
  - **Expected Output**: From the examples: Diameter = 8.75 In., Pitch = 8.25 In., Propeller Type = Not relevant for drones., and Diameter = 12 In., Pitch = 6 in., Type = Electric Propeller.
  - **Output**: This step took a lot of iterations to get right. The type identification worked as intended, finding all drone relevant propellers in all tests. The pitch and diameter were initially not identified correctly (Diameter = 875 In. instead of 8.75 In. for the first example) so this was corrected for. The same was done for the pitch, which required all other extraneous characters (EMRFSNWHCX()DATBPG) to be removed from the end of the filename string first. A final test of all propellers with filenames, diameter, pitch and propeller types printed side by side proved that the program did now correctly identify all propeller diameters and pitches.
  - **Conclusion**: After performing some additional tests to check the program was verified to be able to identify propellers correctly.
- **Data reading**:
  - **Test goal**: Checking if the program correctly reads all provided propeller data.
  - **Input:** A few example data files to build the base file reader, and then the entire database to test for any errors.
  - **Expected Output:** Lists of the RPM increments, and corresponding thrust and power increments at static thrust for all propellers. These will be checked on correctness with some sample datafiles.
  - **Output:** The tool provided the expected output for most datafiles. It turned out that there were 2 different data file structures, with the most common one working correctly, and with some outliers (16 files) having more columns than expected, thus creating errors. These outliers were removed from the database.
  - **Conclusion:** After running additional tests to check if the data the tool produced was actually correctly based on the actual data files, the tool was considered verified as no discrepancies between the datafiles and read data could be found.

The listed tests were the most important ones performed. Other tests included: testing if the 'interp1d' numpy function correctly interpolated between the data point lists, testing if propellers that exceeded the maximum propeller diameter were filtered out correctly, and tests on if conversion between imperial units and SI units were performed correctly. This section would become too long if all tests were described. Furthermore, the 100 % correct functioning of this tool is not critical to this design, as it ended up merely being used as an indication for the propeller choice rules.

9.5.2. Propulsion system model

The propulsion model described in section 9.4, also requires verification. First, the usual 'sanity checks' were performed, such as verifying conservation of energy. Moreover, the expected magnitude of the numbers was checked. For example, comparable drones in terms of size, weight, propeller size, and battery capacity such as the DJI Inspire 2 have a hovering endurance of about 15 - 25 minutes [31], and thus an endurance of less than 5 minutes or larger than 40 minutes (resulting from inputting the parameters shown in Table 9.7) should be regarded with suspicion since there is likely a mistake somewhere. Indeed, an initially unexpectedly low result led to re-checking the code, and it was found than when dealing with the thrust per rotor in an equation, the total thrust had not been divided by the number of rotors.

More broadly, to verify the overall implementation of the model, since it was largely based on [43], it was possible to simply input one of their examples and verify that the result was the same. Table II from this paper is shown in Figure 9.8, where all the relevant inputs are shown, as well as the results at the bottom. Note that the table contains environment parameters like temperature and altitude, while this was not treated in section 9.4, these are simply to determine the air density ρ to be used in the thrust equation Equation 9.11. Similarly, I_{eMax} and K_b are simply used to check that the maximum current of the ESC and maximum discharge rate of the battery are not exceeded, but they are not relevant to the calculations otherwise.

Environment	$h = 10$ m, $T_t = 25\,^\circ$C
Basic Parameters	$G = 14.7$ N $> G_p + G_e + G_b + G_m$, $n_r = 4$
Components	$\Theta_p = \{D_p = 10$ in, $H_p = 4.5$ in, $B_p = 2, G_p\}$ $\Theta_m = \{K_{V0} = 890$ r/min/V, $I_{m\,\mathrm{Max}} = 19$ A, $I_{m\,0} = 0.5$ A, $U_{m\,0} = 10$ V, $R_m = 0.101\ \Omega, G_m\}$ $\Theta_e = \{I_{e\mathrm{Max}} = 30$ A, $R_e = 0.008\ \Omega, G_e\}$ $\Theta_b = \{C_b = 5000$ mAh, $R_b = 0.01\ \Omega$, $U_b = 12$ V, $K_b = 45$ C, $G_b\}$
Other parameters	$A = 5, \varepsilon = 0.85, \lambda = 0.75, \zeta = 0.5, e = 0.83, C_{\mathrm{fd}} = 0.015$, $\alpha_0 = 0, K_0 = 6.11, C_1 = 3, C_2 = 1.5, C_{\mathrm{min}} = 0.2C_b$
Results	$T_{\mathrm{loiter}} = 15.8$ min, $\sigma = 54.6\%$, $I_e = 3.6$ A, $U_e = 11.8$ V, $I_b = 15.2$ A, $N = 5223$ r/min

Figure 9.8: Table II extracted from [43]

After inputting these values into the model, the output was verified to be identical up to the accuracy given in [43]. This paper also provides several other examples with results (not included here for brevity), which were consequently also used for verification. Note that the propulsion model here only implements what is labelled as 'problem 1,' the hovering endurance problem, and 'problem 4,' the range problem, since these were the only ones considered relevant to the project, so naturally only these were verified.

9.6. Validation

9.6.1. Propeller Database

The data used in APC's propeller database is the data they themselves use to design their propellers. They specify that it is not suitable for detail design of a full UAV, because there are a lot more factors involved there, but that it can be used on a comparative basis [32]. To support this claim, the datasheets of actual APC propeller measurements made by the university of Illinois [33] was compared to the APC database entries and it was found that the static thrust and static power predictions of the APC model came very close (about a 10% margin up or down at most RPMS) to actual windtunnel static thrust and power measurements. This gave enough confidence to consider the APC data valid for the level of analysis that it has been used for in this report. If the APC data had been used to estimate the actual final performance values of the chosen propeller and motor combination, it would have been validated more rigorously.

[31] `https://www.dji.com/nl/inspire-2/info#specs` [Accessed on 19-06-2020]
[32] `https://www.apcprop.com/technical-information/engineering/#aero` [Accessed on 16-06-20]
[33] `https://m-selig.ae.illinois.edu/props/volume-1/propDB-volume-1.html` [Accessed on 16-06-20]

9.6.2. Propulsion system model

The validation of the model described in section 9.4, which was based on [43], is rather difficult to validate since the best way would be to perform experiments with a drone prototype to measure parameters such as the hovering endurance. Indeed, at a future design stage simple tests could be performed to validate the predictions. Measuring the hovering endurance would be relatively simple, while properly measuring the maximum range and the velocity as a function of pitch angle would be slightly more difficult. Nonetheless, this could be done with the help of the sensor data from the drone, or if necessary with motion tracking equipment.

Apart from that, however, if the input parameters corresponding to a commercial drone are known, the results can be compared to the given specifications from the manufacturer. This is indeed done in [43], where the estimated results are compared to the specifications of the DJI Inspire 1, and the results seem to match well. The estimations are also compared to the results from [34], however this website does not provide a source for its calculations and thus it is questionable whether this is a good comparison at all, even if the website seems to produce sensible results. Finally, experiments with a propeller are performed to validate the thrust-RPM relationship, as well as to validate the ESC current calculation. The results show a good match, but more thorough experimentation with many different propeller sizes would provide further validation. As stated above, while this has been a very useful tool for design and performance analysis at this design stage, it would definitely need to be fully validated through experimentation with a full-scale drone at a later design stage.

9.7. Final Component Visuals

For visual clarification the final selected components are depicted here. The chosen propeller blades can be found in Figure 9.9, with their folding capabilities and them being installed on a motor being shown in Figure 9.10[35]. Finally, the ESC and battery are shown in Figure 9.11, and Figure 9.12 respectively.

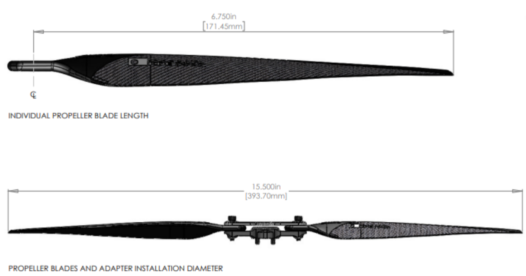


Figure 9.9: KDE Direct 15.5x5.3 Foldable carbon fiber propellers.

Figure 9.10: Folding functionality of the 15.5 inch KDE propellers.

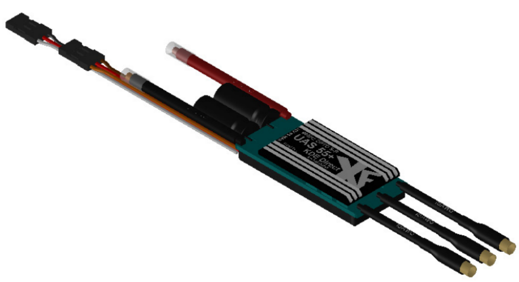


Figure 9.11: KDEXF-UAS55 ESC.

Figure 9.12: Turnigy Graphene Professional 8000mAh 6S 15C LiPo Pack battery.

[34] `https://www.ecalc.ch/xcoptercalc.php` [Accessed on 19-06-2020]

[35] `https://www.kdedirect.com/collections/multi-rotor-propeller-blades/products/kde-cf155-dp` [Accessed on 22-06-20]

10
Aerodynamics

This chapter explains the aerodynamic analysis that was necessary for the design and performance analysis of the drone, and how it was conducted. Note that this chapter breaks from the typical structure used for the subsystem chapters since 'aerodynamics' is not really a subsystem of the drone. This analysis is still needed, nonetheless, since, as stated in subsection 9.4.6 from the previous chapter, a drag model is needed to estimate velocity and range. Thus, the first section provides a brief introduction to aerodynamics in the context of multirotors and the current literature, the second section explains the relevant drag and drag-like effects that a drone experiences, while the third and final section outlines how the drag forces were estimated.

10.1. Multirotor Aerodynamics and Available Literature

In the context of multirotors, the most relevant aerodynamic analysis pertains to the analysis specifically of the rotors (and the thrust,drag, and torques they produce), rather than the aerodynamics related to the flow of air around the multirotor body as it moves. The main reason to analyze the aerodynamics related to the flow around the body and its shape would be to estimate the parasitic drag coefficient, but, in fact, considering the flight envelope for many multirotor applications, which usually involves speeds only up to 10 m/s, this drag component is often neglected in the literature [10–12, 26]. Thus, also in this project, the main focus was to look at the rotors' aerodynamics. As stated in subsection 9.3.1, however, analyzing the rotors' aerodynamics through momentum theory, blade element theory (BET), and blade element momentum theory (BEMT) proved to be very difficult, mainly due to having to solve for the induced velocity. Many of the numerical methods were beyond the scope of this project, and an analytical implementation was found in [9], but unfortunately it was impossible to have it converge when calculating the induced velocity, Results could also vary by up to 30% with very small changes in input, making the reliability of these results questionable.

While the thrust performance of propellers can be found or calculated in alternative ways, such as estimating the thrust coefficient or using manufacturer provided data, it is much more difficult to accurately estimate the drag (which is why the focus of this chapter is on drag). The available literature related to drag estimation for drones usually only deals with the drag in order to model a drone for a control system, and not to design or analyze performance [6, 11, 28, 29]. This means that frequently the relevant equations and models are derived and explained, but they always ultimately have one or more coefficients which must be found experimentally, which is naturally not possible when the drone is in its design stage. Moreover, numbers for these coefficients which the authors might have found in their own experiments are also rarely included, and performing experiments ourselves with a 'similar' drone is also not possible within the scope of this project. Due to these limitations, the drag is instead calculated through rather simple methods using estimated 'lumped' coefficients which take try to take into account the different drag components and effects. The calculations are based on how drag is dealt with in [43] and [10], since these two sources also do provide some suggested numbers for their coefficients. While this estimation can provide enough accuracy for design and performance analysis at this stage, it is important to recognize that a more detailed analysis with computational fluid dynamics (CFD) or experimental methods would be necessary in future design, as also mentioned in chapter 20. Moreover, despite the fact that 'lumped' coefficients will be used, it is still valuable to have some understanding of the different drag components, which are thus briefly explained in the following section.

10.2. Drag and Drag-like Effects

This section describes the different 'kinds' or components of drag that a quadrotor experiences, separating them by the physical effects that cause them.

10.2.1. Blade Flapping

Blade flapping is a commonly known effect with rotary wing aircraft, and has been analyzed extensively, mainly in helicopter literature [25]. This effect occurs when a rotor undergoes translational motion, causing the advancing blade of the rotor to have a higher tip velocity while the retreating blade experiences a lower tip velocity, as shown graphically in Figure 10.1. This difference in velocity will cause a lift imbalance and thus a torque that is aligned with the translational velocity vector. In response, due to the rotor's high angular momentum, it reacts like a gyroscope, tilting 'backwards,' along an axis perpendicular to both the rotor mast and the direction of motion [25, 28], as shown in Figure 10.2. This also means the advancing blade's angle of attack is effectively reduced, 'countering' the extra lift it would produce, while the opposite happens for the retreating blade, thus allowing the rotor to reach aerodynamic equilibrium. As can be seen in Figure 10.2, this effective tilting of the rotor disk by a certain flapping angle also means the thrust vector tilts, effectively adding an 'extra' horizontal component to it which opposes the direction of motion, which is why blade flapping can indeed be modelled as a drag-like effect.

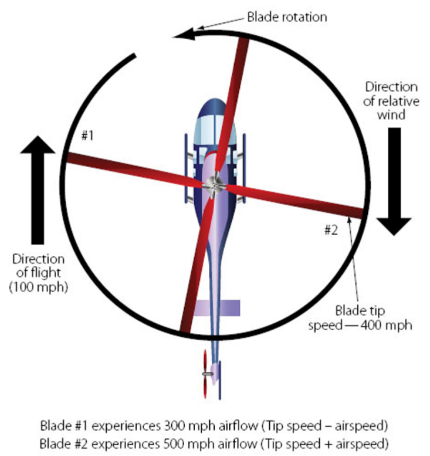


Figure 10.1: Top view of a helicopter in forward motion [a]

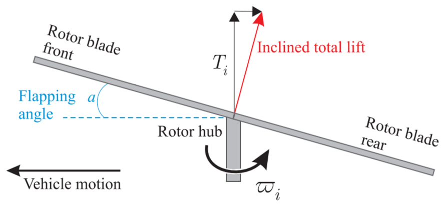


Figure 10.2: Schematic showing blade flapping effect where the rotor disk tilts 'backwards' [32]

[a] `http://avstop.com/ac/Aviation_Maintenance_Technician_Handbook_General/3-58.html`[Accessed on 29-06-2020]

In steady-state, the blade flapping angle β as a function of azimuth angle ψ (in Figure 10.1, a blade pointing downwards would have an azimuth of 0°, and an azimuth angle of 180° when pointing upwards) can be described through a harmonic Fourier series, where only the first harmonic can be considered since the higher order terms have a negligible effect [10]:

$$\beta(\psi) = a_0 - a_1 \cos(\psi) - a_2 \sin(\psi)$$

The derivation of the coefficients a_0, a_1 and a_2 is beyond the scope of this project and the reader is referred to [10, 25] for more details. The relevant result that is of interest in the context of this project is that the coefficients are proportional to the advance ratio μ, the ratio between the freestream velocity (equal to the drone's velocity assuming no wind) and the rotor's linear velocity, and a positive scalar constant related to the blade's geometry [10, 12]. This means that the drag force due to blade flapping can then be written as:

$$D_{flap} = T\left(A_{flap}V + B_{flap}\frac{\Omega}{\omega}\right)$$

Where A_{flap} and B_{flap} are positive constants related to the a_0, a_1 and a_2 mentioned above, T is the thrust, V is the velocity of the drone, Ω the angular velocity of the drone about its 'vertical' axis, and ω the angular velocity of the rotors. In practice the drone's angular velocity can be neglected since it will usually be low compared to the rotor's angular velocity, and in the context of this project the drag is being analyzed in the simple case of pure forward flight either way. This finally leads to a simplified description of the drag due to blade flapping, dependent only on the thrust and velocity, shown in Equation 10.1:

$$D_{flap} = TC_{D_{flap}}V \tag{10.1}$$

Where the constant coefficient A_{flap} has been renamed to $C_{D_{flap}}$. In the following sections it will be shown that the induced drag, which is in fact also closely related to the flexibility and rigidity of the blades and the blade flapping effect, can also be modelled as varying linearly with thrust and velocity, which is why a common lumped drag coefficient can be used. Other forms of drag such as translational and profile drag can also be lumped in a similar way, but these are sometimes neglected in the literature, while blade flapping and induced drag are not since they tend to be the larger components, and these two specifically have frequently been lumped into a single coefficient [6, 10, 11, 28].

10.2.2. Induced Drag

As stated in the section above, due to the asymmetry in lift generation by the rotor when it undergoes translational motion, the blades will flap and the rotor disk will tilt to reach aerodynamic equilibirum. In practice, however, the blades' rigidity will also oppose the flapping, so that it prevents the blade flapping effect to completely compensate for the lift imbalance [28]. For any airfoil producing lift, there will be an associated induced drag due to the backwards tilt of the lift vector caused by the downwash [7]. This induced drag is proportional to the lift being produced, and thus, if the lift imbalance is not fully compensated by blade flapping, the advancing blade will still produce more lift (thrust) and thus more induced drag than the retreating blade. The net result will be that the rotor experiences an induced drag force (equal to the difference between the induced drag produced by the advancing and retreating blades) which opposes the translational motion (again, assuming no wind). According to Bangura [10], this force can thus be modelled as proportional to thrust and velocity, as stated above, shown in Equation 10.2:

$$D_{ind} = TC_{D_{ind}}V \tag{10.2}$$

With $C_{D_{ind}}$ a positive coefficient.

This effect can often be negligible when considering larger rotorcraft (such as helicopters), since their blades tend to be very flexible, while smaller multirotors (with smaller rotors) tend to have more rigid blades making this effect more significant [28].

10.2.3. Other forms of first-order drag

As mentioned before, the drag due to blade flapping and the (net) induced drag associated with the rigidity of the blades are the larger components of the total drag force for a multirotor, especially at low speeds where the parasitic drag is comparatively small. These are thus the components that tend to b considered in the literature, where they also tend to be lumped together. Nonetheless, there are two other sources of drag mentioned by Bangura [10], and since they can also be considered to be bi-linearly proportional to the thrust and velocity (or apparent wind, if there is wind), they can similarly be lumped together with the induced and blade flapping drag. The first one is the translational drag, also called momentum drag, which is "...caused by bending of the induced velocity streamtube of the airflow as it goes through the rotor during translational motion." The second one is the profile drag, "...caused by the transverse velocity of the rotor blades as they move through the air." The reader is referred to [10] for more details; in the context of this project it is only important to know that these two more 'minor' drag components can also be lumped along with induced and blade flapping drag into a single coefficient.

10.2.4. Parasitic drag

Finally, there is also the well-known parasitic drag, coming from the non-lifting elements of the quadcopter such as the airframe, motors, and sensors. It is proportional to the square of the velocity unlike the forms of drag presented above, as shown by Equation 10.3 [7]:

$$D_{par} = \frac{1}{2}\rho C_{D_{par}} S V^2 \tag{10.3}$$

Where ρ is the air density, S the relevant cross-sectional area, and $C_{D_{par}}$.

Note that this drag cannot be lumped with the other components mentioned above, since it is not linearly proportional to the velocity but rather quadratically proportional.

10.3. Drag Models

In [43], a model for the drag is used since it is needed to estimate velocity and range as explained in section 9.4. Unfortunately, the justification behind the model is not explained very well, but presumably it was assumed that parasitic drag is dominant, since the following was proposed [43]:

$$D_{total} = \frac{1}{2} C_D(\theta) \rho V^2 S \tag{10.4}$$

With S being the maximum cross-sectional area. Furthermore, the following function for the drag coefficient as a function of θ, the pitch angle, is proposed:

$$C_D(\theta) = C_1(1 - \cos^3(\theta)) + C_2(1 - \sin^3(\theta)) \tag{10.5}$$

Where the constants C_1 and C_2 should supposedly be found through CFD simulation of one's particular drone, and their suggested values are $C_1 = 3$ and $C_2 = 1.5$. Values for S are not given but can be estimated given that there are example results given in [43], it seems a value of about 0.1 m^2 was used, which also makes physical sense considering the typical square area of a quadcopter and how much of it is empty.

While this model yields results which seem sensible at first glance, it is problematic that the reasoning behind it is not fully explained. Moreover, as stated above, it seems this model is based entirely around only parasitic drag, since it only has a V^2 term. As explained in the previous subsection, however, there are other important drag components arising mainly from blade flapping and induced drag which scale linearly with velocity that are not explicitly included, making this model's validity questionable. It is also known that the drag coefficient for specifically parasitic drag is actually much lower than calculated by Equation 10.5, thus it seems like this coefficient was somehow 'inflated' to give sensible velocity results, meaning it technically could be said to include other effects of drag, eve if somewhat improperly. The velocities calculated through this model however, especially at high pitch angles, seem to be heavily underestimated, since from the DJI website (`www.DJI.com`) most of their drones can achieve 18 - 26 m/s, while this model would estimate velocities of about 12 m/s for some of these drones. In conclusion, while the model is useful at this stage, it would need a lot of further validation and potentially just large modifications to be used. Since it seems to be overestimating the drag anyway, and the performance estimations of range and speed already meet requirements, even despite the model's inaccuracies it can still be said that the requirements are met.

The second option, suggested by Bangura in [10], is to model the blade flapping, induced, translational, and profile drag all together with a single lumped coefficient, since they can all be modelled as proportional to the thrust and velocity, as shown in Equation 10.6:

$$D_{total} = TVC_{D_{lump}} \tag{10.6}$$

Note that the coefficient $C_{D_{lump}}$, would not be a dimensionless coefficient, however. While Bangura neglects the parasitic drag, for our application this is not entirely valid since the flight velocities will potentially go to 10 m/s and above. This can simply be added as another component to the total drag using Equation 10.4 with a constant, and much lower parasitic drag coefficient. This means that a quadratic equation must now be solved to solve for the velocity, but this does not add considerable complexity. Then, estimations for $C_{D_{lump}}$ can be found in [10, 44], while wind tunnel experiments done with a quadrotor can be found in [40], where an indication for the magnitude of the parasitic drag coefficient $C_{D_{par}}$ can be found. While the source and justification of this model is better than that of the first one, the problem still remains of the validity to the application of this project, since the research papers mentioned above used smaller drones and generally performed tests at very low velocities (<5 m/s). Nonetheless, this was the best available possibility, and thus it is used for the drag calculations, mainly related to calculating the velocity at a given pitch angle as explained in subsection 9.4.6. As a precaution, drag coefficients on the higher end were taken, meaning the drag force is overestimated and thus the velocity underestimated. Thus, if the calculations find a velocity and range that meets the requirements, this should remain true regardless of the relatively large uncertainty. Similarly as with the first model, comparison of the estimated results with the top speed of commercial drones (again, mainly DJI drones [1], since they tend to provide the most specifications) seemed to confirm the overestimation of the drag since the estimated top speeds are lower than those in the specifications. Nonetheless, as stated throughout the chapter, experimental results would be the only true way to validate and calibrate the drag estimation, thus this is likely the aspect of the drone performance estimations that would benefit the most from experimental validation in future design phases.

[1] `https://www.dji.com/nl` [Accessed on 21-06-20]

11
Structural design and release mechanism

This chapter will describe all considerations, calculations and decisions made towards the release mechanism and the load bearing structure of the drone as well as the landing gear system. First the materials that were considered in the design process will be presented. Then a section will explain the design of the arms that connects the propellers to the body of the drone. Next, the release mechanism that connects the drone and the helicopter to each other will be visualised and discussed. Afterwards the layout of the drone is presented. Then a section is dedicated to the main body or airframe of the drone. Lastly the landing gear configuration and considerations along with a trade-off between different concepts is performed.

11.1. Functions

The function of the structural design includes:

- (De)coupling mechanism to helicopter.
- Landing gear retracting and deploying.
- Assembly of the drone structure.
- Maintenance and accessibility to certain components.
- Carry the loads on the drone.

11.2. Subsystem Requirements

- **HD-STRC-01**: The drone shall be able to withstand a load factor of 3.5 G.
- **HD-STRC-02**: The drone shall survive a landing at an acceleration of 2 G.
- **HD-STRC-03**: The drone shall be statically stable on the ground up to an angle of 15 degrees.
- **HD-STRC-04**: The axial eigenfrequency of the drone shall be above <tbd> Hz.
- **HD-STRC-05**: The lateral eigenfrequency of the drone shall be above <tbd> Hz.
- **HD-STRC-06**: The drone structure shall be able to withstand the aerodynamic loads generated by the downwash of the helicopter.
- **HD-STRC-07**: The maximum vertical deformation of the drone arm shall not exceed 20 mm.
- **HD-STRC-08**: The design stresses in the drone shall not exceed the yield stresses of the used materials.
- **HD-STRC-09**: The drone shall be able to perform 1000 sorties.
- **HD-STRC-10**: The user shall be able to replace any non structural components of the drone within 60 minutes.
- **HD-STRC-11**: The drone shall be able to be attached to the skids of the helicopter.
- **HD-STRC-12**: The attachments on the skids shall not impede the ground clearance of the helicopter
- **HD-STRC-13**: The sensors vision should not be obstructed by the landing gear. The landing gears lowest point during normal flight conditions should be higher than the sensors.
- **HD-USR-SYS-02**: The drone's dimensions shall be at most 535x535x250 mm.
- **HD-USR-SAFE-01**: The drone's deployment shall not endanger the safety of the HEMS helicopter.
- **HD-SYS-02**: The drone shall have a mechanical case protection of IP56.

11.3. Overview of material

Before deciding on the material choices, it is necessary to know the most commonly used materials in the drone industry. Then, understand criterion factors that are important for the design. These materials will be scaled on each criterion without weighting yet because a different part of the drone requires different material properties.

11.3.1. Material options

Here is the table of the material and its properties which include density, young modulus, and yield strength. The material categories metal for aluminum, polymer for carbon fiber reinforced polymer, thermoplastic for nylons, and polycarbonate, and thermoset for polyester[1].

Table 11.1: Material options and properties for the design [8]

Material	Density $[kg/m^3]$	Young's modulus [GPa]	Yeild strength [MPa]	Tensile Strength [MPa]
Aluminium	2500-2900	68-82	30-500	58-550
Carbon fibre reinforced polymer	1500-1600	69-150	550-1050	550-1050
Polystyrene	1040-1050	2.28-3.34	28.7-56.2	35.9-56.5
Polycarbonate	1190-1210	2.24-2.52	55.9-68.9	60.7-74.8
Polyester	1040-1400	2.07-4.41	33-40	41.4-89.6

11.3.2. Criterion Factors

5 criterion factors are important for design the drone which includes Strength/density ratio, corrosion-resistant, and recyclability. Cost is not part of the criteria because the cost of the material is must lower than the cost of the sensor or motors.

- **Strength/density ratio** - This is the most important criteria because having a lower weight in total with high strength is ideal for our application. The strength will be the maximum yield strength instead of tensile strength because it is more important that structure does not deform than its failing.
- **Corrosion resistant** - The fact that the environment for the mission is in the high humidity area, it is important for the material to have high corrosion-resistant for the long term.
- **Recyclability** - It is directly requested by the client that 80% of the material shall be recyclable (HD-SYS-SUST-03).

During the design process, the material choice will be decided by these criteria. However, the weighting of each criterion will be different depending on part of the drone as mentions before. The weighting for criteria will be explained in the design of the part itself. The trade of the material selection will be qualitative. The scoring and the explanation for each criterion can be shown below.

- **Yield Strength/Density ratio & Tensile strength/Density ratio**
  Excellent [3 point] - Higher than 0.5
  Solvable [2 point] - Higher than 0.1
  Unacceptable [1 point] - Lower than 0.1
- **Corrosion resistant**
  Excellent [3 point]- If the material does not require any additional coating for corrosion resistant.
  Unacceptable [1 point]- Require addition coating.
- **Recyclability**
  Excellent [3 point]- The material is reusable and remain its properties
  Solvable [2 point] - The material is reusable but its loses the original properties.
  Unacceptable [1 point]- The material cannot be recycle.

[1] `https://matmatch.com/blog/what-are-drones-made-of/` [Accessed on 22-06-2020]

Table 11.2: Trade-off result for material selection without weighting

	Criterion		
Material	Strength/Density ratio	Corrosion resistant	Recyclable
Aluminium	2	1	3
Carbon fibre reinforced polymer	3	3	2
Nylons	1	3	3
polycarbonate	1	3	3
Polyester	1	3	2

11.3.3. Material selection

Table 11.3: Trade-off for arm material selection

	Criterion			
Weighting	0.50	0.25	0.25	
Material	Strength/Density ratio	Corrosion resistant	Recyclable	Result
Aluminium	1.0	0.3	0.8	2.0
Carbon fibre reinforced polymer	1.5	0.8	0.5	2.8
Nylons	0.5	0.8	0.8	2.0
Polycarbonate	0.5	0.8	0.8	2.0
Polyester	0.5	0.8	0.5	1.8

From the requirement, the structure of the drone includes the arm and the frame of the drone shall withstand a high load factor. Hence the beam must have a high strength to density ratio so the weighting of Strength to Density ratio is set to 0.5. Meanwhile, the Corrosion resistance and recyclability are set the weighting equally with 0.25. Using this weight to multiple with the score in the Table 11.2 , the trade-off can be made. The result is shown in the Table 11.3. Carbon fiber reinforced polymer has a high score in the Table 11.3 so it will be used for the arm and frame of the drone.

Table 11.4: Trade-off for body shell material selection

	Criterion			
Weighting	0.333	0.333	0.333	
Material	Strength/Density ratio	Corrosion resistant	Recyclable	Result
Aluminium	0.7	0.3	1.0	2.0
Carbon fibre reinforced polymer	1.0	1.0	0.7	2.7
Polystyrene	0.3	1.0	1.0	2.3
Polycarbonate	0.3	1.0	1.0	2.3
Polyester	0.3	1.0	0.7	2.0

The body shell that will cover all the electronics, the weightings are all equally spread for all the criteria. This is because the shell should able to handle some impact from the object but it does not carry any load. Meanwhile, it should have good resistance to corrosion and should be recyclable. The result can be shown in the Table 11.4. As you can see, the Carbon fiber scores highest again but the material selection for body shell will go to polycarbonate. The main reason is that the cost and manufacturing of carbon fiber is a lot more expensive and complicated than thermoplastic. Besides polycarbonate, polystyrene will satisfy the requirement too but will have a slightly lower strength than polycarbonate which is shown in the Table 11.1.

11.4. Arm design

The Arm is defined as the component that holds the motor and propeller and connects it to the body of the drone. It also protects the wires required to power the motor. First the configuration will be determined, which is the shape the arm has looking from the top of the drone. Then calculations and considerations regarding the thickness and cross-sectional shape will be presented.

11.4.1. Configuration

In this section a small trade-off is performed for the shape that the arms will have. First of all during the midterm design phase the drone concept had an arm configuration as seen in Figure 11.1.

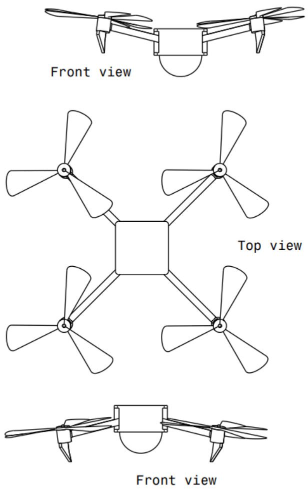


Figure 11.1: Midterm concept

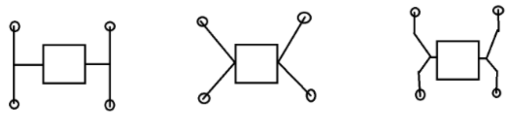


Figure 11.2: Top view of the drone arm concepts. On the left is the so called 'T-beam',the middle is the X-beam, and on the right is the V shaped arm.

Notice that the arms are able to move up and down so that the landing gear does not obstruct the view of the sensors during flight but is still able to land protecting the sensors. This feature demands a powered system that can rotate the arms. This would mean that there would be four arms to be rotated which would require four motors. To reduce the complexity and weight the design was updated to let the arms meet in the middle of the structure so that only two powered joints were required. There are different ways in which this can be shaped. Three concepts were considered as can be seen in Figure 11.2.

Starting at the left configuration in Figure 11.2. This design would allow for not only two joints but also two arms opening up the opportunity to save even more weight. This would be a risk as well however, as a collision could cause two propellers to malfunction and leaving the drone uncontrollable. Also this configuration would have slightly larger issues with vibrations and deflections due to 2 variable forces acting upon it.

The concept in the middle of Figure 11.2, the more X shaped arms, there is reason for concern about the orientation of the propellers, since the moving arms would not allow the propellers to adjust in orientation rendering the efficiency to unacceptable amounts.

The concept on the right, the V-shaped arm is redundant,Unlike the T shaped concept damage to one arm would not render 2 propellers in danger as easily. It also offers the opportunity for a joint to rotate the propellers, it is less subject to flexing or vibrations. Therefore the decision has been made to go for this design. A more detailed image of the shape can be found in Figure 11.3.

11.4.2. Sizing

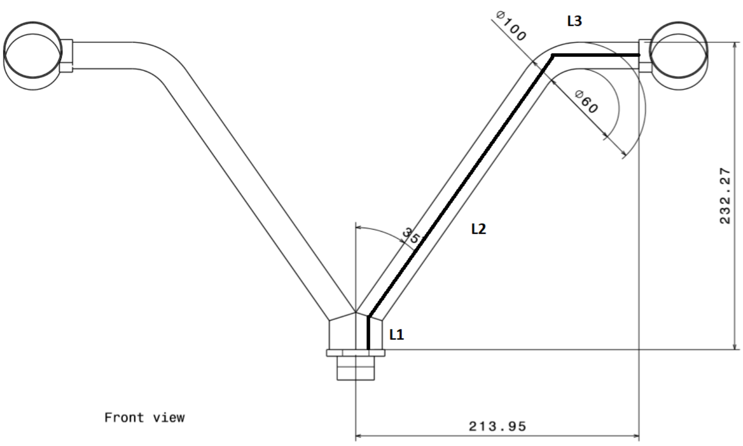


Figure 11.3: Shape of the beam from a top view perspective. In it you can see the axis along which deflection is calculated.

The beam will be modelled as a cantilever beam with sections 1,2 and 3 as seen in Figure 11.3. The maximum force that will be modelled is the thrust at an magnitude of ~60N directly pointing outwards of the paper at the end of section 3. The weight of the motor/landing gear and of the beam will be ignored in this case. This is acceptable since the weight would be around a factor 10 smaller than the thrust and the weight will only lower the loads on the sections because it is opposite to the thrust so this model will overestimate the load in that regard, which means it is conservative modelling. Further assumptions are that the aerodynamic loading is currently not considered. The quantity of this is not estimated for the current design phase. However the aerodynamic load can be estimated as a sin component of the thrust as the drone tilts forward or backwards and equals the drag which is always less than the maximum thrust upwards. Also in free fall or vertical climb there is never a load that is larger than the 3.5G maximum thrust that is being generated. This analysis is assuming that a carbon fibre is being used and that it can be assumed it is isotropic and its strength simply scales by thickness linearly. This would basically mean that the layers are equal in thickness and that doubling the strength would simply mean doubling the thicknesses of all layers. Calculation of the maximum moment and torque at the base of the arm has revealed that the material will not be pushed to it maximum elastic strengths at the current design thickness. What is more important however is the deflection of the arm, which could cause the thrust to point in an unwanted direction, the deflection will be estimated in the following section.

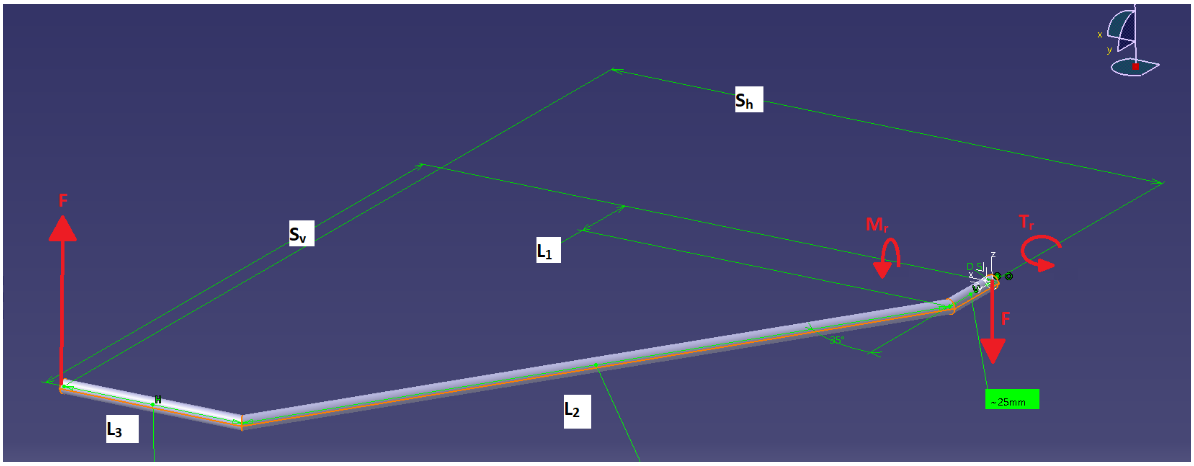


Figure 11.4: Isometric view of The cantilever beam model with dimensions, this beam will be split up into 3 sections as depicted in Figure 11.3

Deflection

To calculate the deflection of one arm the arm will be split up into 3 sections as can be seen in Figure 11.3. These 3 sections will be super imposed. This means that section 2 and 1 will have a moment and torque at the end of the beam due to the translation of the thrust force.

The method used to calculate the deflection is unit-load method. The unit-load method is an application of the principle of virtual work. The method is described in [30]. The equation that will be solved is defined as follows

$$w_e = w_i \tag{11.1}$$

$$1\Delta = w_i \tag{11.2}$$

which states that the external work and internal work are equal. For the right hand side of the equation, w_i, The following applies

$$w_i = \beta \int_L \frac{S_a S_v}{GA} dz + \int_L \frac{M_a M_v}{EI} dz + \int_L \frac{T_a T_v}{GJ} \tag{11.3}$$

Where E is the E-modulus of the material, G the shear modulus, A the cross-sectional area, β is a form factor. S is the shear force, M is a moment and T is a torque. The subscript 'a' stands for actual load and 'v' for virtual load. The virtual load is the load that the structure would be subjected to if the unit load was applied to it. The actual load in this case will be the thrust load. They are both a point force acting upwards at the end of section 3 as described earlier, however they differ in magnitude. All values are calculated in SI units. The following assumptions are used in this model:

- The cross section is a circular thin-walled shaft of equal dimensions everywhere along the beam. This means that E, I, and J are constant along the beam as well as A.
- The material is assumed to be linear-elastic.
- This structure is very slender and therefore the contribution of the shear force deflection is neglected in Equation 11.3.
- The shape of the beam is assumed to have the geometry of Figure 11.4.
- The forces are point loaded.

