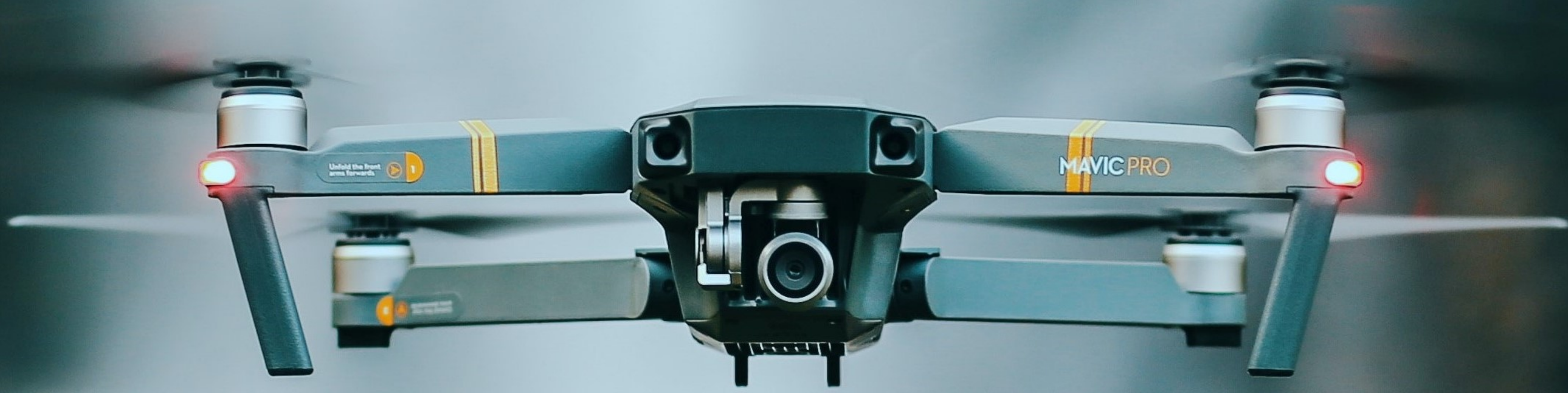
# AIgle

# Midterm Report

## Group 19




TU Delft

# Aigle

## Midterm Report

by


## Group 19

| | |
|---|---|
| Dries Borstlap | 4648099 |
| Friso Dam | 4297148 |
| Nadine Duursma | 4665236 |
| Weronika Dziarnowska | 4551117 |
| Victor Guillet | 4488636 |
| Yestin van Haaren | 4667581 |
| Danny Huang | 4669045 |
| Max van Huffelen | 4678214 |
| Jeroen Riessbacher | 4438051 |
| Georg Strunck | 4680421 |
| Reinier Vos | 4663160 |

| | |
|---|---|
| Tutor | Christophe de Wagter |
| Coach | Bertrand Mercier |
| Coach | Yi Zhang |



| Version | Change | Date |
|---|---|---|
| 0.1 | Draft | June 2, 2020 |

Cover image by [42].

TU Delft

# Contents


**Nomenclature** ii

**Executive Overview** 1

**1 Introduction** 7

**2 Organisation** 8
2.1 Team Roles . . . 8
2.2 Team Procedures . . . 10
2.3 Work Division . . . 10
2.3.1 Work Flow Diagram . . . 10
2.3.2 Work Breakdown Structure . . . 10
2.3.3 Gantt Chart . . . 10

**3 Interface Definition** 16

**4 Engineering Design and Analysis** 18
4.1 Hardware Block Diagram . . . 18
4.2 Software Block Diagram . . . 18
4.3 Data Handling Diagram . . . 19
4.4 Engineering Analysis Diagrams . . . 20

**5 Requirements Engineering** 23
5.1 Revisions . . . 23
5.2 Revised Requirements List . . . 24

**6 Design Option Tree** 26

**7 Design Option Structuring** 28
7.1 Components Elaboration . . . 28
7.2 Final Concepts . . . 29
7.2.1 COMP_C1: AI/Processing Power Focus Concept . . . 30
7.2.2 DUR_C2: Durability Focus Concept 31
7.2.3 SENS_C3: Sensor Focus Concept 32
7.2.4 LWQ_C4: Lightweight Quadrotor Concept . . . 33
7.2.5 LWT_C5: Lightweight Trirotor Concept . . . 34
7.3 Concept Selection Methodology . . . 35
7.3.1 Performance . . . 35
7.3.2 Structure . . . 37
7.3.3 Computing . . . 41
7.3.4 Sensors . . . 42
7.3.5 Flight Controllers . . . 43
7.3.6 Power and Propulsion . . . 44

**8 Verification and Validation Procedures** 47
8.1 Simulations . . . 47
8.1.1 Verification . . . 47
8.1.2 Validation . . . 47
8.2 Midterm Report: Results . . . 47
8.2.1 Verification of Sizing Calculations 47
8.2.2 Validation of Sizing Calculations . 48
8.3 Product . . . 49
8.3.1 Verification . . . 49
8.3.2 Validation . . . 49
8.4 Final Design: Results . . . 50
8.4.1 Mass Requirement: Contingency Management . . . 50
8.4.2 Flight Time Requirement: Effect on Mass Estimate . . . 50

**9 Technical Risk Assessment** 51
9.1 Risk Overview . . . 51
9.2 Risk Mitigation Strategy . . . 51

**10 Sustainable Development Strategy** 54
10.1 Life Cycle Assessment . . . 54
10.2 Sustainability Criteria . . . 55

**11 Trade-off** 56
11.1 Trade Method . . . 56
11.1.1 Autonomous Navigation Performance (ANP) . . . 57
11.1.2 Flight Performance (FP) . . . 58
11.1.3 Sustainability (Sust) . . . 58
11.1.4 Risk . . . 59
11.1.5 Mass . . . 60
11.1.6 Cost . . . 61
11.2 Trade-off of Concepts . . . 61
11.3 Sensitivity Analysis . . . 62

**12 Operations Logistic Concept** 64
12.1 Operations . . . 64
12.2 Repairs . . . 64
12.3 Support . . . 65
12.4 Maintenance . . . 65
12.5 Logistics . . . 66
12.6 Disposal . . . 66

**13 Conclusion** 68

**Bibliography** 69

# Nomenclature

## List of Symbols

| | | |
|---|---|---|
| $\epsilon$ | Error percentage | [/] |
| $\phi$ | Bank angle | [°] |
| $\rho$ | Air density | [kg/m$^3$] |
| $\theta$ | Pitch angle | [°] |
| $a$ | Acceleration | [m/s$^2$] |
| $C_D$ | Drag coefficient | [/] |
| $D$ | Drag | [N] |
| $F$ | Force | [N] |
| $I_{dry}$ | Current without propulsion | [A] |
| $m$ | Mass | [kg] |
| $m_{dry}$ | Dry mass | [g] |
| $m_{p+b}$ | Propulsion system & battery mass | [g] |
| $m_{prop}$ | Propulsion system mass | [g] |
| $m_{total}$ | Total drone mass | [g] |
| $n$ | Load factor, T/W | [kg] |
| $R$ | No. of rotors | [m] |
| $r$ | Radius | [m] |
| $S$ | Surface area | m$^2$ |
| $T$ | Thrust | [N] |
| $V$ | Velocity | [m/s] |
| $W$ | Weight | [N] |
| C | Capacity | [mAh] |
| I | Current | [A] |
| k | Linear constant | [/] |
| t | Time | [s] |

## List of Abbreviations

| | |
|---|---|
| ABS | Acrylonitrile butadiene styrene |
| AHP | Analytical hierarchy process |
| AI | Artificial intelligence |
| AIO | All in one |
| AM | Additive manufacturing |
| ANP | Autonomous Navigation Performance |
| ASA | Acrylic styrene acrylonitrile |
| CNC | Computer numerical control |
| COMP_C1 | Computational concept |
| DoD | Depth of discharge |
| DOT | Design option tree |
| DSE | Design/synthesis exercise |
| DUR_C2 | Durability concept |
| EDA | Electronic design automation |
| ESC | Electronic speed controller |
| FDM | Fused deposition modelling |
| FOV | Field of view |
| fps | frames per second |
| GPS | Global positioning system |
| hd | High definition |
| IDE | Integrated development environment |
| IMU | Internal measurement unit |
| IO | Input-output |
| IROS | International Conference on Intelligent Robots and Systems |
| Laser | Light amplification by stimulated emission of radiation |
| LED | Light emitting diode |
| Lidar | Laser imaging, detection, and ranging |
| LiPo | Lithium polymer |
| LWQ_C4 | Light weight quadrotor concept |
| LWT_C5 | Light weight trirotor concept |
| MIPI | Mobile Industry Processor Interface |
| MMOI | Mass moment of inertia |
| PC | Polycarbonate |
| PCB | Printed circuit board |
| PLA | Polyactic acid |
| PS | Propulsion system |
| PSU | Propulsion system unit |
| R/C | Radio control |
| RAM | Random access memory |
| RF | Radio Frequency |
| RoHS | Restriction of Hazardous Substances |
| RPM | Rounds per minute |
| SENS_C3 | Sensor concept |
| SLA | Stereolithography |
| SLM | Selective laser melting |
| SLS | Selective laser sintering |
| SoC | System on Chip |
| T/W | Thrust over weight ratio |
| TA | Teaching assistant |
| TOPs | Tera operations per second |
| UoP | University of Pennsylvania |
| US$ | United States dollar |

# Executive Overview

## Project Objectives

Currently there are many piloted drone races being held which has set the base for autonomous racing drones competing against each other. In order to have a fair competition the participants should all be flying the same drone during the competition and they should be able to practice with the actual drone beforehand.

The AIgle Design Team aims to provide a concept of such an autonomous drone that can complete an entire race track on its own based on artificial intelligence. Furthermore, it should be designed to be an open-source project, allowing the participants and organizers to build the drone at small cost of 2500€ using simple manufacturing techniques. This midterm report proposes five different details in more detail and provides a trade-off selecting the final design concept that will then enter the detailed design stage

The goal of this design project is to further the research on AI and autonomous flying robots. Furthermore, the TU Delft might benefit from publishing this concept.

## Organisation

Everyone in the AIgle team has one managerial role and one engineering role. The managerial roles have been changed and will become active after the midterm review. They consist of the Team Leader, a Secretary, one Motivation Manager, the Internal Relations Manager, one External Relations & Business Manager, the Sustainability Manager, the Risk Manager and three Quality Control roles, which are split into the Completionist, the Monitor and the Editor. Furthermore, there are two System Engineers, one of which responsible for the Hardware and one responsible for the Software. They are active both on the managerial side of the team roles as well part of the engineering side. The roles of the engineers have remained unchanged with two engineers in the Electronics & Power Department, one Aerodynamics Engineer, two Propulsion & Performance Engineers and two engineers in the Structures Department on the hardware section. The Software section has two Control & Stability Engineers and one engineer for each the Navigation Department and the Machine Vision Department.

The changes in roles took place only in the management part of the team. The secretary has become a task that will rotate between all the teammates and a third quality control person who is responsible for editing. Besides that the External Relations Manager role has been merged with the one of the Business Manager. Also a new role has been created for the Motivation Manager, who is taking care of intra-team bonding and making sure everyone in the team has a contact person for issues adversely affecting them.

## Interface Definition with N2 Charts

In order to achieve a good overview of the relations between the different components of the system, an N2 chart was developed. This chart allows for a clear and effective overview to be achieved, showing clearly the interaction, inputs and outputs of the various major components. To read the chart, the horizontal rows represent outputs, and vertical column the inputs.

## Engineering Design and Analysis

Following the N2 charts, three more diagrams were developed to further represent the different components of the system and their connections/interactions. The hardware block diagram shows the interaction of the various electronic components in the system. The software block diagram depicts on a higher level the software pipeline that will be implemented to perform the various tasks required by the drone. Four major blocks were defined; the general input, the Machine vision and state estimation block, the navigation, and finally the control block. Each of these handle a specific part of the task and allow for efficient autonomous or manual operations to be performed while keeping the risks to a minimum.

Finally, the communication flow diagram describes the flow of information around the system. It again describes on a high level what information flows between the various component of the system (both in the hardware and software).

## Requirements Engineering

The requirements have been defined in more detail, leaving no requirements with <tbd>, but assigning values to each requirement. Three key requirements have been found to be driving the design to an unacceptable extent when considered together. The requirement to reach a top speed of 30 m/s, the requirement to fly for 5 minutes and the requirement to stay below 1 kg of total mass. This has lead to remove the maximum speed requirement such that the next limiting requirement demands the drone to have a thrust to weight ratio of at least 4. The flight time has been considered to be too large and a compromise is being considered to change it to something closer to 1 minutes of flight time and 2 minutes of standby time (where the drone is activated, but no propellers turning). The mass requirement of 1 kg has been considered less important than the other two requirements above, but it is a preference that the mass does not exceed the 1 kg by more than 100-200 g and the requirement remains unchanged.

## Design Option Tree

In chapter 6 the design options are portrayed in a design option tree (DOT). This DOT differs from the previous DOT in the Baseline Report by being less broad, more detailed and only investigating the really feasible and promising options.

## Design Option Structuring

This chapter explains the reasoning behind the concept generation and is introducing the final concepts.