The cross section of the beam is a hollow circular shaft, the second moment of area I assumed to be thin-walled and is equal to:

$$I = \frac{\pi D^3 t}{8} \tag{11.4}$$

The polar moment J, is equal to

$$J = \frac{\pi t D^3}{4} \tag{11.5}$$

where D is the diameter of the section and t is the thickness. Formulae for all unknowns in Equation 11.3 are presented in Table 11.5. Note that s_1,s_2 and s_3 denote the position in the section 1, 2, and 3 respectively. if $s = 0$ then you are at the outward position of the section and if $s = L$ then you are at the point of the section closest to the center of the drone body.

Table 11.5: Set up for the virtual work equation 11.3.

Section	M_v	M_A	T_V	T_A
1	$(S_v - L_1) + s_1$	$(S_v - L_1)F + s_1 F$	S_h	$S_h F$
2	$sin(35°)L_3 + s_2$	$Fsin(35°)L_3 + Fs_2$	$cos(35°)L_3$	$cos(35°)L_3 F$
3	s_3	$s_3 F$	0	0

Substitution in Equation 11.3 gives:

$$\Delta = \frac{1}{EI}\int_0^{L_1} (S_v - L_1)^2 F + s_1^2 F + 2s_1(S_v - L_1)Fds + \frac{1}{GJ}\int_0^{L_1} S_h^2 Fds + \frac{1}{EI}\int_0^{L_2} sin(35°)^2 L_3^2 F + Fs_2^2 + 2Fs_2 sin(35°)L_3 ds + \frac{1}{GJ}\int_0^{L_2} cos(35°)^2 L_3^2 Fds + \frac{1}{EI}\int_0^{L_3} s_3^2 Fds \tag{11.6}$$

This last equation is being solved by a Python script and gives an estimate of the upwards deflection at the point where the thrust force is applied. It was estimated that the deflection would be 19.63 mm at this point of application with the diameter of the shaft of $25mm$ and a thickness of the carbon fibre composite of $1.8mm$. This would satisfy requirement HD-STRC-07. Table 11.6 gives the inputs for the dimensions and properties that have been used to get this result.

Verification - unit testing

Unit tests and sanity checks on intermediary results have been done for this method. For example for Table 11.5, it can be easily checked that all dimensions are correct. Do keep in mind that the virtual load is equal to 1 N and therefore it might seem that moments and torques are not in the unit $N \cdot m$. Dimensional tests can also be performed on the cross-sectional property formulae.

Additionally unit tests were performed on intermediary results of Equation 11.6 by hand calculating certain integrals and checking them against the script. The resulting error was simply the rounding error and is therefore neglected. Also flipping the direction of the applied force also changes the deflection as expected. Furthermore, increasing and decreasing I and J by the same factor should linearly change the magnitude of the deflection. This test has also passed.

Table 11.6: Inputs for the unit-load method that are used to check for requirement HD-STRC-07.

Property	Value
D	$25 \cdot 10^{-3}[m]$
t	$1.8 \cdot 10^{-3}[m]$
E	69 GPa
G	3.85 GPa
F	$SafetyFactor \cdot MaximumThrust$ $1.5 \cdot 35[N]$
L_3	$66 \cdot 10^{-3}[m]$
L_2	$241 \cdot 10^{-3}[m]$
L_1	$25 \cdot 10^{-3}[m]$
S_v	$222 \cdot 10^{-3}[m]$
S_h	$204 \cdot 10^{-3}[m]$

11.4.3. Arm mechanism

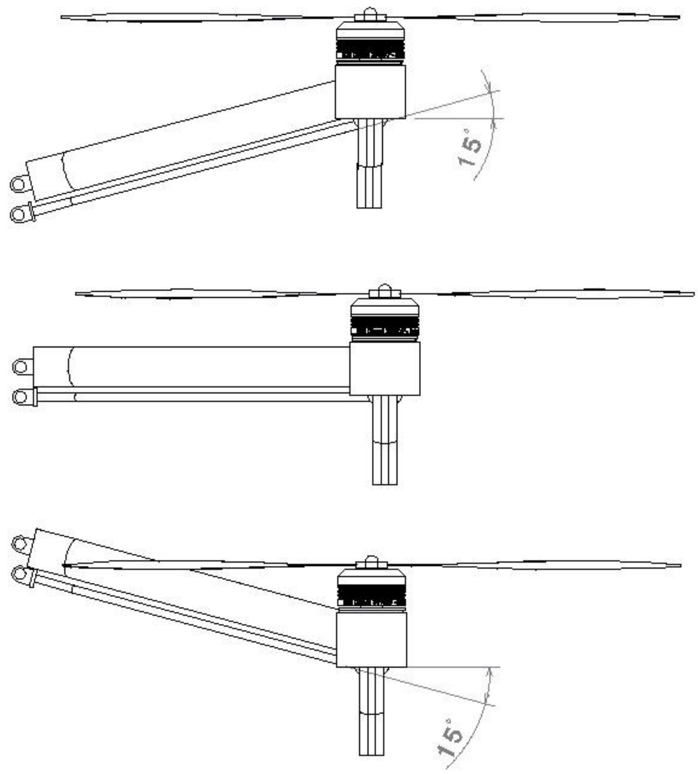


Figure 11.5: Orientation of the arms and rotors in the different arm positions

Underneath the arms. a smaller secondary structure is present. This is to conserve the orientation of the motors when the arms rotate up and down. In Figure 11.5 it is shown how the arms will look at the most upward position (15 degrees), the neutral position (0 degrees), and the most downward position (minus 15 degrees). The alternative would have been to place small actuators at the motors. The main advantage of the current system over additional actuators is in the increased reliability due to the simplicity. The secondary arms are smaller because they do not carry loads, but are purely there for keeping the motors orientated upwards. This system allows the drone to land, but not obstruct the vision of the sensors, thus complying to requirement HD-STRC-13.

11.5. Release mechanism

The release mechanism is the device that will connect the drone and helicopter during flight. Its main purpose is to protect the drone from the environment during helicopter flight as well as releasing the drone safely when it is activated by the drone controller. Secondary functions of the release mechanism are to protect the helicopter from potential risks such as a drone fire as well as have an indication system about the status of the drone (e.g. undeployed, deployed, fire detection warning). First a trade-off will be performed on where the release mechanism is best placed on the helicopter. Then a layout of the conceptual design is given. Next, deploying a drone from an flying helicopter brings along risks, and a section is dedicated to risk mitigation for this reason. Lastly the main components and materials required to manufacture the release mechanism are laid out.

11.5.1. Trade-off

For the release mechanism the design choice was made early on to choose a place that would geometrically always release the drone at a point lower than the aerostructure of the helicopter. This is for the reason that the drone should not collide with the helicopter in any deployment circumstance. Secondly the release mechanism should also not be attached in a position on the helicopter where there is already equipment that would be obstructed if the release mechanism would be placed there. The areas that are conform to this second rule are given in Figure 11.6. [2]

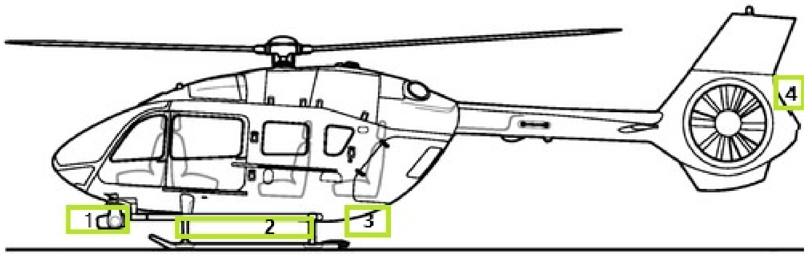


Figure 11.6: Areas that were considered for the attachment of the drone to the helicopter highlighted using green coloured rectangles.

A small explanation on each position and its (dis)advantages will be given now. Starting from the back at position 4 to the front.

Position 4

For position 4, on the tail of the helicopter, the advantage would be that the deployment would happen from a great distance from the rotors of the helicopter and thus not form a risk regarding collision with the rotors. However the drone system will weigh around 5-10 kg with the release mechanism and thus the balance of the helicopter might be largely influenced due to the drone hanging at the tail. Also vision on the drone from the operators position in the helicopter would be difficult and the structural integrity of the tail might not allow the release mechanism without structural reinforcement. One might also notice that this position breaks one of the rules to release the drone beneath the aerostructure of the helicopter however the horizontal distance to the lowest point in this position would be sufficiently large not to hit the cabin.

Position 3

Position 3 would be ergonomically easily accessible however the release mechanism would be attached to the fuel tank or very close to it at least which is not favourable as well. Also position 3 is currently already holding an ELT system for some Dutch HEMS helicopters. Ground clearance might be an issue as well but that was not further investigated at this moment.

Position 2

Next, for Position 2, the release mechanism would have to be placed asymmetrically laterally to access the release mechanism while on the ground. This position offers the skids as structural mounting point which is beneficial as Supplemental Type Certificates (STC) for skid mounting are more commonly used and safer and therefore cheaper to certify as already investigated in the Market Analysis. The largest disadvantage of this position would be the ground clearance. The landing position of HEMS operations is an unknown and therefore there is a strong need for the helicopter to be able to land on uneven surfaces. Mounting the drone in position 2 would therefore introduce the risk to 'beach' the helicopter on the release mechanism.

[2] `https://www.the-blueprints.com/blueprints/helicopters/helicopters-a-b/74275/view/airbus_helicopters_ec145_t2/` [Accessed on 29-06-2020]

Position 1

Lastly position 1, just like position 2, is also on the skid but using the camera mounting point at the front of the upper horizontal skid bar. Currently the decision for this conceptual design has been made to place the drone here because it has the following advantages. First of all the drone is in sight of the copilot meaning that he/she will be able to see the release mechanism. This means a visual cue can be added to the release mechanism to show the state of the release mechanism. This would add an extra layer of safety and security in the system. Secondly, the drone would be released in a guided path by the release mechanism doors that would extend vertically downwards meaning the risk of the drone hitting the skids upon release is mitigated. Thirdly, the position of the release mechanism here offers very easy access to the mechanism on any kind of ground. This is favourable because the drone can be stowed back easily and quickly and the whole release mechanism can be detached by a mechanic from the helicopter with less effort compared to the other positions. Disadvantages to this position are that it might partially block the downward view of the copilot. Also the aerodynamic effect of having the release mechanism there will require some testing on the flight mechanics/dynamics of the helicopter. However the Market Analysis already points out that this would have to be done for any attachment position, but it might have a slightly bigger effect here compared to the other positions.

11.5.2. Layout

Here the final concept of the release mechanism will be visualized.

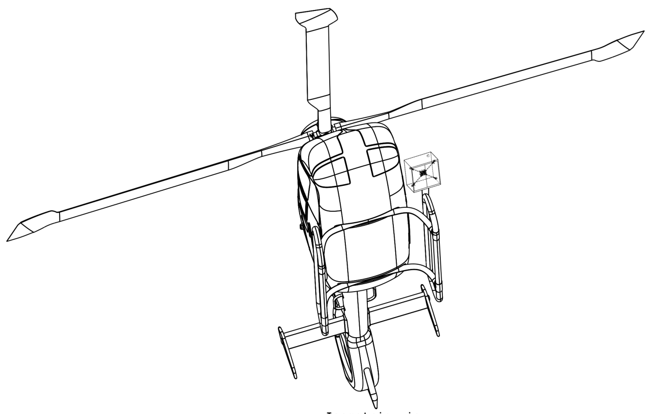


Figure 11.7: Isometric view of the helicopter with the release mechanism attached.[3]

[3] `https://grabcad.com/library/ec-135-helicopter-1` [Accessed on 29-06-2020]

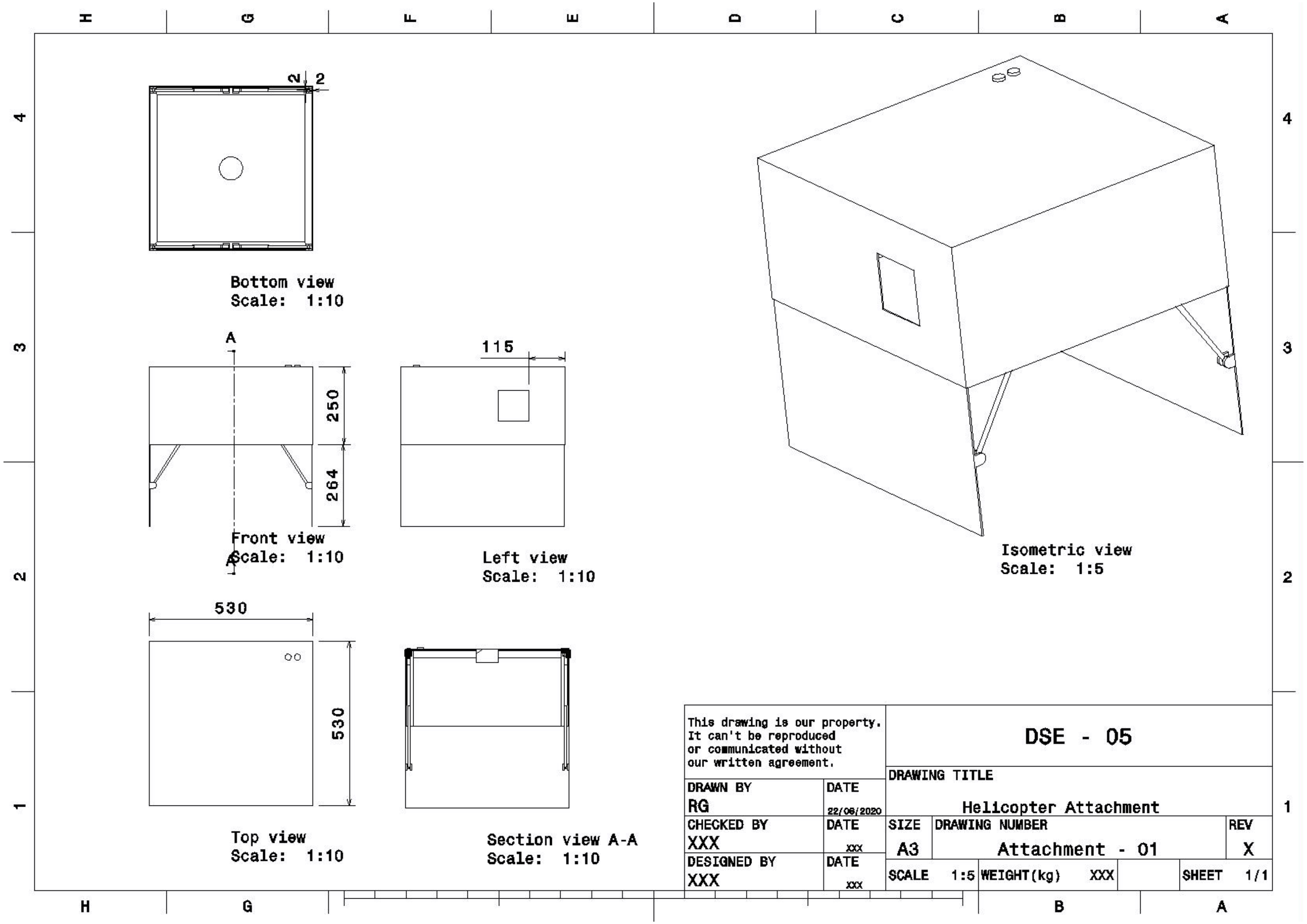


Figure 11.9: Preliminary layout of the attachment pod.

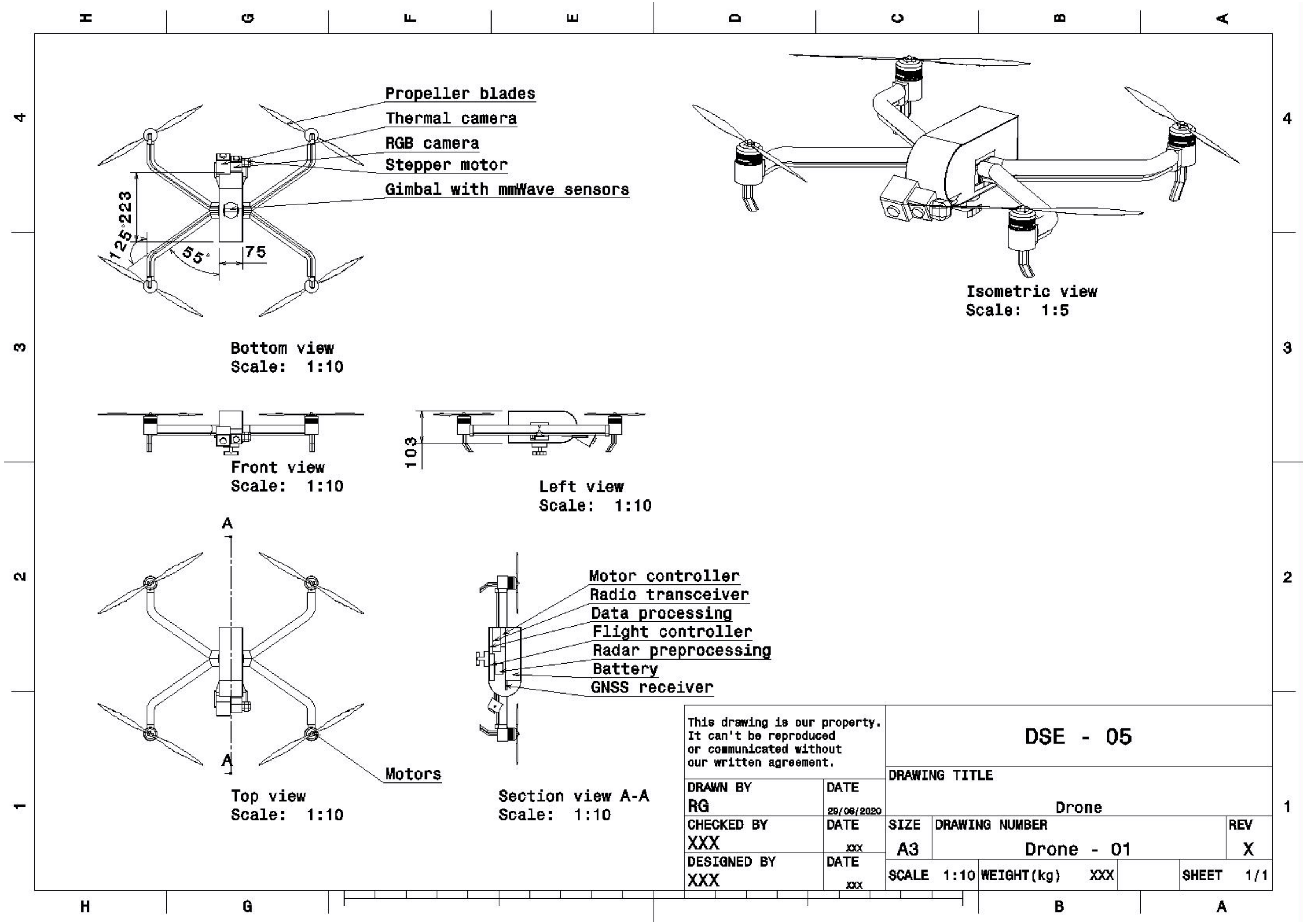


Figure 11.10: Internal and external layout of the drone.

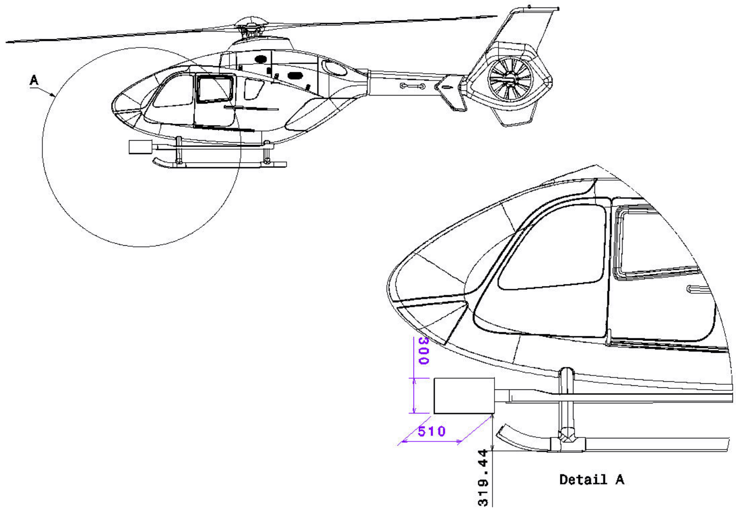


Figure 11.8: Left view of the helicopter with the release mechanism attached.[4]

Risk mitigation

The placement choice of the release mechanism does bring along risks. Due to the more forward and relatively higher placement of the mechanism, there is an increased probability of the drone colliding with the helicopter upon release in forward flight. To mitigate the risk of collision, the goal would be to have the drone clear the helicopter as soon as possible. This is achieved in two ways, by the use of a spring mechanism and by using the enclosure bay doors.

With a spring mechanism, when the drone is released it will be given extra downwards momentum by the applied spring force. This extra momentum will help it clear the helicopter underside quicker, reducing the risk of collision.

Furthermore, the enclosure bay doors can be used to shield the drone from the frontal air velocity that threaten to push the drone backwards into the helicopter. By opening the doors in such a way that it creates a "dead zone" for the oncoming wind, the drone has the ability to create more vertical distance between itself and the helicopter, before being pushed backwards. Additionally the other door would shield the drone from the skids and preventing it to get an downstream velocity at the early stage of the drop.

A final mitigation that could be considered in later stages is to release the drone while performing a banking maneuver to the right. This could allow for the drone to create more distance between itself and the helicopter in less time, again reducing the risk of collision.

Preliminary drone pod components choice

For the budgets shown in chapter 8 some preliminary components for the drone-containing pod were chosen. The risk mitigation for lithium batteries (see chapter 7) suggests a fireproof box and a temperature sensor connected to an emergency release mechanism. As Lithium battery fires run intensely hot (1000 °C)[5] fireproofing will be an issue regardless of material. Aluminum was chosen as a preliminary material for the box. 2 mm thickness was chosen for the plates. These plates would be stiffened at the corners with equilateral angle profiles of 25mm sides and a 2 mm thickness.[6] The electronics consist of 4 parts: 1 or more indicator lights [7] for visual aid to the crew, a temperature sensor [8] to monitor the battery for fire, a spring mechanism to aid in pushing the drone out of the box, and 4 linear actuators [9] to open the doors. The results can be seen in Figure 11.9.

[4] `https://grabcad.com/library/ec-135-helicopter-1` [Accessed on 29-06-2020]
[5] `https://www.forbes.com/sites/rrapier/2019/03/01/a-rocket-science-solution-to-lithium-battery-fires/` [Accessed on 19-06-2020]
[6] `https://www.aluminiumopmaat.nl/` [Accessed on 19-06-2020]
[7] `https://www.aliexpress.com/item/32583130189.html` [Accessed on 19-06-2020]
[8] `https://www.ti.com/tool/TMP117EVM` Retrieved on 19-06-2020
[9] `https://www.aliexpress.com/item/4000844453382.html` 300mm stroke and DC12V 800N 10mms [Accessed on 19-06-2020]

11.6. Airframe

In order to protect all the internal components from the elements, an airframe needs to be present.

11.6.1. Sizing

The airframe was fitted by taking the internal components and designing a shell around them. After that, a structural frame was added to prevent deformations. The frame and final layout of the drone can be seen in Figure 11.10 and Figure 11.11.

11.6.2. Internal Layout

The internal layout, as can be seen in Figure 11.10, was determined by first looking at where to place the battery. The battery was chosen because it is by far the biggest component and it should be placed around the edge of the drone because it has to be easily removable. After the battery was taken as a fixed point, the other components were placed around it. Extra care was taken in this process to keep the attachment of the arms roughly in the center of the drone. Furthermore, the two computers are also placed at the edge because it might turn out to be useful to have for instance a serial bus port for updating software. The cameras and the camera stepper motor are placed in front of the drone, as indicated in 13.3. Finally the preprocessing hardware for the radar is also placed internally, leaving only the radar sensors on the gimbal underneath the drone.

Figure 11.11: Preliminary rendering of the drone

11.7. Landing gear Trade-off

As stated earlier in Section 11.4.1 an important design function and requirement of the sensors is that there is no obstructions in the field of view. Therefore there is a need for a retractable landing gear.

11.7.1. Criteria

The first and foremost criteria is safety. The drone will have to land near the helicopter landing site during operations. This means that the downwash of the helicopter is also an issue during the drone landing. Depending on the performed operation, the drone might be subject to the downwash of the helicopter when the drone has landed and the helicopter is about to land. It is naturally desired that the drone will not drift or slide over the ground and especially not flip over as that would damage the drone considerably.

Secondly, the weight of the system is also important, a more lightweight design will have preference, for a multitude of reasons like endurance, higher thrust to weight ratio etc.

Lastly, the complexity of the landing gear solution is also considered. A simpler design is generally easier to maintain and has a higher reliability.

11.7.2. Concepts

There are two concepts that were considered to achieve this.Concept 1 was already depicted in Figure 11.1. Here the landing gear is connected to the arms. The second landing gear solution is a bi-pod system that moves up and down. It is depicted in Figure 11.12.

Figure 11.12: Body attached landing gear.(Concept 2) [10]

11.7.3. Trade-off

The decision has been made to go for concept 1. This is simply because the safety criteria has the largest weight in this trade-off. Concept 1 offers a wider base meaning that the drone will be much more stable while on the ground. Also concerning the weight, both systems will need 2 servo's/motors so there wouldn't be a large difference in that regard. However since the propellers thrust will have to point up at all times a joint needs to be introduced to ensure that the rotation of the arms to move the landing gear are not rotating the propellers to cause the thrust vector to have a horizontal component.

Grading for each criteria is as follows:

Tip-over risk:

4: The distance between the landing gear is wider than the drone.
3: The distance between landing gear is as wide as the drone.
2: The distance between the landing gear would still make the design viable.
1: Tip over risk is too significant.

Mass:

4: All weight of the landing gear is simply there to support the loads and the landing gear does not obstruct the vision of the sensors.
3: Additional mass other than the load bearing structure however, this additional mass is independent of the mass of the drone without the landing gear. The landing gear does not obstruct the vision of the sensors.
2: Additional mass other than the load bearing structure that is dependent on the mass of the drone without the landing gear. The landing gear does not obstruct the vision of the sensors.
1: Mass is too significant pushing the design to not viable extent or the landing gear obstructs the vision of the sensors.

Complexity:

4: System is directly off the shelf.
3: System requires some redesign of an off the shelf existing product.
2: System requires significant computer aided analysis or real life testing to ensure reliability.
1: Design is not viable or very expensive.

Table 11.7: Trade-off table for the landing gear concepts.

Weighting	0,7	0.15	0.15	Results
Criteria	Tip-over Risk	Mass	Complexity	
Concept 1 Arm attached landing gear	3	2	2	2.7
Concept 2 body attached landing gear	2	3	3	2.3

[10] http://www.regimage.org/drone-retractable-landing-gear/ [Accessed on 29-06-2020]

11.7.4. Sizing

The landing gear is currently sized at a height of 65.6 mm, this means that the drone has 50 mm ground clearance. The landing gear can easily be resized at a later stage of the development and mostly testing out the drone in the later stages of the design will bring light to whether or not this ground clearance is sufficient, too much or insufficient. It has a slight bend to allow the landing gear to bend slightly under impact, absorbing the shock for a small amount. Further detailed analysis is required to optimize the performance over the thickness(and thus the weight) of the landing gear. Also the contact surface with the ground might need resizing and/or a change of material to allow for more friction if required. This is beyond the scope of this project and is therefore also classified as post-DSE development.

11.7.5. Tip Over Angle

To satisfy requirement HD-STRC-03, which says that the angle at which the drone must be able to land without tipping over is 15 degrees. the maximum tip over angle is based on the width of the landing gear l_b and the height of the centre of gravity cg_z. For this calculation a cg_z is taken at $0.25m$ which is the highest it can go since the drone is $0.25m$. The tip-over angle ϕ in deg is then equal to:

$$\phi = arctan(\frac{l_b}{2cg_z}) = arctan(\frac{0.52}{2 \cdot 0.25}) = 46^{\circ} \tag{11.7}$$

11.8. Validation

To validate the requirements compliance, there is a need for detailed FEM analysis or real life testing. For example for the landing gear, fatigue and optimization of the shock absorbing capabilities might be in order to validate the design. Also real life fatigue tests should be done on the body of the drone to test component malfunction due to shocks. Further iterations could then be introduced to the drone body to allow for more shock resistance. For the load bearing structure in the body, Finite element (FEM) Analysis or something similar would be recommended to minimize the weight of the structure and to validate requirements HD-STRC-01,HD-STRC-02,HD-STRC-04,HD-STRC-05. Also a method has to be defined that validates requirement HD-STRC-09(perform 1000 sorties). For the drone structure, this would for example be fatigue testing in addition to vibration tests to simulate 1000 sorties.

For the release mechanism as already stated a lot of testing and iteration would be required to obtain a safe system, that is certified and trusted by all stakeholders. The release mechanism should be rigidly testing using simulated and then real life test flights. Simulation would be used to get an initial estimation about trajectory of the drone when it is dropped as well as looking into what orientation/speed the helicopter can be flying at with no hazard for the release of the drone.

12
Control & Stability

In order to perform its mission, the drone needs to be able to fly according to specified inputs from the pilot, without losing control. For this a control system must be implemented. In this chapter, the functions of the control system are described, the requirements are listed to which it must adhere, and quadcopter control is explained briefly. Then the flight controller model is explained, verified and validated followed by the simulation results. This chapter ends with future development plans.

12.1. Functional Analysis

The function of the control system is to provide stability and controllability throughout the flight. In Figure 12.1 the basic functional flow of this system is displayed. The system functions by first indicating reference states set by the user or autonomous control system, such as a desired position and orientation, and compares it to the current state of the system provided by the on board sensors such as the GPS and IMU. The error between the reference and actual states is fed into the flight controller. Here, the errors are translated to roll, pitch, yaw, and total thrust commands. These commands are fed through a PID (Proportional Integral Derivative) controller, where the gains are adjusted. The tuning of these PID controllers is of paramount importance to acquire a stable and controllable system. These commands are then transformed into commands for the individual motors, which will cause the drone to physically react. The sensors will then measure the drone's reaction to the commands and its reaction to external forces from the environment, and feed back the current states to the beginning of the system, thereby closing the feedback loop of the control system.

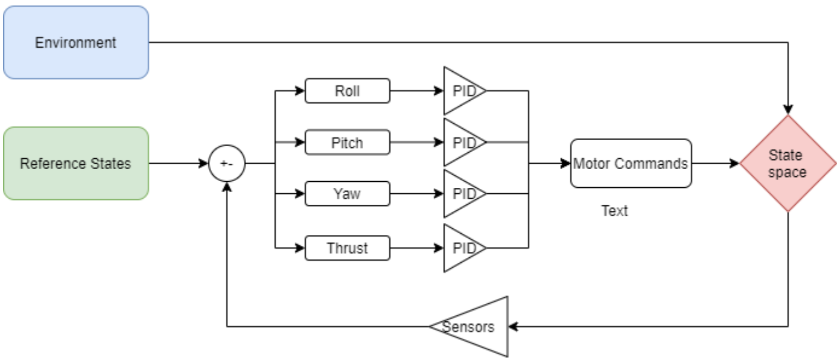


Figure 12.1: Functional Flow Control System

12.2. Subsystem Requirements

In this section, the requirements set on the control and stability subsystem are given and discussed. The requirements were set in [2] and later refined throughout the design process.

- **HD-CRST-01**: The drone shall be controllable at 138 m from the source of the downwash.
  - Due to the extreme wind velocities caused by the helicopter downwash, the drone is not expected to fly in close proximity to the rotors. It should however be able to regain stability and control when it reaches a certain distance from the rotors. This distance follows from [34]. Where the relation between the velocity deficit caused by the rotors and the distance to the rotors is described by: $\frac{\Delta \bar{u}}{\bar{u}_\infty} = \frac{1-\sqrt{1-C_T}}{(1+2k_t x/d)^2}$. The drone is deemed controllable when the wind velocity has returned to 95% of its initial state, so $\frac{\Delta \bar{u}}{\bar{u}_\infty} = 0.05$. Using $C_T = 0.008618$ using values from [19], and a k_t of 0.04

from [34]. An $\frac{x}{d}$ of ±9 is acquired. Using the d of the EC135 of 10.2 m [19], a minimal distance of 92 m is needed for controllability. Using a safety factor of 1.5, the distance at which the drone should be controllable is 138 m.

- **HD-CRST-02**: The drone shall recover from tumbling after deployment before losing 138 m of altitude.
  - This follows directly from **HD-CRST-01**.
- **~~HD-CRST-03~~**: The drone shall be able to recover from an upside down position within 0.5 seconds.
  - This requirement will not be stated as it is already stated in **HD-CRST-02** that the drone should be able to recover from tumbling after deployment within 138 m, including if it is upside down.
- **~~HD-CRST-04~~**: The drone shall be fully controllable with one motor inoperable.
  - Even though this requirement is theoretically possible, it requires a highly complex control system adaptation. It can however be implemented in a later development stage.
- **~~HD-CRST-06~~**: The roll rate of the drone shall be <tbd> degrees/s.
  - The roll rate, pitch rate, and yaw rate dictate how maneuverable the drone is but these parameter does not define the stability of the drone. Thus the requirement is replace with new HD-CRST-05 and HD-CRST-06.
- **~~HD-CRST-07~~**: The pitch rate of the drone shall be <tbd> degrees/s.
- **~~HD-CRST-08~~**: The yaw rate of the drone shall be <tbd> degrees/s.
- **HD-CRST-05**: The drone shall be controllable with winds of up to 13.89 m/s from any direction.
  - The drone should be able to operate in different weather conditions and thus also with wind. This means that the drone should be able to be fully controllable in a windy environment [1].
- **HD-CRST-06**: The roll of the drone shall not exceed 45 degrees during cruise.
  - Beyond 45 degrees in normal cruise, there is a higher risk of (partially) losing drone controllability.
- **HD-CRST-07**: The pitch of the drone shall not exceed 45 degrees during cruise.

12.3. Control System Design

12.3.1. Quadcopter control

A multicopter in general can not become statically stable as an aircraft could. A constant stream corrections is needed to maintain stability and for control. Firstly, the basics of quadcopter control & stability need to be analysed. A quadcopter has 4 rotors, allowing it to independently change roll, pitch and yaw states (attitude), and also control its altitude by changing the total thrust. However, there are 6 degrees of freedom that need to be controlled, roll, pitch, yaw, forward/backwards, left/right, up/down, see Figure 12.2. This means that this system is under-actuated. To overcome this problem, the control system can couple attitude and thrust to account for the "missing", translational degrees of freedom.

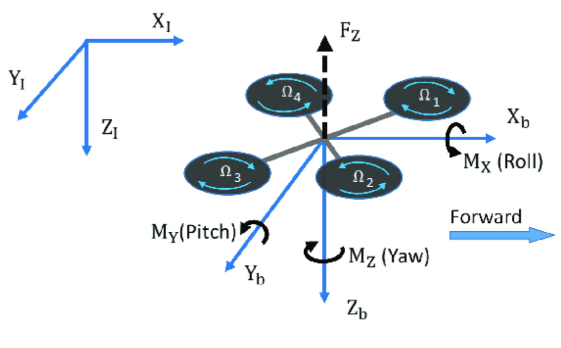


Figure 12.2: Quadcopter reference frame [31]

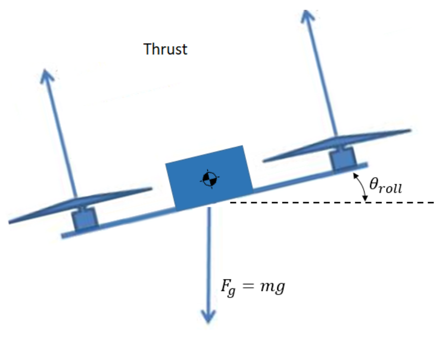


Figure 12.3: Coupling of attitude and translation

To design the control system, the 4 states that can be controlled independently are firstly taken into account. These are roll, pitch, yaw, and altitude. Again looking at Figure 12.2, the altitude is changed by simply increasing the thrust of rotors 1 through 4. To introduce a pitch up/down angle, a torque needs to be created along the y-axis. This is done by increasing/decreasing thrust on rotors 1 & 2, and decreasing/increasing thrust on rotors 3 & 4. Similarly, the same thing can be done to introduce a roll left/right angle by increasing/decreasing thrust on rotors 1 & 4, and decreasing/increasing thrust on rotors 2 & 3. The torque is given by:

[1] `https://www.nws.noaa.gov/directives/sym/pd01008012curr.pdf`. [Accessed on 22-06-2020]

$$M_y = (T_1 + T_2) - (T_3 + T_4) \quad M_x = (T_1 + T_4) - (T_2 + T_3) \tag{12.1}$$

Introducing a yaw angle is also done by changing the thrust distribution over the 4 rotors, but is based on another principle. As seen in Figure 12.2, rotors 1 & 3 turn clockwise while rotors 2 & 4 turn counter-clockwise. The use of counter-rotating rotors is done to balance out the reaction torques introduced by the rotor blades. For instance, when a rotor is rotating clockwise, a counter-clockwise reaction torque is produced due to the aerodynamic drag on the blade. This is the reason that the same rotational directions are always across from each other and never next to each other, as then when introducing a pitch or roll angle will also introduce a yaw angle.

To introduce a yaw angle, a torque needs to be created around the z-axis. Using the reaction torque principle, an expression for the yaw torque is given by:

$$M_z = k(T_1 - T_2 + T_3 - T_4) \tag{12.2}$$

Where k is a constant depending on the drag characteristics of the rotors.

In order to also obtain translation control in the x and y direction, a force needs to be applied in the x and/or y direction. To achieve this control, a coupling of attitude and translation needs to take place. This is done by deconstructing the thrust force, see Figure 12.3. The forces are given by:

$$F_x = (T_1 + T_2 + T_3 + T_4) * \sin\phi \quad F_y = (T_1 + T_2 + T_3 + T_4) * \sin\theta \tag{12.3}$$

12.3.2. Simulation Model

In this model, the Simulink package in MATLAB will be used to simulate the behavior of the drone in different situations. The overview of the schematic of the simulation can be shown in the Figure 12.4. The simulation model includes Desired input, Flight controller, 6 degrees of freedom Quaternion, Gravity, Environment, and Visualisation.