### Final Concepts

First there have been setup five different concept goals which lead to five different conceptual designs: the processing concept, the sensors concept, the durability concept, the lightweight quadrotor concept and the lightweight trirotor concept. In general every drone concept fulfills the requirements with exception of the mass budget, the flight time and the maximum speed requirements. Also all concepts use the same flight controller, which has not bee set yet but allotted a mass, size and electric current budget and the frames are made out of carbon fibre. The propulsion unit for each concept has been calculated and no specific hardware chosen yet.

The **COMP_C1: AI/Processing power focus concept** focusses on processing power. This concept strives for the most powerful processor, partially at the expense of mass and size. It houses the Nvidia Jetson Xavier AGX processor, which is the most powerful companion computer on the market for drones. The sensors that will provide information to the computer consists of three cameras, which can provide frames at high speeds of up to 100 fps and depth mapping with stereo imaging at 60 fps. The frame will be an HX-Hybrid allowing for space to mount the large processor and the propulsion system will weigh 154 g and the battery has a mass of 403 g.

The **DUR_C2: Durability focus concept** is designed to maximize the impact resistance and lifetime of the components together with easy replacability of drone parts. This aims at having a minimum downtime to allow for more intensive training and robustness during the races. The companion computer of this concept will be the Nvidia Jetson Xavier NX, like for all concepts except the computational concept. It has only one single camera as sensor, which just satisfies the requirements, in order to minimize the breakage possibility. The structure of this concept includes propeller guards and the propellers placed in such a way on the deadcat frame that the onboard systems are encircled entirely except the front for maximum protection. The propulsion system will weigh 154 g and the battery has a mass of 215 g.

The **SENS_C3: Sensor focus concept** is putting its emphasis on providing a wide range of data for the drone to plan its path. The companion computer of this concept will be the Nvidia Jetson Xavier

NX, like for all concepts except the computational concept. The sensors that are being used on the sensors concept are one single camera facing forward and one depth imaging solution consisting of two cameras also facing forward. additionally one lidar system is mounted facing downward. In order t provide maximum visibility a concept is chosen with pusher propellers (facing downwards) and a deadcat frame for wide field of view towards the ground as well. The propulsion system will weigh 154 g and the battery has a mass of 241 g.

The **LWQ_C4: Lightweight quadrotor concepts** design goal is to achieve a more balanced compromise between different aspects of the drone. The companion computer of this concept will be the Nvidia Jetson Xavier NX, like for all concepts except the computational concept. It has only one single camera as sensor, which just satisfies the requirements, in order to minimize the breakage possibility. The frame will be a Deadcat frame allowing for a good field of view and the propulsion system will weigh 154 g and the battery has a mass of 177 g.

The **LWT_C5: Lightweight trirotor concept** is similar to the lightweight quadrotor with its aim, while still being able to investigate a trirotor concept. The companion computer of this concept will be the Nvidia Jetson Xavier NX, like for all concepts except the computational concept. It has only one single camera as sensor, which just satisfies the requirements, in order to minimize the breakage possibility. The frame will be a Y-frame allowing to minimize the mass and the propulsion system will weigh 127 g and the battery has a mass of 204 g.

**Concept Selection Methodology**

The methods that have been used for the concept selection are much more in depth for each engineering department.

The **flight performance** of the drone concept and the related requirements are analyzed. The most critical T/W requirements come from the turning performance requirement and the maximum speed requirement. The former demands that the drone shall be able to make a turn with 3 m radius when flying at 10 m/s. For this requirement a T/W ratio of 4 is needed. The latter demands that the drone shall be able to reach 30 m/s. For this, a T/W ratio of 6.5 is needed. It has been found that this is not realistically achievable, and therefore the T/W ratio of 4 is used to perform the sizing for the trade-off.

The **structural discussion** of the drone is split up into the possible manufacturing processes, the materials that could be used, the drone frame shapes and further structural considerations. The manufacturing processes are limited to 2D milling and 3D printing. The material choice for 2D milling is mainly depending on the cutting tool that needs to be used. 3D printing incorporates many different techniques which all rely on adding material to create the product by 'building up' the part layer by layer. 3D printing techniques can use many different materials. The materials that are to be used in building the drone frame and other structures have to be highly lightweight, stiff enough to provide structural integrity and strong enough to withstand crashes onto the floor or into gates. Different material groups have been investigated by comparing different material properties. From this comparison carbon fibre emerges as best option, because of its low mass combined with high strength and stiffness. The structure of the drone needs to provide a base frame to mount all components on, needs to provide protection of these components and provide the aerodynamic shell of the drone. There are many different frame types that heave been considered.

Different **computing processors** have been considered with two overall favourites. The first of them is the Nvidia Jetson Xavier AGX, which is currently the most powerful processor for AI drone applications with up to 31 TOPs. On the other hand it is large and heavy and has therefore only been chosen for the computationally strong concept. The other concepts are making use of the also powerful (up to 21 TOPs) but much lighter and smaller version with the new Nvidia Jetson Xavier NX. The carrier board for the Xavier AGX has been chosen to be the one that is already included in the Development Kit of the same processor. For the Xavier NX the Quark Carrier board has been selected due to its good characteristics and low mass.

Many different **sensors** have been investigated in order to find all possibilities for gathering the best navigation data for the drone. The various sensors that have been investigated are mono cameras for image recognition, stereo cameras for depth imaging, lidars for distance measurements, satellite based navigation services (GPS), ultrasound for 3D images, inertial measurement units (IMU's) for attitude knowledge and optical flow sensors. For the sensors to be selected it is of course important to be as lightweight and small as possible but also to be able to rely the gathered data quickly and reliable to the processor.

The **flight controllers** for the drone have found to be varying largely in mass and size. Besides the need to minimize those two properties, it is also desired to have a fast controller that is already flight proven, which is the case with the F7 classified models that has also enough connecting channels. Furthermore it is required that the flight controller supports the BetaFlight control software and it would be beneficial for the controller to be also able to perform the power distribution reducing the complexity of the drone design. Additionally it would be useful if the flight controller includes a communication module as well as vibration damping, which is beneficial for controlling the drone. Because there are many different flight controllers that fulfill these needs at low size and mass, the final selection is being left up to the detailed design. For the concept calculations a dimension of 4 by 4 by 1.5 cm, a mass of 10 g and a current of 1 A has been reserved.

After the dry mass of the drone has been determined the propulsion elements can be designed. These consist of the battery and the motor and propellers. Because a battery with higher mass requires a motor with higher thrust and a higher thrust motor a stronger current and therefore a heavier battery again, this process is an iterative process. For the choice of **battery** the team only focused on LiPo batteries because of their low mass to capacity ratio. Also the motors that provide the range of thrust are categorized by nominal voltage the battery supplies and range from 4S to 6S, where the number in front of S denotes the number of battery cells and S stands for cells in 'Series'. Each battery cell has a nominal voltage of 3.7 V. The mass per capacity and the cost per capacity of these batteries have been established as a linear relationship. Together with a motor that flies at 100% throttle for one minute the mass, capacity and the cost have been estimated for each of the four concepts for a 4S battery. The mass of the batteries is ranging from 227 g to 401 g, the capacity is ranging from 1920 mAh to 4100 mAh and the cost ranges from 23 € to 38 €, where for each properties the computational concept is on the high end and the lightweight quadcopter on the low end of the range. The **motor**, propeller and electronic speed controller (ESC) have been estimated similarly by creating a database. For the sizing of the motor the same propeller and ESC have been used for better comparison. From this database only a proper linear relationship could be found for the current required versus thrust provided. The mass and cost varied more irregular, but for estimation the total average per motor of ≈31 g for the mass and of ≈20 US$ could be used.

After all this has been done the different concepts could be set up with defining the total dry mass, the mass of the battery and the mass of the propulsion system. This **total mass estimate** of the drone then also includes an additional safety margin resulting in the total masses of the computational concept to be 1631 g, the sensors concept to be 978 g, the durability concept to be 1066 g, the computational concept to be 838 g and the mass of the trirotor to be 813 g as seen in Table 7.1.

A **flight time** versus drone mass analysis has been made revealing an exponential increase in mass with increasing flight time. The shapes of those graphs look rather similar for each of the concepts, where it is only noted that the heavy computational drone is increasing in mass a little faster and that the lightweight quadrotor concept is increasing less fast in mass than the trirotor, allowing to be more lightweight for a flight time of 1.3 minutes onwards.

## Verification and Validation Procedures

Verification and validation is done with regard to the mass estimates computed for the concepts. The computations done are verified by using a different model and consistently provided the same results. Validation is done with regard to the two statistical relationships used in the mass computations. The actual UoP drone's [34] properties are obtained and compared to the verified model to check the adequacy of the statistical relationships. This showed that both relationships lead to overestimations. However, the overestimates are still in the same order of magnitude and should not pose a problem

at this design phase.
This chapter also includes provides verification of requirements on the mass and flight time. Mass estimates using by adding the statistical errors are given to give an indication of the potential upper limit of the mass estimate. Also, it is clearly shown that a flight time requirement of 5 minutes at full power will have to be cut down to ≈1-2 minutes in order meet all the other requirements.
Finally, the procedures which will be used for verification and validation of both final design and eventual product are given, including a list of simulators which might be used in this process.

## Technical Risk Assessment

A risk analysis is performed to identify the risks certain events bring. The events are given a ranking in probability, so how big is the chance an event will occur, and the impact, how big are the consequences when an events occurs. These are all displayed in a table, together with a ranking and for a good overview also put in a risk map. Then a mitigation strategy is set up, this is done to reduce the probability and impact, in order to lower the risk. The mitigation strategy is also displayed in a table and mapped in a risk map. Which then can be compared to the risk map before mitigation. From the risk map after mitigation, it is clear that some of the risk have to be watched closely, while others especially risks concerning a crash need more research and action in further design.

## Sustainable Development Strategy

A sustainability development strategy is implemented in order to balance the environmental, social and economic impacts of the race drone. The strategy starts by conducting a life cycle assessment of the drone to thoroughly find out the different ways that sustainability of the product can be affected. Each phase of the product's life is analysed, from raw material acquisition to the end-of-life phase. During this analysis, which was done in the baseline report [11], a list of 14 sustainability aims were identified, which indicate ways in which sustainability can be improved. These sustainability aims were then translated into a list of sustainability criteria. At this stage of the design process, a lot of detailed information about each concept is unknown, and therefore only three of the sustainability criteria were chosen to be used during the concept sustainability trade-off. The other sustainability criteria are documented for future possible sustainability evaluations. The three sustainability criteria are related to power usage, material volume, and durability. They were each given a weight factor of 40%, 20% and 40%, respectively, based on their estimated influence on sustainability. The criteria are then used to evaluate the concepts in the trade-off section.

## Trade Off of Concepts

After defining five concepts, a trade-off was performed to select the best concept for the final design. Six trade-off criteria were defined to do so. The first trade-off criteria is autonomous navigation performance, which is quantified based on computational power, obtained from the processor specifications, and the number of sensors. Secondly flight performance was evaluated based on the mass moment of inertia, the frame type and the wheelbase indicating the diameter of the largest circle that can be drawn around the drone frame. Those values were derived from the 3D model made with the Catia software.

Then the third criteria sustainability was set based on a concept its power consumption, volume and durability or impact resistance. The fourth criteria, risk, was quantified based on a concept its structural and electrical risk, as well as the design method reliability.

The last two criteria are mass and cost, that were both evaluated quantitatively by summing up the cost of all open-source components as found on the internet, like the computer, flight controller, battery and camera. The mass of the frame was estimated from the Catia model.

After defining the criteria, the criteria weights were set based on an AHP (Analytical Hierarchy Process) method, team discussions, and the consultation with the client. Autonomous navigation performance got the highest weight of 35%, as the mission need statement of facilitating development of artificial intelligence systems needs to be satisfied. The next most important criteria are the flight performance and risk, which both receive a weight of 20%. Optimizing the flight performance allows for a faster and more agile drone, which is crucial in racing, and minimizing the drone risk reduces the down time that would be spent on fixing the drone upon failures. Then, the sustainability and mass are of equal importance having both a weight of 10%. And finally, the concept cost is given a small weight of 5%. After scoring all concepts with a score ranging from 0 until 5 for every criterion, the COMP_C1 and LWT_C5 were removed from the trade-off as they received unacceptable scores in one criterion, which disqualifies a concept from further analysis. The three remaining concepts did not differ significantly in score. Therefore, to find the true winning concept, a sensitivity analysis was performed where the weights and scores per concept were varied. This resulted in multiple scoring systems that gave different winning concepts each time. However, one concept won in a significant number of scoring systems and that was the DUR_C2 concept, which was thus concluded to be the overall winning concept that will be used in the final design phase.

## Operations Logistics Concepts

Operating a drone requires more than just hardware and software. There needs to be support for the drone to be able to charge or connect to a computer, the open source design needs to be accessible to everyone, there needs to be a manual with instruction on how to repair the drone and so on. All things concerning the drone that are not part of the hardware or software will be discussed in the chapter operations and logistics.

Operations and logistics is a vague term, and therefore it will be further subdivided into five categories. The first is operations, which includes all aspect of the drone during normal use. Second is repairs, which explains how to repair often breaking components of the drone. Third is support, which discusses how the open source design will be made available to the public. It will also discuss possibilities for question forums and specify how/where to get certain parts. The fourth category is maintenance, which elaborates on how to properly maintain the drone for ensuring a longer lifetime. Fifth comes logistics, which elaborates on other support items for the drone. This includes for example charging stations for the drone batteries, cables needed to connect the drone to a computer and a case in which the drone can be easily transported.

# 1 Introduction

Autonomous drone racing has taken the interest of both the scientific community and the general public since its beginning in 2016 with the IROS Autonomous Drone Race [36]. In these races, the competition is for the different teams to make the best software to pilot their drone to complete the circuit as quickly as possible. To make the deciding factor the quality of the software, races such as the Artificial Intelligence Robotic Races organised by the Drone Racing League have opted to use the same hardware for every team. However, this had a number of downsides. For example, some teams were not able to test their programs as well as the drone having undesirable characteristics such as high weight and poor controllability and aerodynamic characteristics. In an effort to alleviate these issues, group 19 of the TU Delft 2019/2020 DSE aims to design open-source hardware for teams and race organisations to use for autonomous racing purposes.

The aim of this report is to give a clear overview of the process that resulted in the final design concepts, and how a choice between them was made. This includes a description of the organisation of the team, how the analyses on risk and sustainability and the requirements were performed and requirements were updated. Furthermore, the methods used to find the different design options for components, how this lead to the design concepts will be described also.

The content of this report is divided into chapters. The organisation of the team will be described in chapter 2, followed by the technical risk assessment in chapter 9, sustainable development strategy in chapter 10 and the gathered requirements in chapter 5. The design options will be gathered in a design options tree in chapter 6, and structured further in chapter 7. chapter 7 also describes the final concepts that will be used in the trade-off in chapter 11. This is followed by chapter 3, chapter 4 and chapter 12 which describe the N2-chart, the engineering design and analysis and the operations logistic concepts respectively. Lastly, the verification and validation procedures are found in chapter 8 and a conclusion is given in chapter 13.

# 2
# Organisation

This chapter will describe the various designated roles within the team developing the AIgle autonomous racing drone and list their responsibilities. This, along with the organogram will be shown in section 2.1. Furthermore, a description of the procedures that have been instated to allow for an efficient and healthy work environment will be given in section 2.2.

## 2.1. Team Roles

The team consists of eleven members who have been assigned two roles each. One of these roles is a technical role, the other is a managerial role. The managerial role is focused on ensuring the workflow in the team is efficient and sustainable such that everyone can work efficiently. The technical role focuses on accomplishing technical tasks. The technical tasks have been divided in 7 divisions, each of which is focused on a particular aspect of designing the drone.

As can be seen in the organogram, Figure 2.1, the Systems Engineers report to the Team Leader who manages the entire team. The Systems Engineers are the link between management and the technical departments. Compared to the organogram in [12], an observant reader will notice that some changes in roles have been made. Firstly, rather than assigning the secretary role to a single person, it has been chosen that the secretary role will rotate between team members on a weekly basis to allow for more flexibility. Furthermore, the External Communications role has been removed, as the general consensus in the team was that this role did not have much to do. It's responsibilities have now been added to other roles, mostly the Business Manager, defined in previous reports, who coordinates external contacts. Furthermore, new roles have been added as well. The first is the Quality Control (Editor), whose responsibility is ensuring that reports have correct spelling and grammar and improving the overall readability. Secondly, it has been noticed that the current situation surrounding the COVID-19 pandemic and its quarantine has had a serious demoralizing effect on the entire team. The lack of social activities and genuine human contact makes maintaining a healthy mentality and consequentially productivity hard. The Motivation Manager role has been designated in an effort to help alleviate these effects by organising recreational activities for the team outside of the normal working hours. These activities are not mandatory. Besides this, the Motivation Manager will be available to all team members should they ever feel the need to talk about anything that might be affecting them. The full list of responsibilities of each role can be seen below. An overview of each role, and who has been assigned to it can be seen in Figure 2.1.

**Team Leader**

- Determine and distribute the agenda for every team meeting.
- Monitor and manage time spent on tasks.
- Update planning and work divisions in the case of delays or other disruptions of the planning (managing the Gantt chart is included in this).
- Lead and steer meetings and discussions.
- Conflict resolution in the case of technical or personal conflict within the team.
- Organise the reviews after deliverables.
- Ensure everyone gets to voice their opinion during team meetings.

**Internal Relations Manager**

- Facilitate clear communications between team members and between the team and the tutor, coaches and TA.
- Send out reminders to everyone about the upcoming events, deadlines and meetings.
- Hand in reports before the deadline.

**External Relations & Business Manager**

- Ensure the market analysis is kept up to date in the case of shifting markets.
- Analyse the costs and ensure they fit within the financial budget.
- Communicate with the subteams to make sure all costs fit the budget.
- Determine a market strategy and a promotion plan that fits it.
- Update the integration plan in the case of shifting situations.
- Coordinate contact with external parties, such as specialists or companies.

**Sustainability Manager**

- Help the team incorporate sustainability in design trade-offs.
- Research and maintain a list of methods that can be used to make the design more sustainable.
- Make suggestions to other team members that can improve the level of sustainability.
- Monitor and raise the amount of environmental, economical and social sustainability in the team.

**Risk Manager**

- Identify new risks and provide suggestions to help minimize their impact and probability.
- Develop and manage contingency strategies for all risks present in the project.
- Monitor the status of risks within the project.

**Quality Control Engineer (Completionist)**

- Ensure that the quality of the technical writing done by each team member is sufficient.
- Ensure consistency of lay-out and content in the report.
- Provide suggestions on possible improvements in the report to team members.
- Ensure all references in the report are correct.

**Quality Control Engineer (Monitor)**

- Ensure all used equations are correct.
- Ensure all used methods are correct.
- Ensure all underlying concepts are correct.
- Check for errors in used computer scripts.
- Ensure feasibility of the selected concepts.
- Check that proper methodology for the verification and validation of the deliverables is used.

**Quality Control Engineer (Editor)**

- Notify team members of mistakes in the spelling, grammar and sentence construction in the report.
- Make suggestions to improve the readability of reports.
- Ensure and lay out a structured approach to set up the report from the start.

**Motivation Manager**

- Organise team activities to promote intra-team bonding and social sustainability within the team.
- Organise activities for team members to unload stress and clear their mind.
- Ensure an environment where people can talk about personal issues and help people resolve things adversely affecting them.

**Systems Engineer 1 - Hardware**

- Coordinate relations and communications between technical hardware departments to promote an efficient information flow.
- Work together with Systems Engineer 2 to facilitate a good integration of hardware and software.
- Ensure proper integration of the design after each iteration of technical hardware subsystems

**Systems Engineer 2 - Software**

- Coordinate relations and communications between technical software departments to promoe an efficient information flow.
- Work together with Systems Engineer 1 to facilitate a good integration of hardware and software.
- Apply and maintain a software pipeline and an overarching architecture for the development of software.
- Maintain the team's Git repository.

## 2.2. Team Procedures

In order to ensure a smooth workflow and a healthy working environment, a number of procedures have been set up. These procedures will ensure that there is a correct structure to the work done, that flows of information are clear and that everyone can give voice to their input to the project and towards its final result. These procedures have not changed since the Project Plan, and can be seen in [12].

## 2.3. Work Division

Structuring and dividing work is a crucial part of having a successful project. Tools are made to help do this efficiently. These tools include a work flow diagram, a work breakdown diagram and a Gantt chart. These will be used throughout the remainder of the project as a reference for deadlines and all necessary work that needs to be done before them.

### 2.3.1. Work Flow Diagram

The work flow diagram can be seen in Figure 2.2 and is meant to show the flow of tasks which need to be performed in order to come to the end goal. It is structured chronologically so that tasks linked to '10.0 create detailed design' will need to be performed first and so on.

### 2.3.2. Work Breakdown Structure

The work breakdown structure, as seen in Figure 2.3 is built around deliverables and what makes up these deliverables. Main goals are split up into sub-tasks, which are again split up until sufficient level of detail is achieved.

### 2.3.3. Gantt Chart

The Gantt chart can be seen in Figure 2.4. It is the go-to for the project manager, as it allows for having a good overview on the timeline of a project and what tasks need to be worked on at every point in time. It is useful to keep progress and verify that the group is on schedule. It is also used to appoint certain people to certain tasks, although this is still flexible.

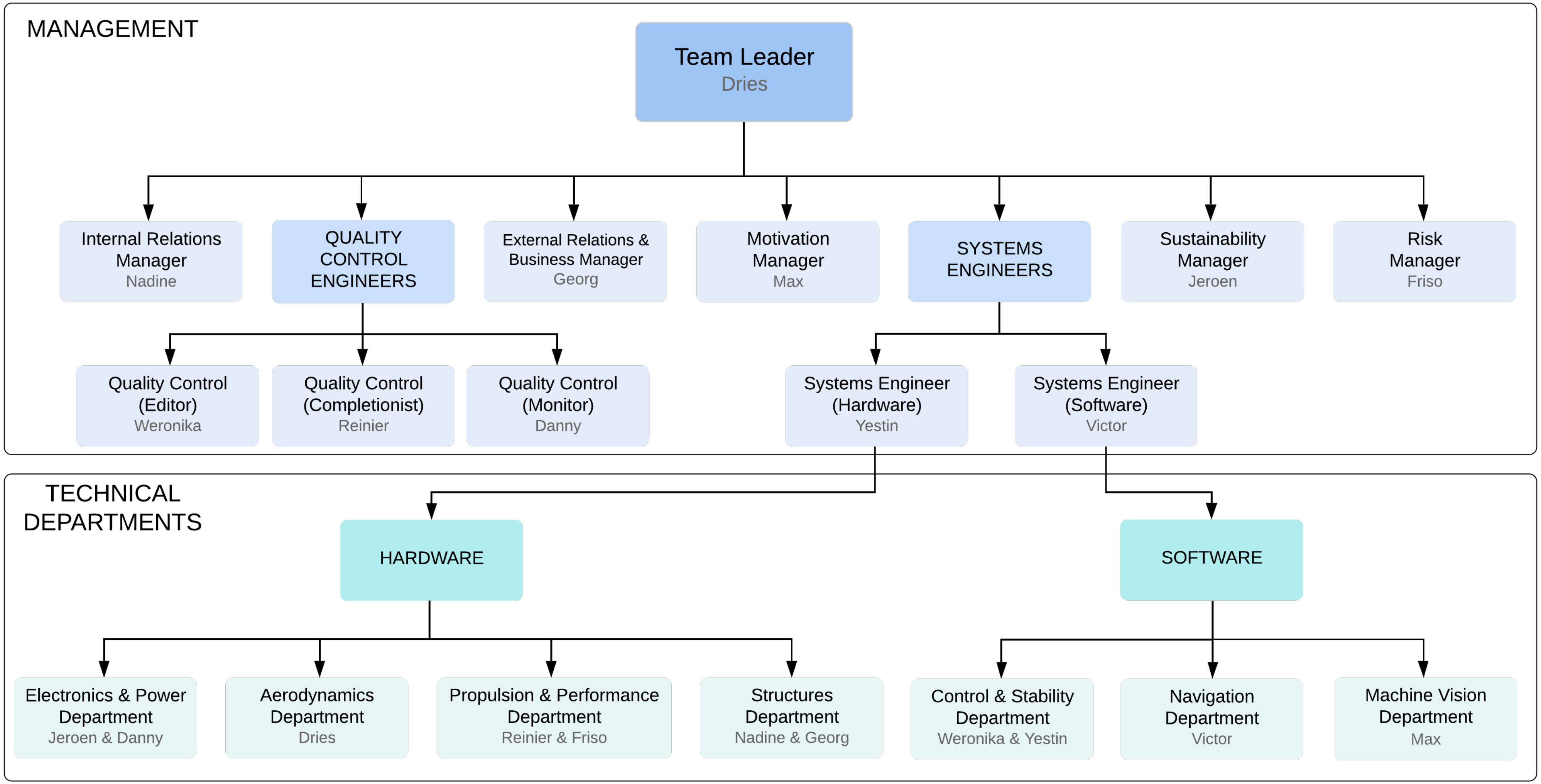



Figure 2.1: Organogram of the team.