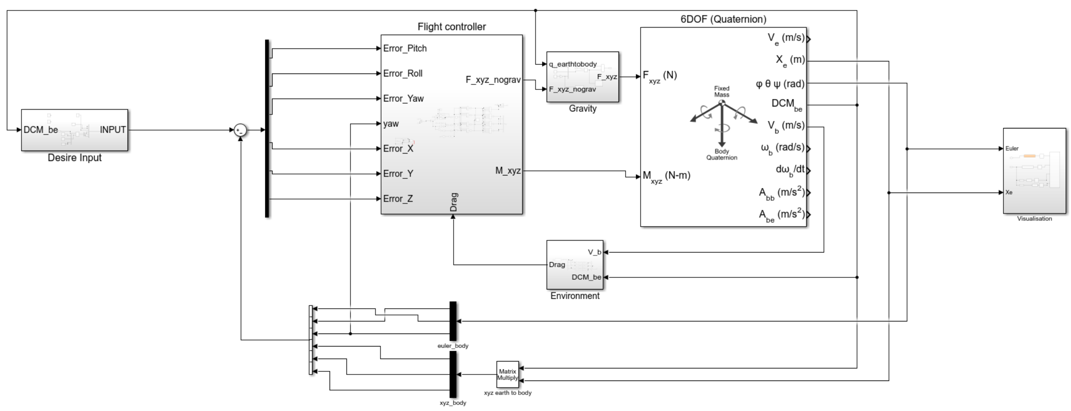


Figure 12.4: Overview the schematic of the simulation

Assumptions & Limitation

Assumptions have to be made to simplify the model and allow it to be finished within the given time frame. This may lead to some limitations in the model's performance. A list is given below of the assumptions made and how these assumptions may limit or cause an inaccuracy in the model.

- The drag coefficient of the whole drone is assumed to be 1.5 for all directions. The main purpose of this assumption is to introduce drag into the system and understand how the drag affects the behavior of the drone. Using the wrong value of the drag coefficient will result in an error offset but it can later correct with correct values and fine-tune the drone which will correct this error.
- The drag is only applied onto the center of gravity of the drone. This leads to an inaccuracy of the moment in x and y because the location of the drag is likely to be near the plane of the motors. This would add an extra moment in the x and y.

- The gusting wind has no effect on the thrust of the motor. This assumption has the biggest effect on the behavior of the drone. Clearly, the thrust of the motor is related to the angle of attack on the propeller. This assumption was made as else, a set of complex aerodynamic analyses was required on the airflow effects of the rotors at various angles, which could not have been completed with the given time and resources.
- The pitch, roll, and yaw angles have no effect on the thrust magnitude of the rotor. The reasoning is the same as the above assumption because the angle of attack on the propeller changes when the drone is at a certain pitch or roll angle.
- The air density is assumed to be constant. The value is taken at a cruise altitude of 3000 ft. This assumption has a negligible impact on the drone because the air density at sea level and 3000 ft are 1.225 kg/m3 and 1.112 kg/m3 respectively. The error is only 0.113 kg/m3.
- The noise from the IMU and GPS is assumed zero. In the real world, there will be noise in the sensor data for sure. These will filter digitally with Kalman or complementary filter and using a silicon damper on the flight controller board will further reduce the vibration noise into the IMU data. However, this model will be in the ideal world for simplicity.
- The simulation model will assume all the parts, such as motors, ESCs, battery, etc are all placed symmetricaly, eliminating the mass moment of inertia in xy,xz,yz,yx,zx,and zy. This allows the PID values to have the same magnitude or range for roll and pitch control which means less complexity to Tune for stability. Also, as the drone design is mostly symmetrical, these values can be regarded as negligible.

Flight controller

This sub-system will control the thrust value of each motor to correct the error between the desired state (the input) and the actual state. The PID controller will be implemented into the flight controller to define the thrust value. There are six inputs that will be used to calculate the thrust of each motor. The inputs are error in pitch, roll, yaw, and error in x,y,z position. The drone coordinate system can be seen in the Figure 12.2. The z-axis of the drone is positive downward.

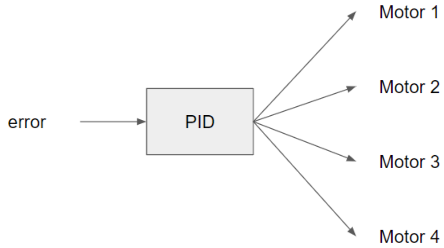


Figure 12.5: PID controller

Here is how to determine the thrust value for a stable drone of each input and the diagram of the PID controller schematic is shown in the Figure 12.5. The control of the quadcopter drone is explained in the subsection 12.3.1. In addition in the controller of the quadcopter, when the drone rotates around itself 180 degrees and there is a positive error of 1 m in the x position of earth reference. Normally if there is no frame transformation in the yaw axis, the drone will move away from the desired by 1 m so in the scenario frame transformation is required on the pitch and roll. The equation can be seen below.

$$\begin{bmatrix} \phi_c \\ \theta_c \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix} \begin{bmatrix} \phi \\ \theta \end{bmatrix} \tag{12.4}$$

The flight controller will consist of two, independently tuned, systems. One for the drop recovery after deployment from the helicopter, and one for normal flight. The need for two flight controllers arises from the different functions to be performed. The drop recovery requires an aggressive system focused on stabilizing its orientation above all else, while the normal flight system requires a more smooth approach, taking into account more than only the orientation.

The flight systems differ in the PID setup and settings. The drop recovery system has PID's tuned for an extremely fast response time and high aggressiveness in order to recover from a tumbling drop from any orientation. To achieve this, this system does not take x and y location into account in order to devote all its available thrust into stabilizing the drone attitude.

When stabilized, the normal flight mode takes over. The PID's are tuned for smoother reactions to disturbances, and withstand wind gusts. This system does take into account the x and y location in order to navigate from A to B.

6 Degree of freedom (Quaternion)

Initially, the physical model of the drone started as a linear state space model. Using this model, the basic control system layout was made. This was later changed into a non-linear model to improve the accuracy and realism of the results and to improve the implementation of the body and Earth coordinate systems. The coordinate systems of the Earth and drone body are shown in the Figure 12.6. In MATLAB, the 6 degrees of freedom (Quaternion) module is used to represent a non-linear model which provides a function for transformation from Earth coordinates to body coordinates.

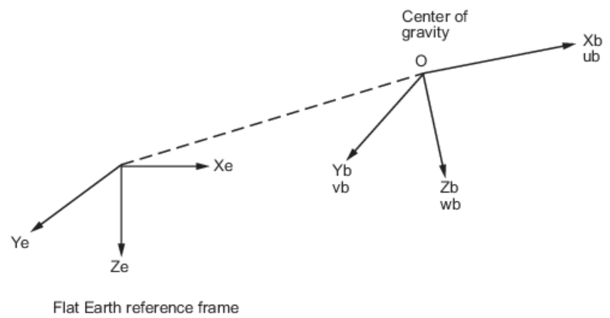


Figure 12.6: Earth coordinate and the body coordinate system [2]

The module requires total forces and moments acting in the x,y, and z-axis of the body reference frame as the input. Furthermore, it requires the initial state-input consisting of the initial position in the Earth reference frame, initial Euler orientation, initial rotation rates, initial velocities, initial mass, and mass moment inertias [**?**].

The expressions for the translational motion of the drone body coordinate frame is shown in Equation 12.5, where the forces in x,y, and z are act on the center of gravity.

$$
\begin{aligned}
\bar{F}_b &= \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = m\left(\dot{\bar{V}}_b + \bar{\omega} \times \bar{V}_b\right) \\
A_{bb} &= \begin{bmatrix} \dot{u}_b \\ \dot{v}_b \\ \dot{w}_b \end{bmatrix} = \frac{1}{m}\bar{F}_b - \bar{\omega} \times \bar{V}_b \\
A_{be} &= \frac{1}{m}F_b \\
\bar{V}_b &= \begin{bmatrix} u_b \\ v_b \\ w_b \end{bmatrix}, \bar{\omega} = \begin{bmatrix} p \\ q \\ r \end{bmatrix}
\end{aligned}
\tag{12.5}
$$

The formula for the rotational dynamics of the body is shown in the Equation 12.6, where L, M, N are the moments in x, y, and z with the respect to the center of gravity [**?**]. The same reference is applied to the mass moment of inertia I. Then, the relation between the body-fixed angular velocity vector and the Euler rate vector can be determined using the Equation 12.7.

$$
\begin{aligned}
\bar{M}_B &= \begin{bmatrix} L \\ M \\ N \end{bmatrix} = I\bar{\omega} + \bar{\omega} \times (I\bar{\omega}) \\
I &= \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix}
\end{aligned}
\tag{12.6}
$$

[2] `https://www.mathworks.com/help/aeroblks/6dofeulerangles.html` [Accessed on 29-06-2020]

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = J \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} 1 & (\sin\phi\tan\theta) & (\cos\phi\tan\theta) \\ 0 & \cos\phi & -\sin\phi \\ 0 & \frac{\sin\phi}{\cos\theta} & \frac{\cos\phi}{\cos\theta} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \tag{12.7}$$

The outputs are a total of nine parameters that include a coordinate transformation [3x3] matrix from the Earth to body reference (DCM_{be}), position, velocity and acceleration in the Earth reference frame. Also, the Euler rotation angles, angular acceleration and rates of the body. Lastly, the acceleration, and velocity of the body reference frame. On a side note, the coordinate transformation [3x3] matrix from Earth to body reference (DCM_{be}) is not provided in the documentation of the 6DOF (Quaternion). However, in the book Introduction to Multicopter Design and Control [37], this matrix was found, see Equation 12.8.This transformation matrix will be needed for Gravity and drag correction.

$$DCM_{be} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\phi & \cos\theta\sin\phi \\ 0 & -\sin\phi & \cos\theta\cos\phi \end{bmatrix} \tag{12.8}$$

Gravity
From the output of the Flight controller, the forces on the drone body in x y z does not include gravity yet. When applying a gravitational force on the body, the gravity force always has to point downward in the Earth reference frame. Thus a correction is needed for converting the Earth reference frame to the body reference frame. The correction is shown in Equation 12.9.

$$\begin{bmatrix} F_{g_x} \\ F_{g_y} \\ F_{g_z} \end{bmatrix} = DCM_{be} \cdot \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix} \tag{12.9}$$

Environment
In the sub-system of the environment, the drag caused by the velocity of the drone and gust is calculated. However, the gust velocity and the air velocity on the drone do not use the same coordinate system. The gust velocity is with respect to the Earth reference. Thus a conversion from Earth reference frame to the body reference frame is needed, see Equation 12.10. Then the drag can be calculated, see Equation 12.11.

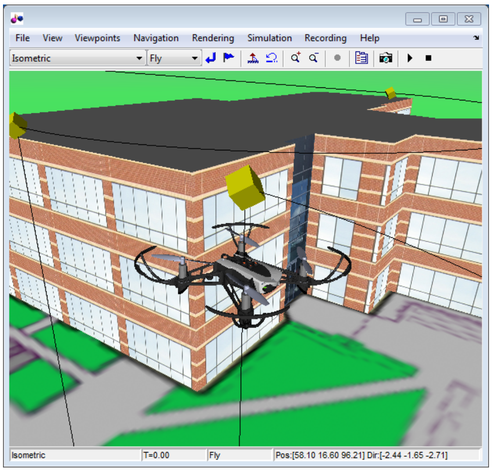
$$\begin{bmatrix} V_{gust_{x-c}} \\ V_{gust_{y-c}} \\ V_{gust_{z-c}} \end{bmatrix} = DCM_{be} \cdot \begin{bmatrix} V_{gust_x} \\ V_{gust_y} \\ V_{gust_z} \end{bmatrix} \tag{12.10}$$

$$\begin{aligned} F_{D_x} &= 0.5 C_{D_{ave}} \rho S (u_b + V_{gust_{x-c}})^2 \\ F_{D_y} &= 0.5 C_{D_{ave}} \rho S (v_b + V_{gust_{y-c}})^2 \\ F_{D_z} &= 0.5 C_{D_{ave}} \rho S (w_b + V_{gust_{z-c}})^2 \end{aligned} \tag{12.11}$$

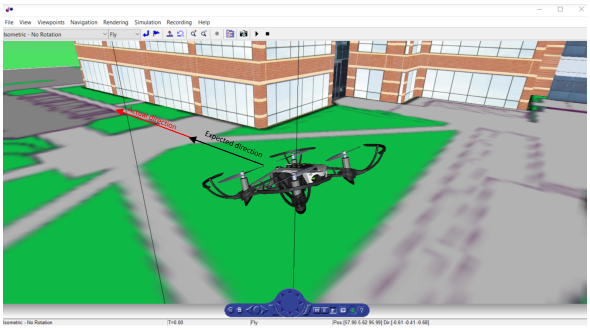
12.4. Verification

12.4.1. Visualisation

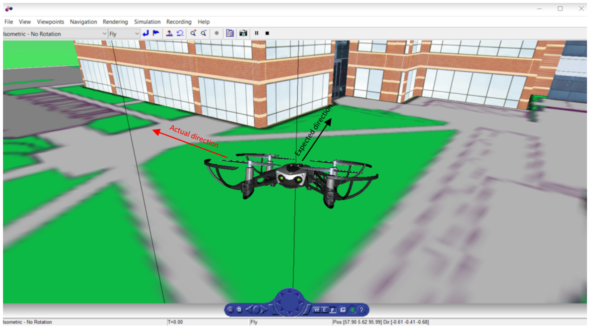
One of the most important verification tools is seemingly the most simple, a visual reference. Having a visual reference gives a clear indication of how the system would behave in the real world, rather than only looking at numerical data produced by the model. The visual system was adopted from the Aerospace Blockset in MATLAB which contained a pre-made quadcopter model [14]. Examples of this visual reference can be seen in Figure 12.7. Note: the drone displayed is a 3D model of a Parrot Mini Drone, it is not a representation of the final design of the HEMS Reconnaissance drone.



(a) Body and Earth reference systems aligned



(b) Direction with $yaw = 0[rad]$



(c) Direction with $yaw = 1[rad]$

Figure 12.7: Visual reference of drone model

By using this visual reference system the implementation of the reference system was verified. During this process, it was discovered that the reference systems were not implemented correctly. There are 2 reference systems, the body and Earth reference system, see Figure 12.6. In Figure 12.7a they are perfectly aligned. When introducing a pitch up disturbance as shown in Figure 12.7b, it is expected that the drone reacts by moving in the backwards in the negative x-direction according to its body reference frame (black arrow). When tested it was found that this indeed happens (red arrow).

When introducing this same disturbance to the drone with a yaw offset of 1 rad, see Figure 12.7c, the same reaction is expected. The drone should move backwards in the negative x-direction with respect to its body reference frame (black arrow). However, when testing it was found that the drone moved backwards according to the Earth reference frame (red arrow). This led to a revision of the reference systems and their transforms. After implementing the 6dof quaternion (Equation 12.3.2), the reference system transforms behaved correctly. This was again tested using the visual reference system, verifying the body and Earth reference system implementation in the model.

12.4.2. Unit testing

Mass

To test whether the relation of mass and thrust is correct, the mass was varied and the thrust response was checked. In this test, the mass was varied throughout 4 tests. In the first test, the mass was set close to zero ($m = 1.0e - 10kg$), but not at $m = 0kg$ as then singularity errors arise due to the presence of $1/m$ statements in the model. Then, the mass was set to 1 kg, 5 kg, and 10 kg. What is expected, as the mass approaches 0, the thrust should also approach 0, while for the other masses, the thrust should approach $Thrust = mass \cdot g$. The result of this test can be found in Figure 12.8, where the total thrust of the 4 individual engines combined is given over time. Here it can be seen that the mass-thrust relation is correct, verifying the relation between mass and thrust in this model. It can also be seen that at $m = 10kg$, the thrust maxes out at 100 N. This also verifies that the set maximum thrust of 25 N per engine is implemented correctly.

The oscillations in the graph are from the system reacting to initial altitude errors. When the desired altitude is reached the thrust eventually levels out and stabilises.

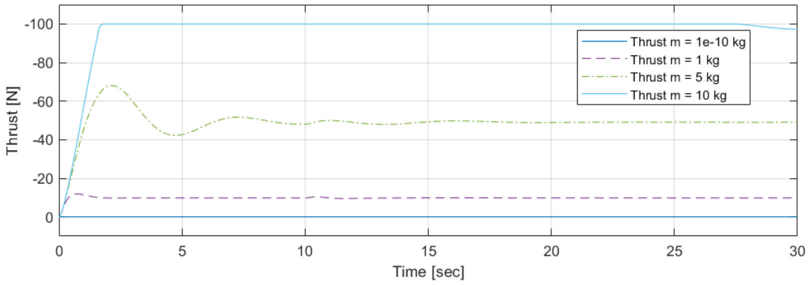


Figure 12.8: Mass - Thrust Relation Test

Aerodynamic Forces

The correct implementation of aerodynamic forces is a critical part of making a realistic flight model. The most crucial aerodynamic force in this case is drag. To test if the drag model is implemented correctly and if the system reacts accordingly to the external force, a free fall is simulated where the only velocity component is downwards. When in free fall, the drag eventually equals the weight at the so called critical velocity, in this state the velocity should remain constant. The results for this test can be found in Figure 12.9. Here it can be seen that the system reacts as it should, verifying that the application of external forces on the model, in this case drag, is implemented correctly.

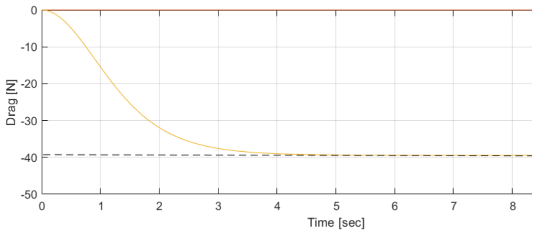


Figure 12.9: Free Fall Test

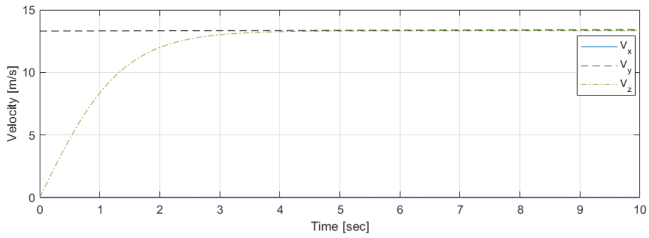


Figure 12.10: Terminal Velocity

Also, to test the drag model separately, the terminal velocity can be calculated by hand. The calculation is done by rewriting Equation 12.11 using $V_{gust_{z-c}} = 0[m/s]$, $C_{D_{ave}} = 1.5$, $\rho = 1.184[kg/m^3]$, $F_{D_z} = mg = 4.0190 \cdot 9.81 = 39.426[N]$, and $S = 0.250[m^2]$, see Equation 12.12.

$$V_{term} = \sqrt{\frac{F_{D_z}}{0.5 C_{D_{ave}} \rho S}} = \sqrt{\frac{39.426}{0.5 \cdot 1.5 \cdot 1.184 \cdot 0.250}} = 13.33[m/s] \tag{12.12}$$

Looking at Figure 12.10, it can be seen that the velocity approaches the calculated V_{crit}, verifying the drag equations and their implementation.

Orientation

To be able to control the drone, the ability to correctly orient the drone is crucial. For this reason, the implementation of the orientation states in the drone model is tested. The test is based on the basic properties of angles, where $0\,[rad] = k \cdot 2\pi\,[rad] = 0\,[rad]$ for any integer k. When the system is given an initial orientation state with angles of $k \cdot 2\pi [rad]$, it is expected to behave the same as when it is given an initial value of $0\,[rad]$. To test whether this happens or that the system reacts by rotating k times to end up at $0[rad]$, the reaction of the system is tested with initial values of $[\phi\,\theta\,\psi] = [0\,0\,0]$ and $[\phi\,\theta\,\psi] \approx [2\pi\,2\pi\,2\pi]$. The results can be seen in Figure 12.11 and Figure 12.12. These figures indicate the error of the orientations state over time. As expected, the error of $[\phi\,\theta\,\psi] = [0\,0\,0]$ is zero, and the error of $[\phi\,\theta\,\psi] \approx [2\pi\,2\pi\,2\pi]$ is close to zero, on the order of magnitude of $10^{-5}[rad]$. This is due to the fact that π was only inserted up to 5 digits. Thereby verifying the orientation implementation.

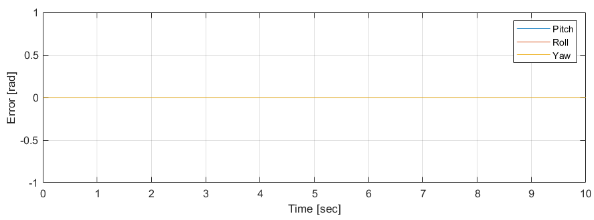


Figure 12.11: $[\phi\,\theta\,\psi] = [0\,0\,0]$

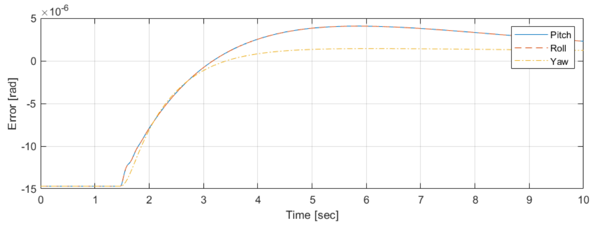


Figure 12.12: $[\phi\,\theta\,\psi] \approx [2\pi\,2\pi\,2\pi]$

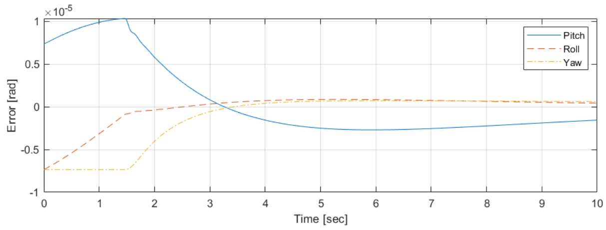


Figure 12.13: $[\phi\,\theta\,\psi] \approx [\pi\,\pi\,\pi]$

Also, the system was tested with initial values of $[\phi\,\theta\,\psi] \approx [\pi\,\pi\,\pi]$ to test if rotation matrices have been implemented correctly. In theory, according to the general rotational matrices as shown in Equation 12.13, the total rotation applied to a body is given by Equation 12.14.

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \quad R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \quad R_z(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{12.13}$$

$$R = R_z(\psi)R_y(\theta)R_x(\phi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \tag{12.14}$$

When applying $[\phi\,\theta\,\psi] \approx [\pi\,\pi\,\pi]$:

$$R = R_z(\pi)R_y(\pi)R_x(\pi) = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{12.15}$$

From this it can be concluded that for these rotation angles, the total orientation should remain the same. Looking at Figure 12.13, it can be seen that the orientation indeed stays the same, apart from again a small error on the order of $10^{-5}[rad]$ due to the limited digits. This verifies the correct implementation of the body rotations.

12.5. Validation

To analyse if the model is representative of the real-world behaviour, the model has to be validated with real-life data. Unfortunately the data for validation of this quadcopter, in general, are rare to be found. However, there is a similar quadcopter simulation model that is made by Simulink, based on PARROT series mini-drone. This simulation model is called the Quadcopter Project. It has been used in courses at MIT by Professor Sertec Karaman and also, this simulation model was used in MathWorks Mini drone competition [3]. This model incorporates noise in the sensor readings and the aerodynamic characteristic of the rotor behavior of the PARROT mini drone. Therefore the validation of the model will be based on the characteristics of the PARROT mini drone and not the drone that is designed for this DSE project. The main reason is the lack of detail for the HEMS drones such as the characteristic of the rotors, motor, and sensors for the HEMS simulation model. The implementation of the PARROT mini drone characteristics will however give us the capablility to validate the HEMS drone model in general.

[3] `https://www.mathworks.com/hardware-support/parrot-minidrones.html` [Accessed on 22-06-2020]

12.5.1. Inputs for the HEMS drone simulation model

Mass	0.063
Ixx	5.83E-05
Iyy	7.17E-05
Izz	0.0001
Sx	0.0025
Sy	0.0025
Sz	0.01
Cd	0

Table 12.1: Parrot mini drone [4]

Figure 12.14: Parrot mini drone [5]

Table 12.1 shows the necessary input for the HEMS drone model. Then, the PID controllers are tuned for the HEMS drone model for 5 different scenarios. The first three cases are an impulse of 0.5 rad in the pitch, roll, and yaw, which is activated at 5 seconds into the test. The reaction and stabilisation will be compared between the two models. Moreover, the drone should also correct for x,y, and z position when the impulse acts on the drone. The fourth case is for the drone to take-off from an altitude of -0.1 m to -11.1 m. The last case is where the drone will be dropped from an altitude of -100 m to -10 m. In both models, the positive z coordinate is pointed downward.

12.5.2. Validation result

All the 5 cases were analyzed for both models, however the PID controllers were tuned with different values. This is because the assumptions that are made in the HEMS drone model are different from those made in the Quadcopter Project model. This is investigated by going through the Quadcopter Project model itself. For example, the Quadcopter Project model correlated the motor torque and thrust of the motor so the PID controller is tuned with the relation to the torque. Whereas the HEMS drone model directly feeds the PID controller to the thrust value which means the behavior of the motor is not as accurate as of the Quadcopter Project model. All of the results in the section will show this inaccuracy in the error but the behavior of the drone should be similar.

Case		The HEMS drone model	The Quadcopter Project model
Pitch Impulse	Error in pitch [rad]	-5.09E-05	1.06E-03
Roll Impulse	Error in pitch [rad]	1.51E-06	3.43E-04
Yaw Impulse	Error in pitch [rad]	1.88E-15	3.45E-11
Pitch Impulse	Error in X-direction [m]	-0.01135346698	0.011151245
Roll Impulse	Error in Y-direction [m]	-0.03670955763	0.0034191769

Table 12.2: Error when Impulse is act on the drone after 30 seconds

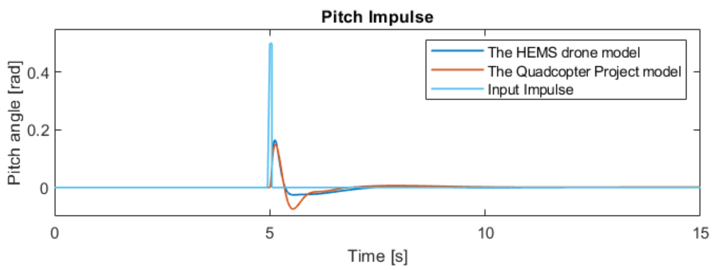


Figure 12.15: Drone stability on the pitch impulse in pitch angle

[2]https://www.mathworks.com/academia/student-competitions/minidrones.html [Accessed on 22-06-2020]
[3]https://www.mathworks.com/help/aeroblks/quadcopter-project.html#d120e109033 [Accessed on 22-06-2020]

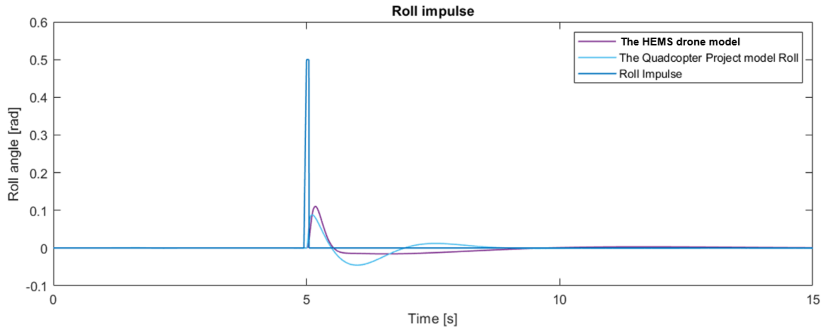


Figure 12.16: Drone stability on the roll impulse in roll angle

Figure 12.15 and Figure 12.16 show the drone behaviour in the Euler angle after an impulse is introduced at 5 seconds. The analysis in both models show the similar reaction behaviour, and both go to back to zero angles after 15 seconds. The result after 30 second of the Euler angle in pitch and roll can be seen in Table 12.2. The main difference in both models is the magnitude and the damping factor of the PID controller. In the HEMS drone model, the drone is highly damped compare to the Quadcopter Project model.

Furthermore, the drone also has to correct for X-direction when a pitch impulse is introduced the drone. The correction results of pitch impulse and roll impulse are shown in Figure 12.17 and Figure 12.18. The HEMS drone model is clearly overshooting significantly more than the Quadcopter Project model. However, after 30 seconds the HEMS drone model was able to correct the attitude error and the error in x and y direction, see Table 12.2. The HEMS drone model is stable but The response time of the HEMS drone too slow. This can be improved with a finer tuning of the PID controller of the HEMS drone model. On the other hand, the change in the PID controller to improve the response time in X and Y direction will directly affect the stability and response time in the pitch and roll angles.

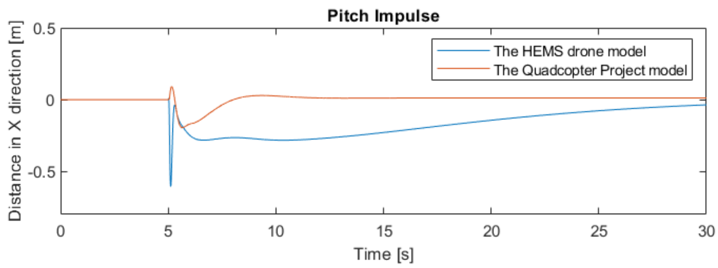


Figure 12.17: Drone stability on the pitch impulse in x direction

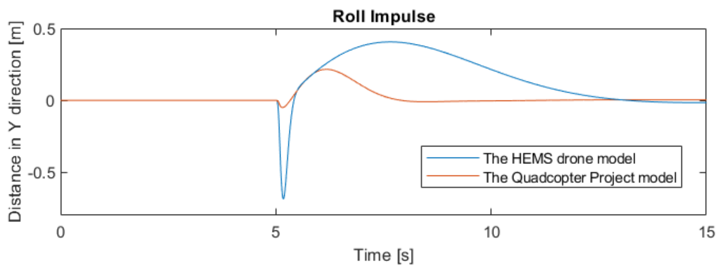


Figure 12.18: Drone stability on the roll impulse in y direction

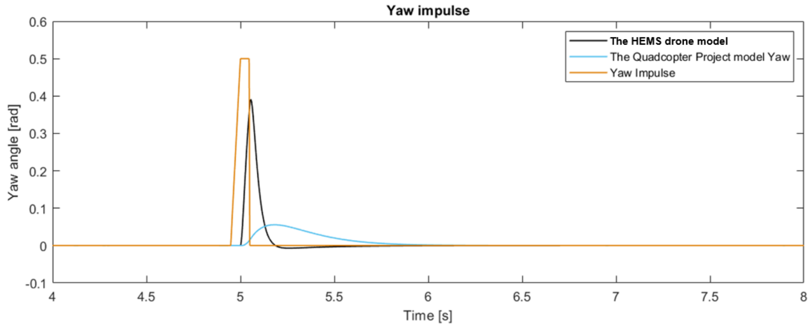


Figure 12.19: Drone stability on the yaw impulse in yaw angle

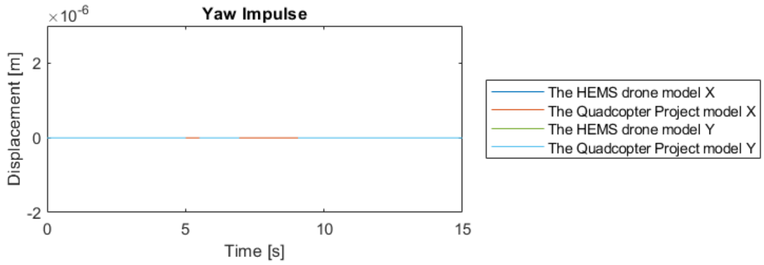


Figure 12.20: Drone stability on the yaw impulse in x and y direction

In the third case, there is a big difference in the yaw response time of the HEMS drone model. This is excepted since the HEMS drone does not have a relation from the torque of the motor to thrust values. Aside from having a different response time, the system is shown to be stable. In the process of correcting the errors from the yaw impulse, there should not be any displacement in any direction. This is true and it is shown in Figure 12.20.

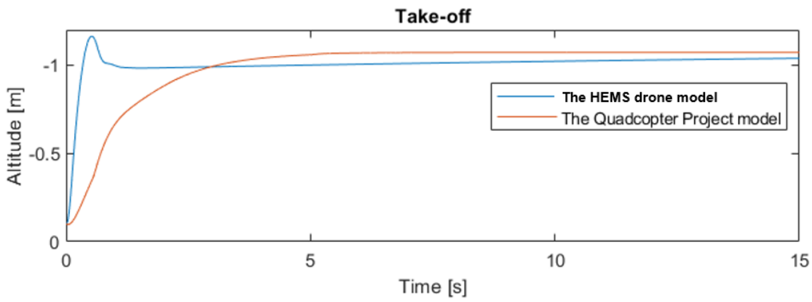


Figure 12.21: Take-off from -0.1 m to -1.1 m

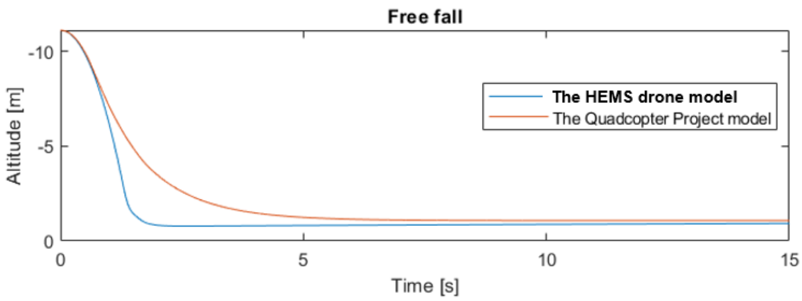


Figure 12.22: Free-fall from -11.1 m to -1.1 m

	The HEMS drone model		The Quadcopter Project model	
Case	Z position	error [%]	Z position	error [%]
Take-off	-1.07085	2.65002	-1.07301	2.45408
Free-fall	-1.01569	7.66476	-1.07301	2.45408

Table 12.3: Error of z position after 30 seconds

In the last two cases, both of the models show stability. The main differences are in the response time and an offset in the z position after 30 seconds. The HEMS drone model indicates a much faster response than the Quadcopter Project model which shows that the PID controller in the Quadcopter Project model is more damped. However, the offset in the z position in the HEMS drone model is slightly greater than the Quadcopter Project model, see Table 12.3.

In conclusion, the HEMS drone model is a good representative of the behavior of the drone in the real world except for the yaw characteristic. This is because the model needs a characteristic of the the torque of the motors and this can be found experimentally. The HEMS drone simulation is tested with the PID value from the Quadcopter project and the system of the HEMS drone model is still stable, but there is a big offset in the final values. Which is why different PID values are needed for both model because the flight controller setup and assumptions in the model are different. This means that the setup for the flight controller could be used in the HEMS drone but the final, real world, PID values are likely to be different from the simulation.

12.6. Simulation Results

In this section, the capabilities of the control system are shown by having the system perform its 3 main functions, drop recovery, translation, and wind resistance.

12.6.1. Drop Recovery

In order to be able to perform its mission, the drone first needs to be able to recover from being released from the HEMS helicopter. This drop is modelled in Simulink with the initial conditions implemented such that it simulates a drop where the drone is traveling downwards at its critical velocity at around the cruise altitude of the EC135 while tumbling due to the turbulent conditions. The initial conditions can be seen in Table 12.4.

The system reaction can be seen in Figure 12.24. Here, the error between the actual, and reference state is given over time. The system reacts to the initial disturbance by trying to get the errors to zero. It does this by varying the thrust of the 4 rotors, see Figure 12.23. As can be seen, the rotors react quickly to the initial pitch and roll disturbance, cancelling out the initial offset and angular momentum in ± 1 second. The yaw offset takes slightly longer to correct, two full rotations is made, depicted by the sudden drops from π to $-\pi$. Within around 2 seconds however, the system has completely stabilized the drone's attitude.

Parameter	**Value**	**Unit**
$[\phi\ \theta\ \psi\ ]$	[1 -1 0]	Rad
$[\dot{\phi}\ \dot{\theta}\ \dot{\psi}]$	[2 2 2]	rad/s
$[x_{start}\ y_{start}\ z_{start}]$	[57 95 -100]	m
$[x_{ref}\ y_{ref}\ z_{ref}]$	[50 90 -50]	m
V_z	12.5	m/s
$[V_{gust_x}\quad V_{gust_y}]$	[9.82 9.82]	m/s

Table 12.4: Initial Conditions

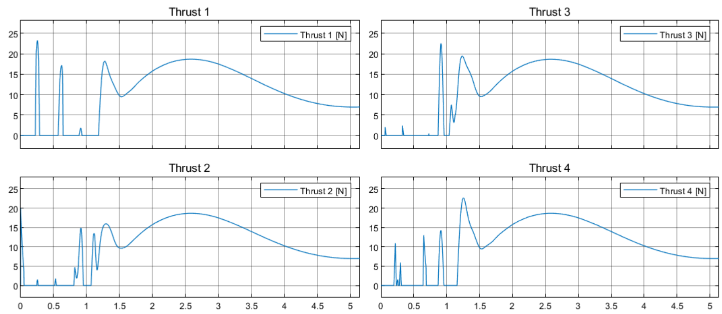


Figure 12.23: Drop Recovery Thrust

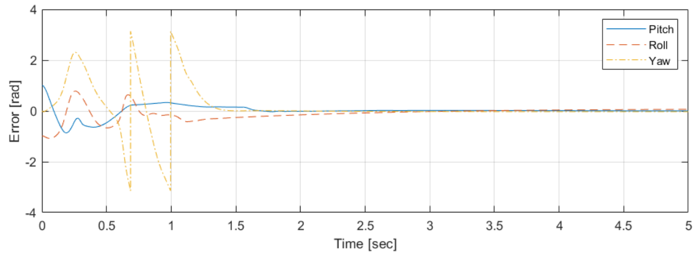


Figure 12.24: Drop Recovery Orientation

12.6.2. Translation

The ability for the drone to move from A to B is of the upmost importance if it is to perform its scanning mission. To show this capability, the same initial conditions are used as described in Table 12.4. Again, the only parameter the system can actuate is the thrust level of the 4 motors, only now, a closer look is taken into the x,y,z error data acquired from the system's reaction, see Figure 12.25. This graph shows the location error in the Earth reference frame over time, note that this time span differs from Figure 12.24. Looking at the start of the graph, the initial location conditions can be seen, where the offset of x,y, and z of 7 m,5 m, and -50 m can be seen respectively.