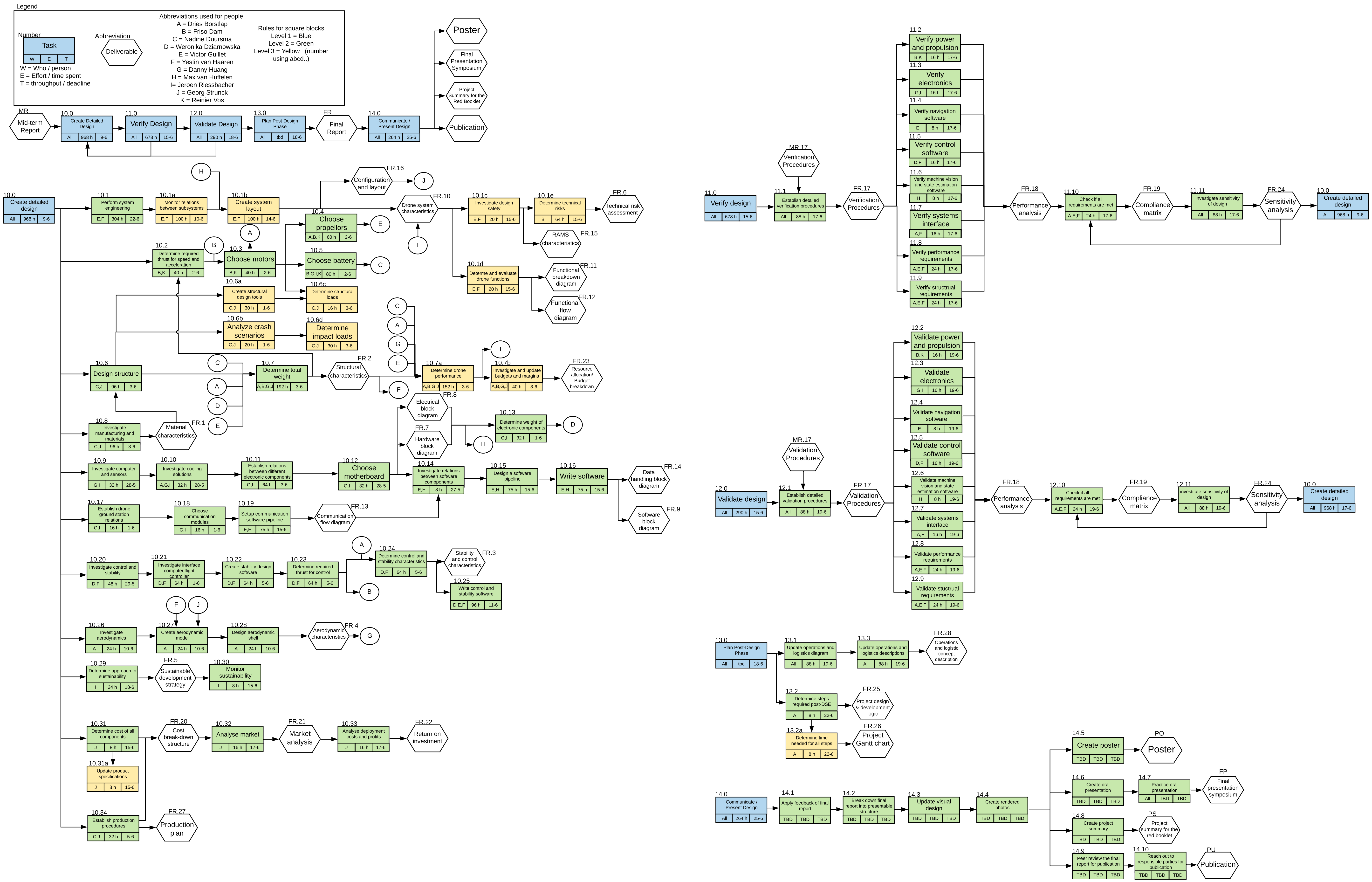



Figure 2.2: The Work Flow Diagram

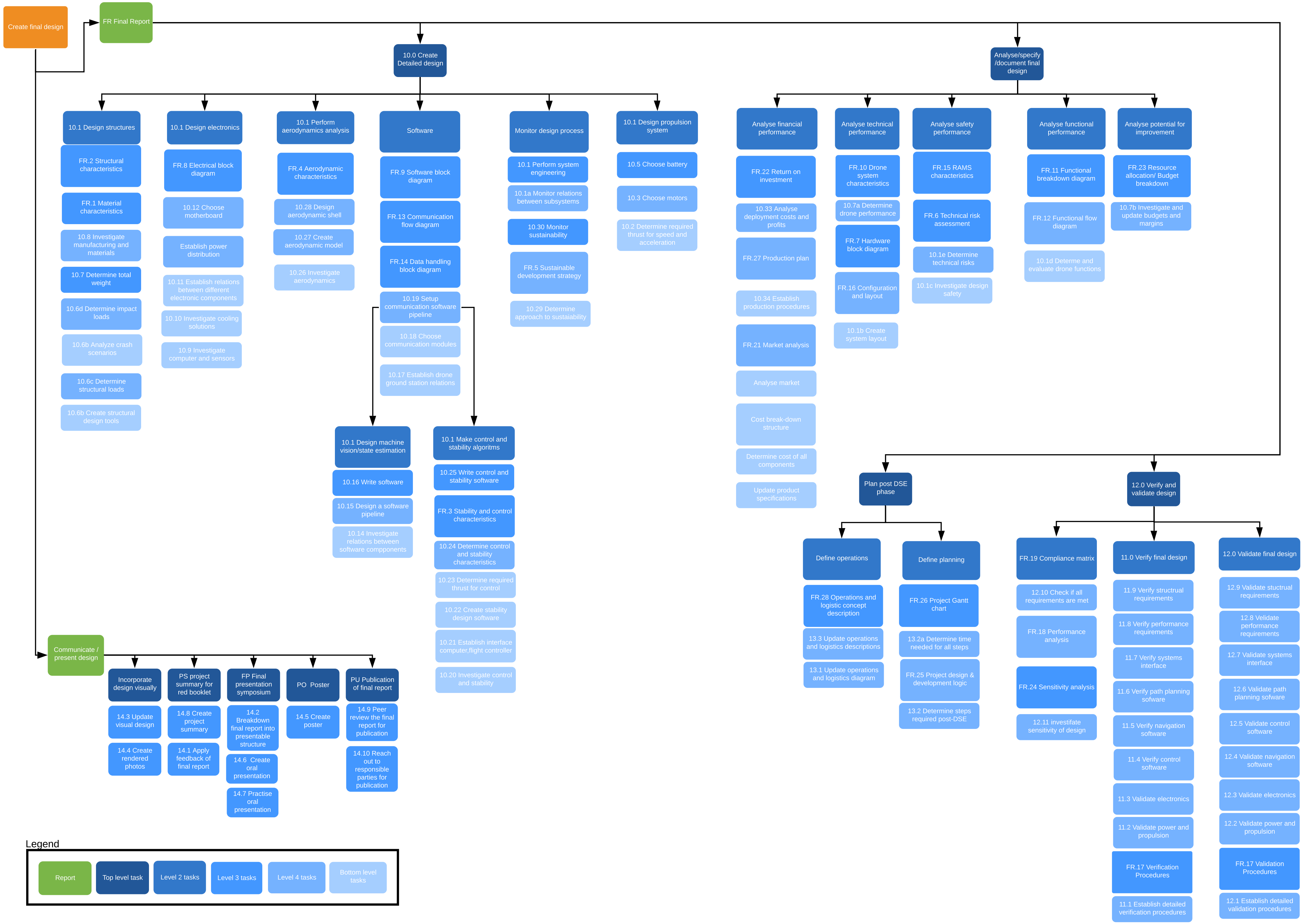



Figure 2.3: The Work Breakdown Diagram

| Task Name | Duration | Start | Finish |
|---|---|---|---|
| **Project AIgle** | **46 days?** | **Mon 20-4-20** | **Mon 22-6-20** |
| **1 - Project Plan** | **5 days** | **Mon 20-4-20** | **Fri 24-4-20** |
| **2 - Baseline Report** | **5 days** | **Tue 28-4-20** | **Mon 4-5-20** |
| **3 - Mid-term Report** | **11 days** | **Wed 6-5-20** | **Wed 20-5-20** |
| 7.1 - Peer review | 4 hrs | Wed 6-5-20 | Wed 6-5-20 |
| 7.2 - Assign technical/mangerial roles | 4 hrs | Wed 6-5-20 | Wed 6-5-20 |
| 7.3 - Review all previous work | 1 hr | Wed 6-5-20 | Wed 6-5-20 |
| 7.4 - Identify tasks and time sequence | 2 hrs | Wed 6-5-20 | Wed 6-5-20 |
| 7.5 - Establish structural breakdown of tasks | 2 hrs | Wed 6-5-20 | Wed 6-5-20 |
| 8.1 - Structure different concepts | 1 day | Thu 7-5-20 | Thu 7-5-20 |
| 8.2 - Visualise relations between different concepts | 1 day | Thu 7-5-20 | Thu 7-5-20 |
| 8.3 - Visualise interaction of different subsystems | 2 days | Thu 7-5-20 | Fri 8-5-20 |
| 8.4 - Analyse different lay-outs | 2 days | Mon 11-5-20 | Tue 12-5-20 |
| 8.5 - Perform detailled analysis of each concept | 3 days | Tue 12-5-20 | Thu 14-5-20 |
| 8.6 -Create subsystem block diagrams | 1 day | Fri 8-5-20 | Fri 8-5-20 |
| 8.7 - Specify concept characteristics | 1 day | Fri 15-5-20 | Fri 15-5-20 |
| 8.8 - Establish technical risks | 1 day | Fri 15-5-20 | Fri 15-5-20 |
| 8.9 - Evaluate sensitivity of different risks | 1 day | Mon 18-5-20 | Mon 18-5-20 |
| 8.10 - Determine how verification and validation will be done | 2 days | Fri 15-5-20 | Mon 18-5-20 |
| 9.1 - Define selection criteria from sources | 2 days | Wed 6-5-20 | Thu 7-5-20 |
| 9.2 - Define selection criteria weights from sources | 1 day | Thu 7-5-20 | Thu 7-5-20 |
| 9.3 - Make design trade off table | 2 days | Mon 18-5-20 | Tue 19-5-20 |
| 9.4 - Summarise trade off | 2 days | Tue 19-5-20 | Wed 20-5-20 |
| Mid-term Report | 0 days | Wed 20-5-20 | Wed 20-5-20 |
| **4 - Final Report** | **23 days** | **Thu 21-5-20** | **Mon 22-6-20** |
| 10.1 - Perform system engineering | 19 days | Wed 27-5-20 | Mon 22-6-20 |
| 10.2 - Determine required thrust for speed and acceleration | 5 days | Wed 27-5-20 | Tue 2-6-20 |
| 10.3 - Choose motors | 5 days | Wed 27-5-20 | Tue 2-6-20 |
| 10.4 - Choose propellors | 5 days | Wed 27-5-20 | Tue 2-6-20 |
| 10.5 - Choose battery | 5 days | Wed 27-5-20 | Tue 2-6-20 |
| 10.6 - Design structure | 6 days | Wed 27-5-20 | Wed 3-6-20 |
| 10.7 - Determine total weight | 6 days | Wed 27-5-20 | Wed 3-6-20 |
| 10.8 - Investigate manifacturing and materials | 6 days | Wed 27-5-20 | Wed 3-6-20 |
| 10.9 - Investigate computer and sensors | 2 days | Wed 27-5-20 | Thu 28-5-20 |
| 10.10 - Investgate cooling solutions | 2 days | Wed 27-5-20 | Thu 28-5-20 |
| 10.11 - Establish relations between different electronic components | 4 days | Fri 29-5-20 | Wed 3-6-20 |
| 10.12 - Choose motherboard | 2 days | Wed 27-5-20 | Thu 28-5-20 |
| 10.13 - Determine weight of electronic components | 2 days | Fri 29-5-20 | Mon 1-6-20 |
| 10.14 - Investigate relations between software components | 1 day | Wed 27-5-20 | Wed 27-5-20 |
| 10.15 - Design a software pipeline | 14 days | Wed 27-5-20 | Mon 15-6-20 |
| 10.16 - Write software | 14 days | Wed 27-5-20 | Mon 15-6-20 |
| 10.17 - Establish drone ground station relations | 2 days | Fri 29-5-20 | Mon 1-6-20 |
| 10.18 - Choose comunication modules | 2 days | Fri 29-5-20 | Mon 1-6-20 |
| 10.19 - Setup communication software pipeline | 14 days | Wed 27-5-20 | Mon 15-6-20 |
| 10.20 - Investigate control and stability | 3 days | Wed 27-5-20 | Fri 29-5-20 |
| 10.21 - Investigate interface computer/flight controller | 4 days | Wed 27-5-20 | Mon 1-6-20 |