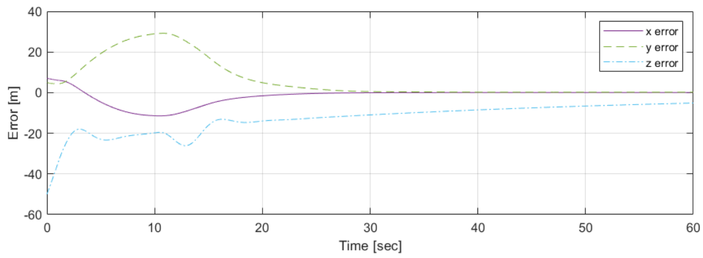


Figure 12.25: Location Reaction

Also, due to the initial attitude offset, an offset of x and y location also occur. However, this error is not immediately corrected as can be seen by the ever increasing x and y error in Figure 12.25, where the drone seems to drift further and further away from its reference location. This is due to the setup of the system. At first, the system's priority is to correct the attitude of the drone from a tumbling free fall. To ensure all its resources are available for this maneuver, the system does not take the x and y error into account yet. After stabilisation has been achieved, the drone switches over to its secondary flight control system designed specifically for normal flight. In this case, this is done after 10 seconds. The switch to the secondary flight control system can be seen in Figure 12.25, where after 10 seconds, the x and y error start to decrease and eventually stabilize at 0. The altitude, or z location in this case, also converges to 0. The fast drop at the start is due to the initial terminal velocity from the free fall, whereafter the system decreases the vertical velocity by increasing the total thrust and then converges to its reference altitude.

12.6.3. Wind resistance

Aside from drop recovery and translation, the flight control system also has to be able to cope with wind disturbances. From **HD-CRST-05**, it is given that the drone should be operable with winds up to 13.89 m/s. This wind is introduced in the Environment subsystem of the flight model. It introduces an increased velocity in the x, y, and/or z direction of the body reference frame. In this case, a wind gust of 9.82 m/s was introduced in both the x and y direction after 30 seconds, giving a total wind magnitude of $\sqrt{9.82^2+9.82^2} = 13.89 m/s$. Looking at the attitude reaction in Figure 12.27, it can be seen that the drone changes its pitch and roll orientation. This is done to counteract the incoming gust. The pitch responds by initiating a negative (downwards) pitch, causing a positive pitch error. The roll responds by initiating a positive (right) roll, causing a negative roll error. The introduced gust is not instant, but rather it builds up until it has reached its set magnitude. It can be seen that at around 45 seconds, the orientation remains constant to counteract the introduced wind.

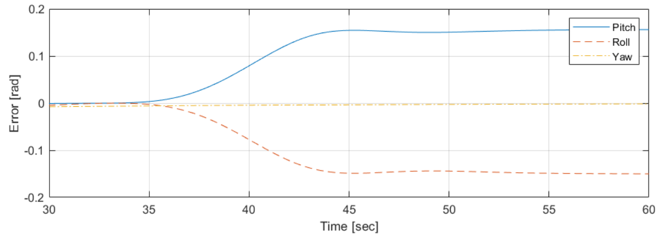


Figure 12.26: Wind Attitude Reaction

The sudden introduction of wind does cause an offset of the x and y location. This offset does stabilize however due to the attitude reaction of the system. The system is still in a controllable state with the introduction of this wind, thus complying with **HD-CRST-05**.

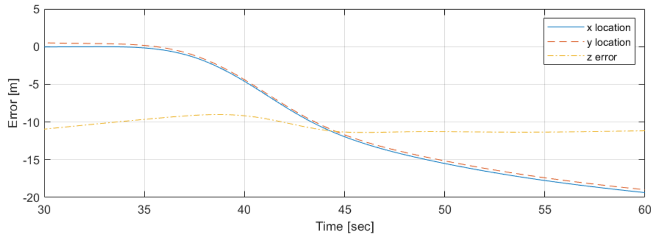


Figure 12.27: Wind Location Reaction

12.7. Development Plans

As of now, the control system is able to perform its primary function on a rather high level. In future development, further refinement is necessary for this system to become flight ready. This development would include the correct integration of the on board sensor system, the implementation of the autonomous flight system and the addition of emergency protocols.

12.7.1. Sensor, ESC, and Motor integration

As of now, the model uses "perfect" data from the simulation directly for reference. In the real world application, the sensors would be imperfect and have a certain degree of noise. This is not a big issue seeing as such sensors are already wildly used in the drone industry, but is something that has to be implemented. The HEMS drone model has excluded the characteristic of the ESC and motor rotor that makes the model less reliable overall. The ESC and the motor are already setups in the subsection 9.4.2 and subsection 9.4.3. Thus, integrating these ESC properties can be implemented easily and will make the simulation more robust overall.

12.7.2. Autonomous flight system

The drone will primarily be controlled by an autonomous system, and such a system must thus also be implemented correctly which include the ability to navigate on GPS and follow a pre-determined path. The system however can already travel to a set location reference point, so this implementation should not cause much problems.

12.7.3. Emergency protocols

The biggest development will be in the integration of emergency protocols as described in chapter 6. A manual override for instance of the flight control system requires an entirely new input system. In general the emergency protocols are closely integrated with the flight control system, looking motor shutoff, autolanding, etc. The correct integration of these protocols are of the upmost importance as to insure the safety of the drone, HEMS crew, and bystanders throughout the mission.

12.7.4. Quadcopter flying with 3 motors

As mentioned in the HD-CRST-04, a one engine inoperable situation is possible to solve[6]. Having an emergency flight system that allows the drone to fly with one broken propeller or motor is desired for its application. It is possible to implement this system in a later stage.

[6] `https://newatlas.com/quadcopter-failure-algorithm/30031/` [Accessed on 22-06-2020]

13
Sensors and communication

In this chapter, the sensors and communication subsystem is presented. First, the functions of the subsystem are presented, after which the subsystem requirements and their respective changes are discussed. Following, the different components used and mutual communication in the subsystem are presented, and choice on their inclusion is discussed. Subsequently, different algorithms to be used for data processing are presented and finally, a plan for verification and validation for sensor and communication components is provided, followed by the chapter conclusion.

13.1. Functional analysis

The function of the sensors and communication subsystem is to provide the drone with the required information of the environment in order to perform a controlled flight. Furthermore, the subsystem will record the surroundings in order to create a three dimensional representative model of the planned helicopter landing site. The sensors and communication system will also provide a communication link between the drone and the helicopter, which will be used to send control input from the drone operator to the drone and to send different types of observed data to display to the helicopter pilots.

13.2. Requirements

During the requirement discovery phase, a large amount of requirements were set for the sensors and communication subsystem. This section presents these requirements. Some of the requirements were found to be not relevant or unnecessary after the midterm design phase. Therefore some requirements are ommitted, these requirements are marked by the addition of a cross through their identifier. Furthermore some requirements are added after the midterm design phase, these are the requirements with an identifier larger than 12 for sensors and 11 for communication.

- ~~**HD-SENS-01**~~: The spatial resolution of the sensors shall be at most 1 cm in heavy fog conditions at a distance of 5 m.
  This requirement was canceled due to wrong understanding of radar resolution.
- **HD-SENS-02**: The measurements shall have a maximum deviation of 0.5 m.
  0.5 meter is chosen as this will be an achievable but still safe deviation from the radar sensors.
- **HD-SENS-03**: The position of the drone shall be known at all times with a margin of error of 0.5 m.
  This requirement is set so the deviation of the data eventually presented to the pilot does not propagate to an unreliable magnitude.
- **HD-SENS-04**: The absolute position of the helicopter shall be known with a maximum error of 0.5 m.
- **HD-SENS-05**: The drone pitch angle shall be determined with a maximum error of at least 5 degrees.
- **HD-SENS-06**: The drone roll angle shall be determined with a maximum error of at least 5 degrees.
- **HD-SENS-07**: The drone yaw angle shall be determined with a maximum error of at least 5 degrees.
- **HD-SENS-08**: The horizontal field of view of the sensor shall be 360 degrees.
  This requirement was set in order to allow scanning to be performed fully at every section a drone passes
- **HD-SENS-09**: The vertical field of view of the sensor shall be 90 degrees.
- **HD-SENS-10**: The sensing equipment shall not interfere with the helicopter's instrumentation.
- ~~**HD-SENS-11**~~: The sensing system shall have a peak power consumption of <tbd> W.
  This requirement was canceled as no actual restrictions came from the electrical power subsystem. Actually, its sizing is performed, based on the sensor and communication power consumption and not the other way around.

- ~~**HD-SENS-12**~~: The sensing system shall have an average power consumption of <tbd> W.
  This requirement has been canceled for the same reason as HD-SENS-11.
- **HD-SENS-13**: The Gimbal shall rotate at max 4π rad/s and at least 2π rad/s.
- **HD-SENS-14**: The sensors shall detect objects at 200 m distance.
  200 meters is set as this will allow the drone to start the optical flow navigation using all characteristic topography of the user requirement landing site area.
- **HD-SENS-15**: The system shall detect objects of at least 10 cm in the landing area.
- **HD-SENS-16**: Gnss receivers shall be EGNOS compatible.
  EGNOS compatibility will allow the GNSS receiver to achieve a higher level of accuracy, which is desired.
- **HD-SENS-17**: The cameras shall be able to rotate 90 degrees in 5 seconds.
  This requirement is set, so the drone operater will have the ability to change the drone camera viewing angle in a fast manner.
- **HD-SENS-18**: The rgb camera shall have a resolution of 1920 x 1080 pixels. *This resolution is set in order to present the drone operator with a high detail visualisation of the drone environment, as done in many other UAV systems.*

- **HD-COMM-01**: The communication shall work in heavy fog conditions.
- **HD-COMM-02:** The communication system shall have a signal range of 2000m.
- ~~**HD-COMM-03**~~: The BER shall be lower than <tbd>.
  This requirement is canceled as it requires too much detail from the system design at this point in the design phase.
- ~~**HD-COMM-04**~~: The SNR shall have a value of <tbd>.
  This requirement is canceled as it requires too much detail from the system design at this point in the design phase.
- **HD-COMM-05**: There shall be a downlink rate of 10 megabits/s.
- **HD-COMM-06**: There shall be an uplink rate of 1 megabits/s.
- ~~**HD-COMM-07**~~: The frequency to be used shall be <tbd> GHz.
  This requirement is canceled since no reason for its excistance is found at this moment in the design process, besides possible interference with helicopter equipment, for which, a requirement has already been set.
- ~~**HD-COMM-08**~~: The transmission power shall at most be <tbd>W.
  This requirement has been canceled for the same reason as HD-SENS-11.
- **HD-COMM-09**: The data transmission shall not interfere with other transmissions.
- ~~**HD-COMM-10**~~: The communication subsystem shall have a peak power consumption of <tbd> W.
  This requirement has been canceled for the same reason as HD-SENS-11.
- ~~**HD-COMM-11**~~: The communication subsystem shall have an average power consumption of <tbd> W.
  This requirement has been canceled for the same reason as HD-SENS-11.

13.3. Subsystem components

In this section, all individual components that together make up the sensors and communication system are elaborated upon. A brief description of its functions and characteristics is given per component. For some components, reference off the shelf components are also presented.

Located on helicopter

H1 Display / Visualisation

The Display will show all acquired data. The drone operator will see information of the drone orientation and system conditions, as well as the RGB and infrared camera feed. The sensor data will be presented to the helicopter pilot through a heads up display. As a reference off the shelf component, the Collins Airspace Compact HUD is considered[1]. This display will present data based on the helicopter's location and display orientation relative to the data. Though if allowed through certification, a cheaper option might be developed utilizing a fixed display instead of a heads up display. However, it is too early in the design phase of the system and not enough information is yet available in order to estimate whether this certification could be possible.

[1] `https://www.collinsaerospace.com/what-we-do/Business-Aviation/Flight-Deck/Head-Up-Display` [Accessed on 21-06-2020]

H2 Controller
The controller will be held by the drone operator. This device will allow the drone operator to provide control input for the drone. This input can be for semi autonomous control (tell the drone to fly in a certain direction) or manual (manual control over drone speed, pitch, roll, thrust etc.).
H3 Computer
The computer will combine all data sent from the controller and the communication system. The controller input will be processed in the computer and sent to the communication system. All data obtained from the communication system will be processed such that it can be output to the Display system and the drone controller.
H4 Positioning beacons
The radio beacons attached to the helicopter will allow the drone to find its position relative to the helicopter. This can be achieved by using triangulation and trilateration methods applied to phase and/or time of flight measurements gathered from the radio beacons. Due to time and budget restrictions, no further research into this component has been performed during this project.
H5 Helicopter communication link
The communication link device on the helicopter will be the device allowing for communication with the drone. All communication with the drone, with the exception of the positioning beacons, will be led through this component. An identical communication unit will be present on the drone. The choice for this component is justified in the corresponding section in section 13.3.

Located on drone

D1 Radar
The radar will at a high rate acquire data on the distances of the surrounding environment. The radar sensors chosen are the TI AWR 2243 [2]. This sensor is a cheap millimeter wave radar. Usage of this sensor in a reference design provided by the manufacturer. a total of eight sensors will be present on the drone. [3] showed expected compliance with **HD-SENS-02**, **HD-SENS-08**, **HD-SENS-09**, **HD-SENS-10**, **HD-SENS-14** and **HD-SENS-15**.
D2 On-board computer
The on-board computer will process the data from the Radar, cameras and navigation unit, gimbal and inertial measurement unit such that the live camera feeds and processed radar data can be sent to the communication link. Furthermore, the on-board computer will continuously perform calculations using radar and IMU data in order to align the data of different measurements done by the radar and create a point cloud representing the landing site surrounding. The computer used will be the raspberry pi 4 [4]. As the total data rate will not be higher than 10 megabit per second, it is expected that the calculations performed continuously by the on board computer will not require more than 2 GB of random access memory.
D3 Cameras
The cameras (a full HD 1920 x 1080 30 Hz rgb camera and a 640x512 25 Hz infrared camera) will record the light and infrared spectrum of the front field of view of the drone.

D4 Drone communication link
The drone communication link will perform the same function as the helicopter communication link, but this is the other end of the data link. In this device the data obtained from the helicopter will be output to the on board computer and the flight controller. Also the relevant outputs from the on board computer and flight controller will be sent to the helicopter. This data will include:

- Processed radar location data (point cloud).
- Live Infrared video.
- Live rgb video.
- IMU, motor, gimbal and camera rotator data.

In order to provide an estimated mass and power consumption for the communication link, a reference component was selected, which is a 2.4 GHz duplex radio transceiver[5]. According to the information provided

[2] `https://www.ti.com/product/AWR2243` [Accessed on 16-06-2020]
[3] `http://www.ti.com/lit/ug/tiduen5a/tiduen5a.pdf?&ts=1589373408286` [Accessed on 16-06-2020]
[4] `https://static.raspberrypi.org/files/product-briefs/200521+Raspberry+Pi+4+Product+Brief.pdf` [Accessed on 16-06-2020]
[5] `http://www.cofdmvideotransmitter.com/sale-11000627-2-4ghz-full-duplex-cofdm-wireless-video-transmitter-for-uav-drone-syst html`[Accessed on 29-06-2020]

by the manufacturer, this component will meet the requirements set on the communication bit rates (HD-COMM-05 and HD-COMM-05) as well as the requirement of signal range (HD-COMM-02). Furthermore, this component is capable of using 65 different carrier frequencies between 2405 MHz and 2470 MHz, using a bandwidth of 2 MHz. As it is not found what radio frequencies are used by the HEMS helicopter, compliance of requirement HD-COMM-09 on signal interference cannot be estimated at this point in the design phase. At last, it is expected that requirement HD-COMM-01 on communication is also met using this reference component, as "for waves greater than 5cm in length,the effect of ordinary rain or fog on the absorption is negligible."[45].

D5 Navigation unit

The navigation unit will consist of a EGNOS compatible GNSS receiver, which will be able to allow for up to 4 m precise absolute location determination [6]. Furthermore, radio receivers will be present to pick up the signal from the positioning beacons. This will allow the drone to determine its distance and orientation from the helicopter by comparing the propagation time and phase of the radio waves.

D6 Flight controller

The Flight controller will process all control input and output and determine what signals will be sent to the propulsion system and other control systems to achieve the desired flight conditions and sensor orientations. The final choice of a flight controller is to be made in a later design phase, as more required specifications will flow from the design of the control system. So in order to have an estimate on the mass, size and power consumption of the flight controller in the drone design, a reference component is used. This component is the pixhawk 4[7]. Furthermore, a contingency factor of 25% is added to the expected flight controller weight to deal with possible future deviations from the reference design.

D7 Inertial measurement unit (IMU)

The inertial measurement unit will register linear accelerations and rotational rates of the drone at xxx samples per second. two inertial measurement units are located on the above mentioned flight controller reference design. These IMU's are the BMI-055 [8]. As stated by the manufacturer the angular acceleration resolution is around 0.004°/s. Using integration and with the use of the magnetometer and linear acceleration measurements, this acceleration can provide a thorough approximation of the absolute orientation of the IMU[50] and corresponding, the drone.

D8 Electrical speed controller

The electrical speed controllers will regulate the current that the rotors will receive. A unit is needed per rotor, so in total, four electrical speed controllers will be located on the drone. Each controller will receive a unique signal from the flight controller, used to generate the rotational velocity corresponding to the given throttle setting. The choice of the electrical speed controller is presented inchapter 9.

D9 Gimbal

The gimbal in this system will be the link between the drone and the radar sensors. A reference off the shelf component used for estimation of power consumption, size and mass is the X-cam A10-3H [9]. Unfortunately no reference gimbal is found with a rotational velocity meeting the requirement from **HD-SENS-13**. It was chosen not to design this component as this would be too detailed for the current design phase. Therefore, a contingency factor of 20 perscent is added the the reference mass and price of the gimbal. This will then compensate for the better performing yaw electromotor that will be required.

D10 Camera rotator

The camera rotator is an electrical stepping electro motor, which will be able to rotate the rgb and infrared cameras. it will take control input from the flight controller and will send data on the rotation to the flight controller. The rgb and infrared camera will be attached to the stepping motor as shown in Figure 13.1 where the cameras are attached to a shaft through their centroid.

Attachment system

A1 temperature sensor

The temperature sensor will observe the temperature within the drone storage system. This information is constantly provided to the helicopter on board computer, which in turn can send the data to the display system, allowing the helicopter pilot to be warned at a temperature increase in the storage box.

A2 Release system

[6] https://www.gsa.europa.eu/european-gnss/egnos/services/performance-overview [Accessed on 16-06-2020]
[7] https://docs.px4.io/v1.9.0/en/flight_controller/pixhawk4.html [Accessed on 18-06-2020]
[8] https://www.bosch-sensortec.com/products/motion-sensors/imus/bmi055.html [Accessed on 189=06-2020]
[9] https://www.firstquadcopter.com/download/x-cam-a10-3h-user-manual/ [Accessed on [18-06-2020]

The release mechanism will send feedback on the deployment status and receive control input from the drone operator.

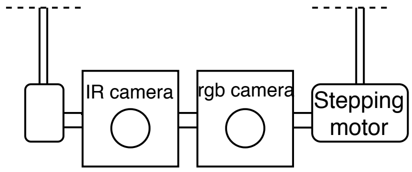


Figure 13.1: Demonstration of attachment system used for rgb camera, infrared camera and stepping motor.

The stepping motor used for the rotation of the cameras is [10]. According to requirement **HD-SENS-17**, the cameras should be able to rotate 90 degrees in 5 seconds. In order to see if the stepping motor performance is sufficient to achieve this rotational acceleration, the following calculation was performed: First the mass moment of inertia of both cameras is calculated according to Equation 13.1.

$$I = \frac{m\left(h^2 + w^2\right)}{12} \tag{13.1}$$

Also the required angular acceleration and deceleration required are computed using Equation 13.2:

$$\theta = \frac{1}{2}\alpha t^2 \tag{13.2}$$

Following, the required moment to achieve this acceleration with the calculated mass moment of inertia is found using Equation 13.3

$$M = \alpha I \tag{13.3}$$

During this calculation, the following is assumed:

- Camera centroids assumed to be located on rotational axis of the electromotor.
- The electromotor is assumed to switch the direction of its applied moment instantly.
- No angular velocity is assumed to be present at the moment the camera rotation starts.
- The mass distribution inside the infrared and rgb camera is assumed to be uniform, resulting in a constant density in the volume.

Resulting from the calculation, a moment of $0.03175 Nmm$ was found to be required in order to meet requirement **HD-SENS-17**. However, as this is a very small moment compared to performance of the smallest stepping motors and quite some assumptions are made, it was chosen to pick a stepping motor with a maximum moment of 10 times as large.

External components

E1 Mapping database

The mapping database will provide data on the surroundings as recorded and saved in the data base, for instance 3D data of buildings, ground elevation and infrastructure could be available and provided by this database. This data can be alligned with the radar data to provide a clear overview of the surroundings through the system display.

E2 GNSS and EGNOS Satellites

GNSS and EGNOS satellites will transmit signals that will be received by the GNSS and EGNOS compatible receiver on both the helicopter and the drone. this will allow the system to determine its location up to 4 meter accuracy.

[10] `http://www.mercateo.nl/p/2949E-240(2d)7920/Greenwich_Instruments_GSM_2_Stepper_Motor_Controller_2_A_61_x_46_x_15mm.html` [Accessed on 15-06-2020]

13.4. Data Handling and communication

Data communication and processing is of the essence for proper functioning of the system. Data will be recorded on a different aircraft than the display and the used aircraft is controlled remotely. Therefore, data must be continuously communicated not just by wire, but also through a wireless connection. Furthermore, the system will make use of external infrastructure in order to record and display data. An overview of all data handling components in the system and their interactions is provided in Figure 13.2. This following section will provide a description of all data handling components presented in Figure 13.2. The subsequent section will discuss the data that is communicated between the components.

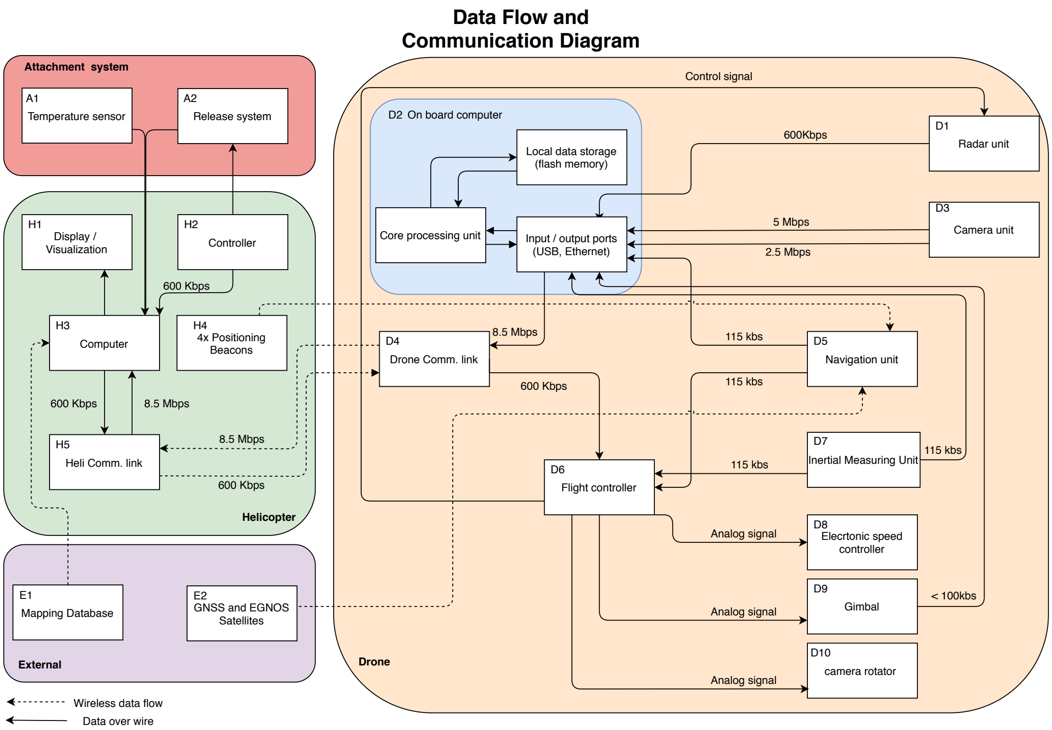


Figure 13.2: Communication diagram presenting interactions between data producing or handling components.

Sensors and simple components

Radar sensor

Each sensor on the radar will have a resolution of 1.4 degrees, with a field of view of 70 degrees for each pixel. this will result in 2500 data points per measurement. each data point shall represent an orientation and a distance, the distance shall have 4 digits to maintain accuracy and shall be provided in decimeters. A maximum required distance of 2000 decimeters shall be picked up by the sensor. this number can be represented in 11 bits. Furthermore, approximately 2500 orientations are available per measurement. If a predefined sequence of these orientations is sent to the on-board computer continuously, then no extra bits are required from the radar sensors. Therefore, the data flow from the radar sensors to the on-board computer, with a sample rate of 20 Hz is estimated to be 600 kilobits per second. This bit rate does not include bits that are related to data transfer or compression.

Cameras

The 1920 x 1080 pixels, 30Hz compressed video output from the rgb camera (D3) is expected to be around 5 megabit per second[11] and the infrared camera bit rate is expected to be around 2.5 megabit per second as the resolution will be around 640 x 512, at 25 Hz.

[11] https://help.encoding.com/knowledge-base/article/understanding-bitrates-in-video-files/ [Accessed on 8-6-2020]

GNSS receiver
The GNSS receiver will produce around 115 kilobits per second as described in a similar design [12].

Intertial measurement unit
The IMU will sample infromation at 500 Hz, with an output bitrate of approximately 115 kilobit per second [13]. This information will be sent to the flight controller for control purposes and the on board computer for assistance in data fitting.

Gimbal
The gimbal will output data on its orientation, this should be done at the same rate as the radar sensor sampling rate. and the data that will be sent is information of a single angle, so this bit rate is expected very low also considering the radar sampling rate will be around 20 Hz. therefore, it can safely be assumed that the bit rate from the gimbal to the on board computer will be less than 100 kilo bit per second.

Electronic speed controllers
The electronic speed controllers will receive throttle input from the flight controller through four respective pulse width modulated signals created in the flight controller. [14].

On-board computer

The on board computer will perform calculations for every sample using the following data: Radar sensor measurement, gimbal orientation, IMU parameters. The information from these sources are sufficient to string together all radar measurements by fitting the position data observed per measurement. The radar data obtained per measurement is converted to a point cloud relative fixed on the surrounding using the sensor orientation and the observed distances. The created point cloud will be appended to the point cloud containing the previous measurements. Since no accurate data on the location of the drone is available, the new point cloud is oriented and translated as determined by an iterative closest point (ICP) algorithm as described in[39]. In this design phase it is too early to go into depth on which exact ICP algorithm will suit best for the design.

For every new measurement successfully appended to the main point cloud, the on board computer will send the update on the point cloud data to the communication link (D4). This data only contains the new point cloud data after its transformation to fit the main point cloud is performed. This will result in a smaller bit rate required for communication to the helicopter. This cycle will be repeated at the rate of the radar sampling frequency.

Besides computing a coherent point cloud, the on board computer will also convert the infrared and rgb camera video streams and navigation data to a format which can efficiently be sent through the communication link to the helicopter.

Finally the following data will be output by the on board computer to the communication link:

- Newly obtained and correctly transformed point cloud data.
- rgb and infrared video
- Navigation data

Flight controller

The flight controller will receive control input from the drone operator in the helicopter through the communication link. this data rate is estimated to be about 600 kilo bits per second "To enable remote control for drones, certain data rate and latency requirements should be met. In terms of data rate, the downlink (from BS to drone) data rate requirement is about 300-600 kbps in many application scenarios" [49]. This data will then be turned into individual signals which will be sent to the following components:

- Throttle setting is sent to the four electronic speed controllers.
- rotational speed throttle is sent to the gimbal.
- Control signal will be sent to the radar sensor.

[12] `https://docs.rs-online.com/c0e9/0900766b80df94d1.pdf` [Accessed on 8-6-2020]
[13] `https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120009954.pdf`, [Accessed on 8-6-2020]
[14] `https://www.getfpv.com/learn/new-to-fpv/all-about-multirotor-fpv-drone-electronic-speed-controller/` [Accessed on 8-6-2020]

- Rotation setting signal will be sent to the camera rotator.

Since the above mentioned signals are all concerning the control of a single parameter per signal, it is assumed that the signals will be analog, and the to be controlled components will respond to the signal characteristics. Hence, no bit rate is provided.

13.4.1. Communication link

The communication link is the most considerable component in both the drone and the helicopter, with respect to data transfer. All measurements and computations performed on the drone that are provided to the system operators in the helicopter, are communicated using this component. Therefore a reliable and extensive data link is required. The data transfer from the drone to the helicopter will be provided by the on board computer and the flight controller. the combination of the input from these components will result in the transfer of data and corresponding data rates as shown in Table 13.1:

Data type	Estimated bit rate (Mega bit per second)
Processed point cloud data	0.60
rgb video	5.0
Infrared video	2.5
Navigation data	0.23
IMU data	0.12
Total	8.5

Table 13.1: Overview of drone data and corresponding bit rates, continuously communicated to the helicopter through the communication link component.

From the helicopter, only control is communicated to the drone, This data rate is around 600 kilo bits per second as mentioned in Figure 13.4.

13.4.2. Helicopter computer, display and controller

The computer located on the helicopter will send and receive all data from the communications link. Furthermore, all control input is passed to the computer by the drone operator, which will again be around 600 kilo bits per second. Next to the control input device, also the display system is connected to the computer. The display system will consist of two different displays. One display will be used by the drone system operator in order to view the drone status, camera feed and progress. The other display in the system is the head up display, which will be used by the helicopter pilot to view the 3D environment, as scanned by the drone. This display will also provide the helicopter on board computer with IMU data, in order for the computer to display the correct orientation of the observed data.

13.5. Data Pre-processing

13.5.1. Histogram Equalization

Histogram equalization is an image processing method which involves adjusting the contrast in an image by using the image histogram of said image. This image histogram is, in essence, simply a type of histogram which provides a graphical representation of the tonal (typically the degree of lightness) distribution. This image processing method, most typically, entails the increasing in the global (whole image) contrast of an image. This transformation is achieved by spreading out the most frequent intensity values found in the image histogram.

The reasons for as to why it was decided to make use of histogram equalization to transform the RGB images captured by the RGB camera sensor on-board of the drone are the following:

- The general familiarity and intuitiveness of human beings with standard 2D visual display formats gives rise to the belief that it could only be more beneficial, than not, to provide an enhancement to his/her 2D visual display.
- The second reason for this is attributed to the user requirement HD-USR-SENS-01.
- The enhancement of an image using this method takes place without any loss of information.

13.5.2. Point Cloud Data

To get the displacement of the drone, multiple scans have to be 'stitched' together and their relative displacement has to be determined. This is done using a iterative closest point (ICP) algorithm using a point-to-plane fitness estimator. This algorithm first determines the planes in the point cloud generated by the radar. Next it will estimate the normal vectors to that plane for each point. Finally it will iteratively determine the best fit by computing the RMSE of the points to that plane in the direction of the normal vectors. Having now found the transformation matrix required to stitch the scans together, we can find the movement of the drone by simply stating that (most of) the scanned area is stationary. Thus the transformation of the terrain obtained from the ICP algorithm can be interpreted as the transformation of the drone itself.
This method of navigation requires the following conditions to be true:

- The terrain has enough features
- There is enough overlap between scans to accurately determine the transformation
- The data does not contain too much noise

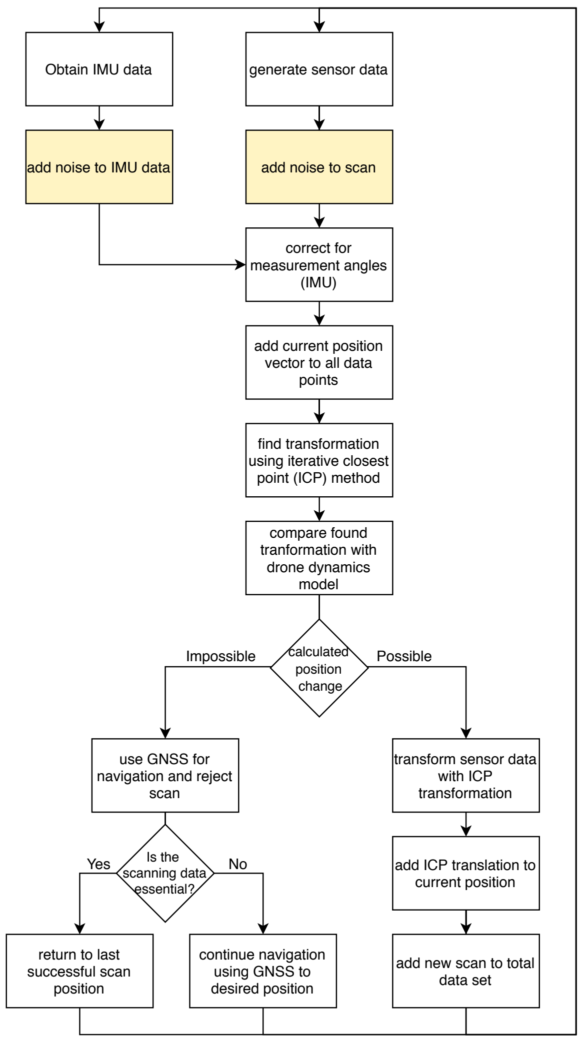


Figure 13.3: Flow diagram of 3D optical flow algorithm.

Additionally, in a future version of the algorithm the gathered data will be compared to existing height data from, for example, Actueel Hoogtebestand Nederland (AHN) Figure 13.4 to increase positional accuracy and improve path finding. This height data can also be used in the planning phase of the mission to give the operator a better overview of the situation.

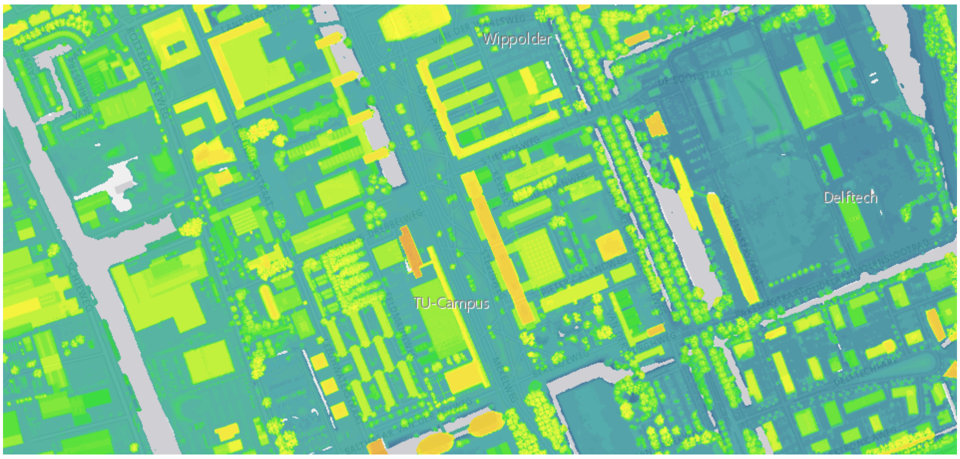


Figure 13.4: Height map from AHN of the TU campus.

13.6. Verification

In order to design the sensors and communication subsystem, some calculations were performed. Verification is done to make sure that these calculations are proper and with certainty it can be said that the corresponding requirements are met.

In order to verify the setup of the radar sensors and gimbal with the characteristics as provided by the manufacturer, a model was made and using this model, a test is performed. As this simulated testing setup is quite comprehensive, the procedure and results are presented in chapter 14.

Requirement Verification

Beside the setup of the radar sensors, a number of off the shelf components is selected to provide an indication of the possible performance and the related mass, volume and price for multiple components. Compliance with the set requirements on sensors and communication is stated by the manufacturers of the following components:

- rgb camera
- Drone and helicopter communication link
- localisation radio transmitters
- GNSS receiver

For the above mentioned components, verification is simple as it is performed through inspection.

The off the shelf gimbal used in the design does not meet the requirement HD-SENS-13, as Its maximum rotational velocity is as stated by the manufacturer. Therefore a modification to the component must be made. Future verification of the modified component could be performed through inspection, by rotating a mass similar to the sensors mass at the desired rotational velocities.

Compliance with requirement HD-SENS-05, HD-SENS-06 and HD-SENS-07 Can be verified later in the design phase through a test. In this test, the output of the IMU or a simulation of this output will be input to the algorithm as provided in [50]. Using this setup, then the IMU will be calibrated and following, the orientation estimations as provided by the algorithm will be compared to the known angles it is oriented in. As verification of this component's compliance is at this moment in the design process too detailed, and as it is expected that the requirements will be met as the used IMU in [50] has near identical performance as the IMU in the design, this verification will be performed later.
An overview of the sensor and communication requirements and their respective verification can be found in the requirement compliance matrix in Figure 15.1.

13.7. Validation

To confirm all real life compliance with set requirements, validation must be performed. In the case of the sensors and communication setup, a lot of selected reference components like the GNSS receiver, IMU, rgb camera, infrared camera etc. have validated and well documented performance. However, simple test still need to be performed to validate the component performance. This can be done with every component physically available. For instance the minimum camera rotation time can be recorded to assess performance. These type of tests shall be performed for every component in order to validate their compliance.

Some real tests were performed on a reference design for the radar sensors used, showing results satisfying the set requirements for the drone system [15].

At this moment, these measurements provide confidence in the selection of the respective radar sensors. However, a more relevant validation is of the final setup, which will use the sensors in a different way, combined with all other components, which will allow more errors to propagate. Therefore, for validation, first an actual setup should be made, which will be used to perform tests in order to assess the compliance with the right requirements. This however, can only be done with all involved physical components in a test setup. Furthermore, in order to get desired data from this setup, an extensive amount of software is to be developed. This is possible in later phases of the design process.

13.8. Conclusion

A set up for sensors, data handling hardware, and communication components has been presented. Each component required to perform mission successfully from a sensors and communication perspective, is presented in this chapter. For each component, a reference off the shelf component is selected to be used in the system. For each component not satisfying set requirements, a suggested modification is presented.

As an additional note, the final decision of employing a millimeter wave radar as the primary means of performing scanning was directly influenced by the goal of satisfying the requirements put in place. More specifically, these were the requirement regarding the availability of limited funding in addition to the requirement stipulating the nature of low visibility in the scenery of the environment the drone would be operating in.

the two key influencing requirements which

An overview has been created in order to present in more detail, how exactly each relevant component will communicate with each other. This overview is presented in Figure 13.2.

Besides hardware, also the designed software solutions are presented. This includes image processing in order to provide the drone operator with a better view, as well as a proposed method for appending radar measurements and localization using these measurements.

Furthermore, verification is proposed in order to assess the compliance with requirements for individual components. Finally, Future validation methods have been proposed for the sensor and communication setup.

[15] `https://www.ti.com/lit/ug/tiduen5a/tiduen5a.pdf?&ts=1589373408286` [Accessed on 21-06-2020]

14
Simulation Modelling

14.1. Introduction

The process of simulation modelling, in essence, involves, at first, the creation of a "digital/virtual prototype" of a real-life physical model. This is achieved by using the key parameters/properties of the real-life physical model in order to construct mathematical model of it. After this, an analysis of the resulting simulation model is carried out so as to be able, for instance, predict the performance of the simulation model as if in the real world.

Despite there being a consensus on the matter of real-life experimental tests being of greater trustworthiness, the high complexity & cost, time required and omnipresence of bureaucratic regulations, associated with real-life experimental tests are often rather off-putting as compared to with the usage of simulation model tests.

A simulation model testing platform, built for a complex system, enables the discovery of various possible/potential unexpected fault modes, via the fast & massive repetition of experiments. This, in turn, accelerates the pace at which research, development & prototyping can take place. As such, this then results in the ability to more promptly respond and adjusting to the certification rules & regulations which are imposed by governments. This last point is of particular noteworthiness within the research & development field of Unmanned Aerial Vehicle's (UAV's).

14.2. Functional Analysis

The functional role which is fulfilled by the simulation framework, at its most abstract level, is that of being the provider of the means of evaluating the feasibility, performance and safety of varying design concepts. As for on a more concrete level, the simulation frameworks functional role can be broken down into the following tasks:

- The functional testing of the drone as a while or of a particular (sub)system or component of the drone, i.e., "does the drone, along with its on-board sensors, work properly under normal operating conditions or not?".
- The acceleration of prototyping and optimization tasks, i.e., determination of the maximum allowable velocity at which the drone may fly along a particular segment of a scanning coverage path.
- The generation of "virtual" scenery & conditions which are representative of the real-life operating environment, i.e., imitating appropriate weather & atmospheric conditions within a particular environment.

14.3. Simulation Framework

The framework of the simulation system, can, as a whole, be split up into three main subsystems. The first being the vehicle's simulation subsystem. This main subsystem is responsible for the generation of the vehicles various states in accordance with the control signals it receives. The second major subsystem component is the 3D environment simulation subsystem. The role of this subsystem is to generate visual data by using the various states of the vehicle. Third and lastly, the sensor simulation subsystem fulfills the task of generating sensor signals by making use of both information on the vehicles various states & visual data generated. Figure 14.1

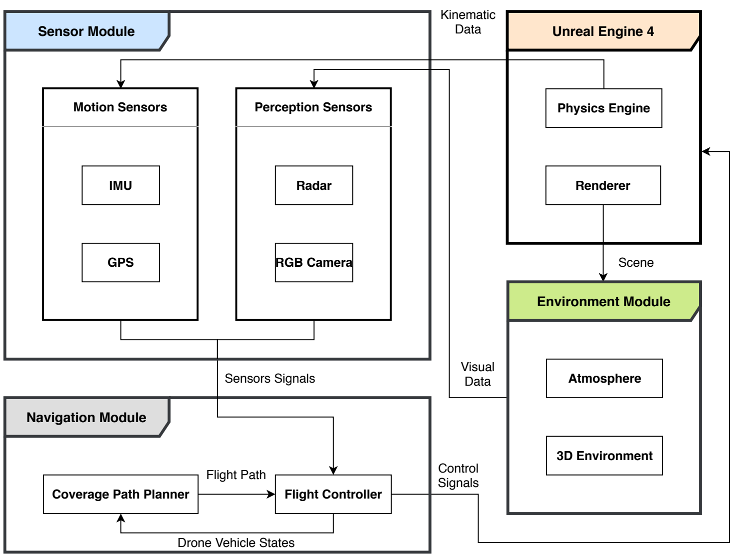


Figure 14.1: Schematic overview of the simulation framework architecture

14.3.1. Unreal Engine 4

Unreal Engine is a game development engine which was developed by Epic Games and launched in 2014. Although being a piece of software marketed primarily to those involved in the development of games, Unreal Engine 4 has, for roughly the past 3 years, been experiencing an increasing rate of adoption by individuals seeking to make use of the software various novel ways. One such example of this has been the increasing number of individuals and entities making use of the software as their means of performing simulations of autonomous vehicles. With AirSim, an open-source simulator for autonomous vehicles built on Unreal Engine (& Unity) and developed by Microsoft's Aerial Informatics and and Robotics (AIR), one is very straightforwardly able to generate simulations of high visual and physical fidelity[41].
By using the AirSim Python package, a user is able to retrieve data and take control of the vehicles present within the simulation environment running in Unreal Engine 4. This is achieved by making use of the numerous Application Programming Interface's (API's) which are exposed to the user by the AirSim package.

14.3.2. Environment Module

The environment simulation module takes on the responsibility of setting and adjusting environmental factors and conditions such as the time of day and geographical location of the environment within Unreal Engine 4. Most important of all, however, is the fact that this is the module responsible of adjusting the weather conditions present within the environment, with the help of weather API of AirSim[42]. Most crucially so, this provides the ability for the amount of fog within the drone's operating environment to be tailored at will. It is this feature which provides the greatest assistance in the pursuit of satisfying requirement HD-USR-SENS-01.

14.3.3. Sensor Module

The sensor simulation module consists of two components, a perception sensor component and a motion sensor component. The perception sensor component is responsible of receiving visual data obtained from sensors such as radars, laser range scanners and/or optical cameras. The motion sensor component, on the other hand, is responsible of ingesting kinematic data as input. It is the output data of the sensors which is processed to obtain information on the motion of the drone and 3D structure of the surrounding environment. This fusion and processing of motion and perception sensor data is crucial in order to deal with the coupling between the motion of the drone and the surrounding environment structure.

14.3.4. Navigation Module

The simulation platforms navigation module is composed of a coverage flight path planner component and a flight controller component. The flight controller plays two key roles. The first involves providing the coverage path planner component with the vehicle states it computes as a function of the input sensor signals it receives as input from the sensor module. Its second role involves the generation of control signals from the aforementioned input sensor signals which are then supplied to the physics engine of Unreal Engine 4.

14.4. Verification

14.4.1. Radar Sensor Verification

In order to verify the method of environmental mapping, a test must be performed to assess the performance of the scanning and data processing system. Resulting from this test should be the compliance with the following requirements:

- **HD-SENS-03**: The position of the drone shall be known at all times with a margin of error of <tbd> m.
- **HD-SENS-01**: The spatial resolution of the sensors shall be at most 1 cm in heavy fog conditions at a distance of 5 m.

Airsim[1], the UAV simulation software by Microsoft provides the possibility of modeling a perfect lidar sensor in a 3D environment and outputting the point cloud data as recorded by this model. This will allow the simulation of the radar sensor by processing the point cloud data provided, such that it will represent the output of the mm wave radar sensors that will be used on the drone. This section will provide insight in how Airsim's lidar model data is modified in order to represent the radar as used in the design concept.

The radar sensor used in the design will be the TI-AWR2243. This sensor has a field of view of 70 degrees and an azimuth angular resolution of 1.4 degrees, as stated by the manufacturer [2]. As a contingency factor, it is assumed that in practice, the sensor will have a resolution that will be half as detailed. Therefore, the assumption is made that the sensors will have an azimuth angular resolution of 2.8 degrees.
With the resolution set, it is assumed that objects appearing with an angle lower than the angular resolution, will be observed by the radar sensor, but this will result in the object's size appearing as large as the angular resolution, which is larger than in reality.
The main type of noise in radar measurements is speckle. Speckle noise is characterised to be random multiplicative noise[23]. This results in an increase of noise deviation amplitude corresponding to an increase of measured distance. Therefore a formula is used to add speckle noise to the perfect data. this is done using Equation 14.1:

$$\sigma_v = \sqrt{\frac{\mathtt{VAR}(z)}{\bar{z}}} \tag{14.1}$$

In this equation, $\bar{z}$ is the true distance of an object as seen from the radar sensor, $\mathtt{VAR}(z)$ is the variance of the observed distances of the object and σ_v is the model standard deviation. In order to model the speckel, the perfect distance data from the lidar model is considered $\bar{z}$, then using the appropriate σ_v to model the sensor, an expected variance will result according to Equation 14.1. The modeled radar data is then sampled using a normal distribution with as mean the actual distance and as standard deviation, the assumed variance as provided by Equation 14.1.

The range resolution of the distance provided by the radar sensor, defined as: "the ability of a radar system to distinguish between two or more targets on the same bearing but at different ranges"[3]. will be about 0.60 m as stated by the manufacturer. Unfortunately, the perfect lidar senor provided in airsim does not provide the ability to distinguish multiple objects in the same bearing so only the closest object in a bearing will appear in a measurement.

Unfortunately, the rotational speed of the perfect lidar sensor can not be modeled to be around 1 rotation per second. This results in the perfect lidar sensor always providing a full rotational measurement from a single location. This is however not the case in reality, as the sensor will be sampling at 15 Hz while rotating at 1 rotation per second and whilst the drone is flying at a velocity higher than 4 meters per second. this will result in a point not being in the field of view of the radar sensor for more than half a second. at a drone velocity of 4 m/s, this will already result in at least 2 meter deviation from reality between two measurements if the

[1] `https://microsoft.github.io/AirSim/` [Accessed on 10-06-2020]
[2] `http://www.ti.com/lit/ug/tiduen5a/tiduen5a.pdf?&ts=1589373408286` [Accessed on 05-06-2020]
[3] `http://www.ti.com/lit/ug/tiduen5a/tiduen5a.pdf?ts=1591705074270` [Accessed on 11-06-2020]

drone's propagation is not taken into account.
This deviation can be reduced by using the IMU and GNSS data to estimate the drone's propagation during the measurements. It is however, too early in the design phase to develop such a comprehensive algorithm. Therefore, for now, it is assumed that a single 360 degree measurement is performed by the radar sensor every second. when in reality this would be 15 different measurements with a field of view of 70 degrees. another mitigation in reality could be to append every measurement individually to the point cloud, assisted by the gimbal (and corresponding radar) orientation.

An overview of the differences between the real radar sensors and the radar sensors as simulated is shown in Table 14.1 and a visualization of the simulated radar scanning pattern is given in Figure 14.2.

Characteristic	radar	radar simulation
field of view	70°	360 °
Sampling rate	15 Hz	1 Hz
Azimuth horizontal resolution	18°@1rpm	3°
Speckel noise standard deviation per meter	to be determined	0.01
Range resolution	60 cm	No objects detectable in same bearing
IMU data standard deviation	to be determined	3°

Table 14.1: Differences between real radar and simulation

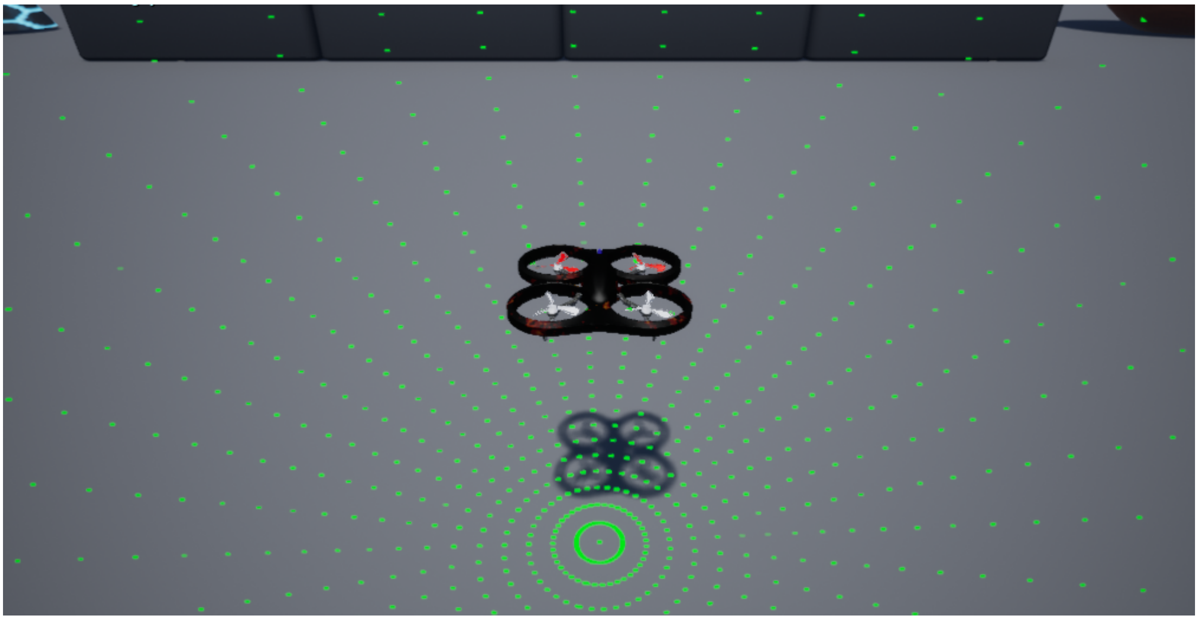


Figure 14.2: Visualization of simulated radar scanning pattern.

14.4.2. Algorithm verification

To verify the accuracy and stability of the algorithm, the drone was made to fly a pre-programmed path and its actual position was compared to position given by the sensor module. Since the accuracy of the radar sensor is unknown, the algorithm was tested with different levels of noise. Below the error measurements are plotted for different noise levels, the first graph shows the development of the error over time whereas the second graphs shows the histogram of the error measurements.

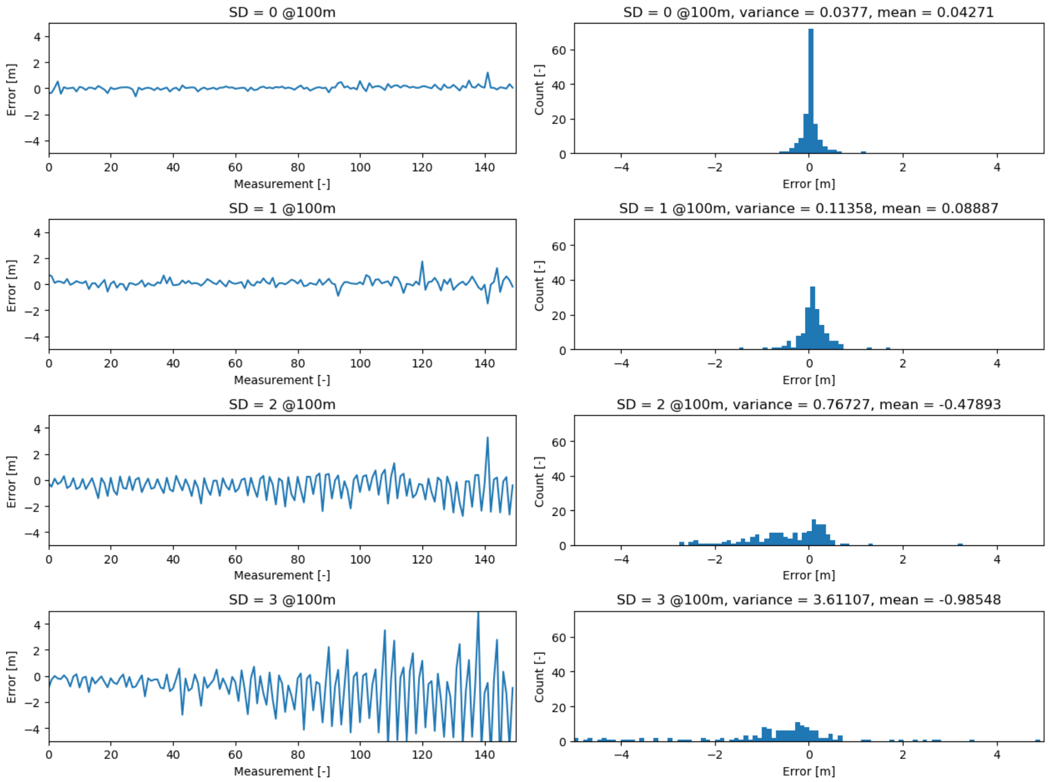


Figure 14.3: Error plots for different values of the noise standard deviation (Fs = 2Hz).

As can be seen, the position error grows significantly with increased noise. Furthermore, the error seems to oscillate around zero. No investigation has been done into the cause for these oscillations, for further development it would be interesting (necessary even) to do further research on this subject.

According to the manufacturer's specification, the actual performance would be comparable to the SD = 1 @100m plot. Also note that no noise reduction or filtering has been applied to the sensor data. It is expected that performance would be significantly improved when the data is properly denoised and the output is compared to a model of the drone kinematics. As mentioned before, using existing height map data can help reduce drift and increase accuracy as well.

14.5. Validation

Before moving onto making any further assumptions regarding the potential additional help which may be provided by histogram equalized enhanced images, it would first be wise to analyse the results of performing such image processing within the simulation framework. In particular, such an analyse of the potential of this image processing technique to deliver any assistance of the sorts to the helicopter pilot, would require setting the weather conditions within the drones simulation environment to be representative of those expected in real life. The result of enhancing the RGB images captured by the RGB camera in a simulated environment with a level of fog of 95%[4] can be seen below in Figure 14.4.

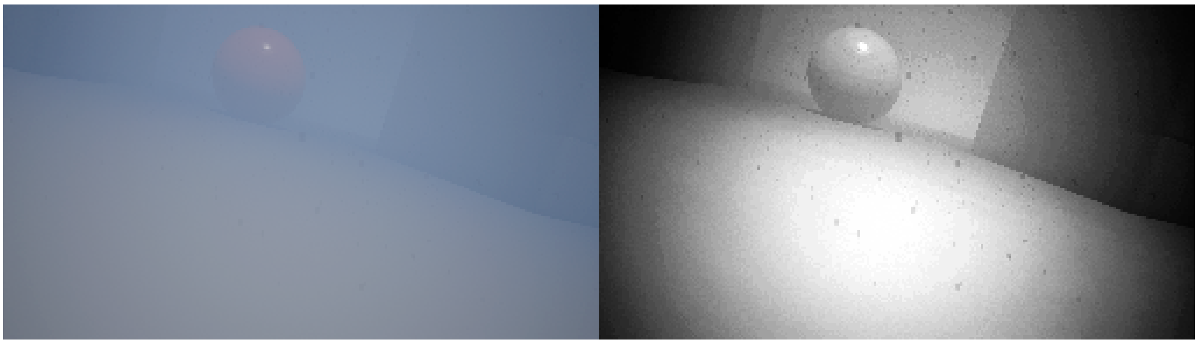


Figure 14.4: Comparison between (left) a raw RGB image and (right) the result of applying the histogram equalized

14.6. Simulation Results

After implementation of different simulation systems, a three dimensional scan of the environment is created. A visualization of a small number of scans and a larger number of scans are shown in Figure 14.5 and Figure 14.6 respectively. The color of the scanned points indicate the distance from which the point was scanned. It is important to keep track of this information, since the accuracy of the radar decreases with range. This way scanned points can be replaced by more accurately measured points once the drone gets closer. Furthermore, the red ball indicates the position of the drone at the moment the image was taken.

[4] This fog percentage value is set using the environment module of the simulation framework. However, due to the lack of documentation in the AirSim source code, it was not possible to further investigate its origin.

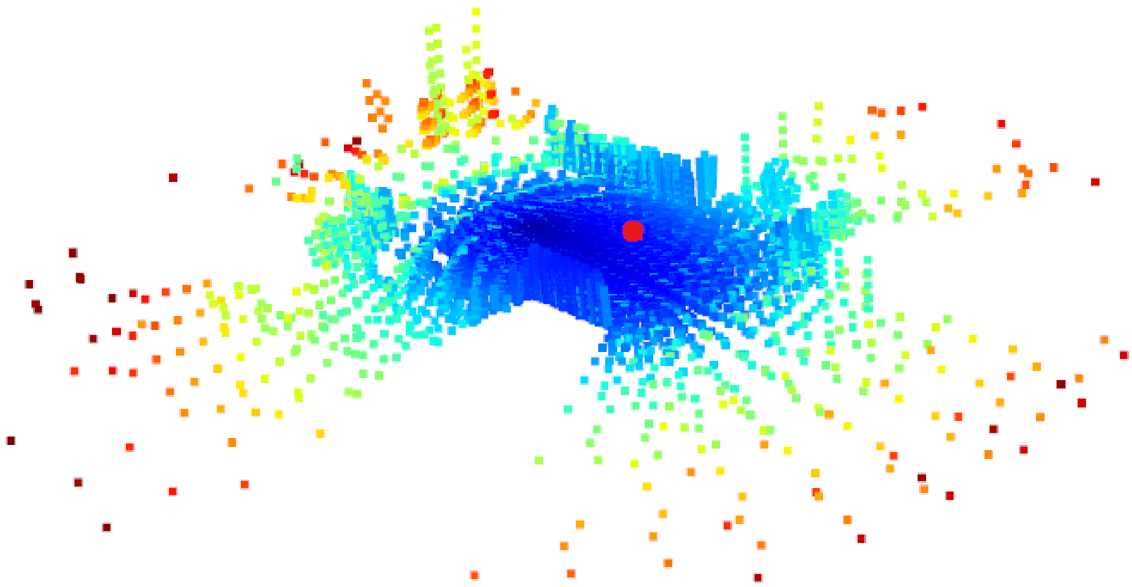


Figure 14.5: Example image of a small number of scans.

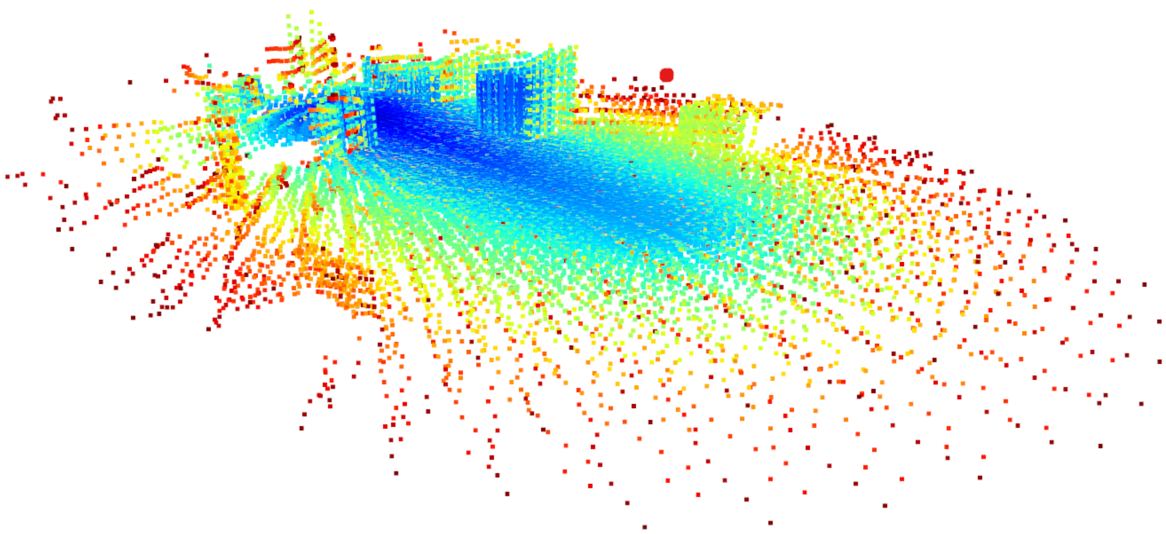


Figure 14.6: Example image of a larger number of scans.

15 Requirement Compliance Matrix

As a final check on the progress of the design so far a Requirement Compliance Matrix (Figure 15.1) has been made. In this matrix all of the requirements that are important for the design of the drone are listed. For each requirement the Design Value, which is the value the design achieves or is likely to achieve as of now, and the Required Value, which is the value the design must achieve based on the requirement, are mentioned.

There are 3 levels of compliance. 'Yes' means that the design as it is now complies, or is likely to comply upon testing. 'Unknown' means that it is not known whether the requirement is complied with or not, this can be because of a lack of information, or because confirming if the requirement is complied with is not reliably possible without actual testing. 'No' means that the design does not comply with the requirement as it is now. This does not mean that the design is impossible, but it does mean that special attention will have to be paid to this in future design phases, to either comply with the requirement or adjust it in such a way that the mission is still possible. This is explained for every non compliant requirements in the matrix, as a form of feasibility analysis.

Finally, every requirement is assigned a verification method with which the requirement can be verified eventually.

Requirement	Design Value	Required value	Design Compliant?	Verification Method	Explanation
User Requirements					
HD-USR-PERF-03	8.5 minutes	10 minutes	Yes	Demonstration	As mentioned in the sensitivity analysis, a mission time of about 8.5 minutes is expected by the performance model. The sensors should be able to keep up at speeds of up to 15 m/s. Performance simulation flies at 11.2 m/s, well below this sensor limit. This will have to be demonstrated in full mission tests.
HD-USR-SENS-01	No negative impact from fog conditions	No negative impact from fog conditions	Yes	Test	The usage of radar sensors in the concept will allow for sensing which is not distorted by humidity or fog.
HD-USR-SAFE-01	No Helicopter Endangerment	No Helicopter Endangerment	Yes	Analysis/Demonstration	The design as of now is specifically made to not endanger the safety of the helicopter in any way by dropping the drone straight downwards. This wil have to be supported by further simulation analysis and mission testing.
HD-USR-SAFE-02	No Helicopter Endangerment	No Helicopter Endangerment	Yes	Inspection	The drone is no longer retrieved by the helicopter, so its retrieval will not endanger the helicopter.
HD-USR-SYS-01	3.8 kg	10 kg	Yes	Inspection	Drone weighs around 3.8 kg with contingencies up to 4.3kg
HD-USR-SYS-02	535x535x250mm	535x535x250	Yes	Inspection	With permission of the customer the dimensions of the maximum box were changed to 535x535x250 to fit the drone exactly while accounting for 15.5 inch propellers and 1/4 propeller diameter spacing between them.
HD-USR-SYS-SUST-01	Unknown	1000 sorties	**Unknown**	Analysis/Test	Currently it is unknown whether all components will be able to achieve 1000 sorties. It will require more detailed testing and analysis to be able to determine. The off the shelf components were picked to be durable, so those should come a long way.
HD-USR-SYS-SUST-02	Lithium Polymer	Lithium Ion	**No**	Inspection	This requirement is not complied with because it was found that using Lithium-Ion batteries would be more or less impossible with the C-rates required for the drone to operate. The initial consideration for using lithium ion batteries was because they were supposedly safer than Lithium-Batteries, but from the analysis performed it seems that both battery types would be subject to a large amount of scrutiny in the certification phase. Mitigation methods were put into place to make sure this risk is manageable.
HD-USR-SYS-SUST-03	Zero-emission	Zero-emission	Yes	Inspection	A logical result from the drone running on batteries. No other sources of greenhouse gasses are present on the drone.
HD-USR-OPS-02	Mission Not Negatively Affected by Downwash	Mission Not Negatively Affected by Downwash	Yes	Analysis/Demonstration	Currently the drone should be able to perform its full mission without being negatively impacted by the helicopter downwash. Any downwash disturbances produced can as of now be corrected by the control system during deployment. There should not be any other points in the mission when the drone operates in the helicopter downwash. A caveat to this is that it is unknown whether the downwash can damage the drone structurally, so this will have to be analysed/demonstrated in the future, along with real life analysis and demonstration of the drone dropping through the helicopter downwash.
HD-USR-SYS-CST-01	€51,651	€60,000	Yes	Inspection	The cost breakdown structure results in a price pre drone of €51,651 at 360 drones sold. This includes an expensive HUD.
Stakeholder Requirements					
HD-STKH-01	Makes it possible to reach patient in low visibility conditions.	Makes it possible to reach patient in low visibility conditions.	Yes	Test/Demonstration/Analysis	The entire design is tailored to make this possible. Will of course require heavy amounts of testing and certification, but as of now the design makes it possible to safely reach the patient/landing site.
HD-STKH-02	Does not comply with regulations.	Complies with regulations.	**No**	Demonstration/Analysis/Test	Currently the drone does not comply with regulations. It complies with most normal drone regulations, but it does not comply with regulations on autonomous flight and being dropped from a helicopter. This drone will require amendments to the regulations, but for the sake of this project it has been assumed that the regulations will be able to change for this drone's usecase. If that were to happen in the future, the design would comply with regulations as of now.
HD-STKH-03	Does not put bystanders at unacceptable risk.	Does not put bystanders at unacceptable risk	Yes	Test/Analysis	No risks that pertains to bystanders is below the yellow diagonal of the risk maps, thus being deemed acceptable. The design for now being considered safe will of course have to be checked with rigorous testing and certification.
HD-STKH-04	<tbd>	Hard to define, depends also on the specific mission. Would need to do extra research	**Unknown**	Test/demonstration	Both autonomy and the fact that the drone is used during a phase where the HEMS operator has the time to operate the drone means this should not prove to be a problem. However, unknown because very hard to determine exact value

Requirement	Design Value	Required value	Design Compliant?	Verification Method	Explanation
Structures					
HD-STRC-01	5G	3.5G	Yes	Test/FEM analysis	This has been proven, however still preferably be validated using test/fem analysis
HD-STRC-02	2G	2G	**Unknown**	Test/FEM analysis	The landing gear itself still has to be tested and analysed, since this involves impact analysis
HD-STRC-03	45 deg	15 deg	Yes	Test	This is simply proven by a statically determinate model, it can be tested as well pretty easily
HD-STRC-04	unknown	<tbd>	**Unknown**	Test/FEM analysis	This has not been analysed for this phase
HD-STRC-05	unknown	<tbd>	**Unknown**	Test/FEM analysis	This has not been analysed for this phase
HD-STRC-06	Unknown. CFD analysis is required.	Withstand downwash	**Unknown**	Test	Because there are limited resources for aerodynamic analysis this has not been explored yet.
HD-STRC-07	19.61 mm	20mm	Yes	Test/FEM analysis	This has been analysed using a virtual work method with some assumptions that simplify reality, therefore validation using test/FEM analysis is still.
HD-STRC-08	generally around 20% of the strength	Tensile strength/shear strength	Yes	Test/FEM analysis	Structural components are designed to be below yield stress for all phases of the mission.
HD-STRC-09	Unknown	1000 sorties	**Unknown**	Analysis	Not currently known. Detailed analysis on this will be required in detail design.
HD-STRC-10	Unknown	60 minutes	**Unknown**	Demonstration	Compliance is likely, but it would have to be demonstrated first.
HD-STRC-11	Can be attached to skids	Can be attached to skids	Yes	Inspection	Drone is currently designed for attachment to the frontside of the skids of the helicopter.
HD-STRC-12	320mm	Unknown	**Unknown**	Testing	This requirement cannot be proven as there is no clear literature on what the ground clearance should be.
HD-STRC-13			Yes	Inspection	The landing gear is currently designed such that it does not obstruct the view of the sensors
Propulsion					
HD-PROP-01	180 s	20 s>	Yes	Demonstration	Manufacturers data.
HD-PROP-02	3.5	3>	Yes	Test	Manufacturers data.
HD-PROP-04	Not Specified	170 hours>	**Unknown**	Test/Analysis	Lifetime not specified by manufacturers. Will require testing and analysis to verify.
HD-PROP-05					
HD-PROP-06					
HD-PROP-07	2.625	1.5>	Yes		From design value for HD-PROP-02
HD-PROP-08	Specifically Designed for LiHV Battery Voltage Range	22.8 to 26.1 Volts	Yes	Test	Manufacturers data.
HD-PROP-09	Not specified, but likely to comply for upper ranges.	-40 to 35 degrees celsius ISA	**Unknown**	Demonstration	Not mentioned by motor manufacturer, but likely to comply for upper ranges.
HD-PROP-10	2.2 kg	<2.5 kg	Yes	Inspection	All propulsion component masses added up.
HD-PROP-11	Each propeller separately controllable	Each propeller separately controllable	Yes	Demonstration	ESCs allow for individual propeller control
HD-PROP-12	Propellers Foldable to within box	Propellers Foldable to within box	Yes	Demonstration	15.5 Inch propeller can be folded to be within the size requirement box.
HD-PROP-13	1/4 Propeller diameter	1/4> Propeller diameter	Yes	Inspection	Follows from drone configuration.
HD-PROP-14	15.5 In.	<16 In.	Yes	Inspection	Manufacturers data.
HD-PROP-15	175 g	<200 g	Yes	Inspection	Manufacturers data.
HD-PROP-16	Unknown (All components mentioned to be water and dust proof)	IP56	**Unknown**	Demonstration	Individual components are listed as water and dust proof, but how water and dust proof is unclear. This will have to be tested by demonstration to be sure the system can hold up to water and dust.
HD-PROP-17	15C	5C>	Yes	Inspection/Test	Manufacturers data.
HD-PROP-18	30C	25C>	Yes	Inspection/Test	Manufacturers data.
HD-PROP-19	55A	36A>	Yes	Inspection/Test	Manufacturers data.
Sensors					
HD-SENS-02	<0.5 meter	0.5 meter	**Unknown**	Test	It is expected that this deviation is less than 0.5m, as provided by the manufacturer of the radar sensors. However, a test must be performed in order to verify.
HD-SENS-03	Unknown	<|0.5 m| error	**Unknown**	Test	Optical flow localization concept is to be proven by test with the physical radar sensors
HD-SENS-04	Unknown	<|0.5 m| error	**Unknown**	Test	Helicopter localization concept is to be proven with physical radiotransmitters.
HD-SENS-05	Unknown	<|5 degrees| error	**Unknown**	Test	This design value is the result of integration of the sensor data, therefore verification can only be done with the actual component and correct software.
HD-SENS-06	Unknown	<|5 degrees| error	**Unknown**	Test	This design value is the result of integration of the sensor data, therefore verification can only be done with the actual component and correct software.
HD-SENS-07	Unknown	<|5 degrees| error	**Unknown**	Test	This design value is the result of integration of the sensor data, therefore verification can only be done with the actual component and correct software.
HD-SENS-08	360 degrees	360 degrees	Yes	Review of design	Gimbal will rotate continuously, creating a synthetic field of view of 360 degrees
HD-SENS-09	90 degrees	≥ 90 degrees	Yes	Review of design	Curved allignment of radar sensors will allow for a 90 degree field of view visisble.
HD-SENS-10	Unknown	None	**Unknown**	Test	It is at this point unknown what equipment of the helicopter could be interfered with, therefore, assesment can not yet be performed.
HD-SENS-13	2 pi rad/s	4 pi rad / s	Yes	Inspection	
HD-SENS-14	350 meter	≥200 meter	Yes	Test	As stated in manufacturers data.
HD-SENS-15	Unknown	≤ 10 cm	**Unknown**	Test	With the physical radar, tests can be performed
HD-SENS-16	yes	yes	Yes	Demonstration	
HD-SENS-17	5 seconds	≤ 5 seconds	Yes	Test	
HD-SENS-18	1920 x 1080	1920 x 1080	Yes	Review of design	Manufacturers data.
Communication					
HD-COMM-01	Unknown	yes	**Unknown**	Demonstration	It is expected that communication will not suffer from presence of fog. However, this can only be verified through a demonstration using the physical components.
HD-COMM-02	>40 kilometers	2000 meter	Yes	Demonstration	Cannot find information from manufacturer
HD-COMM-05	12 megabits per second	10 Megabits per second	Yes	Demonstration	Manufacturers data.
HD-COMM-06	12 megabits per second	600 kilobits per second	Yes	Demonstration	Manufacturers data.
HD-COMM-09	Unknown	None	**Unknown**	Test	It is at this point unknown what equipment of the helicopter could be interfered with, therefore, assesment can not yet be performed.
Control and Stability					
HD-CRST-01		138 meter	**Unknown**	Analysis	The drone shall be controllable at 138 m from the source of the downwash. The control system in the HEMS drone model is not able to analysis this reqirement because of the assumption that is made in the model. The assumption was the thrust of the motor does not affacted by the wind at all. It is still possible to simulate how the drone react to the downwash vertically but it is not going to be a reliable result.
HD-CRST-02	<<138 m	138 meter	Yes	Analysis	The drone is able recover from tumbling after deployment before losing 138 m of altitude within a few seconds.
HD-CRST-05		13.89 m/s	**No**	Analysis	The drone shall be controllable with winds of up to 13.89 m/s from any direction. The drone shows a sign of stable but the error in the desire x and y location is huge.
HD-CRST-06	<45	<45	Yes	Analysis	The roll of the drone does not exceed 45 degrees during cruise
HD-CRST-07	<45	<45	Yes	Analysis	The pitch of the drone does not exceed 45 degrees during cruise

Requirement	Design Value	Required value	Design Compliant?	Verification Method	Explanation
Power					
HD-PWR-02	8000 Mah	6462 Mah	Yes	Test	
HD-PWR-03	600 cycles	1000 Cycles	**No**	Analysis	Based on manufacturers data.
HD-PWR-08	No warning implemented	Warning at 3.7V	**No**	test	A system for providing a warning on battery status has not been designed yet, but can be implemented relatively effortlessly in the future.
Flight Performance					
HD-PERF-01	10-12	9.2	Yes	Test	Current estimations put the drone at an achievable cruise speed of about 10-12 m/s, exceeding the 9.2 m/s minimum velocity requirement.
HD-PERF-02	Unknown	5 m/s	**Unknown**	Test	The current maximum achievable vertical velocity can not be estimated yet, but considering the thrust to weight ratio it is very likely to comply once it is tested.
HD-PERF-04	8 km	7km	Yes	Test/Analysis	Performance estimations put the drone at a range of 8km at a cruise speed of 9.2 m/s.
System:					
HD-SYS-01	Unknown	Land autonomously	**Unknown**	Demonstration	At this point, no design is made on automated landing, so compliance with this requirement cannot be assessed. However, autonomous landing is implemented in various similar multicopter systems, therefore it is expected that this requirement will be satisfied.
HD-SYS-02	Unknown	IP56	**Unknown**	Test	Not every component used is rated IP56 or more, however, encasing will be designed in a more elaborate way, allowing the system to be rated IP56. This, however is not done during this phase in the design process.
HD-SYS-04	Unknown	2000 meter	**Unknown**	Inspection	This is dependent on the certification as provided by the airworthiness authorities. Too litlte information is yet available in order to assess compliance with this requirement.
HD-SYS-05	Identifyable as belonging to emergency medical services	Identifyable as belonging to emergency medical services	Yes	Inspection	The UAV system colors will be coherent with the corresponding HEMS helicopter.
HD-SYS-06	-15 to 35 degrees	-40 to 35 degrees celsius ISA	**No**	Test	The system shall be able to operate within an environment temperature range of -40 to 35 degrees celsius ISA
HD-SYS-CST-01	unknown	€5,000	**Unknown**	Analysis	No estimation has yet been performed on the yearly operation cost
HD-SYS-RISK-01	all electrical equipment with the exception of the gimbal	all electrical equipment	**No**	Inspection	No off the shelf gimbal with required characteristics was found. However, an off the shelf gimbal was found that would perform as required with a minor modification.
HD-SYS-RISK-02	all electrical systems for control	all electrical systems for control	Yes	inspection	
HD-SYS-RISK-03	Unkown	All off the shelf components	**Unknown**		The off-the-shelf equipment used in the drone shall have a TRL of at least 7
HD-SYS-SAFE-03	unkown	Stop at crash	**Unknown**	Test	A system has not yet been designed in order to stop motors during a collision
HD-SYS-SAFE-04	No interference	No interference	**Unknown**	Test	Tests of drone deployment and collision avoidance system shall verify compliance with this requirement.
HD-SYS-SAFE-05	No backup release mechanism is present	Backup release mechanism present	**No**	inspecition	No back up release mechanism has yet been designed. This will be done in a later design stage.
HD-SYS-SUST-03	unknown	80%	**Unknown**	inspection	
HD-SYS-REG-01	Likely not to comply yet.	Complies with EASA UAS regulations	**No**	Test/Demonstration/Inspection	The design as it is now will likely not comply with EASA regulations yet. Items like the attachment/drop system and the batteries will likely have to be iterated multiple times for the EASA to certify them.
HD-SYS-REG-02	Unknown	Does not influence CS-27 certification	**No**	Inspection	The CS-27 certifications are very extensive, and at this stage it is unclear whether the helicopter would still be CS-27 certified with this system, the likely assumption is that it would not be, requiring some iteration of the drone system to comply with helicopter regulations, but similar systems like the drop beacon and the heavy police cameras on the front of the helicopter have been certified for use, so it is likely a matter of iteration and extra safety matters, which should be feasible in the future.
HD-SYS-REG-03	Unknown	Certified for IFR	**Unknown**	Test/Demonstration/Inspection	The idea is that the system would make the helicopter certified for IFR flight, but as of now it is uncertain whether it fully would. This would have to be analysed in more detail in the future project phases.
HD-SYS-REG-04	Control inputs override autonomous controls	Control inputs override autonomous controls	Yes	Test/Demonstration	The control system is not entirely done yet, but it should be relatively trivial for it to comply with this requirement as the design is now.
Miscellaneous					
HD-MISC-01	Unknown	Batteries can be tested without disassembly.	**Unknown**	Demonstration	Not much attention has been paid to this requirement for now, but it should be relatively straight forward to implement in the future. The current progress towards this functionality is unknown.
HD-MISC-02	Deleted after each sortie.	Deleting after each sortie	Yes	Demonstration	The drone's collected data shall be deleted after each sortie.
HD-MISC-03	1 person	1 person	Yes	Demonstration	With the drone's dimensions and weight, it shall be easy for a person to pick up the drone, this can be demonstrated
HD-MISC-04	x				The production time of the system shall be less than <tbd> hours.
HD-MISC-06	Unknown	No limiting on helicopter avionics	**Unknown**		The controls and display of the drone shall not limit the use of the helicopter avionics.
HD-MISC-07					Any added controls and display shall be able to easily be removed from the avionics dashboard.
HD-OPS-04	unknown	Refuelingtime	**Unknown**	Demonstration	The refueling time is not known at this moment, and also it is too early in the desgin phase to make an accurate estimate of the maintanance time
HD-OPS-05	1 person	1 person	Yes	Analysis	Since no manual deployment is done, a single person can deploy and operate the drone, later in the design phase, a more elaborate description of all operator tasks can be made and from this analysis it can be concluded whether normal responsibilities are limited too much by the drone operation.
HD-OPS-06	unknown	30	**Unknown**	Demonstration	It is at this point not possible to produce an accurate estimate of the inspection time of the drone, therefore, the compliance with this required
HD-OPS-08	All critical components accessible	All critical componenta accessable	Yes	Demonstration	Can be linked to layout given in structures.
HD-OPS-09	yes	2 minutes	Yes	Demonstration	It is not yet backed by calculations, but no reason is found on why boot up time should be more than 2 minutes

Figure 15.1: Requirement compliance matrix

16
Sensitivity analysis

The design of an integrated system is an iterative process, and deviations can and will occur in the expected inputs and outputs between subsystems. Most likely, during a later phase in the design process, some system performance parameters will be different than initially expected. Thus, it is useful to check the robustness of the design, and how sensitive it is to different changes, through a sensitivity analysis. Different relevant parameters will be varied and the consequences on the total system will be evaluated. The calculations in this sensitivity analysis are performed using the calculation tools presented in section 9.4 to calculate the hovering endurance and maximum range.