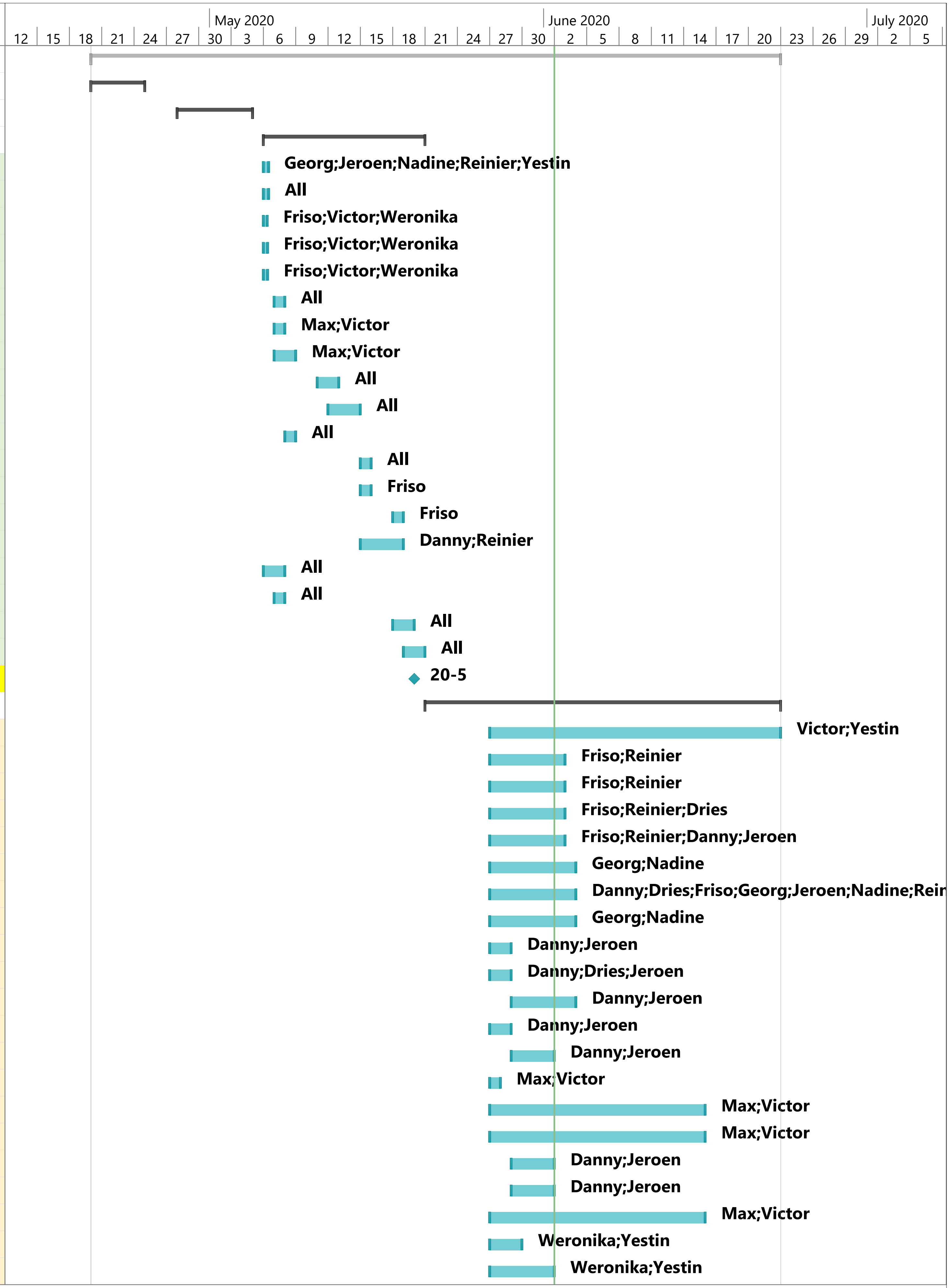
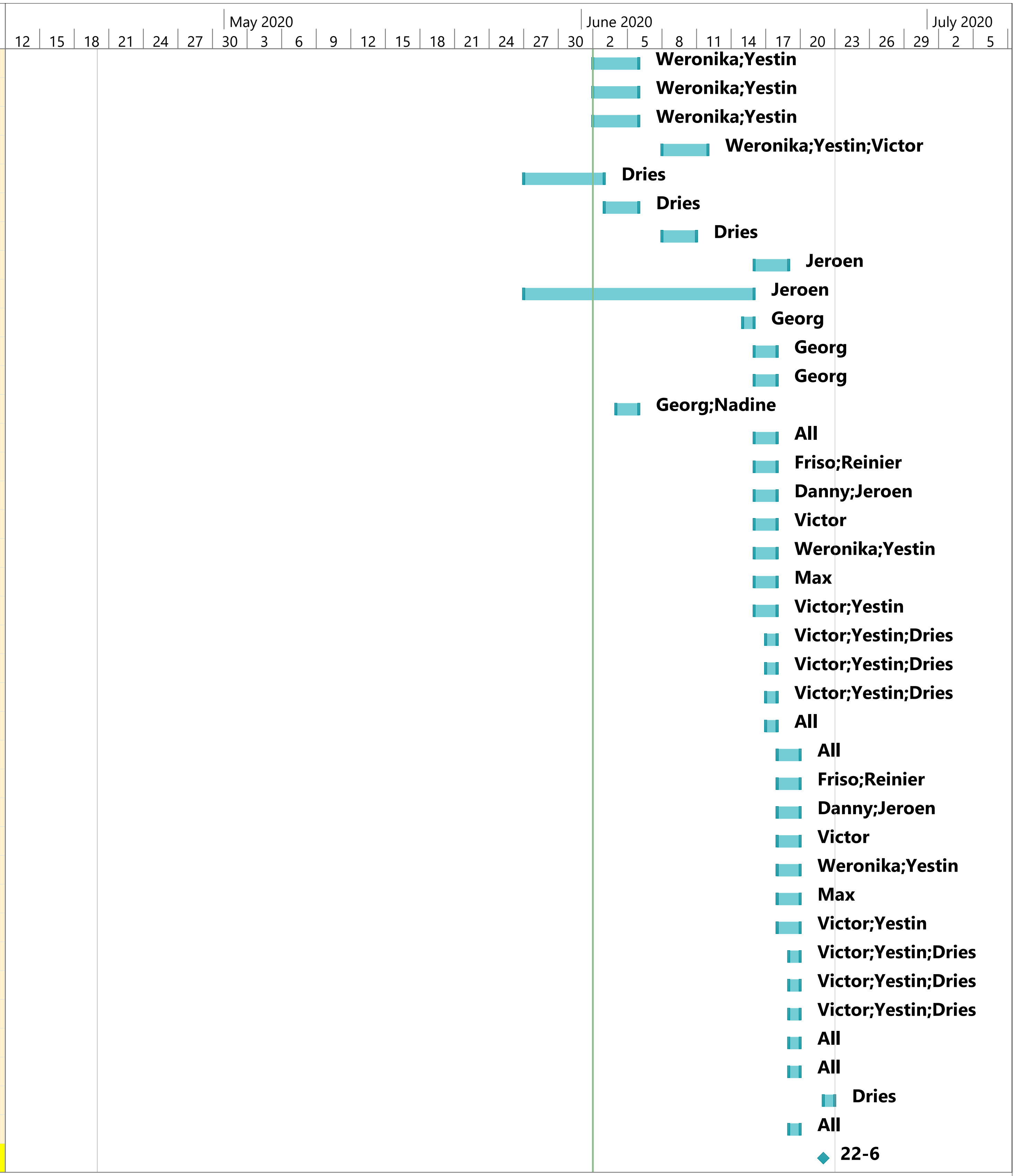





Figure 2.4: The project Gantt chart

| Task Name | Duration | Start | Finish |
|---|---|---|---|
| 10.22 - Create stability design software | 4 days | Tue 2-6-20 | Fri 5-6-20 |
| 10.23 - Determine required thrust control | 4 days | Tue 2-6-20 | Fri 5-6-20 |
| 10.24 - Determine control and stability characteristics | 4 days | Tue 2-6-20 | Fri 5-6-20 |
| 10.25 - Write control and stability software | 4 days | Mon 8-6-20 | Thu 11-6-20 |
| 10.26 - Investigate aerodynamics | 5 days | Wed 27-5-20 | Tue 2-6-20 |
| 10.27 - Create aerodynamic model | 3 days | Wed 3-6-20 | Fri 5-6-20 |
| 10.28 - Design aerodynamic shell | 3 days | Mon 8-6-20 | Wed 10-6-20 |
| 10.29 - Determine approach to sustainability | 3 days | Tue 16-6-20 | Thu 18-6-20 |
| 10.30 - Monitor sustainability | 14 days | Wed 27-5-20 | Mon 15-6-20 |
| 10.31 - Determine cost of all components | 1 day | Mon 15-6-20 | Mon 15-6-20 |
| 10.32 - Analyse market | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 10.33 - Analyse deployment costs and profits | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 10.34 - Establish production procedures | 2 days | Thu 4-6-20 | Fri 5-6-20 |
| 11.1 - Establish detailed verification procedures | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 11.2 - Verify power and propulsion | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 11.3 - Verify electronics | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 11.4 - Verify Navigation software | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 11.5 - Verify control software | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 11.6 - Verify machine vision and state estimation software | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 11.7 - Verify systems interface | 2 days | Tue 16-6-20 | Wed 17-6-20 |
| 11.8 - Verify performance requrements | 1 day | Wed 17-6-20 | Wed 17-6-20 |
| 11.9 - Verify structural requirements | 1 day | Wed 17-6-20 | Wed 17-6-20 |
| 11.10 - Check if all requirements are met | 1 day | Wed 17-6-20 | Wed 17-6-20 |
| 11.11 - Investigate sensitivity of the design | 1 day | Wed 17-6-20 | Wed 17-6-20 |
| 12.1 - Established detailed validation procedures | 2 days | Thu 18-6-20 | Fri 19-6-20 |
| 12.2 - Validate power and propulsion | 2 days | Thu 18-6-20 | Fri 19-6-20 |
| 12.3 - Validate electronics | 2 days | Thu 18-6-20 | Fri 19-6-20 |
| 12.4 - Validate navigation software | 2 days | Thu 18-6-20 | Fri 19-6-20 |
| 12.5 - Validate control software | 2 days | Thu 18-6-20 | Fri 19-6-20 |
| 12.6 - Validate machine vision and state estimation software | 2 days | Thu 18-6-20 | Fri 19-6-20 |
| 12.7 - Validate systems interface | 2 days | Thu 18-6-20 | Fri 19-6-20 |
| 12.8 - Validate performance requrements | 1 day | Fri 19-6-20 | Fri 19-6-20 |
| 12.9 - Validate structural requirements | 1 day | Fri 19-6-20 | Fri 19-6-20 |
| 12.10 - Check if all requirements are met | 1 day | Fri 19-6-20 | Fri 19-6-20 |
| 12.11 - Investigate sensitivity of the design | 1 day | Fri 19-6-20 | Fri 19-6-20 |
| 13.1 - Update operation and logistics diagram | 1 day | Fri 19-6-20 | Fri 19-6-20 |
| 13.2 - Determine steps required post DSE | 1 day | Mon 22-6-20 | Mon 22-6-20 |
| 13.3 - Update operations and logistics description | 1 day | Fri 19-6-20 | Fri 19-6-20 |
| Final Report | 0 days | Mon 22-6-20 | Mon 22-6-20 |



# 3
# Interface Definition

This chapter will describe the thoughts behind designing the N2 chart for this project.

An N2 chart is a chart depicting the interfacing of various parts of the project. This is done by creating a grid with all interfacing parts of the project on the diagonal. All spaces in the same row as the part show the interfaces it has with other parts while all spaces in the same column show everything it 'receives' from the other components.

The N2 diagram was made by identifying all main components of the final drone design, following which a thorough analysis was performed to define as many use cases and situations as possible to find all manners in which case interfacing is possible. Aerodynamics are not in the N2 diagram as the aerodynamic model is included in various other components.

Regarding the information flowing from the machine vision/state estimation to the navigation, the pre-processed data includes any information required by navigation (such as position of the gate with respect to the drone, angle of the gate). The specifics of the data will depend on the software used to perform the different tasks, and is team-specific.

It should be noted that the control module validates the navigation's requests, raising a flag when unrealistic or erroneous. Furthermore, the drone will be outfitted with a 'safety mode' that will be activated automatically in the case of malfunctions or other trouble to prevent accidents. When Sensors notice a perilous or risky situation, the safety mode will be activated in Navigation and Control which will issue commands designed to prevent accidents. The N2 chart can be seen in Figure 3.1.

Once compiled, the diagram was then used to further establish interface requirements, ensuring that no interaction was overlooked.

| | User | Structure | Propulsion System | Transmitter/ receiver | Power | SOC | Sensors | ISP | MV/SE | Navigation | Control |
|---|---|---|---|---|---|---|---|---|---|---|---|
| User | **User** | | | - Provide manual commands | | | | | | | |
| Structure | | **Structure** | - Provide load support<br>- Provide protection | - Provide support<br>- Provide protection<br>- Enable access and replacement of components | - Provide support<br>- Provide protection<br>- Enable access and replacement of components<br>- Passively cool the electronics (channels air flow) | - Provide support<br>- Provide protection<br>- Enable access and replacement of components<br>- Passively cool the electronics (channels air flow) | - Provide support<br>- Provide protection<br>- Enable access and replacement of components<br>- Passively cool the electronics (channels air flow) | - Provide support<br>- Provide protection<br>- Enable access and replacement of components<br>- Passively cool the electronics (channels air flow) | | | |
| Propulsion System | | - Apply thrust | **Propulsion System** | | | | | | | | |
| Transmitter / receiver | - Relay data back | | | **Transmitter / receiver** | | - Provide manual commands | | | | | |
| Power | | | - Provide power | - Provide power | **Power** | - Provide power<br>- Provide data to be processed and stored | - Provide power | - Provide power | | | |
| SOC | | | | - Provide FPV images | - Control power delivery | **SOC (System on Chip)** | | - Provide processing power | - Provide processing power<br>- Deactivate in case of manual control | - Provide processing power<br>- Deactivate in case of manual control<br>- Trigger safety mode | - Provide processing power<br>- Relay manual commands<br>- Trigger safety mode |
| Sensors | | | | | | - Provide data gathered by sensors | **Sensors** | - Provide data gathered by sensors | | | - Provide data gathered by sensors |
| ISP | | | | | | | | **ISP (Image Signal Processor)** | Provide data gathered by sensor translated to digital form | | |
| MV/SE | | | | | | - Provide data to be stored | | | **Machine Vision / State Estimation** | - Provide pre-processed data | - Provide state estimate |
| Navigation | | | | | | - Provide data to be stored | | | - Provide next waypoint | **Navigation** | - Provide next waypoint |
| Control | | | - Provide commands | | - Provide commands | - Provide data to be stored | | | | - Validate navigation orders | **Control** |

Figure 3.1: The N2 chart.