16.1. Subsystem parameter variation

The first type of variation that is analysed is the variation in subsystem parameters. These parameters are those estimated for a given subsystem using the requirements that are then used in order to design and estimate other dependent subsystems. In this case, mainly the sensors subsystem (since this is the payload) parameters which were used to design the propulsion subsystem. The variations are the following:

- Payload (sensors subsystem) mass increase of 400 g (abut 10% of total weight increase)
- Payload power consumption increase from 50 W to 100 W

Payload mass

Payload mass is a parameter that will heavily influence the propulsion subsystem, whereas this parameter itself is independent from other subsystems and determined by what sensors are required. Hence it is a logical parameter to vary and include in the sensitivity analysis. Moreover, the overall mass of the drone has a contingency of 10% from chapter 8, so it is sensible to analyze the consequences of increasing mass. Thus, an increase of 400 g is considered, equivalent to an overall mass increase of about 10%. With this 400 g increase in payload mass, the general drone performance remains at a sufficient level. The hovering endurance has decreased to 12.2 minutes. The maximum range has decreased to 9.4 km, which is still larger than the expected mission range of 5.5 km determined in subsection 17.2.3. This increase in mass required from the sensors subsystem would thus not endanger compliance with any requirements.

Payload power consumption

This has a similar influence on the system as the payload mass, since increased payload power consumption means there is less energy available for the motors. Currently, the payload power consumption is estimated to be about 50 W. However, quite some uncertainty is involved in this estimation. For a large number of components, it is hard to estimate what the average power consumption will be, as little information is provided manufacturers. An increase with a factor of 2 is considered in this sensitivity analysis. With 100 W of power required for the sensors components, the hovering endurance becomes 13.3 minutes and the maximum flight range has decreased to 10.1 km. Both flight characteristics are, as in the previous parameter change, still complying with all requirements from the system.

16.2. Assumed component performance

During the detailed design phase, quite some assumptions are made on subsystem performance or characteristics. These assumptions are often based on data provided by component manufacturers or statistics. If these characteristics are different than initially assumed, this deviation will propagate to different subsystems, just like the subsystem outputs. Therefore a change in these assumed values will also be considered during the sensitivity analysis. The following assumed values will be altered and their impact on the total system will be assessed:

- Static thrust measurement data from propeller/motor manufacturer

- Power consumption data from propeller/motor manufacturer
- Battery parameters as given by manufacturer

Static thrust measurement data from propeller and motor manufacturer

The static thrust measurement data from manufacturers is likely a good estimate for the current design phase. However, a different environment than the manufacturer's testing environment will likely result in different behaviour, and additionally, the thrust produced will also vary with forward flight and wind. Thus it is important to vary the thrust relationship and see the effect on the main performance parameters. To do this, the thrust coefficient c_T, which relates the thrust to the square of the angular velocity (and had been found from manufacturer data), could simply be reduced by a factor of 10%.

As would be expected, this reduction meant that a higher RPM was needed to generate the same thrust as before, thus increasing also the power required by the motors and reducing the hovering endurance from 14.2 minutes to 12.3. Nonetheless, the range was only reduced from about 10.8 km to 9.4 km, which means the mission should still be achievable in this situation since the distance to be covered during the mission is only 5.5 km, as estimated in chapter 17. In fact, the coefficient can be reduced by a factor of up to 30% while still having enough range. In that case, however, the endurance does continue to reduce significantly, meaning the drone would need to maintain close to maximum speed at all times to be able to cover the needed distance, whereas in the original case the speed can be well below maximum while still covering the required 5.5 km.

Power consumption measurement data of motor and propeller from manufacturer

Again, as mentioned in section 16.2, a different environment can result in a different performance of motor and propeller parameters. Hence a variation in how much power the motor required for a given RPM is also interesting to examine. As with the case just above, since the torque coefficient c_M, which relates the torque to the square of the angular velocity, was found from the manufacturer data, this coefficient can also be reduced by 10%. Note that as mentioned in section 9.4, the torque coefficient is also equal to the power coefficient, so varying it is indeed the equivalent to varying the power consumption.

Similarly to the case above, reducing this coefficient meant more power (or equivalently, more torque) was needed to achieve a given RPM, causing similar effects such as reducing the endurance. Nonetheless, the reductions were slightly lower than for the c_T case: the hovering endurance was reduced from 14.2 to 12.8 minutes, while the range was reduced from about 10.8 to 9.7 km. Regardless, this distance is well above the required 5.5 km, so the mission would still be achievable. Similarly as for the thrust case, this coefficient could even be reduced by a factor of 30% while still having enough range, but again a high speed would have to be maintained constantly.

Battery parameters as given by manufacturer

Batteries specifically are subject to a change in performance with different air temperatures, their capacity reducing to up to half of their optimum in $-20°C$[51], so different performance than provided by the manufacturer is expected during the operation of the system. It is assumed that the only relevant deviation from perfect conditions is a decrease in usable capacity of the battery. Therefore, a reduction of the available battery capacity is analyzed. In the calculation tool, a factor of 0.5 is multiplied with the initial battery capacity, reducing the battery capacity from 8000 mah to 4000 mah.

The reduction of battery capacity resulted in a shorter hovering endurance of 6.7 minutes. The maximum range is reduced to 5.0 km, which is shorter than the expected range of 5.5 km required in order to successfully perform the mission. Achieving this 5.0 km range would also require the drone to constantly be travelling at maximum velocity, which is virtually impossible. With the above mentioned changes, success of a mission is deemed unlikely as the battery will not have the capacity to provide enough power to scan the required volume. In order to just meet the requirements on mission range and hovering duration, the battery shall have 60 percent of its normal capacity available. This would correspond approximately to an operation temperature of $-15°C$. Resulting from this analysis, a clear overview should be made in order to provide users with information on operational capabilities in different environmental situations.

16.3. User requirement variation

Besides Subsystem performance, also the performance as expected from user requirements will be varied in order to assess the system's performance. The requirements to analyze are:

- **HD-USR-PERF-03:** The drone shall perform the entire mission within 10 minutes.

- **HD-USR-PERF-01:** The drone shall be able to sense a cylindrical volume with a radius of at minimum 200m and a height of at minimum 100m.
- **HD-USR-SYS-02:** The drone's dimensions shall be at most 535x535x250 mm.

These are chosen since they are the main driving requirements related to performing the mission successfully, and also the ones which will affect the design of the drone.

Mission time

The maximum allowed time for the drone to complete its mission is a key requirement, as this requirement will determine the minimum velocity the drone will have to achieve. The given user requirement is that the drone should preferably complete scanning within 10 minutes. From the operational analysis of the drone in subsection 17.2.3, it is estimated that the drone will have to cover a distance of 5.5 km during its mission. Consequently, to cover this within 10 minutes a velocity of at least $5500/600 = 9.17 m/s$ is required. With the chosen design parameters (total weight of 3.8 kg, chosen components described in section 9.7 and section 20.3), at the flight condition for optimal (maximum) range, the drone can achieve a velocity of up to 17 m/s (calculated using the model described in section 9.4), leading to a completion time of about 5.4 minutes, which meets the requirement. Note that in practice the drone will not be able to maintain the max speed all the time even if this is desired, since maneuvering is necessary.

It is then interesting to reduce this maximum mission time requirement, and see how it affects the design. If the maximum time was reduced by 40%, down to 6 minutes, for example, would the drone be able to achieve this? The drone's estimated top speed is 17 m/s, which would yield a minimum mission time of 5.4 minutes, meaning the drone would not meet this new requirement. To examine if the design could be modified to achieve a higher top speed, first some analysis on how this top speed is achieved (and also modelled in this case) is necessary. This top speed is achieved by having the drone tilt to its maximum pitch angle, assumed to be about 35°. Note that the drone is technically not limited to this angle because of its thrust-to-weight ratio, in fact when tilted to 35° the thrust-to-weight ratio required for equilibrium is about 1.3: looking at Figure 16.1, the vertical component of the thrust must be equal to the weight, and thus the required thrust-to-weight ratio for equilibrium is simply $1/cos(\theta)$, with θ being the pitch angle. Thus, considering the thrust-to-weight ratio of the drone can go up to about 3.5, a pitch angle of 70° should be possible. However, this is only looking at the static or steady-state case, and the moment equilibrium is not considered for this simple point mass analysis. In practice, the maximum pitch angle will be limited by these other factors, thus why it was limited in the calculations to 35°. Similar drones (similar in total and payload weight) such as the DJI inspire 2 or the DJI Matrice 200 V2 also have maximum pitch angles of about 35 – 40° [1] [2].

The problem then arises, however, that the maximum speed at level flight cannot be increased without increasing the pitch angle. If the thrust is increased to accelerate the drone to a higher speed without increasing the pitch angle, the drone will then also accelerate upwards since the vertical component of the thrust will exceed the weight. By looking at Figure 16.1, it can be seen that the drag is what balances the forward component of the thrust, and since drag (or at least a component of the drag) is proportional to velocity, this is also what ends up determining the velocity achieved by the drone. Consequently, an interesting option would be to attempt to reduce the drag, however, a large component of the drag and drag-like effects actually arise from the rotor aerodynamics and not from the profile drag of the body itself (See section 10.2), and thus making the body "more aerodynamic," will likely not significantly increase the top speed. As also explained in section 10.3, however, the drag estimations have a relatively high level of uncertainty themselves, which then also introduces uncertainty into the velocity results. As a mitigation measure, the uncertainty is mainly on the "upper" side, thus the drag is likely to be over- and not underestimated, meaning the top speed is likely higher and not lower.

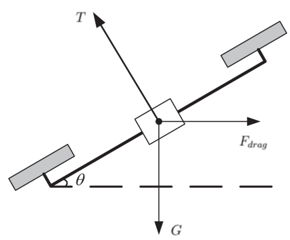


Figure 16.1: Free body diagram of drone at some arbitrary pitch angle [43]

In conclusion, it is not likely that a more stringent requirement for the mission time lower than 5.4 minutes is achievable without considerable design changes. As mentioned above, however, the velocity calculations

[1] `https://www.dji.com/nl/inspire-2/info#specs` [Accessed on 22-06-2020]
[2] `https://www.dji.com/nl/matrice-200-series-v2/info#specs`[Accessed on 22-06-2020]

are heavily dependent on the drag calculations, which are uncertain themselves, and thus this is also an important aspect to analyse in the next design stage with more detail, potentially involving a full CFD simulation and/or experimental results. Nonetheless, since the drag is more likely overestimated than underestimated (as explained in section 10.3), the estimated times will likely be lower. Moreover, even if the drag force was underestimated, it can still increase by a factor of 20% and the drone would still be able to cover the 5.5 km in just under 10 minutes, meaning the 10 minute requirement should be met even in a "worst-case" scenario.

Mission range

The required space to be reconnoitred during the mission is also a driving requirement, as a larger space to be scanned would imply a longer flight path. Currently, the requirement **HD-USR-PERF-01** state that the drone should be able to sense a cylindrical volume of 200 m radius and 100 m height, and the requirement **HD-USR-PERF-02** also states that the drone should be able to perform the scan at a distance of 2000 m from the helicopter. Taking this into account, it was estimated in subsection 17.2.3 that the drone would have to cover a distance of about 5.5 km to complete is mission. Note that this number indeed includes a 2000 m distance of cruising to the scanning area to consider the limiting case, but in practice this number will likely be lower for some missions meaning the distance to be covered is slightly lower. While it is not necessarily straightforward to relate the extra distance that would need to be covered if the volume of the space to be scanned increased, it is still possible to look at the current limits of the drone.

From the model described in section 9.4, the maximum range of the drone was calculated to be about 10.8 km. This means the current estimate on the distance that needs to be covered could increase by about 50% and the drone would still be able to cover it. Looking back at the analysis made in subsection 17.2.3, where circular perimeters were considered to calculate the scanning distance, the two mentioned perimeters could double in diameter and the total distance would still be under the maximum achievable of 10.8 km. At the same time, it is worth mentioning that the drone has to maintain its speed at the optimal 17 m/s, meaning the 10.8 km would be covered in 10.6 minutes, and thus the requirement on mission time would not be met in this case, and, again, more realistically, the drone cannot maintain this velocity for the entire time. Regardless, it can be concluded that the design has a good margin regarding maximum distance it has to cover, and this flexibility is also useful since it means range can be exchanged for speed if necessary.

Drone dimensions

The allowed dimensions of the drone are another driving requirement for the design. As explained in subsection 9.3.1, a larger rotor is generally desired for better efficiency. This is why for the the largest rotors that still allowed the drone to fit within the required 530 x 530 mm box were used for the design. Thus the main consequence of this requirement becoming more stringent would be the implied reduction of the rotor diameter so that the drone can fit within a smaller box. During the design phase some smaller propeller options were considered, and while going down to 13 inch propellers (from the chosen 15.5) seemed feasible, going further down to 9 inches, for example, was not since enough thrust could not be generated efficiently. It is difficult to connect the reduction in rotor diameter to a respective reduction in the 'box' size: the arm lengths can be reduced if the rotors now need less distance between each other due to their lower diameter, but this is hard to translate directly to the size of 'box' the drone requires. Nonetheless, it is still useful and important to be aware that the design can be highly sensitive to this specific requirement, since the rotor diameter cannot be reduced too much without making the design unfeasible.

Sensitivity Analysis Results Summary

The effects on the design, mainly on the maximum range and hovering endurance, are shown and summarized in Table 16.1.

Changed Parameter	Maximum range	Hovering endurance
Original	10.8 km	14.2 minutes
Payload mass increase by 10% (400 g)	9.4 km	12.2 minutes
Payload power consumption increase from 50 W to 100 W	10.1 km	13.3 minutes
Thrust coefficient (derived from test data) reduced by 10%	9.4 km	12.3 minutes
Torque coefficient (derived from test data) reduced by 10%	9.7 km	12.8 minutes
Battery capacity reduced by 10%	5.0 km	6.7 minutes

Table 16.1: An overview of different characteristic parameters

17
Operations and Logistics

Two critical components of every design are the operations and logistics. These aspects of the mission will be further elaborated upon in this chapter in order to give a clear overview of how the drone can be operated and maintained.

17.1. Requirements

From the requirements defined in the baseline report [2], the following ones are the most relevant to the operations and logistics:

User and Stakeholder Requirements

- **HD-USR-PERF-01:** The drone shall be able to sense a cylindrical volume with a radius of at minimum 200m and a height of at minimum 100m.
- **HD-USR-PERF-02:** The drone shall be able to perform the scan at a distance of 2000m from the HEMS helicopter.
- **HD-USR-PERF-03:** The drone shall perform the entire mission within 10 minutes.
- **HD-USR-SAFE-01:** The drone's deployment shall not endanger the safety of the HEMS helicopter.
- **HD-USR-SAFE-02:** The drone's recovery after the operation shall not endanger the safety of the HEMS helicopter.
- **HD-STKH-02:** The drone shall comply with government regulations.
- **HD-STKH-03:** The drone shall not put any bystanders at risk of significant harm.

System Requirements

- **HD-SYS-REG-01:** The drone shall comply with EASA and UAS regulations, where applicable for the mission.
- **HD-OPS-04:** The drone's maintenance cycle between sorties shall take no more than 30 minutes by a trained employee.
- **HD-MISC-02:** The drone's collected data shall be deleted after each sortie.

17.2. Operations

For the description of operating the drone, the mission will be split up in separate aspects will be elaborated upon further. A graphical representation of the mission operations can be found in Figure 17.1.

17.2.1. Pre-flight Inspections

At the beginning of each shift an assessment can be made using the current information on the weather, to see whether or not it will be beneficial to take along the drone. This decision is to ensure that the drone is not brought along on days where it is not required and is only a source of extra drag and weight to the helicopter.

At the beginning of each HEMS shift the helicopter has to be inspected by the pilot, which takes half an hour. During this time frame the new shift is not allowed to fly yet, so the old shift will deploy if required. During this period the drone can be then be inspected by the HEMS crew member. During the pre-flight inspection it is important to make sure that the software of the drone is booted up and tests are run, the batteries are charged, and no structural damage can be found on either the drone or the attachment to the helicopter. This is to ensure that the drone is always ready for operations.

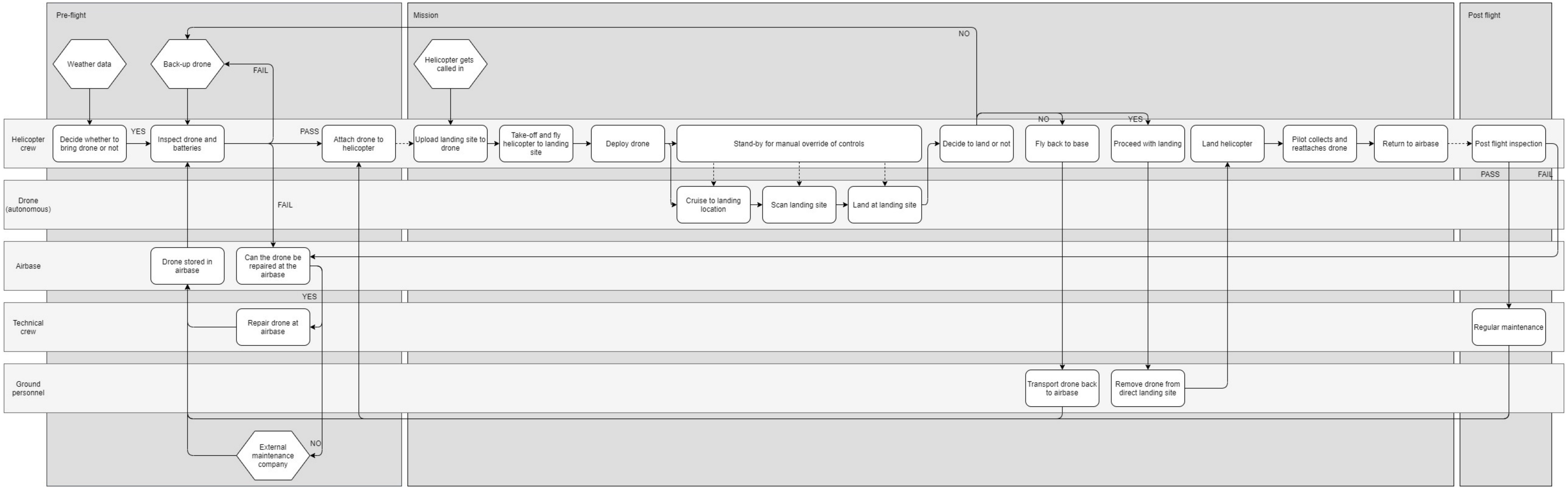


Figure 17.1: Operations diagram for the drone and involved parties.

17.2.2. Deployment

If it is decided to take the drone along on the mission. The HEMS crew member can then upload the preferred landing location into the drone during the cruise of the helicopter which is a time frame of somewhere around ten minutes. After this the drone can be deployed when it is not safe for the helicopter to get any closer to the landing site. On the deployment mechanism of the drone, an indicator will be present to inform the HEMS crew member that the drone is successfully deployed from the helicopter. If this is not the case, the mission should be aborted and the cause of the failure should be investigated further and resolved. If the drone deploys successfully, the drone will stabilise outside of the downwash and continue to cruise towards the landing site. This will be done autonomously using the information uploaded by the operator. During the entirety of the process the controls of the drone can be overwritten manually in case of software errors.

17.2.3. Scanning

During the mission, scanning will take up a large portion of the mission duration. The goal of this mission phase is to map the landing site and identify an approach path and a possible escape path if the landing is aborted at the last moment. In order to make sure scanning is done in a satisfactory way, it is crucial to first identify the possible obstacles that can be encountered. These are:

- **Buildings** - Buildings are most definitely the easiest obstacles to scan because of their large sizes.
- **Trees (or other vegetation)** - Trees are slightly harder to detect because of the fact that they are quite a bit smaller. However, they should still be relatively easy to map.
- **Bridges** - Bridges are interesting because they can potentially cross the airspace from side to side without being detectable on ground level. However, their large size should make them easy to map.
- **Cranes** - The challenges posed by cranes vary depending on the exact type of the crane. Tower cranes, for instance, give rise to the same sort of issue as previously discussed regarding bridges. On the other hand, tower cranes, situated not necessarily within the airspace zone but in close proximity, may give rise to the possibility of a long diagonal obstacle protruding into the airspace at an angle/
- **Power lines** - Power lines have the potential of being particularly problematic. Not only do they pose a challenge in terms of being obstacles within the airspace, but also in terms of their significantly smaller sizes as compared to the aforementioned examples.

The main problem that needs to be addressed is the fact that the power lines can be very hard to detect. There are a few possible solutions to this problem. The easiest solution would be to extend the time limit of the mission. However, this is not viable because the mission time is critical for emergency operations.

Another option is using third party data for the locations of power lines. This would make the scanning for power lines a lot faster because it is only required to verify that the cables are where they should be. The main drawback and the reason that this is not a good solution is the fact that there is no way to be absolutely sure that all data is up to date.

The third option is to change the sensor layout to make it easier to detect power lines. Radar can actually detect long objects that are thinner than the resolution. The problem here is the fact that the radar would still have to be a lot bigger and heavier than is possible in the drone. It could also be possible to use sensors for the electromagnetic radiation, but no suitable sensors that provide good enough results were found.

The final options is to make a preliminary scan of a slightly bigger area where the drone looks for power pylons. Power pylons are generally a little less than 400 meters apart, meaning that if there are power lines through the center of the scanning site the power pylons should be detectable when scanning the perimeter of a circle of 500 meters diameter (this gives a scanning range of 450 meters, while the requirement states 200 meters). The time this initial scan takes is definitely manageable and if a pylon is found, the drone can fly over to it and perform a detailed scan to see the direction the cables go from there. This final option was selected because it allows the mission to still be finished on time to meet the requirements and it provides a robust way of detecting potential power lines.

After the initial scan looking for power lines, the drone can come down and perform an initial pass through the center of the scanning area looking for a possible approach. If no approach is found, the data from the first pass can then be used to select the trajectory for a second pass resulting in an approach path for the pilot. A preliminary mission time estimate is given in Table 17.1.

Table 17.1: Rough estimation of mission time for a drone speed of 10 m/s

Distance	Cruise	2000 m
	Perimeter scan	500π m
	Fly towards pylon	2*200 m
	Fly around pylon	2*30 m
	Scanning of area	2*400 m
	Reposition for second pass	200π m
	Total	5459 m
Time		546 s

When the drone finishes scanning, it lands at the landing site. When the helicopter pilot has made the decision on whether to land or not, the drone can be picked up by a police officer on the scene that has been informed by the helicopter of the exact location of the drone. The drone is taken away from the landing site to protect it from being blown away by the downwash of the helicopter. If the landing site is inaccessible for ground personnel, the drone will have to be landed further away from the helicopter to protect it against the strong winds. Further research could be performed to explore the minimum distance the drone would have to have to withstand the downwash by itself.

17.2.4. Post Flight Inspections

After the HEMS operation, the same checks for structural damage should be performed as during the pre-flight inspection. Next to this, the batteries of the drone should be swapped. This can be done at the same time as the refueling of the helicopter. The used batteries can start charging, which can take multiple hours meaning that multiple reserve batteries should be present on the airbase. In the case the helicopter did not land, a backup drone should be put onto the helicopter and the pre-flight procedures should be followed. The retrieval of the drone is further elaborated upon in subsection 17.3.4.

17.2.5. Communication With Helicopter

During the previous design phases, it was found that the communication to the drone will be facilitated by radio transmissions. During the cruise of the helicopter, the preferred landing site is sent to the drone while it is still attached to the helicopter. After that the communication will consist of data being sent from the drone to the helicopter and control inputs from the helicopter to the drone if required.

17.2.6. Emergency Protocols

There are multiple things that can go wrong during the mission, as also described in chapter 7 and chapter 19. Because it is impossible to fully mitigate all of these risks it is important to have protocols in place something goes wrong. During HEMS operations there are three emergency severities. These result in:

- **Land when practical** - This is for problems that do not endanger flying the helicopter, but still mean that the mission will be aborted and the helicopter should land at the nearest practical spot, being for example a helipad or the airbase.
- **Land when possible** - This is for problems that pose a significant danger to the helicopter and means that the helicopter needs to land on the closest field where it is reasonably safe to land.
- **Land immediately** - This is for the most extreme cases and means that the helicopter needs to land, regardless of what is below the helicopter at that moment.

These protocols can still be applied to the helicopter, leaving what to do with the drone to still be considered. Some of the main emergencies to be operationally considered are:

- **Loss of connection to the drone** - This can happen both while the drone is still attached or when it is already detached. If the drone is still attached, the helicopter can land when practical and abort the mission. If the drone is already detached, the helicopter should still land where practical and abort the mission, but the drone should detect the loss of connection and land autonomously and try to send a distress signal for the police or other ground personnel to pick it up.
- **The drone hitting an obstacle and crashing** - The drone will be fitted with collision avoidance, but in case this fails the drone might crash. Depending on the altitude of the drone it might be possible to try and restabilise or deploy a parachute. For the helicopter, once again it should land as soon as practical.

- **The drone suffers from technical failures during flight** - This is similar to the drone hitting an obstacle, the main difference is that depending on the specifics of the failures the drone might still be able to be landed regularly whenever possible.
- **Drone deployment fails** - The deployment can fail by either the drone not deploying or not being able to stabilise. If the drone does not deploy, the same actions as the connection loss scenario can be taken. If the drone is not able to stabilise, the same actions as the drone hitting an obstacle can be taken.
- **The batteries catch on fire** - If the drone catches on fire while still attached, the fire might be contained in the fireproof box and the helicopter should land as soon as possible. If, however, the fire is threatening to spread to the helicopter the helicopter should land immediately. In the case of the drone already being deployed, the helicopter should land as soon as practical and the drone should be as soon as possible be landed safely if still possible.
- **The drone collides with the helicopter** - If this happens, depending on the damage to the helicopter, the helicopter should land as soon as possible or even immediately. The drone could still try to land depending on the sustained damage, or a parachute could be deployed to limit the risks for bystanders.

17.2.7. Other Operational Considerations

A final consideration considering operations is what to do if no possible approach path is found towards the initially selected landing site. If this is the case, it might be still be possible to select another landing site that is close provided that the drone still has enough energy left in the batteries to perform a second scan. However, due tot the fact that the batteries are designed for at least two mission as a safety margin, it is highly likely that a second scan is possible. The main drawback is the fact that the mission will most likely greatly violate the requirement that the mission shall be performed within ten minutes. Even though the requirement is violated, this is only a mitigation measure in cases that will be rare and this will still be a better alternative than aborting the mission.

17.3. Logistics

Next to the operations of the drone, it is also important to keep the logistics of the operations in mind. A few key logistical aspects of the final product will be elaborated further upon. These aspects are manufacturing, testing, maintenance, and other potential challenges.

17.3.1. Manufacturing and Assembly

When optimising the manufacturing process a lot of factors have to be considered. These include, but are not limited to quality, time, money, volume, and regulations. Within this section both the non-recurring and recurring processes will be analysed.

Non-Recurring Processes

Non-recurring processes are the processes that need to be performed once and can then be used for multiple drones. These processes are only required for the parts that are not off-the-shelf, these can be imported from third parties. The components that are imported from third party companies are the motors, propellers, sensors and batteries. This mainly leaves the structure and final assembly to be done. Due to the fact that the expected series size is relatively small as can be seen in the market analysis, no assembly lines will be required. The main non-recurring process will be constructing the mould for the structure. The mould will have to be specifically made for this drone because it is designed to fit this certain combination of components.

Recurring Processes

The recurring processes are the processes that have to be executed for every delivered drone. A lot of these processes will be executed by third party companies. Due to the limited series size, importing parts will most likely be cheaper than the non-recurring costs of setting up the facilities to produce them. This leaves the recurring processes to producing the structure and assembling the drone. Both processes can most likely be done at the same facility, once again due to the limited series size.

17.3.2. Testing

Within the aerospace industry it is crucial to test all products properly in order to increase reliability and safety. This testing is performed both during the design phase, to make sure that the product works as intended, and after the design phase, to make sure that the product is assembled with adequate quality.

During the design phase, the testing will be used performed according to the requirements given in government legislation. The main goal of this testing is to get all the required certification to be allowed to operate the drone. Apart from verification using analytical analyses, the testing will mostly have to be done with prototyping and more advanced software. These will only be considered in the later phases of this project.

After the design phase, the testing will be performed both on the incoming materials and parts and on the produced assemblies. In order to test it is important to make sure that facilities and equipment are available. The testing can be done in the same facilities as the manufacturing. The only extra thing that needs to be taken into account is potentially some extra equipment, but these can also be taken care of in a later design phase.

17.3.3. Maintenance

Simple maintenance can be performed at the airbase itself. This maintenance consists of swapping easily accessible parts. The main advantage of doing maintenance this way is the limited downtime of the drone. If the structure or wiring or other more complicated parts need to be repaired or replaced, this can be done at the same place as manufacturing of the drone.

17.3.4. Other Logistical Problems

Removing the mid air retrieval as requirement made the overall design significantly simpler. However it also introduced a big logistical problem that has not yet been addressed. This problem lies in the fact that the drone needs to be transported back to the airbase where the helicopter is stationed in situations where the pilot decides not to land the helicopter. In order to solve this problem, the following options were considered:

- **Brought back to base by first responders (either police or ambulance personnel)**
- **Brought back to base by a third party**
- **Recovered by personnel from the airbase itself**
- **Not recovering the drone at all**

The first option would most likely be the fastest option because the first responders are already on site when the drone lands. The main problem however is the fact that driving the drone back to the airbase takes quite some time which the ambulance personnel definitely cannot miss and the police most likely also not. Especially considering that traffic accidents and emergencies alike are more frequent and more severe on days with bad visibility [5]. This means that the first option is not viable.

The second option has the advantage that it does not take any time away from the first responders. There are still disadvantages, however. These consists mainly of the cost and the extra time it takes the drone to get back to the airbase, thus limiting the availability of the helicopter unless multiple backup drones are present. Even though the cost will likely not be that big of a problem, the extra time is. The helicopters in the Netherlands cover an area with a radius of approximately 130 km[1]. This means that worst case it can take longer than two hours to get the drone back to the base if the courier starts driving as soon as the drone lands meaning that there has to be an extra drone at the airbase to cover this time making this option unfavorable.

The third option is quite similar to the second option except for the fact that the cost will be significantly smaller and that the car can probably dispatched earlier. It is also possible to take equipment for repairs or transport if required. This option is preferred over the second option due to the overall reduction in cost.

The fourth and final option is to leave the drone and replace it. This option is outclassed by the other options in basically every aspect. First of all, the cost of a new drone will be way higher than the cost of a courier. Second, the time to replace the drone the drone will be higher than the courier and finally this option is not sustainable due to the waste and all the extra resources and energy spent in manufacturing.

Looking at the advantages and disadvantages of these four options, it seems best to go for the third option because it is the cheapest and fastest option (apart from the first option, which is not viable). This means that if the pilot decides not to land, a car will be dispatched from the airbase to pick up the drone at either the landing site or a nearby police station, depending on which one is more convenient. It is also required, depending on the needs of the operator, to have a second drone at the airbase ready for deployment to cover the time the original drone is transported.

This still leaves the problem of the drone landing in an area that is inaccessible for ground personnel, hence the call for a HEMS operation. If this is the case there is no easy way to get the drone back. In this case

[1] https://www.umcg.nl/NL/UMCG/Afdelingen/mobiel_medisch_team_MMT/voertuigen/helikopter/Paginas/default.aspx [Accessed on 08-06-2020]

there are two main options. The first one is to fly the drone to a more accessible location and the second one is to leave the drone and get a replacement. First of all it is noted that in general the odds of this happening are very low. However, from a sustainable and economical point of view it would be a waste to just leave the drone. This leaves the preferred option of having the drone operator manually fly the drone to a spot where it can be recovered. Ultimately this decision will be made by the crew aboard the helicopter and will be based on the charge left in the drone, the fuel left in the helicopter, and whether or not the extra time can be spared. The last criteria also means that the decision heavily depends on the exact location of the drone and the closest recovery point.

17.4. Design Recommendations

From these observations, multiple recommendations can be made. The most notable is to keep spare parts and batteries on the airbase to perform maintenance at the base if possible. Furthermore, from a logistical standpoint it is important to keep one or multiple drones as reserve in case the helicopter does not land.

18
Sustainability Analysis

Sustainability has been a troubling subject for this project. This is because of the conflict of interest between saving a life the best way currently available and conserving resources so as not to burden the planet, today and in the future. The relevant stakeholders in this situation can be divided along the sides of this conflict. However, these groups overlap as the people of today have both an interest in saving the lives of themselves today, but also in retaining a livable situation in the future, for themselves and the people they care about that will exist and live in this future, that is shaped by the actions of today. Thus the question of sustainability of this possibly lifesaving project wanders into the realms of philosophy and morality.