# 4

# Engineering Design and Analysis

This chapter describes the various aspects of the system in more details. The hardware block diagram, discussed in section 4.1, describes all the major hardware components of the drone, and their relations. The software block diagram is analysed in section 4.2, and depicts the software pipeline used in the design. Finally, the data handling diagram, discussed in section 4.3, gives further details about the flow of information around the system.

## 4.1. Hardware Block Diagram

Figure 4.1 shows how the various electrical hardware components within the drone and outside the drone are connected. The arrows shows the direction of power and data transfer.

Most blocks are self-explanatory, however, the communication is discussed in more detail. The transmitter is used to control the drone, while the ground station is just receives telemetry data from the drone using a separate RF module. Furthermore, the receivers only receive commands from the transmitter in this case. For the final design, SmartPort telemetry is also considered, in which there is two-way communication between the receiver and transmitter.

Important to note is that this hardware block diagram only gives a preliminary overview of the hardware and connections, and will be updated during the final design phase. For example, the diagram contains a back-up R/C receiver in case the main one fails. This is a design option, and may or may not be incorporated in the design.

## 4.2. Software Block Diagram

The software block diagram in Figure 4.2, depicts the general software pipeline employed by the drone. It should be noted that it is kept general as the actual software embedded in the drone shall be designed by the different teams attending the competition. It is as a result a representation of the general pipeline teams would be expected to follow. The details of the implementation, such as the specifics of the state estimation, or the navigation methodology, along with the data generated and stored between the various blocks is not to be defined by us (demonstration software will be present in the final design, and it's specifics will be addressed appropriately when necessary, however it is purposely excluded from this diagram for the above mentioned reasons).

The diagram can be divided into 4 main parts.

The external operations, represented by all the boxes outside of the colored sections, all require or are a result of direct user input and interaction. These allow for manual control/manual takeover and other remote operations to be performed.

The machine vision/ state estimation block (depicted in the blue box) handles all the initial image processing and inferring. It ensures the resulting data is formatted correctly and useful information (such as the position of the drone w.r.t. the gate) is extracted effectively. An evaluation of the quality of the data gathered is also performed, and the resulting "rating" recorded. If the rating is too low, the data point is rejected, and the data is either reprocessed or a flag is raised (flag handling is explained further down).

The data is then packaged, recorded, and forwarded to the navigation block (depicted in the green box). The navigation block focuses on determining the path to be followed by the drone based on the state it finds itself in. Upon receiving the processed data, the navigation sets the next way point for the drone. The way point is then evaluated (checking for whether the way point is realistic/achievable, and the "rating" of the data provided) and either forwarded to the control block, or rejected while raising a flag.

Finally, the control block (depicted in the purple box) handles translating the provided way point into a set of instructions for the various drone components. The control block also handles the flag log. Flags can be raised by various section of the software at various locations in the pipeline. The flags are all logged, and based on their provenance, type, and frequency, the Control block is able to switch to various levels of safety mode. These range from hovering in place, all the way to completely killing the drone.

The diagram was written following UML conventions. This means that for the Software Block Diagram arrows indicate the order of activities and in the Data Flow Diagram they indicate from where to where information flows (and which information).

## 4.3. Data Handling Diagram

The data handling diagram in Figure 4.3 aims at effectively describing the data flows between the various components making up the system. This enables better clarity and insight in understanding what data is produced, where, and when in the system. The various system groups were depicted using different colors is the diagram to more easily determine the various component's grouping. The color scheme adopted here is maintained consistent with the color scheme adopted in Figure 4.2. The components are represented using a lighter variation of the subsystem color to further improve clarity.

Information is stored at various locations of the system as shown in the diagram. While depicted as different data storage here, it should be noted that the actual physical storage location is unique and unified for all information.

# 4.4. Engineering Analysis Diagrams

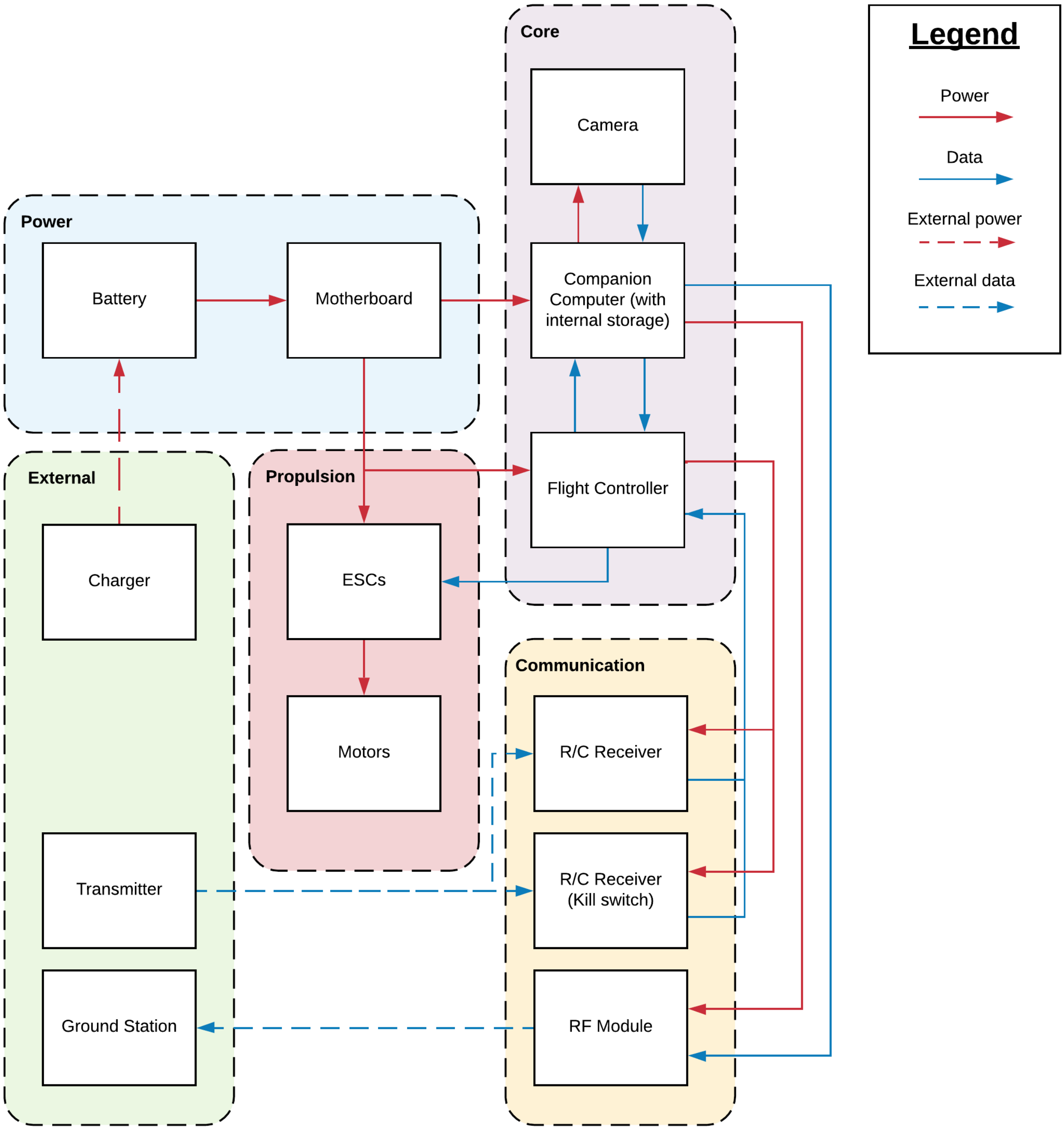



Figure 4.1: The hardware block diagram depicting the major hardware components and their relations

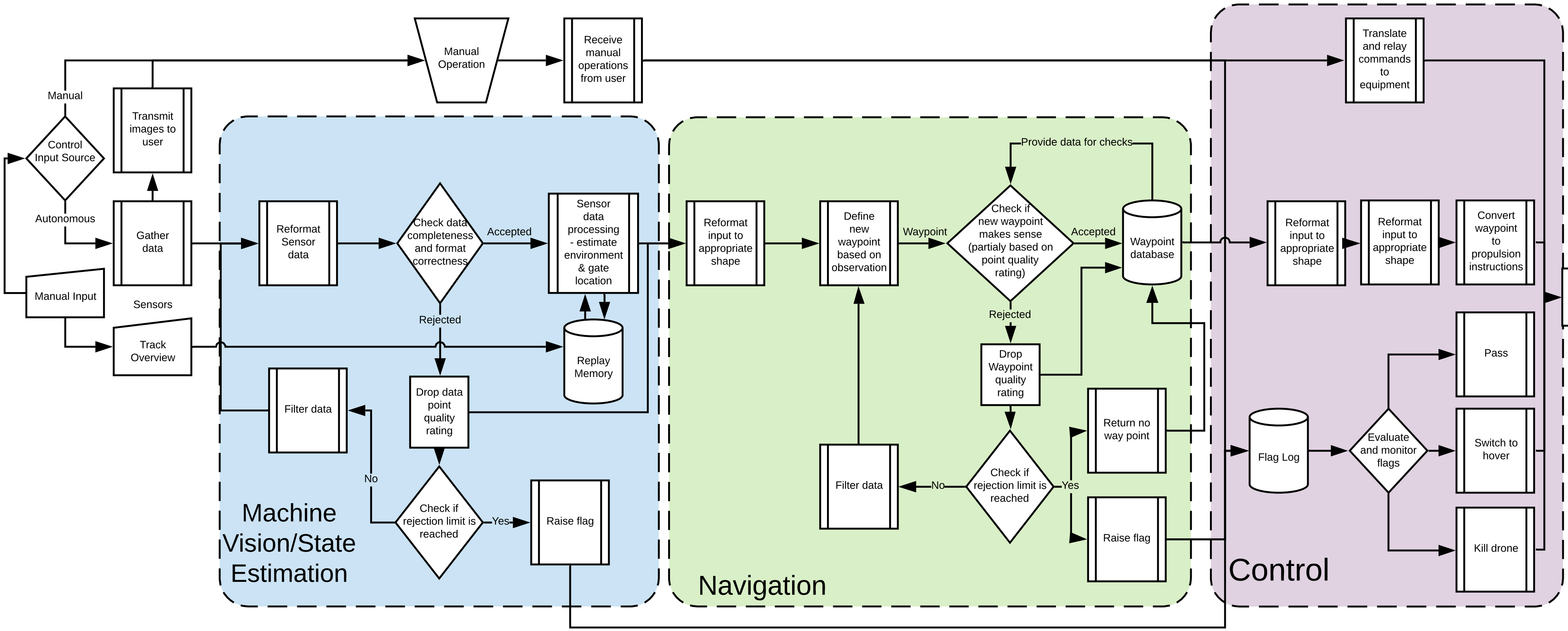



Figure 4.2: The software block diagram depicting the major software components and their relations

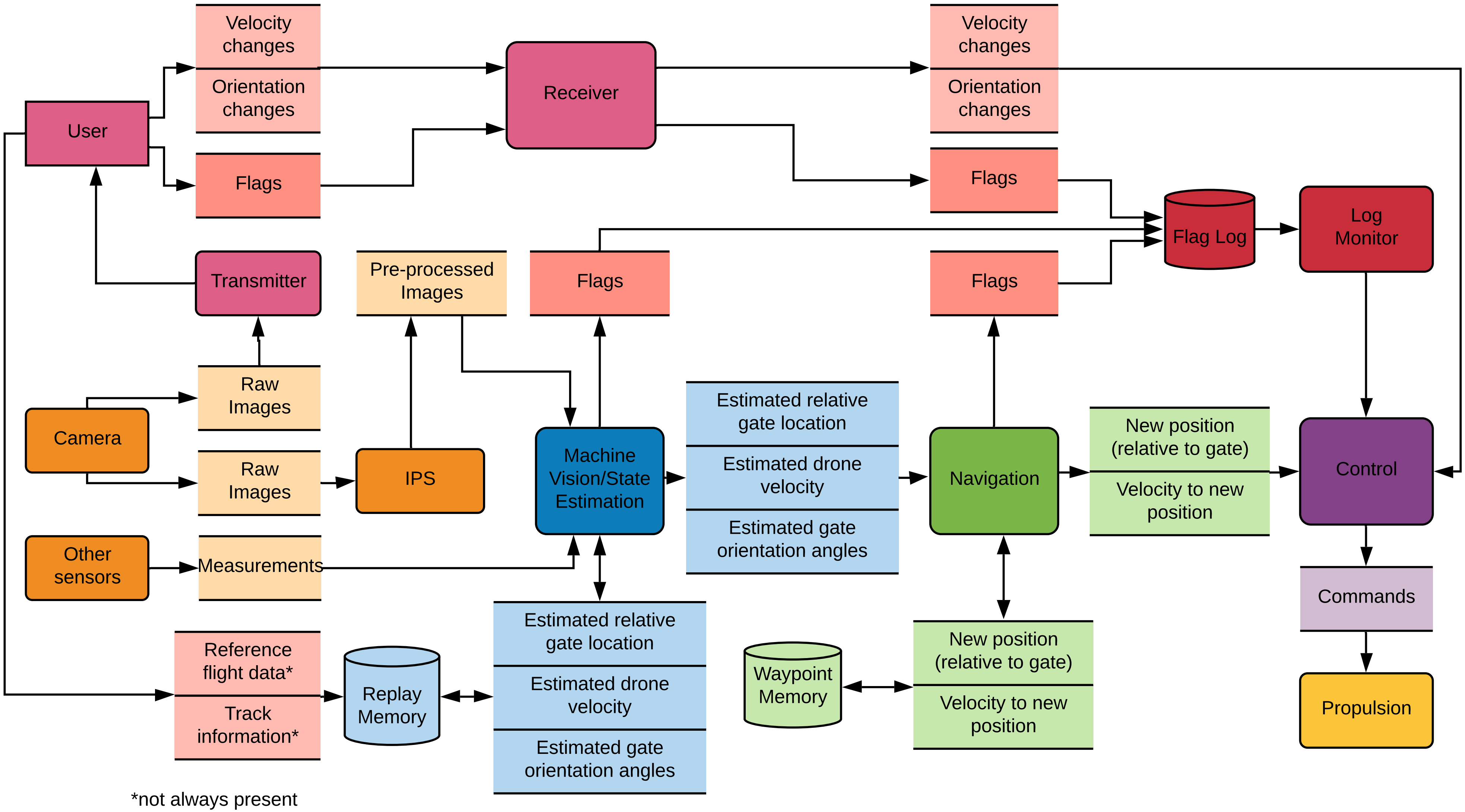



Figure 4.3: The data handling diagram, depicting the movement of information around the system

# 5 Requirements Engineering

Now that during the concept phase more design details have become known, requirements had to be revised, updated and renegotiated. This chapter explains what changes and updates were made and why. First section 5.1 explains which requirements were changed and why. Then section 5.2 shows the list of all updated requirements. This list is a partial version of the list which had been developed in the baseline report [11]. It only shows the requirements which were updated or changed.