Previous Work

At the start of the project, a strategy was laid out as to leave the decisions in this moral problem to the relevant policymakers. Analyses on environmental sustainability would be made as to guide the policymakers by providing information comparing the option of using this product to other options. The waste management hierarchy was introduced as a tool for exploring more sustainable design options for subsystems. It is best summarized as "the 5 R's": refuse, reduce, reuse, recycle and rot. In that order, these present options for end-of-life waste reduction. Furthermore life cycle assessment is a metric that can be used to determine environmental impact of a product during all the stages of the life cycle of a product. This could be used for trade-offs, but was eventually only extensively used for the final product. [4]

When investigation design options to set a baseline, a few items were pruned from the tree for being unsustainable, usually tied to being single-use, which violated user requirement HD-USR-SYS-SUST-01 on being suitable for a 1000 sorties. [2]

After multiple meetings with the client, it became clear that sustainability would be a low priority trade-off item for the design. As the concept choice did not have a clear winner, sustainability was, amongst others, used as an additional consideration. Sustainability justifies not using a concept involving multiple drones, as the extra material and energy used during manufacturing, and the extra waste at the end of life, would make this concept more unsustainable than the other concepts considered. Another item discussed with the client was dropping the mid flight retrieval requirement. To solidify this change, some comparisons were made. First it was assessed what the effect of waiting for the drone to scout would be on CO2 emission over a year. There would be a 6 percent increase in CO2 emission if the drone was used on misty days. This is based on 8000 flights over a year and 85 misty days a year. [1] This 6 percent increase would be unfavorable for the drone. But one can question the validity of this comparison, as the drone can enable flights that can't happen in low visibility conditions without it. Therefore a second comparison was made between the current situation where a landing gets aborted and the new situation where the helicopter waits for the drone to scout. Conclusion of this comparison was that the drone could reduce CO2 emissions if 26 percent or more of landings get aborted on misty days. The third comparison ties into the dropped requirement on mid flight retrieval. It compares the CO2 emitted during manufacturing and the CO2 emitted during the helicopter's waiting time during drone retrieval. This resulted in 5 minutes of waiting time, if the drone is lost every mission. However the drone is not lost every mission increasing the favor towards not doing mid air retrieval. Furthermore the topic waste management of current drones was explored. It was concluded that current end of life strategies are bad, and could be better. Some parts are recycled, but a lot is either burned or send to the landfill. [3]

New Work

For this final report a life cycle assessment was made of the drone using CES EduPack 2019, a software tool provided by the TU Delft. In the program, the level 2 sustainability database was used for an Eco Audit, as the

[1] https://www.clo.nl/indicatoren/nl0004-meteorologische-gegevens-in--nederland [Accessed on 18-05-2020]

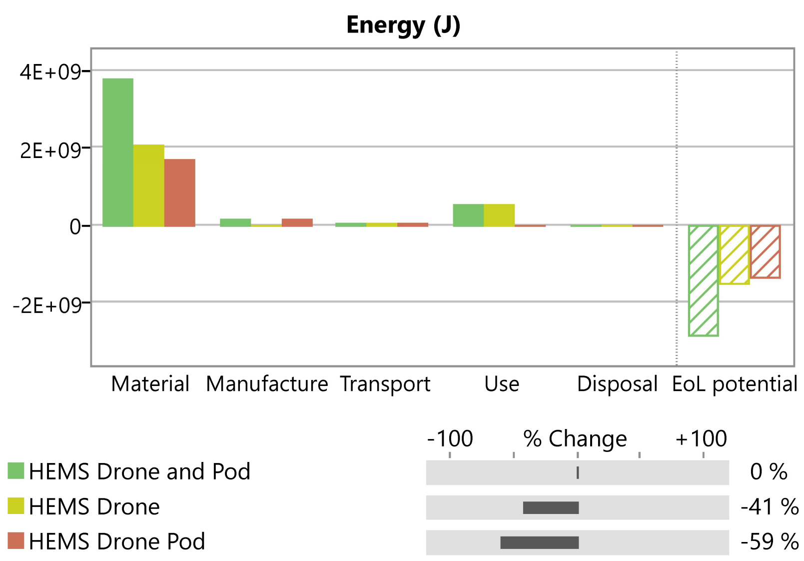


Figure 18.1: Relative contribution of the drone and its pod.

program calls the life cycle assessment. As not all the components had a one to one equivalent some creative substitutions were used. Most notable of these substitutions are the substitution of motors with fans meant for cooling electronic equipment and substituting the sensors with an optical mouse with cable. The detailed breakdown is in Appendix A. In this appendix only the energy and not the CO2 is shown. This was done for brevity as these two factors scale almost linearly.

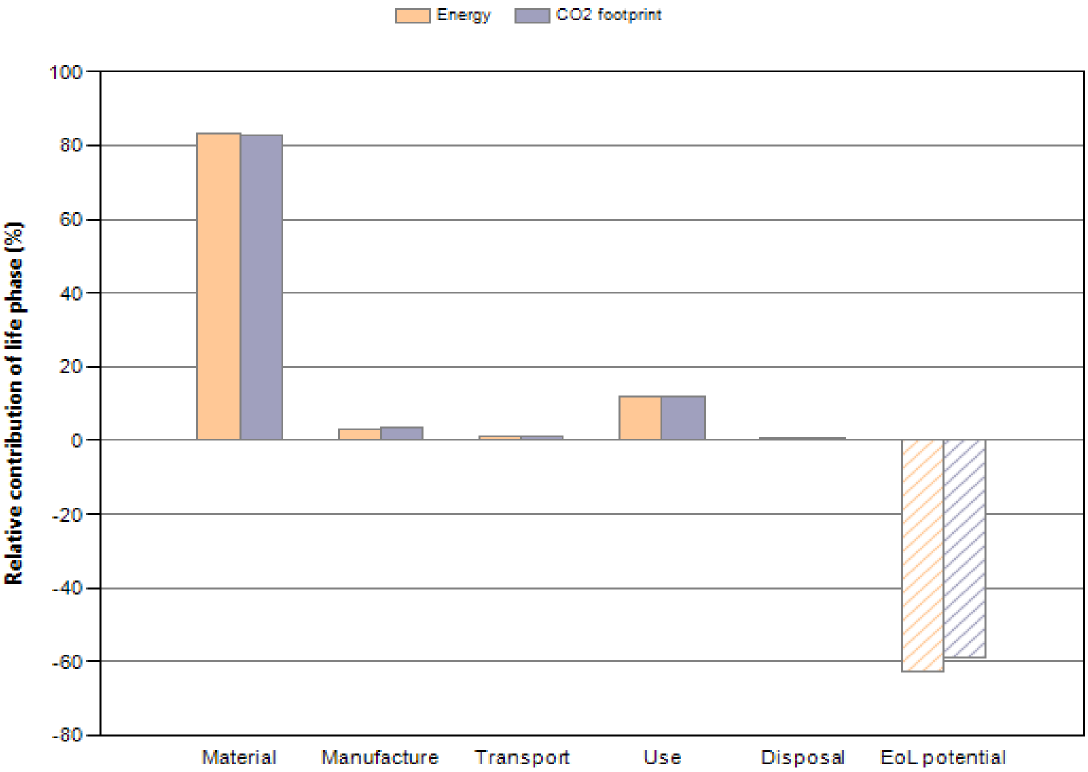
The relative contribution of life phases Figure 18.2 shows material creation is the phase that matters most. This is in part due to the modelling used in CES EduPack. For the electronic components, the manufacturing process is included in the material value. The transport phase is so low due to the low weight and volume of the drone. The relative transport costs between the presumed manufacture of components and assembly are striking. It is assumed components are transported 20000 km from China or some place else in South East Asia via ocean freight. The assembled product is transported from Delft to the Leeuwarden HEMS base, a distance of 200 km, via a 14 tonne (2-axle) truck. The final leg accounts for a twelfth of the transport phase' energy usage although its only a percent of the distance. During the use phase the drone gets charged and its electrical energy gets mostly converted to mechanical energy for the motors. The battery gets charged from the local electricity grid. The energy mix of this grid determines the CO2 emission. The use phase depends most on use time. CES EduPack models use as hours per days per year. A 1000 sorties as based on user requirement HD-USR-SYS-SUST-01 results in three 10 minute flights each of the 85 misty days for 3.92 years. How these flights are actually divided over time is not relevant for the energy usage in the use phase, it is the sum of all these flights over its life cycle that counts. The drone pod features some low power electronics (indicator light and temperature sensor that are on all the time, and some relative high power linear actuators that are on only a fraction of the time. This explains it low use phase contribution. See Figure 18.1. Disposal show the energy used during the different waste management options (reuse, recycle, downcycle, re-manufacture) used for the components. Comparing this to the potential energy saved during the next products material phase, the benefits of these waste management techniques for sustainability are evident. This is shown as the end of life potential. The end of life potential is based on extensive waste management options. If everything was send to the landfill, the end of life potential would be zero.

CES 2019 EDUPACK

Eco Audit Report

Product name	HEMS Drone and Pod
Country of use	Netherlands
Product life (years)	3,92

Summary:



Phase	Energy (J)	Energy (%)	CO2 footprint (kg)	CO2 footprint (%)
Material	3,745E+009	83,5	245,230	82,8
Manufacture	1,410E+008	3,1	10,573	3,6
Transport	5,553E+007	1,2	3,998	1,3
Use	5,375E+008	12,0	35,837	12,1
Disposal	8,352E+006	0,2	0,585	0,2
Total (for first life)	**4,488E+009**	**100**	**296,222**	**100**
End of life potential	-2,810E+009		-175,107	

Figure 18.2: Relative contribution of life phases.

19 RAMS Analysis

The RAMS analysis is a tool that can be used to determine and improve the reliability, availability, maintenance, and safety of a system. In this chapter the system will be evaluated on the four previously mentioned criteria and design recommendations will be made.

19.1. Reliability

For the reliability, an analysis is performed that looks at the different failure modes, their severity, and their probability. Because the exact reliability of all components in the design can not be determined without testing, a more qualitative approach was chosen. First the different failure modes were identified and put into a table according to the Failure Mode and Effect Analysis (FMEA) method [18] including a rough estimate of the probability of certain failures occurring. The severity was classified according to the following convention:

- **Category 1:** Catastrophic - This means total loss of the system or loss of life.
- **Category 2:** Critical - This means major damage to the system or the environment, severe injuries, or loss of the mission.
- **Category 3:** Marginal - This means minor damage to the system or environment, minor injuries, or delay of the mission.
- **Category 4:** Minor - This means that only unscheduled maintenance or repairs are necessary, but the mission is not negatively affected.

As mentioned before, the exact values for the probabilities are unknown. Therefore the probabilities are classified as follows:

- **Level A:** Frequent - This means that the probability is assumed to be greater than 0.20, meaning on average it would happen over 200 times during the lifetime of the drone.
- **Level B:** Reasonable - This means that the probability is assumed to be between 0.10 than 0.20, meaning on average it would happen between 100 and 200 times during the lifetime of the drone.
- **Level C:** Occasional - This means that the probability is assumed to be between 0.01 than 0.10, meaning on average it would happen between 10 and 100 times during the lifetime of the drone.
- **Level D:** Remote - This means that the probability is assumed to be between 0.001 than 0.01, meaning on average it would happen between 1 and 10 times during the lifetime of the drone.
- **Level E:** Extremely unlikely - This means that the probability is assumed to be less than 0.001, meaning on average it would happen less than 1 time during the lifetime of the drone.

The results of this FMEA are shown in Table 19.2. The resulting criticality matrix is plotted in Table 19.1.

Table 19.2: FMEA analysis for the drone

ID	Item	Function	Failure mode and causes	Mission phase	Local effects	Higher level effects	End effects	Severity	Probability
POW-1	Batteries	Provide power	Out of charge caused by damage or improper charging	Entire mission	Power to subsystems cuts off	Drone gets shut down mid air	Drone crashes, failing the mission	2	C
POW-2.1	PDU	Distribute power	Wires fail caused by damage in the wires	Entire mission	Power to single/ multiple subsystems cuts off	Depends on system, but worst case drone loses thrust or control	Drone might crash, failing the mission	2	B
POW-2.2			Software failure in the PDU	Entire mission	Power to single/ multiple subsystems cuts off	Depends on system, but worst case drone loses thrust or control	Drone might crash, failing the mission	2	E
PROP-1.1	Propellers	Convert engine torque to thrust	Structural damage caused by impact, stress, or fatigue	During flight	Loss in thrust	Drone loses thrust and controllability	Drone needs to land and might even crash	2	B
PROP-1.2			Loss of efficiency caused by e.g. icing	During flight	Loss in thrust	Extra power might be required	Loss in controllability and worst case needs to land and might even crash	3	C
PROP-1.3			Propeller connection failure caused by structural damage	During flight	Propeller gets lost mid air	Loss of thrust	Drone needs to land and might even crash	2	D
PROP-2	Motors	Convert battery power to torque	Internal wiring failure caused by structural damage or overheating of the motor	During flight	Loss in thrust	Drone loses thrust and controllability	Drone needs to land and might even crash	2	C
SENS-1.1	RGB camera	Record visible light spectrum	Images are too foggy caused by condensation of vapor on the lens	During scanning	No visual image	Unable to visually detect obstacles	Unreliable imaging	3	E
SENS-1.2			Images are too noisy caused by low voltage or rapid voltage drop	During scanning	No visual image	Unable to visually detect obstacles	Unreliable imaging	3	A
SENS-2	GNSS receiver	Rough position determination	Can not provide correct location caused by interference, spoofing, or signal blockage	During flight	Can not locate drone	Drone can not be properly controlled	Drone might crash, failing the mission	3	D
SENS-3	mmWave radar	Scanning surrounding objects	Can not provide reliable data caused by damage to the sensor or blockage of the sensor	During scanning	Can not scan obstacles	Landing site can not be properly mapped	Mission fails because helicopter can not land	2	E
SENS-4	IR camera	Scan thermal images to complement RGB camera	Images are too noisy caused by low voltage or rapid voltage drop	During scanning	No visual image	Unable to visually detect obstacles	Unreliable imaging	3	A
SENS-5	Radio transmitter	Determine position relative to helicopter	Loss of communication with helicopter caused by limited range	During flight	No data transmission	Operator loses control over drone	Drone might crash, failing the mission	3	D
SENS-6	IMU	Provide absolute orientation and acceleration	Data has an offset caused by faulty calibration	During flight	Unstable flight	Worst case, the drone lose stability	Drone might crash, failing the mission	3	D
STRC-1.1	Drone structure	Provide strength and attachments for other subsystems	Landing gear does not move cause by failing of the actuator	During landing	The landing gear stays in the "up" position	Drone lands on the sensors	Sensors might get damaged	3	D
STRC-1.2			Motor attachment arm fails due to yielding and warping	During flight	One of the arms breaks	One of the motors is lost and falls towards the ground	Drone needs to land and might even crash. Also the detached arm might cause injuries	1	D
STRC-1.3			Motor attachment arm fails due to breaking off	During flight	One of the arms warps	Thrust vectors change directions	Loss in controllability and worst case needs to land before finishing mission	3	C
STRC-2	Deployment system	Release the drone from the helicopter	Deployment fails caused by malfunction of the actuators	During release	Can not perform the mission	The landing site does not get mapped	Mission fails	2	D
SW-1	Flight computer	Provide control signals to PDU/ propulsion	Software crashes caused by faulty inputs or coding errors	During flight	Incorrect or no control signals sent	Drone might fly in wrong directions	Drone crashes and mission fails	2	D
COMM-1.1	Communication system	Upload and download data to and from helicopter	Connection failure caused by disturbances or transmitter failure	Entire mission	No data transmission	Operator loses control over drone	Drone might crash, failing the mission	1	D
COMM-1.2			Too high BER caused by internal or external noise	Entire mission	Data is unusable	Drone needs to scan/ transmit again	Drone takes longer to perform mission	3	C

Table 19.1: Criticality matrix for the drone

Probability of occurance	A		SENS-1.2 SENS-4		
	B			POW-2.1 PROP-1.1	
	C		PROP-1.2 COMM-1.2 STRC-1.1 STRC-1.3	POW-1 PROP-2	
	D		SENS-2 SENS-5 SENS-6	PROP-1.3 SW-1 STRC-2	COMM-1.1 STRC-1.2
	E		SENS-1.1	POW-2.2 SENS-3	
		4	3	2	1
		Severity classification			

Finally, a Fault Tree Analysis (FTA) [18] can be performed to find the weakest link. The results are shown in Table 19.3 and show that all failure modes affect the entirety of the mission. Therefore it is necessary to put in redundancies wherever possible. Special attention should be given in this process to failure modes with either a high probability or a high severity. This will be further elaborated upon in section 19.5

Table 19.3: FTA results for the drone

Layer 1	Layer 2	Layer 3	Layer 4
Mission failure	SENS	SENS-1	SENS-1.1
			SENS-1.2
		SENS-2	SENS-2
		SENS-3	SENS-3
		SENS-4	SENS-4
		SENS-5	SENS-5
		SENS-6	SENS-6
	COMM	COMM-1	COMM-1.1
			COMM-1.2
	PROP	PROP-1	PROP-1.1
			PROP-1.2
			PROP-1.3
		PROP-2	PROP-2
	POW	POW-1	POW-1
		POW-2	POW-2.1
			POW-2.2
	STRC	STRC-1	STRC-1.1
			STRC-1.2
			STRC-1.3
		STRC-2	STRC-2
	SW-1	SW-1	SW-1

19.2. Maintainability

Maintainability will be elaborated before availability because it greatly influences availability. The maintainability consists of both scheduled and unscheduled maintenance. The list of maintenance requirements can be shown below:

- **M-SENS-01:** The power distribution unit shall be check for any voltage drop to ensure constant voltage supply to all the sensors.
- **M-SENS-02:** The infrared and RBG camera shall be clean and applied with anti-fog after every post-flight.
- **M-SENS-03:** The IMU and mmWave radar shall be check if the data is outputting correctly and may require re-calibration if necessary.
- **M-SENS-04:** The radio transmitter shall be check for the strength of the signal of the last logged data.
- **M-SENS-05:** The radio transmitter shall be the forward/reflected power on the main transmitter
- **M-PROP-01:** The propeller shall be clean and check for present of crack after every post flight.

- **M-PROP-02:** The propeller shall be replace every 200 flights [1].
- **M-PROP-03:** The inspection on the wiring and bearing of the motor are required.
- **M-PROP-04:** The motor shall be clean after every post flight and lubricate on the bearing if necessary.
- **M-STRC-01:** The structure and release mechanism of the drone shall be visually check for the present of crack or bends.
- **M-SW-01:** The firmware should be kept updated from all the feedback and issued with drone hardware or features from the customers.
- **M-BAT-01:** The batteries shall be fully discharge and recharge the battery ever 10-20 cycles or if the battery is not used very often than every 3 months [2].
- **M-BAT-02:** The batteries shall be stored in the specific transportation box to avoid damages from external forces [2]. .
- **M-BAT-03:** Discharge the battery to 40 % - 60% when it is not use to avoid permanent damages [2].

The time of the maintenance will be present in qualitatively because the time to repair the drone components are rare to be found. Most of the maintenance can be done relatively quickly since it is mostly cleaning and visual checking on the components. Therefore the mean time to repair and mean downtime are rather low except for the firmware updated which could take a least a week or more [3]. Meanwhile the maintenance frequency factor is quite high if the drone is used frequently because it is recommend to do the cleaning, maintenance and inspecting before and after the flight [2].

19.3. Availability

Availability is defined as the probability that a system is fully operable when called upon at a random time. Availability is therefore strongly related to reliability and maintainability. Because there are no concrete numbers but qualitative analyses for reliability and maintainability, availability will also be approached from a qualitative standpoint. The pre-flight check can be performed in the first few minutes of a new shift and should not limit the availability too much. The same goes for the post flight check, which can be performed by the helicopter pilot before returning to the airbase, meaning that the post flight check will have no negative influence on the availability. This leaves the repair and replacement of parts as the main sources of loss in availability. From the maintainability it follows that the only action that takes a lot of time is the updating of the firmware of the drone. Because the other actions are a matter of minutes, they can most likely be performed during the post flight checks of the helicopter, thus not significantly decreasing the downtime of the system. The most important design consideration is making sure that these additional actions can be performed within these minutes, thus not making some areas extremely difficult to reach. Another aspect that might lower the availability is the charging of the batteries, which can take in the order of magnitude of hours if done properly (a charging rate of somewhere between 0.5 and 1 C, see footnote[4]). This can however be almost fully negated by having a few spare sets of batteries ready at the airbase, reducing the lost time to the time it takes to swap out the batteries.

19.4. Safety

The safety heavily ties in with the reliability. Where reliability is mostly focused on the probability of failures occurring, safety will focus on the severity of certain hazards in the design and the operation. In order to analyse these, first a list of hazards will be made. After this possible effects and mitigations will be explored to increase the overall safety of the design. The main hazards and respective mitigations are:

- The drone might crash as a result of technical failure, human error, faulty communication, or external disturbances. The consequences of a crash could range from damage to the drone to property damage or even loss of life. Possible mitigations are adding a parachute to the drone to limit the severity of the crash or adding, for example, an impact warning system that reduces the odds of the drone crashing.

[1] `https://www.dronepilotgroundschool.com/kb/is-there-a-maintenance-schedule-for-dji-drones/` [Accessed on 22-06-2020]

[2] `https://store.dji.com/guides/properly-maintain-drone/` [Accessed on 29-06-2020]

[3] `https://forum.dji.com/thread-114964-1-1.html` [Accessed on 22-06-2020]

[4] `https://thercdronehub.com/how-to-charge-discharge-and-store-a-lipo-battery/` [Accessed on 29-06-2020]. The chosen battery, marketed as "professional", has a manufacturer specified charge rating of 5C which is uncommon. `https://hobbyking.com/en_us/turnigy-graphene-professional-8000mah-6s-15c-lipo-pack-w-xt90.html?queryID=9a55c348569ac102001b3fae28ae9c05&objectID=71562&indexName=hbk_live_magento_en_us_products` [Accessed on 29-06-2020]

- The lithium-ion batteries in the drone might combust. The probability of this happening is almost negligible if the batteries are handled correctly. The odds dramatically increase if the batteries are subjected to excessive vibrations, elevated heat, or complete discharges. If the batteries were to combust this could endanger the helicopter if the drone is still attached or otherwise endanger the drone, reverting back to the previous entry. The ways to mitigate the severity is to make sure the attachment to the helicopter is fireproof or a fireproof cover is placed around the batteries. The probability can be mitigated by ensuring that the batteries are handled as intended.
- The autonomy in the drone also poses possible risks in case the software fails due to errors in coding or faulty inputs, for instance singularity. These errors might cause the drone to not be able to fly correctly and could potentially propagate very fast. This can be partly mitigated by allowing the operator to override the controls of the drone manually, which is also required by regulations.
- The deployment of the drone should be when there is a strong GPS signal to ensure the stability of the drone [5].

19.5. Recommendations

Looking at this analysis, a few improvements can be made on the design. The most important one is too add redundancies in the design wherever possible because in the reliability analysis a lot of single point failures were identified. Even though some of these failures are impossible to fully mitigate due to the requirements on total size and weight of the drone, some can quite easily be addressed. For example, POW-2.1 can be resolved by having redundant wires as back up in case a wire fails. It should be noted that this will give more parts which may lower the maintainability, but because of the nature of the mission reliability is deemed to be more important.

For maintainability and availability the most important design recommendations are to make sure that the components that are more likely to fail can be repaired using as little time, money, and resources as possible. This can for instance be done by making the batteries easy to swap out if necessary.

When safety was further looked into, there were also other mitigation measures that were found which should be implemented in the design. These mitigations can be argued to be even more important than the redundancies discovered for reliability. This is because the reliability can never actually reach the ideal value of one, meaning that the system will fail and thus making it important to limit the effects of failure as much as possible.

[5] `https://www.dji.com/nl/flysafe` [Accessed on 29-06-2020]

20
Project outlook

Even though this final report phase has generally been referred to as the 'detail design phase' in the past, within an actual engineering project the design stage that this report tackles would still be considered the preliminary design phase or design definition phase, using Figure 20.1 for reference.

If the HEMS reconnaissance drone were to actually go to, a considerable amount of work would still have to be done to complete its design, testing and certification. In this chapter a preliminary planning of the post DSE design activities is given in the form of a Project Design and Development flow diagram, and a corresponding project Design and Development Gantt chart. This Design and Development logic will also be used in part to estimate the further project costs in the cost breakdown structure, as the labor, testing and certification costs that are still to come make up a significant portion of the project costs, as will become clear in section 20.3.

Mission Need Definition / Business opportunity study phase	Concept Exploration/ Design feasibility study phase	Demonstration & validation / Design definition phase	Full scale development phase	Production & deployment / Operational validation phase	Operations & support / Sustained engineering phase	Disposal phase
1.Identify and formulate need	2. System analysis 3. Reqts. Definition 4. Conceptual designs 5. Technology & risk assessment 6. Prel. Cost, schedule & performance of preferred concept	7. Concept design 8. S/S trade-offs 9. Preliminary design 10. Prototyping, test & evaluation 11.Integration of manufacturing & supportability considerations into design	12. Detail design 13. Development 14. Risk management 15. Development test & evaluation 16. System integration, test & evaluation 17. Manufacturing process verification	18. Production rate verification 19. Operational test & verification 20. Deployment	21. Operational support & upgrade	22. Retirement
	Requirements baseline	Functional baseline	Product baseline	Certification baseline		

∇ MDR ∇ SRR ∇ PDR ∇ CDR ∇ AR

MDR Mission Definition Review; SRR System Requirements Review; PDR Prel. Design Review
CDR Critical Design Review; AR Acceptance Review

Figure 20.1: General description of the phases of an engineering design project from [18].

20.1. Project Design and Development Logic Flow Diagram

A preliminary overview of the main design and development activities that still have to be completed to complete the HEMS reconnaissance drone and bring it to market is given in flow diagram in Figure 20.2. Here the product phases and summary tasks are loosely based on the phases mentioned in Figure 20.1 from [18] which are applicable to this product.

20.1.1. Full Scale Development

Full scale development encompasses the real detail design (PD.1.1), integrating the different subsystems correctly (PD.1.2), designing the manufacturing process (PD.1.3) and the first physical design testing (PD.1.4). Following the DSE, the subsystems mentioned in this report have to be worked out in detail. Additional items like CFD analysis (PD.1.1.1) for aerodynamic performance and designing a fitting HUD solution (PD.1.1.6), which could not be treated in the DSE yet, are added in this phase too.

This detail design phase goes hand in hand with detail design of the integration of the subsystems, which is aided by first integrating all of the individual simulations built up until now (sensors, control and stability, path, aerodynamic simulations created from the CFD detail design step) to create a master simulation to be able to simulate the whole system with all of the subsystems working together (PD.1.2.1, PD.1.2.2, PD.1.2.3). Finally, the physical integration of the subsystems is evaluated, and detail design drawings/schematics of a first prototype can be made (PD.1.2.4).

Subsequently, a manufacturing process is designed to accommodate efficient production and assembly of drone components (PD.1.3.1-PD.1.3.6). This could include setting up agreements with contractors to outsource any production steps (likely the plastic/carbon fiber body and landing gear) that would otherwise take significant investments in production assets (PD.1.3.4). This manufacturing process will be continuously updated to accommodate for any changes made to the design as a result of testing or certification efforts.

The business side of things would also ramp up here (PD.1.5). Early adopters, or initial customers can be found among HEMS operators. Further discussion on requirements and design iteration could be required, depending on the feedback possible customers provide. Once discrepancies or disagreements on requirements have been put to bed, some letter of intent style initial orders could be placed to see if the project could be viable.

Once a prototype can be manufactured (PD.1.4.1), physical testing of the system, along with verification of the system and subsystem requirements can commence, which ultimately leads into the Critical Design Review milestone, where the design is checked to see if it can meet the requirements, stay within the cost budget, and can be produced effectively.

20.1.2. Operational validation

Operational validation is the next phase in the development process, and it might prove to be the most critical phase. The HEMS Reconnaissance drone will be systematically tested and certified for separate mission phases and systems (PD.2.1-PD.2.3), and ultimately tested and certified for full missions (PD.2.4). This is accompanied by the creation of training protocols and manuals for proper use of the product (PD.2.5).

If the drone cannot be certified, then some iteration of certain design elements will have to take place. Think for instance of the risks mentioned in 7, even after mitigation, preventing the drone from being certified, like the propellers not folding out by centrifugal force well enough for the drop release, thus requiring a spring loaded mechanism to be developed, or a drone parachute to be installed as a last ditch effort.

As soon as the drone starts approaching the end of certification and testing full scale sales can start to be made (PD.2.6). A review of the design will be presented to customers that have been approached for requirements earlier in the design phase. If customers agree that the requirements have been met and that the system fulfills their needs, then sales can be agreed upon.

An acceptance review will take place once the drone has been fully certified. If the drone is deemed to be a viable product that meets the user requirements and use case set by the customer(s) (HEMS Operations, Mountain search and rescue, Army), it can be brought to market within those specific fields. Drone production will start after this, based on the amount of drones that have been ordered in the earlier business phases.

20.1.3. Drone Operational Support

With a complex (and relatively expensive) product like this, a certain level of technical support (PD.3.2) and special maintenance (PD.3.1) will be required throughout the life cycle of the drone. The drone is designed to be able to be maintained by the technicians at the helicopter base, like discussed in chapter 17, but there are always special cases that will require manufacturer/developer maintenance.

Furthermore, once the product is brought to market and used regularly in actual mission environments, faults that require software/hardware updates will undoubtedly crop up. There must thus be continuous support and design iteration for fixing these types of issues during (the first parts of) the projected market lifecycle of the product (PD.3.3).

20.1.4. Drone Decommissioning

The drone has an operational lifetime of about 1000 missions. At the end of this life time it has to be decommissioned (PD.4.1). In chapter 18 it is predicted that the drone will have a lifetime of about 4 years when it is heavily used. Once the drone has reached the end of its life it can either be repurposed for a less critical use-case (PD.4.1.4) or disassembled and recycled/disposed of correctly in line with the end of life sustainability goals (PD.4.1.1-PD.4.1.3) also included in chapter 18.

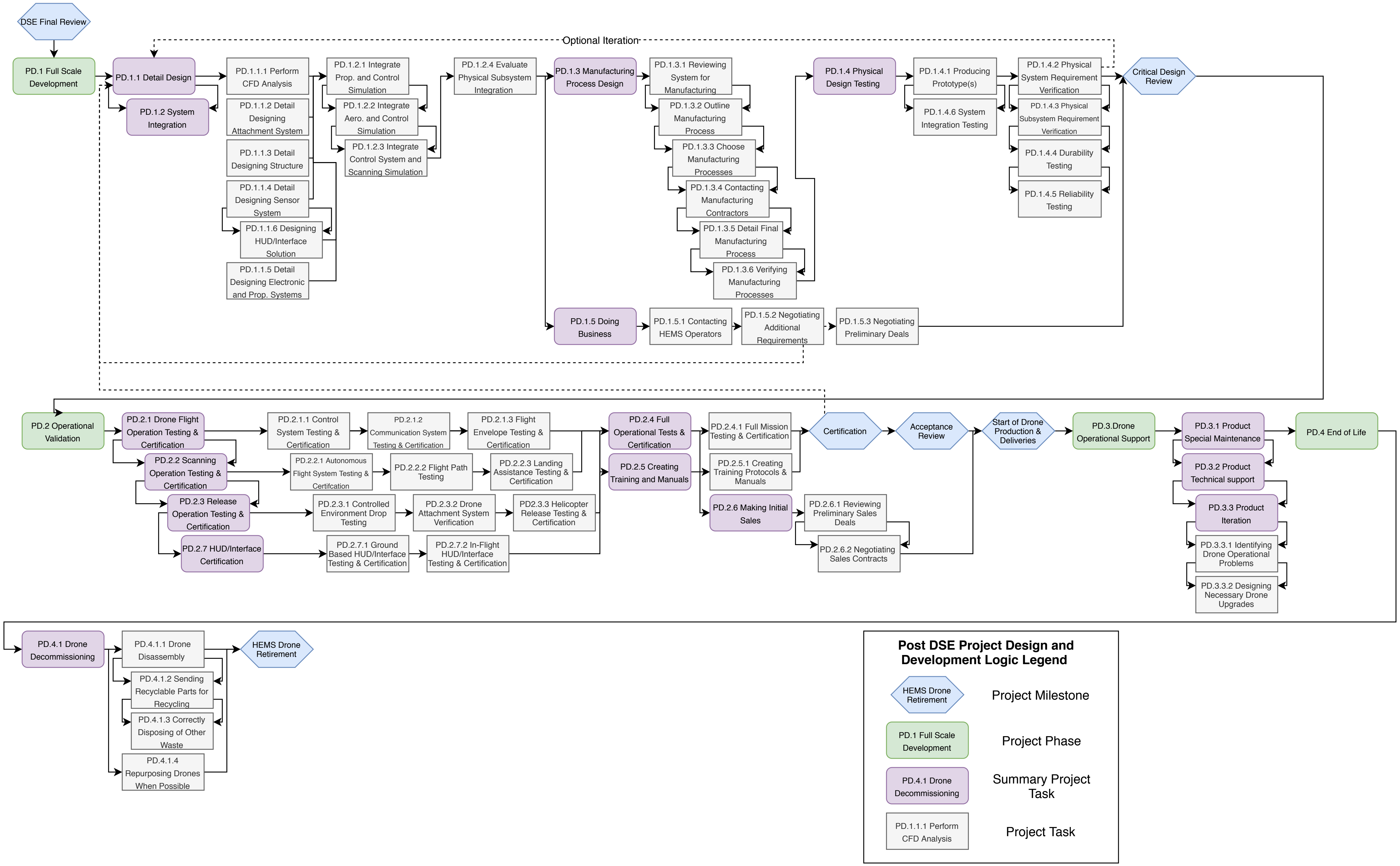


Figure 20.2: Post DSE Project Design and Development logic flow diagram.

20.2. Project Design and Development Logic Gantt Chart

To give a very preliminary calendar overview of the Project Design and Development logic steps first shown in the flow diagram a Gantt chart has been made which shows the Project Design and Development Logic tasks planned out in time. All of the project phases, summary project tasks, and project tasks have been incorporated into the gantt chart and ordered as they are expected to be performed.

It should be noted that the days assigned to every task are total calendar days, not working days. This made it easier to visualize the phases of the project and the time they would take. The times assigned to the project phases and tasks are very approximate, and will likely overshoot the actual time required to perform the tasks. For the cost breakdown a worst case scenario was assumed for most design, testing and certification tasks. As a worst case scenario was assumed for all of these tasks, the relative durations of the tasks are still a good indication of which of the tasks would take up larger parts than others during the later project phases, but the exact numbers are often very rough guesses. The numbers for the first 2 large project phases are assuming a team of 10 full time engineers.

Based on the pace that is currently being worked at in the DSE the full scale development is projected to take about 6 months (180 days) worst case. The drone testing and certification is projected to take about 9 months (270 days) because more detail design will likely be performed as a result of the findings during the testing and certification. Furthermore, this phase is also expected to take longer than the initial detail design because of the limitations in dates for certification tests at the relevant airworthiness authorities (EASA and FAA). This leads to a total projected time to market of about 1 year and 3 months from the time of the final DSE review.

The drone operational support is scheduled for the life cycle of 1 drone that is less heavily used than the one in the example before. Of course, special maintenance and technical support would still be performed for 5 years for a drone bought in 2023, this is just an indication for a drone bought at the end of 2021. This first estimate in these diagrams is based on the 'first batch' of drones that would be sold right near the start of the program. This first batch is what will be used to estimate the price of the drones, therefore it made sense to show only what the lifecycle support would look like for that first batch of drones. It made the most sense to look at it like this, because the sales number estimate used to determine the final price for the drones was calculated assuming only the sales in the first batch. The number of drones sold after this first phase is hard to predict, but it is clear that more drones sold would only push the price of the drones down, thus not affecting the viability of the program if sales are unexpectedly much higher.

The product iteration task is also scheduled for about 5 years, with the expectation being that after 5 years of widespread use and design iteration most if not all operational issues of the design will have been fixed, so design iteration can be phased out after that. The drone operational support can probably be done by a downsized team (2-4 people), because there will be less tasks to perform than during full scale development and testing.

Finally, the drones will be decommissioned over the course of about a week at the end of their life. In this Gantt chart the decommissioning is placed in 2025 for a drone bought in 2021, but a drone bought in 2023 would be decommissioned in 2027.