## 5.1. Revisions

During the most recent phase of the project, revisions were made to the list of requirements. The first and most important revision was the removal of most 'tbd' marks. These were replaced with verifiable figures. Secondly, some requirements were changed or removed. A list of these with the respective reason are listed below:

- AIG-TE-HW-MP-MO2, -MO3, -MO4, -MO5 were removed and replaced by MO7. The previous requirements were too specific and have been replaced by a broader, comprehensive requirement.
- AIG-TE-HW-MP-SM-SDS3: 'The system shall be able to be turned off remotely while within <tbd> m.' was removed since it is redundant considering AIG-TE-HW-MP-SM-SDS4: 'The system shall turn itself off within <tbd> secondsof detecting a malfunction.' and the calculated top speed.
- AIG-TE-HW-MP-SM-CP1: 'The drone shall be able to switch from the autopilot mode to the manual control mode within <15> m.' was removed since it is redundant considering AIG-TE-HW-MP-SM-CP2 and the calculated top speed.
- AIG-TE-HW-MP-SM-SDS4.1 was changed from 'the drone shall shut down' to 'the drone shall safely land' as this is safer and more durable. Also the instead of 'less than <tbd> Joules', '<15>%' was used as this is better applicable to different drone sizes.
- AIG-TE-HW-PF4 and -PF5: 'The drone shall be able to reach a rotational velocity/acceleration of<tbd> rad/s / rad/s/s about any of its own axis while hovering.' were removed. These were removed since they were deemed unverifiable.
- AIG-TE-HW-PF6: 'The maximum operational speed of the drone shall beat least <tbd> m/s' was removed since it was redundant considering AIG-NT-R1: 'The maximum speed of the drone shall be lower than 45 m/s.'
- AIG-TE-HW-S-VE2, -A2, O2: 'The resolution of the velocity/acceleration/angular rate measurements shall be at most <tbd> m/s.' These were removed due to being too specific.
- AIG-TE-HW-C3: 'The computational power of the drone shall be at least<tbd>.' was removed because it was hard to quantify and therefor not verifiable.

Next to this some key requirements were changed. These have major impact on the design and the customer and thus require a more extensive explanation:

First of all, requirement AIG-TE-HW-PF1: 'The drone shall be able to reach a speed of at least 30 m/s when flying in a straight line with gates every 20 m.' was removed. Actually achieving 30 m/s would need a large space which is not available in most circumstances. Therefor the requirement was deemed undesirable. Also, the requirement was deemed hard to achieve, based on the relation between thrust-to-weight ratio and top speed, as visualised in Figure 7.7. For more detailed information, please refer to subsection 7.3.1. This section describes a required thrust-to-weight ratio of 6.5 for meeting the 30 m/s requirement. However, this would lead to an unacceptably high weight for the motors and the battery. Removing this requirement would lead to a drone with a thrust-to-weight ratio of 4, since that is required to comply with requirement AI-TE-HW-PF2:'The drone shall be able to make a 3 m radius arc while flying at 10 m/s.', as explained in subsection 7.3.1. This thrust-to-weight ratio is deemed as still a major improvement over previous drones, while leading to an acceptable weight. For this reason the removal of the requirement was approved by the costumer. Using the relation described in Figure 7.7, the top speed related to this requirement will be approximately 23 m/s.

Furthermore, requirement AIG-TE-HW-P-E1 was changed to 'equal to (100% throttle power plus 100% computer power+100% power of all other systems) times 60 s plus 120 s times 100% computer power' instead of 'to be determined'. This can also be phrased as one minute flight time and two minutes standby time. This was changed from the original top level requirement of five minutes of flight time. This was done in negotiation with the costumer on the basis of Figure 8.1. As can be seen, for flight times longer than one minute, the weight quickly increase to unacceptable values for many of the concepts. Thus in discussion with the costumer it was decided that low weight was more important than long flight time. A one minute flight time is also comparable to other racing drones and thus sufficient for this purpose. Two minutes of standby time were desired by the customer for cases where start up of the drone takes some time.

Lastly, requirement AIG-NT-S4: 'The structural components of the drone shall only consist of recyclable materials.' was changed to 'The sustainability of the drone shall be maximized'. This due to the fact that the use of carbon fibre was found to be crucial to the design. However carbon fibre is generally not a recyclable material. This was discussed with the customer, upon which it was agreed that use of carbon fibre will be permitted, however that research should still be done into other ways of making the drone as sustainable as possible. For example, research shall be done into ways of optimally using the carbon fibre and into possibilities of carbon fibre reuse or recycling techniques which are upcoming. This way the design will still be as sustainable as possible.

## 5.2. Revised Requirements List

This section shows a list of all requirements, which previously had a <tbd> and are now specified, as well as all other requirements which were changed or updated in some way. However for a full list of requirements, please refer to the baseline report [11].

Table 5.1: Hardware requirements.

| ID: AIG-TE-HW- | Requirement (Hardware) |
|---|---|
| -L1 | The drone shall be able to be used for 70 flight hours total before a component needs to be replaced, excluding replacement of components damaged due to accidents. |
| -MP-MO6 | During normal operations, the RPM of the propellers shall not exceed 270,000/diameter [inch]. [40] |
| -MP-MO7 | If the drone loses functionality, it shall automatically switch to safety mode within 0.5 seconds. |
| -MP-SM-SDS1 | The system shall be able to shut down within 0.1 seconds of being ordered to shut down. |
| -MP-SM-SDS4 | The system shall turn itself off within 0.5 seconds of detecting a malfunction. |
| -MP-SM-SDS4.1 | If the system detects the batteries contain less than 15% of battery charge, the drone shall land within 10 seconds. |
| -MP-SM-CP2 | The drone shall be switched from autopilot mode to manual control within 0.5 seconds from the order to switch being given. |
| -LR1 | The elastic deformation strain during normal flight conditions shall not exceed the amount where any of the propulsion units or sensors are offset by more than 10 °. |
| -S-D1 | The distance to the environment shall be measured at least 60 times per second. |
| -S-D2 | The resolution of the distance measurements shall be at most 0.5 m minus the biggest dimension of the drone in m. |
| -S-D3 | The distance from the drone to its environment shall be measured for distances up to 50 m. |
| -S-VE1 | The velocity of the drone shall be measured 60 times per second. |

| | |
|---|---|
| -S-A1 | The acceleration of the drone shall be measured 60 times per second. |
| -S-O1 | The angular rate of the drone shall be measured 60 times per second. |
| -S-V1.1 | The resolution of the front-facing camera shall be at least equal to the minimum required for gate detection at maximum gate distance with the used field of view measured in megapixel. |
| -S-V1.2 | The field-of-view of the front-facing camera shall be at least 90 °. |
| -P-E1 | The battery shall have a begin-of-life capacity of at least equal to (100% throttle power plus 100% computer power+100% power of all other systems) times 60 s plus 120 s times 100% computer power. |
| -P-E2 | The maximum battery discharge rate shall be at least equal to the maximum use, meaning full throttle, full computational power and full power on all other systems in Watt. |
| -CO1 | The latency of communications between the drone system and remote computers shall be no greater than 80 milliseconds |
| -CO2 | The range of remote communications to the drone shall be at least 300 m. |
| -CO3 | The packet loss rate of remote communications shall be no greater than 5 % during normal flight conditions. |
| -CO4 | The rate of data sent from the drone to remote computers shall be at least equal to the data rate of the essential systems, namely the IMU, cameras and other sensors in kB/s during normal flight conditions. |
| -C1 | The RAM of the drone system shall be at least 500 MB. |
| -C2 | The memory storage of the drone system shall be at least equal to the average flight time provided by the battery times the data rate of all system elements times 10 flights in GB. |

Table 5.2: Requirements due to the engineering budget.

| ID: AIG-TE-EB- | Requirement (Engineering budget) |
|---|---|
| -M1.1 | The total mass of the propulsion unit subsystem shall be no greater than 115 g. |
| -M1.2 | The total mass of the electronics subsystem shall be no greater than 420 g. |
| -M1.3 | The total mass of the structures subsystem shall be no greater than 300 g. |
| -M3 | The maximum drone dimension in all length, width and height, shall be smaller than 50 cm. |
| -M4 | The drone shall have enough computational power to process images at 60 Hz and calculate a flight path. |

Table 5.3: Aesthetics requirements.

| ID: AIG-TE- | Requirement (Aesthetics) |
|---|---|
| -A2 | The drone lights shall emit at least 2.5 W.[18] |

Table 5.4: Sustainability requirements.

| ID: AIG-NT- | Requirement (Sustainability) |
|---|---|
| -S3 | The amount of waste material during the production phase shall not exceed 3 kg. |

# 6
# Design Option Tree

In order to ensure that every option for the design is considered, so-called design options trees are made. A design options tree shows all the options for each aspect of the design. This is done by listing every aspect of the design, and listing all possible options for each aspect.

A general Design Option Tree (DOT) was made during the Baseline Report [11]. This Baseline DOT showed every option that could be taken. Within the baseline DOT there were already options highlighted that were obviously not feasible for different reasons, either not being able to meet the requirements, not being safe or not available at this point in time or in the near future. Those options were removed for the Midterm DOT. Besides the obviously unfeasible options there were more options removed during the Midterm conceptual design phase, due to the gain of knowledge. This was done from top to bottom, when a top level option was deemed unfeasible, the lower levels were also removed. Some of the bigger cuts are explained below:

- Wings were found unfeasible, due to the high agility and maneuverability the drone should be able to handle and the extra structural weight it would add to the drone. As a results every option requiring a wing was removed as well.
- A small drone was also deemed unfeasible since it would not have enough space to fit all the electronics used. A very big drone would not be agile enough. Therefore those options were also removed.
- For the amount of rotors a dual rotor was discarded because they generally are less stable and therefore less suited for computer vision. Also the 5+ rotors was removed due to the high weight it would bring.
- Minimum computational power was also left out, because that will not meet the requirements.

Upon researching and developing various concepts, a number of design options where further eliminated. In the light of the new information obtained, some new and some deeper level options were added. The new Midterm Design Option Tree can be seen in Figure 6.1.

The Design Option Tree shows the design options that are considered for the final design phase. The sub-elements of the system are shown in pink color, which is logically structured as an AND gate. The first level decisions are shown in green and the second level decisions in yellow, which are logically structured as OR, meaning that only one can be chosen eventually. Purple is simply used as a header for additional information. Finally, white hexagonal boxes are used to indicate a precondition option choice for a certain option. The elements of the tree that were involved in the trade-off are described in further detail in chapter 7.