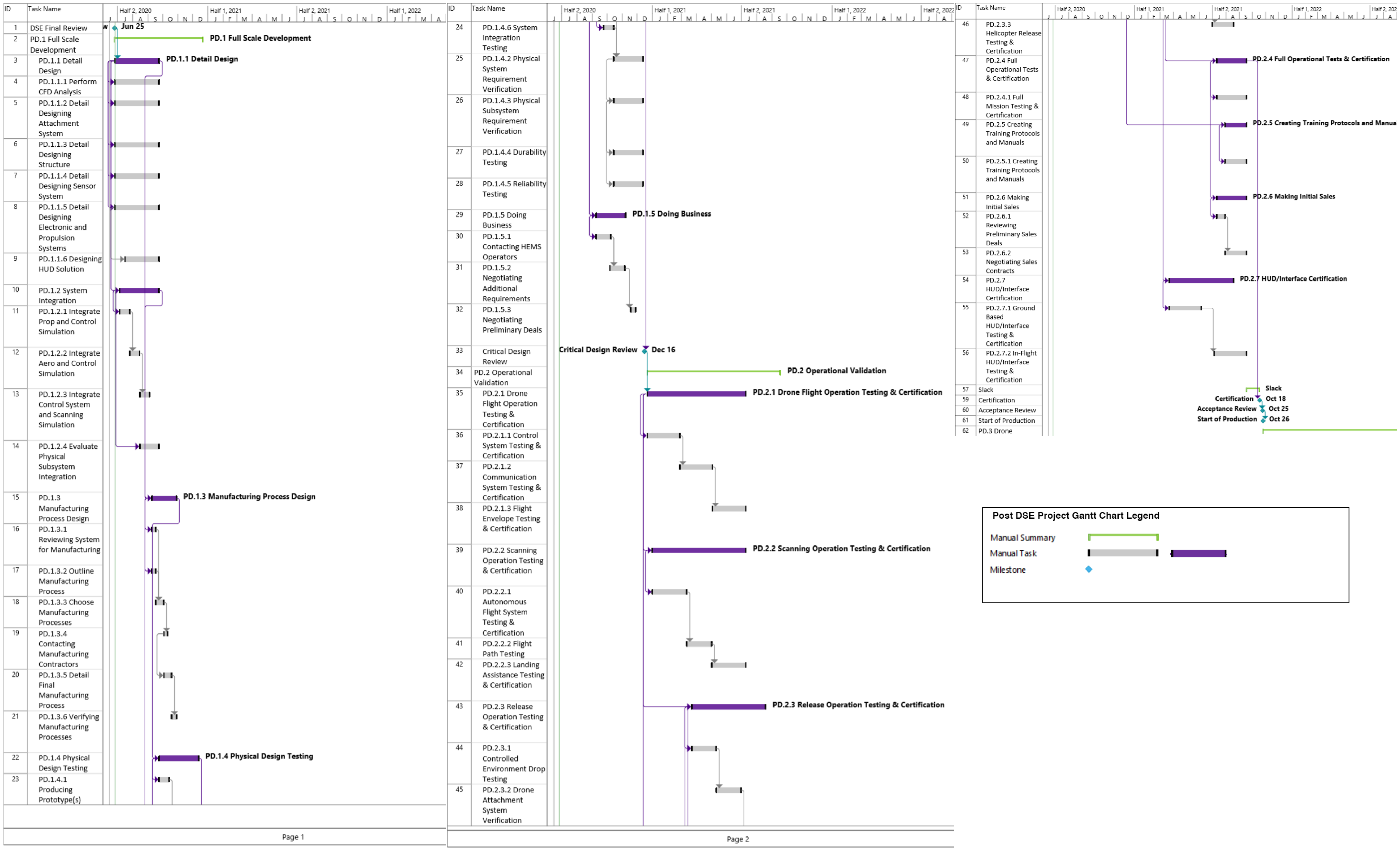


Figure 20.3: Post DSE Project Activities Gantt Chart, based on the Post DSE Project Activities Flow Diagram

ID	Task Name	Duration	Start
46	PD.2.5.1 Creating Training Protocols and Manuals	50 days	Fri 7/30/21
47	Slack	30 days	**Sat 9/18/21**
49	Certification	0 days	Mon 10/18/2
50	Acceptance Review	0 days	Mon 10/25/2
51	PD.3 Drone Operational Support	60 mons	**Tue 10/26/21**
52	PD.3.1 Product Special Maintenance	60 mons	Tue 10/26/21
53	PD.3.2 Product Technical Support	60 mons	Tue 10/26/21
54	PD.3.3 Product Iteration	55 mons	Thu 2/3/22
55	PD.3.3.1 Identifying Drone Operational Problems	55 mons	Thu 2/3/22
56	PD.3.3.2 Designing Necessary Drone Upgrades	55 mons	Thu 2/3/22
57	PD.4 End Of Life	11 days	**Fri 2/7/25**
58	PD.4.1 Drone Decommissionir	7 days	**Fri 2/7/25**
59	PD.4.1.1 Drone Disassembly	3 days	Fri 2/7/25
60	PD.4.1.2 Sending Recyclable Parts for Recycling	4 days	Mon 2/10/25
61	PD.4.1.3 Correctly Disposing of Other Waste	4 days	Mon 2/10/25
62	PD.4.1.4 Repurposing Drones when Possible	7 days	Fri 2/7/25

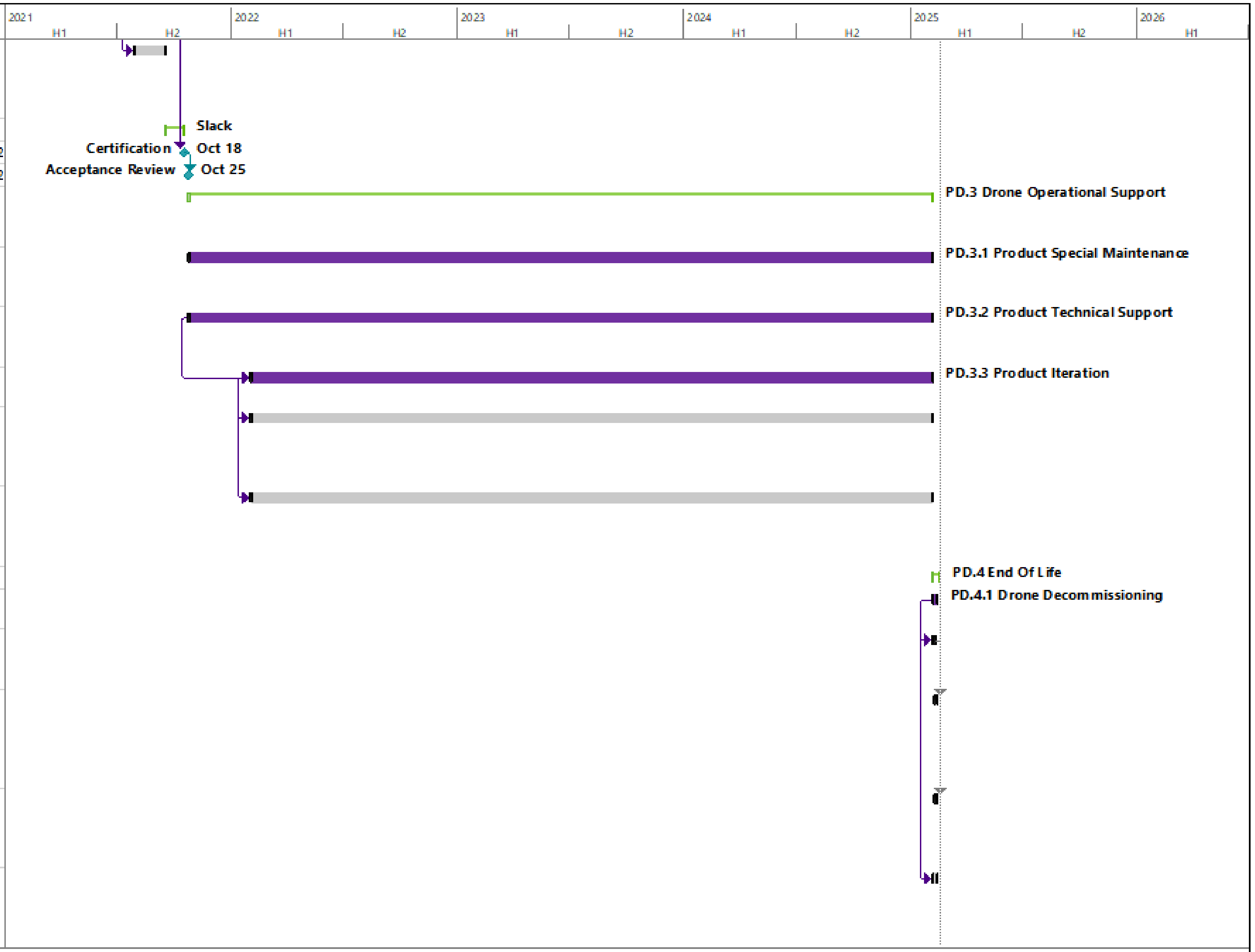


Figure 20.4: Post DSE Project Activities Gantt Chart, based on the Post DSE Project Activities Flow Diagram

20.3. Cost Breakdown Structure

Only a small part of the full design and life cycle of the HEMS Reconnaissance drone will have been completed at the end of the DSE. To estimate the true break even cost of one of these drones, the costs which would be incurred throughout the entirety of the products' design and support lifecycle should be taken into account. The expected sources of costs, derived from the market analysis, the design and development logic above, and other smaller sources in this report, were subdivided in a Cost Breakdown Structure diagram, of which the final result is depicted in figure Figure 20.5, and (generally rough) estimates of the costs associated with these subcategories were made. For some categories it was very hard to give an estimate ahead of time, so approximations were necessary. The expected total budget will get a 30% margin on top to account for these inaccuracies. The margins for the other budgets at this phase were set to about 10% to 15% in the baseline phase (see chapter 8), but the costs are too uncertain to be able to justify such low margins, and there will be some costs that are missed in the initial estimation made here. The exact explanations for how the cost amounts were estimated are given per category in the following list.

- **Labour**: For labour it was assumed that the same team of 10 engineers would be retained at a monthly full time salary equal to the average gross (aero)space engineer salary in the Netherlands, €3,850[1], for the entire design and certification phase of the project (PD.1 and PD.2). Adding the already performed work in the DSE to that time would result in 16 months of payment for 10 engineers. In the PD.3 and PD.4 phases it would make sense to downsize to a smaller team of about 4 engineers, for product support and design modifications that have to be made. This would require 60 months of monthly salary for 4 engineers (PD.3 and PD.4). Whether engineers will be retained after this time depends on the success of the product, but this should cover at least the life cycle of the first batch of drones. Total labour cost: *€1,540,000.00*.
- **Software**: Software is divided into separate software licenses that are expected to be used. Not all 10 team members will require a license for all of the different software programs.
  - **Catia V5**: About 5 Catia licenses are required for 3D modelling, FEM, and CFD analysis for 2 years. Then upon downsizing only 1 license would be retained for the duration of the 5 year product design support life cycle. At €4500[2] per year per license this would come out to a total cost of *€60,075*.
  - **PyCharm Professional**: Professional IDE for Python development. Currently the free Student version of this is being used, but in real operations a professional license would be required for all team members. A professional license costs €199, €159, and €119 [3] euros per year per person, dropping in price the longer the license is maintained. 10 licenses would be needed for the first year at €199, 10 for the second year at €159, and 4 for €119 for 5 years. In total this amounts to *€5,960*.
  - **Matlab**: 5 professional Matlab licences will be required for the control system simulation and other features. At €2,000 per perpetual individual license this amounts to *€10,000* total.
  - **CES Edupack** For material properties and durability assessments 1 licence will be required. This would cost *€178*[4] for the 16 month design phase.
  - **Microsoft Office 365 Business**: Will be required for general use. €10,60 per month per user[5]. With 10 users for 16 months and 4 users for 60 months this adds up to *€4,240*.

  The total software costs then come out to *€80,453*.
- **Test Equipment**: The exact test equipment required is a bit of a shot in the dark. An estimated amount of *€60,000* is assumed.
- **Prototypes**: About 5 prototypes are predicted to be made for testing, each costing roughly €8,000 in material costs (see chapter 8). In total this would be *€40,000*.
- **Test Facilities**: These test facilities are used for preliminary testing outside of the certification phase. It is estimated that about 48 helicopter flight hours are to be made in this phase. The cost number for flight hours mentioned in the market analysis in chapter 4 is the hourly cost for an EC135 helicopter

[1] `https://www.nationaleberoepengids.nl/ruimtevaart-engineer` [Accessed on 19-06-2020]
[2] `https://3dsman.com/catia-pricing/` [Accessed on 19-06-2020]
[3] `https://www.jetbrains.com/pycharm/buy/#commercial?billing=yearly` [Accessed on 19-06-2020]
[4] `https://grantadesign.com/education/ces-edupack/how-do-i-get-it/` [Accessed on 19-06-2020]
[5] `https://www.microsoft.com/nl-nl/microsoft-365/business/microsoft-365-apps-for-business?market=nl&activetab=pivot%3aoverviewtab` [Accessed on 19-06-2020]

that is operated by the owner (€1,500). Using someone else's helicopter for testing will likely result in a steeper price, so a cost of €2,000 per flight hour is expected. At 48 flight hours this would cost a total of €96,000. An estimated €50,000 of other facilities is added to this to come to a total price of *€146,000*.

- **Licences**: Licences are covered under preliminary testing, because the number main reason for getting licenses is generally for the company to be allowed to fly drones, which would already by necessary for preliminary testing. The licence fees mentioned here also cover the licence fees for testing and flying during operational validation.
  - **RPAS Operator Certificate**: The design company would require an RPAS Operator Certificate to be allowed to fly the 4kg drone. This would cost *€2.057*[6].
  - **RPAS Inspection**: The RPAS License requires an initial inspection, and a repeat inspection every 2 years. The initial inspection price is €4,879 with the following inspections every 2 years costing €976[7]. This results in a total inspection cost of *€6,831*.
  - **S-BvL Certificate**: The drone requires an airworthiness certificate which has to be updated yearly. Doing this 6 times at €125 costs *€750*, the source of this cost is on the same page as the source for the RPAS inspection.
  - **RPA-L Certificates + Education**: All engineers will have to get a license to be allowed to fly a 4kg drone for commercial purposes. This license costs €122 per person[8], and the education for this costs about €3500 per person [9]. The total cost for this would then be about €36,220.

  The total licence cost adds up to *€45,858*.
- **Certification Equipment**: Assumed to be roughly equal to the initial test equipment costs at *€60,000*.
- **Certification Fees**: The hourly certification fee of EASA is €247[10]. It is assumed that about half of the working time of the operational validation phase (PD.2, 270 days) is done under supervision of EASA certification. This amounts to half of 5/7ths of 270 days with 8 hour work days. The total cost for this would be *€190,543*.
- **Certification Facilities**: By far the largest cost here would be helicopter flight hours. The skylens HUD took about 200-300 flight hours to certify [11], for this project the HUD is actually connected to a scanning drone, so it would take more flight hours to also certify this drone. The total amount of flight hours for this is estimated to be 400 hours. At €2,000 per flight hour for the helicopter, and a yearly salary of $175,000 for a test pilot, which converts to about €86 per hour [12] for a full time work year of 1820 hours. The total cost in helicopter facilities for certification would then amount to *€834,231* as first estimate. This is assumed to be the only source of cost for certification facilities for now.
- **Workshop**: A workshop would be necessary to assemble drones and perform repairs. Technostarters Delft Vastgoed BV's workshop is seen as a good candidate for a flexworkshop[13] that can be used, without having to invest capital into a complete private workshop. This workshop costs €100 per person for a yearly license, and €10 per hour spent working in the workshop. About a full time working year of fees (1820 hours) is expected to be incurred yearly in all phases of the project (PD.1, PD.2, PD.3, PD.4). With 10 yearly licenses needed for 2 years, and 4 for 5 years. This results in a total cost of *€131,400*.
- **Off the shelf products**: With the projected initial units sold of 360 in chapter 4, and the off the shelf material cost of €6,374 per drone from chapter 8. In addition to the drone, the drone pods attached to the helicopters are made entirely from off the shelf material at €519.36 per pod. Assuming HEMS bases buy a main and reserve drone, 180 pods are sold. This results in a total cost of *€2,388,269*.
- **HUD**: For presenting the information a Heads Up Display can be used. A certified one is available from Collins Aerospace at a cost of less than 50,000$. Cheaper options might be available as discussed in section 13.3, but an investigation in certification should show what's possible. Every helicopter using the drone would need one, so 180 should be included in the cost breakdown structure.

[6] `https://www.ilent.nl/onderwerpen/drones/operator-certificate-roc-drones` [Accessed on 19-06-2020]
[7] `https://www.ilent.nl/onderwerpen/drones/keuringen-en-onderhoud-rpas-drone` [Accessed on 19-06-2020]
[8] `https://www.ilent.nl/onderwerpen/drones/vliegbewijs-voor-beroepsmatig-gebruik-van-drones` [Accessed on 19-06-2020]
[9] `http://droneflightacademy.eu/nl/opleidingen/kosten/#:~:text=De%20kosten%20voor%20deze%20cursus%20bedragen%20%E2%82%AC3500%2C-%20exclusief%20btw,kosten%20voor%20de%20medische%20keuring).` [Accessed on 19-06-2020]
[10] `https://eur-lex.europa.eu/legal-content/NL/TXT/PDF/?uri=CELEX:32019R2153&from=EN` [Accessed on 19-06-2020]
[11] `https://www.ainonline.com/aviation-news/business-aviation/2020-03-18/head-wearable-display-obtains-first-certification` [Accessed on 19-06-2020]
[12] `https://www.salary.com/tools/salary-calculator/test-pilot-v` [Accessed on 19-06-2020]
[13] `https://tdvg.nl/faciliteiten/werkplaats/` [Accessed on 19-06-2020]

- **Tailor made products**: Tailor made products for the structural motor arms and body shell consist of 2 materials: carbon fiber and polycarbonate. Polycarbonate is cheap material at €3 per m³, this means that only the mold really costs money. This was estimated at $765 or €677 for the complex, sizable body shell [14]. A cut 2*100*220mm carbon fiber plate stiffens the body shell. This can be cut out of A4 sized plate this plate costs €25.99 [15]. Furthermore the arms are comparable to standard carbon fiber tubes. These cost $317.98 or €281.43 [16]. A small housing for the camera stepper motor would cost €15, as would the small landing gear legs per piece. [17]. For 360 drones, this cost comes out at *€381,398*.
- **Storage**: Storage of the off the shelf products would be required, so an estimated storage facility space of 15x15 m^2 is taken into account. At the average rates from 2008 to 2016 this would cost at most €60 per m^2 per year to rent in the Netherlands [18], and the price seems stable enough to extrapolate to the 2020's (no better averaged resource could be found). This results in a total storage cost of *€110,250* over the full period.

The lowest level costs from the Cost Breakdown Structure are summarized in Table 20.1, and the Cost Breakdown Structure diagram is given in Figure 20.5 The final costs mentioned in the cost breakdown structure are with the 30% safety margin included. The final costs are all also rounded to the nearest €1,000 increment.

Table 20.1: Lowest level cost breakdown structure costs calculated as listed above.

Cost Source	Estimated Cost	Estimated Cost with Safety Factor	Per Drone Costs
Labour	€1,540,000	€2,002,000	€5,561
Software	€81,000	€105,000	€292
Workspace	€320,000	€415,000	€1,153
Licences	€46,000	€60,000	€167
Test Equipment	€60,000	€78,000	€217
Prototypes	€40,000	€52,000	€144
Test Facilities	€146,000	€190,000	€528
Certification Equipment	€60,000	€78,000	€217
Certification Fees	€191,000	€248,000	€689
Certification Facilities	€834,000	€1,085,000	€3,014
Workshop	€131,000	€171,000	€475
Off the shelf products	€2,388,000	€3,105,000	€8,625
HUD	€8,010,000	€10,413,000	€28,925
Tailor Made Products	€381,000	€496,000	€1,378
Storage Space	€110,000	€143,000	€397
Total	**€14,338,000**	**€18,641,000**	**€52,000**
Cost per Drone at 360 Drones Sold	**€40,000**	**€52,000**	**€52,000**
Total Excluding HUD	**€6,328,000**	**€8,228,000**	**€23,000**
Cost per Drone Excluding HUD	**€18,000**	**€23,000**	**€23,000**

The HUD is the biggest factor at €8,010,000. There is a lot of uncertainty tied to this option. Therefore it was chosen to present totals with and without this option. At the predicted market size of 360 drones the break even cost with the current budget without the HUD with full margins applied is €23,000. This is well below the maximum cost requirement of €60,000 that has been set (HD-USR-SYS-CST-01). The approximations made here were relatively liberal, but even if all costs were to double by including the HUD, the break even cost would still be below €60,000. It can thus be concluded that the drone can likely be designed, tested, certified for use, and supported, while staying below the maximum allowable price.

[14] `https://rexplastics.com/plastic-injection-molds/how-much-do-plastic-injection-molds-costarms` [Accessed on 19-06-2020]

[15] `https://carbonfibreshop.com/product/standard-carbon-fibre-sheet/` [Accessed on 19-06-2020]

[16] `https://www.rockwestcomposites.com/` Tube - Round - INFINITubeV - High Modulus - Plain Weave - Size 07 - 1.125 X 1.231 X 36 Inch [Accessed on 19-06-2020]

[17] `https://www.3dhubs.com/` [Accessed on 19-06-2020]

[18] `https://www.vanthof.nl/wp-content/uploads/Bedrijfsruimtemarkt-2016.pdf` [Accessed on 19-06-2020]

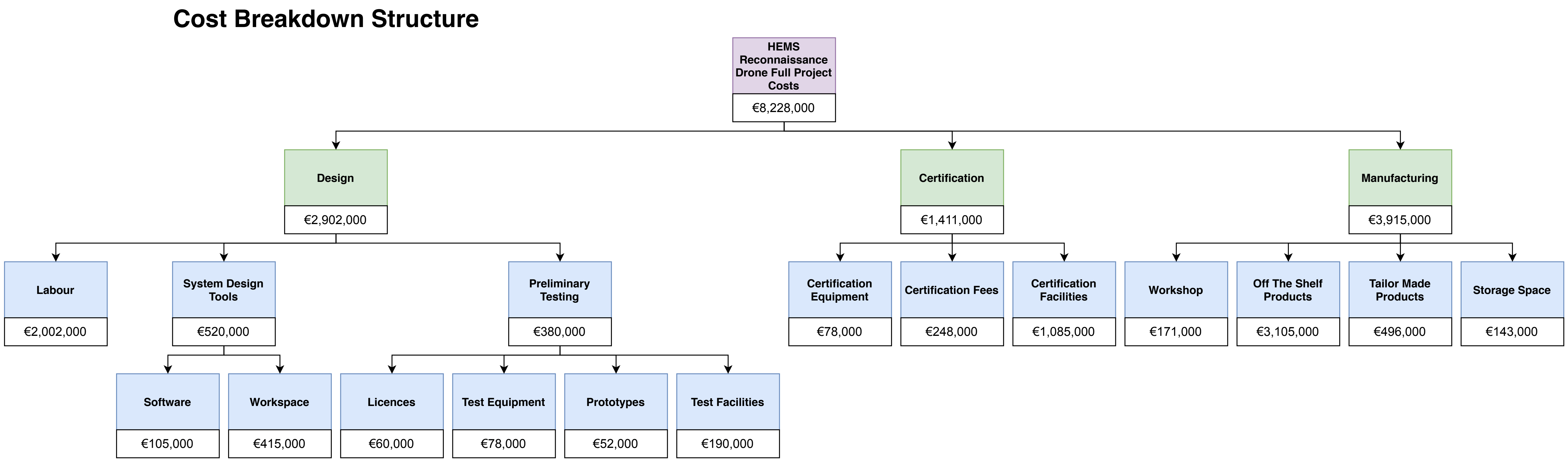


Figure 20.5: Cost Breakdown Structure in the form of an AND diagram of the total projected costs if the HEMS Reconnaissance drone were to be fully developed and released. The cost numbers include a 30% margin.

21
Conclusion

The purpose of this project was to develop a solution for the problem as stated in the mission need statement" "to permit a helicopter emergency medical service pilot to safely perform the approach, landing and take-off in low visibility weather conditions.". This was to be done through the means of a drone system. "A drone that is capable of safely assisting a HEMS pilot in navigation during operating in these conditions." Using a drone to explore a landing site allows for a reduction in system cost, compared to aircraft attached systems visual aid systems.

A list of requirements for the system to perform the respective mission correctly, was provided. In this list, the requirements driving the design of the drone system were the requirements set on drone dimensions, deployment, mission time, and the landing site volume to be scanned.

During the final design phase, A number of analyses were performed both on system and sub system level, to aid the design of the system under the given requirements. Through the market analysis and cost breakdown structure, it was found that the cost of the system is such, that out-pricing of existing aircraft vision enhancing systems is expected. Technical analysis of control and stability demonstrated the feasibility of stabilization after deployment of the drone from a helicopter. It is also demonstrated through analysis of propulsion systems and aerodynamics as well as operations, that the scanning of the required landing site volume within the mission time is feasible. The usage of multiple millimeter wave radar sensors in the designed setup was modeled and an insight in the expected data presentation was provided, showing a good representation of topography is possible. Risks and reliability involved with the system were considered in the risk and RAMS analysis respectively. In the risk analysis, mitigation is analysed for large risks of the system.

With all components and characteristics roughly determined, up until the current design phase, feasibility of the system and a dedicated position in the market is expected. It is therefore recommended to continue design of the system in a more comprehensive way. Some elements in of the drone system need more detailed analysis. The release mechanism and the presentation device for the pilot, need a more in depth design. Concerning the release mechanism in particular, real life testing and CFD analysis of the release trajectory would have high priority in the following design stages. Some other future work concerns for the release mechanism are the exact positioning of the pod on the skid mounting point, and the feasibility of a spring loaded eject system. The certification and integration of the display and the type of display used in the drone system requires a more elaborate design specification in the future. Besides actions in design of the system, also a more elaborate plan should be made for certification of the drone, as well as the release mechanism. The design of a helicopter deployed drone has not been certified before, it is expected that certification will be a big portion of future development activities. Therefore it is recommended that a plan on certification is made as early as possible.

Bibliography

[1] "Commision Implementing Regulation (EU) 2019/2153 of 16 December 2019 on the fees and charges levied by the European Union Aviation Safety Agency, and repealing Regulation (EU) No 319/2014". *Official Journal L327*, 2019.

[2] DSE Group 05. *Baseline Report HEMS Reconnaissance Drone*. Delft, Delft University of Technology, Faculty of Aerospace Engineering, 2020.

[3] DSE Group 05. *Midterm Report HEMS Reconnaissance Drone*. Delft, Delft University of Technology, Faculty of Aerospace Engineering, 2020.

[4] DSE Group 05. *Project Plan HEMS Reconnaissance Drone*. Delft, Delft University of Technology, Faculty of Aerospace Engineering, 2020.

[5] A. Huang H. Choi K. Abdel-Aty, M. Ekram. A study on crashes related to visibility obstruction due to fog and smoke. *Accident Analysis and Prevention*, 43:1730–1737, 2011.

[6] Guillaume Allibert, Dinuka Abeywardena, Moses Bangura, and Robert Mahony. Estimating body-fixed frame velocity and attitude from inertial measurements for a quadrotor vehicle. In *2014 IEEE Conference on Control Applications (CCA)*, pages 978–983. IEEE, 2014.

[7] J. D. Anderson. *Fundamentals of aerodynamics*. Mcgraw-hill Publishing Co., 2007.

[8] M. Ashby, H. Shercliff, and D. Cebon. *Materials Engineering,secience, processing and design*. Elsevier, 225 Wyman street,Waltham,02451,USA, 3rd edition edition.

[9] M. Naldi R. Mahony R. Bangura, M. Melega. Aerodynamics of rotor blades for quadrotors. 2017.

[10] Moses Bangura. *Aerodynamics and Control of Quadrotors*. PhD thesis, College of Engineering and Computer Science, The Australian National University, 2017.

[11] Moses Bangura, Robert Mahony, et al. Nonlinear dynamic modeling for high performance control of a quadrotor. 2012.

[12] Moses Bangura, Hyon Lim, H Jin Kim, and Robert Mahony. Aerodynamic power control for multirotor aerial vehicles. In *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pages 529–536. IEEE, 2014.

[13] R. Whidborne J. F. Krebs G. Luk P. Biczyski, M. Sehab. Multirotor sizing methodology with flight time estimation. *Journal of Advanced Transportation*, 2020, 2020.

[14] Aerospace Blockset. Aerospace blockset user's guide. *The MathWorks, Inc., Natick, MA*, 2007.

[15] M. S. Brandt, J. B. Selig. Propeller performance data at low reynolds numbers. *AIAA Aerospace Sciences Meeting*, 49, 2011.

[16] S. Chapman and Electric Machinery Fundamentals. *New Delhi, India: Tata McGraw-Hill Education*. 2005.

[17] M. Reysset A. Defay F. Delbecq, S. Budinger. Efficient sizing and optimization of multirotor drones based on scaling laws and similarity models. *Aerospace Science and Technology*, 102, 2020.

[18] Ir. R.J. Hamann & Prof. dr. ir. M.J.L. van Tooren. Systems engineering & technical management techniques, 2006.

[19] Eurocopter. *Eurocopter EC135 Technical Data*.

[20] F. Gatti, M. Giulietti. Preliminary design analysis methodology for electric multirotor. *IFAC Proceedings Volumes*, 46, 2013.

[21] M. Gatti. Complete preliminary design methodology for electric multirotor. *Journal of Aerospace Engineering*, 30, 2017.

[22] R. Gill, R. D'Andrea. Propeller thrust and drag in forward flight. *2017 IEEE Conference on Control Technology and Applications (CCTA)*, 2017.

[23] Terry Idol, Barry Haack, and Ron Mahabir. Radar speckle reduction and derived texture measures for land cover/use classification: a case study. *Geocarto International*, 32(1):18–29, 2017.

[24] Alem Kaplan and Kenan Dautovic². Helicopter emergency medical service: the case of bosnia and herzegovina. 01 2019.

[25] J. Gordon Leishman. *Principles of helicopter aerodynamics*. Cambridge University Press, 2017.

[26] Robert C Leishman, John C Macdonald, Randal W Beard, and Timothy W McLain. Quadrotors and accelerometers: State estimation with an improved dynamic model. *IEEE Control Systems Magazine*, 34 (1):28–41, 2014.

[27] D. MacNeill, R. Verstraete. Blade element momentum theory extended to model low reynolds number propeller performance. *Cambridge University Press*, 2017.

[28] R. Mahony, V. Kumar, and P. Corke. Multirotor aerial vehicles: Modeling, estimation, and control of quadrotor. *IEEE Robotics Automation Magazine*, 19(3):20–32, 2012.

[29] Philippe Martin and Erwan Salaün. The true role of accelerometer feedback in quadrotor control. In *2010 IEEE International Conference on Robotics and Automation*, pages 1623–1629. IEEE, 2010.

[30] Ir. J.A. Melkert. Structural analysis, notes lecture 11: Energy methods for determining deformations. tu delft. 2020.

[31] Ashfaq Mian and Wang Daobo. Modeling and backstepping-based nonlinear control strategy for a 6 dof quadrotor helicopter. *Chinese Journal of Aeronautics - CHIN J AERONAUT*, 21:261–268, 06 2008.

[32] Sammy Omari, Minh-Duc Hua, G. Ducard, and T. Hamel. Nonlinear control of vtol uavs incorporating flapping dynamics. 11 2013.

[33] I. Penkov and D. Aleksandrov. Analysis and study of the influence of the geometrical parameters of mini unmanned quad-rotor helicopters to optimise energy saving. *International Journal of Automotive and Mechanical Engineering*, 14:4730–4746, 2017.

[34] Fernando Porté-Agel, Majid Bastankhah, and Sina Shamsoddin. Wind-turbine and wind-farm flows: a review. *Boundary-Layer Meteorology*, 174(1):1–59, 2020.

[35] P. Q. *Liu, Air Propeller Theory and Its Application (in Chinese)*. Beijing, China: Beihang Univ, 2006.

[36] Q. Quan. *Introduction to Multicopter Design and Control*. Springer Singapore.

[37] Q. Quan. *Introduction to Multicopter Design and Control*. Springer Nature, 152 Beach Road, 21-01/04 Gateway East, Singapore 189721, Singapore, 1st edition, 2017.

[38] J. Roskam. *Airplane design. Pt. 1. Preliminary sizing of airplanes*. Roskam Aviation and Engineering, Ottawa, Canada, 1985.

[39] Szymon Rusinkiewicz and Marc Levoy. Efficient variants of the icp algorithm. In *Proceedings Third International Conference on 3-D Digital Imaging and Modeling*, pages 145–152. IEEE, 2001.

[40] Fabrizio Schiano, Javier Alonso-Mora, Konrad Rudin, Paul Beardsley, Roland Siegwart, and Bruno Siciliano. Towards estimation and correction of wind effects on a quadrotor uav. 08 2014.

[41] S. Shah, D. Dey, C. Lovett, and A. Kapoor. Airsim: High-fidelity visual and physical simulation for autonomous vehicles. In *Field and Service Robotics*, 2017.

[42] Shital Shah, Debadeepta Dey, Chris Lovett, and Ashish Kapoor. Airsim common apis, 2017.

[43] Dongjie Shi, Xunhua Dai, Xiaowei Zhang, and Quan Quan. A practical performance evaluation method for electric multicopters. *IEEE/ASME Transactions on Mechatronics*, PP:1–1, 03 2017.

[44] João Paulo Silva, Christophe De Wagter, and Guido de Croon. Quadrotor thrust vectoring control with time and jerk optimal trajectory planning in constant wind fields. *Unmanned Systems*, 06(01):15–37, 2018.

[45] J. A. Stratton. The effect of rain and fog on the propagation of very short radio waves. *Proceedings of the Institute of Radio Engineers*, 18(6):1064–1074, 1930.

[46] B. Theys, G. Dimitriadis, P. Hendrick, and J. De Schutter. Influence of propeller configuration on propulsion system efficiency of multi-rotor unmanned aerial vehicles. *International Conference on Unmanned Aircraft Systems*, 2016.

[47] E. Torenbeek and H. Wittenberg. *Flight Physics: Essentials of Aeronautical Disciplines and Technology*. with Historical Notes, Dordrecht, The Netherlands, 2009.

[48] R van Gent. *Project Guide Design Synthesis Exercise HEMS reconaissance drone*. Delft, Delft University of Technology, Faculty of Aerospace Engineering, April 2020.

[49] Guang Yang, Xingqin Lin, Yan Li, Hang Cui, Min Xu, Dan Wu, Henrik Rydén, and Sakib Bin Redhwan. A telecom perspective on the internet of drones: From lte-advanced to 5g. *arXiv preprint arXiv:1803.11048*, 2018.

[50] S. Yosi, N. J. Agung, and S. Unang. Tilt and heading measurement using sensor fusion from inertial measurement unit. In *2015 International Conference on Control, Electronics, Renewable Energy and Communications (ICCEREC)*, pages 193–197, 2015.

[51] Muhammad Fahad Zia, Elhoussin Elbouchikhi, and Mohamed Benbouzid. Optimal operational planning of scalable dc microgrid with demand response, islanding, and battery degradation cost considerations. *Applied Energy*, 237:697–707, 03 2019.

A

Appendix: Life Cycle Assessment

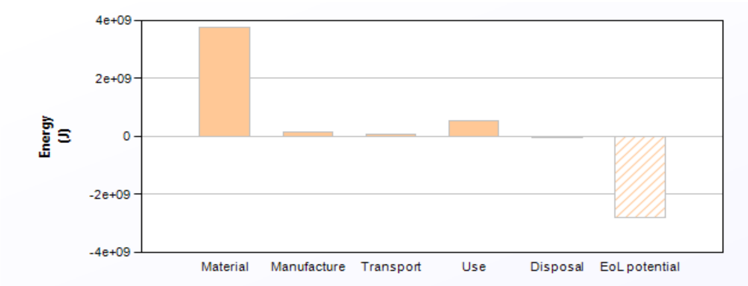
This appendix contains excerpts of the life cycle assessment performed on the HEMS Drone and its pod attached to the helicopter. These excerpts focus on energy and not on CO_2 emission as these scale almost linearly and CO_2 emission was omitted for brevity. More information can be found in chapter 18.

CES 2019 EDUPACK

Eco Audit Report

Summary

Energy Analysis



	Energy (J/year)
Equivalent annual environmental burden (averaged over 3,92 year product life):	1,145E+009

Detailed breakdown of individual life phases

Material:

Summary

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	Energy (J)	%
Propellor	CFRP, epoxy matrix (isotropic)	Virgin (0%)	0,04	4	0,17	1,18E+008	3,2
Motor	Fan	Virgin (0%)	0,18	4	0,70	1,73E+008	4,6
Battery	Li-Ion battery (for scooters)	Virgin (0%)	1,11	1	1,11	3,59E+008	9,6
Flight Controller PixHawk 4	Printed circuit board assembly	Virgin (0%)	0,02	1	0,02	2,59E+006	0,1
On board computer Raspberry Pi 4 B	Printed circuit board assembly	Virgin (0%)	0,06	1	0,06	7,78E+006	0,2
Sensors	Optical mouse, with cable	Virgin (0%)	0,86	1	0,86	6,32E+008	16,9
Body Shell Poly Carbonate	Polycarbonate (PC)	Virgin (0%)	0,17	1	0,17	1,74E+007	0,5
Body Shell Carbon Fiber	CFRP, epoxy matrix (isotropic)	Virgin (0%)	0,04	1	0,04	2,41E+007	0,6
Motor arm	CFRP, epoxy matrix (isotropic)	Virgin (0%)	0,15	2	0,30	2,06E+008	5,5
Various cables	Cable	Reused part	0,10	1	0,10	0,00	0,0
ESC	Integrated circuit, small	Virgin (0%)	0,06	4	0,24	4,29E+008	11,5
Gimbal	Fan	Virgin (0%)	0,32	1	0,32	7,91E+007	2,1
Steppermotor	Fan	Virgin (0%)	0,03	1	0,03	6,18E+006	0,2
Steppermotor controller	Integrated circuit, small	Virgin (0%)	0,01	1	0,01	1,79E+007	0,5
Encasing and supporting structure for camera steppermotor	Polycarbonate (PC)	Virgin (0%)	0,03	1	0,03	2,63E+006	0,1
Aluminum plate	Age-hardening wrought Al-alloys	Typical %	5,56	1	5,56	7,03E+008	18,8
Corner profile 500 mm	Age-hardening wrought Al-alloys	Typical %	0,14	8	1,11	1,41E+008	3,8
Corner profile 250 mm	Age-hardening wrought Al-alloys	Typical %	0,07	4	0,28	3,54E+007	0,9
Indicator light	Diodes and LEDs	Virgin (0%)	0,05	1	0,05	2,32E+008	6,2
Temperature sensor	Integrated circuit, small	Virgin (0%)	0,10	1	0,10	1,79E+008	4,8
Spring	Age-hardening wrought Al-alloys	Typical %	1,00	1	1,00	1,26E+008	3,4
Door Actuator	Age-hardening wrought Al-alloys	Typical %	0,50	4	2,00	2,53E+008	6,8
Total				**45**	**14,24**	**3,75E+009**	**100**

*Typical: Includes 'recycle fraction in current supply'

Figure A.1: Excerpt from the Eco Audit performed on the HEMS Drone and Pod

Manufacture:

Summary

Component	Process	Amount processed	Energy (J)	%
Propellor	Compression molding	0,17 kg	602108,10	0,4
Body Shell Poly Carbonate	Polymer molding	0,17 kg	3,07E+006	2,2
Body Shell Carbon Fiber	Compression molding	0,04 kg	122522,00	0,1
Motor arm	Compression molding	0,30 kg	1,05E+006	0,7
Encasing and supporting structure for camera steppermotor	Polymer molding	0,03 kg	464455,34	0,3
Aluminum plate	Roll forming	5,56 kg	5,30E+007	37,6
Corner profile 500 mm	Extrusion, foil rolling	1,11 kg	2,09E+007	14,8
Corner profile 250 mm	Extrusion, foil rolling	0,28 kg	5,27E+006	3,7
Spring	Extrusion, foil rolling	1,00 kg	1,88E+007	13,4
Door Actuator	Extrusion, foil rolling	2,00 kg	3,77E+007	26,7
Total			**1,41E+008**	**100**

Transport:

Summary

Breakdown by transport stage

Stage name	Transport type	Distance (m)	Energy (J)	%
Manufacturing in the Netherlands	14 tonne (2 axle) truck	200000,00	4,27E+006	7,7
Manufacturing in China	Ocean freight	2,00E+007	5,13E+007	92,3
Total		**2,02E+007**	**5,55E+007**	**100**

Use:

Summary

Static mode

Energy input and output type	Electric to mechanical (electric motors)
Country of use	Netherlands
Power rating (W)	366,90
Usage (hours per day)	0,50
Usage (days per year)	88,00
Product life (years)	3,92

Disposal:

Summary

Component	End of life option	Energy (J)	%	Energy (J)	%
Propellor	Re-manufacture	34400,00	0,4	-1,18E+008	4,2
Motor	Re-manufacture	140000,00	1,7	-1,71E+008	6,1
Battery	Downcycle	555000,00	6,6	0,00	0,0
Flight Controller PixHawk 4	Reuse	4000,00	0,0	-2,59E+006	0,1
On board computer Raspberry Pi 4 B	Reuse	12000,00	0,1	-7,78E+006	0,3
Sensors	Reuse	171000,00	2,0	-6,32E+008	22,5
Body Shell Poly Carbonate	Recycle	115500,00	1,4	-1,13E+007	0,4
Body Shell Carbon Fiber	Downcycle	17500,00	0,2	-3500,00	0,0
Motor arm	Downcycle	150000,00	1,8	-30000,00	0,0
Various cables	Reuse	20000,00	0,2	0,00	0,0
ESC	Reuse	48000,00	0,6	-4,29E+008	15,3
Gimbal	Reuse	64000,00	0,8	-7,91E+007	2,8
Steppermotor	Reuse	5000,00	0,1	-6,18E+006	0,2
Steppermotor controller	Reuse	2000,00	0,0	-1,79E+007	0,6
Encasing and supporting structure for camera steppermotor	Recycle	17500,00	0,2	-1,71E+006	0,1
Aluminum plate	Recycle	3,89E+006	46,6	-5,15E+008	18,3
Corner profile 500 mm	Recycle	778400,00	9,3	-1,03E+008	3,7
Corner profile 250 mm	Recycle	196000,00	2,3	-2,59E+007	0,9
Indicator light	Reuse	10000,00	0,1	-2,32E+008	8,3
Temperature sensor	Reuse	20000,00	0,2	-1,79E+008	6,4
Spring	Recycle	700000,00	8,4	-9,27E+007	3,3
Door Actuator	Recycle	1,40E+006	16,8	-1,85E+008	6,6
Total		**8,35E+006**	**100**	**-2,81E+009**	**100**

Figure A.2: Excerpt from the Eco Audit performed on the HEMS Drone and Pod