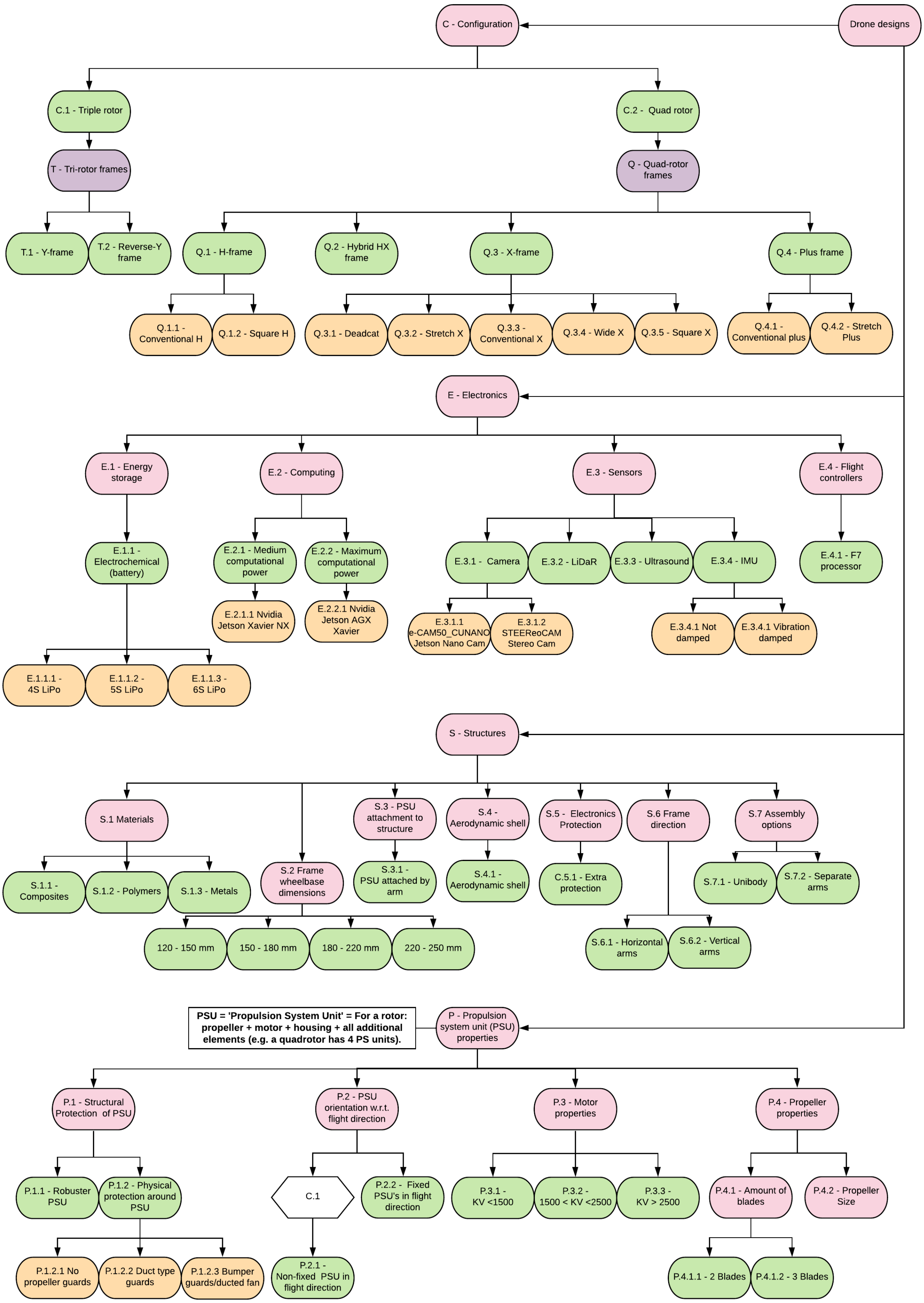



Figure 6.1: The design option tree for the midterm phase

# 7 Design Option Structuring

Five concepts have been proposed for the final design. This chapter will elaborate on those concepts as well as explaining how these concepts came to be. Section 7.1 will bring to light all components considered when making the concepts. Section 7.2 describes the final concepts resulting from this initial design phase and section 7.3 describes the methodology followed for the various subsystems in more details.

## 7.1. Components Elaboration

In order to get a good overview of each potential design, research was done in the major components making up the drone. These include:

- A system on chip (SoC)
- A carrier board (for the SoC)
- A flight controller
- Electronic flight controllers
- Motors
- Propellers
- A selection of sensors
- A Battery
- A base frame
- A protective cover

These were split into two categories. The first is the **dry mass**, which does not include any propulsion related elements. The dry mass includes the SoC, the carrier board, the flight controller, the sensor selection, and the base frame. A margin is included in the dry mass budget for the extra components, such as LEDs, wiring etc... The second category is the **propulsion elements**, which include the electronic speed controllers, the motors, the propellers, and the battery.

The methodology followed varies depending on the components.

For all elements making up the dry mass (excluding the frame), a database of suitable and available components was compiled, and information was collected on their performance, properties, and compatibility.

For the frame and protective cover, research was done on the different production methods available, the different materials, and the different shapes possible. The methodology is described in depth in subsection 7.3.2.

Once the dry mass was established, the propulsion elements were then sized. The methodology is described in subsection 7.3.6.

Various components were then selected for each concept according to their focus and compiled based on the research performed to form one coherent set of proposals. An estimation on the total properties of said concepts as then established based on their respective component's properties, and a simple model of each concept was created to better visualise and evaluate how the different parts would fit together. The different final concepts can be found in section 7.2.

## 7.2. Final Concepts

This section describes all the final concepts that were analysed for the design trade-off. Although each concept was developed separately, the overarching method used is similar for each concept.

Five main concepts were considered, (and their name reflects their focus):

1. **COMP_C1:** Computational concept
2. **DUR_C2:** Durability concept
3. **SENS_C3:** Sensor concept
4. **LWQ_C4:** Light weight quadrotor
5. **LWT_C5:** Light weight trirotor

The design of each concept started by more deeply working out where the exact proposed strengths of the concept would lie and thus also learning which aspects might be the most demanding. Once the key parts of the concepts were identified, possible layouts were looked into. This would be for example how many and what type of sensors the sensor concept could use.

Then, all possible parts for each component of the various layouts were identified and compiled together in a large table to give a clear overview of the advantages and disadvantages of each. Using this, parts were chosen for the layouts based on the previously established requirements and compatibility of the parts. As the different parts all affect each other, both directly and indirectly, via for example the drone weight, this is an iterative process.

After the iterations have yielded a set of components that is deemed sufficient, a final check is performed for each component by a member from its related department. This is done to ensure that all components are compatible and no unintended interactions will occur. If the possibility of a design flaw becomes apparent, a new iteration of the design will be performed to negate these.

The resulting mass budgets can be seen in Table 7.1.

Once all components have been chosen they can be put together. This is done by making sketches to find out how everything fits together best and get a good feeling for the concept. This can be built upon later during the detailed design, while also helping understand the concept thoroughly for the trade-off.

Table 7.1: Concept mass estimate overview

| **Property** | **COMP_C1** | **DUR_C2** | **SENS_C3** | **LWQ_C4** | **LWT_C5** |
|---|---|---|---|---|---|
| AI computer [g] | 650.0 | 76.0 | 76.0 | 76.0 | 76.0 |
| Carrier Board [g] | - | 100.0 | 100.0 | 100.0 | 100.0 |
| Flight controller [g] | 10.0 | 10.0 | 10.0 | 10.0 | 10.0 |
| Sensor 1 [g] | 75.0 | 17.5 | 17.5 | 17.5 | 17.5 |
| Sensor 2 [g] | - | - | 161.0 | - | - |
| Sensor 3 [g] | - | - | 14.6 | - | - |
| Base frame [g] | 180.0 | 165.0 | 132.0 | 144.0 | 118.0 |
| Protective cover [g] | 60.0 | 140.0 | 60.0 | 60.0 | 60.0 |
| Other (e.g. Wires, LED) [g] | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| **Total dry [g]** | **1075.0** | **608.5** | **671.1** | **507.5** | **481.5** |
| Propulsion system [g] | 153.6 | 153.6 | 153.6 | 153.6 | 127.2 |
| Battery [g] | 402.7 | 215.1 | 241.1 | 176.8 | 203.8 |
| **Total wet [g]** | **1631.4** | **977.5** | **1065.8** | **837.9** | **812.5** |
| Volt class | 4S | 4S | 4S | 4S | 4S |
| Propulsion configuration | Quad-copter | Quad-copter | Quad-copter | Quad-copter | Tri-copter |

### 7.2.1. COMP_C1: AI/Processing Power Focus Concept

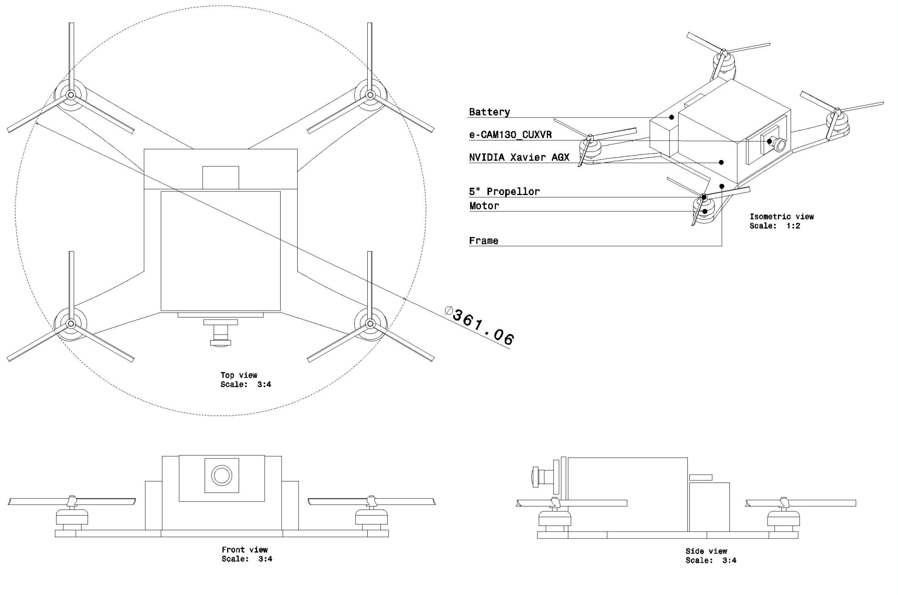



Figure 7.1: COMP_C1 CATIA drawings

#### Concept goal

This concept puts all the emphasis on processing power. This concept would allow for the heaviest algorithms to run, partially at the expense of size and flight performance. A render of the concept can be seen in Figure 7.1 and an overview of the mass estimate for this concept can be found in table 7.1.

#### Payload

The SoC used here is the Nvidia Jetson Xavier AGX. The chip is used with the Nvidia Xavier AGX dev kit. This chip is by far the most powerful chip available on the market for processing at the edge.

Furthermore, the flight controller type that is selected is a micro controller (mass below 10g and surface below 40x40 mm) with an F7 processor and with an efficiently vibration isolated IMU. This provides a significant amount of functionality in a minimal and efficient form factor.

The sensor set selected is the e-CAM130_CUXVR produced by e-con systems. This consists of a set of three sensors run simultaneously. The cameras can be run in sync, allowing for stereo vision to be achieved with frame rates of up to 60 frames per secondor asynchronously with up to 100 fps. These performance combined with the sensor's MIPI connector makes it a appealing solution.

#### Structure

The frame selected use a HX-hybrid layout, which allows for enough space to mount the larger processor, while keeping the low weight of the X-frame. The frame is expected to be made out of carbon fibre.

#### Propulsion and Power

For the sizing of the power and propulsion subsystem the approach in section 7.3.6 is used. This approach yields a propulsion system mass of 153.6 g and a battery mass of 402.7 g.

### 7.2.2. DUR_C2: Durability Focus Concept

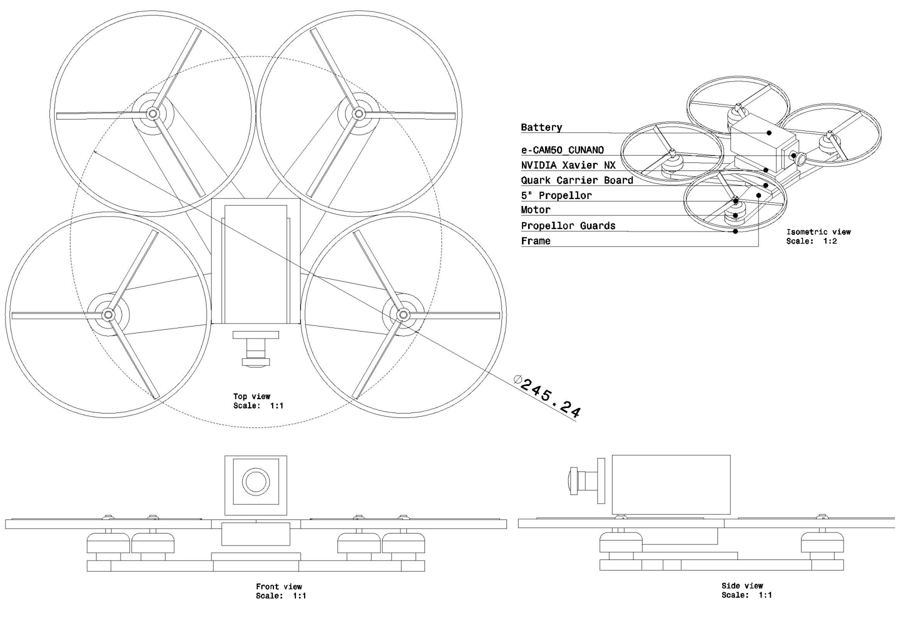



Figure 7.2: DUR_C2 CATIA drawings

#### Concept goal

This concept is designed to minimize the downtime (caused by the drone needing repairs after a crash) and therefore maximizing the training time that AI algorithms can be subjected to. Large impact resistance and a long lifetime for components, together with easy replacability of drone parts is what drives this concept. A render of the concept can be seen in Figure 7.2 and an overview of the mass estimate for this concept can be found in table 7.1.

#### Payload

The SoC selected is the Nvidia Jetson Xavier NX, paired with a Quark board. This solution enable for the SoC footprint to remain small and as such easily protected while providing plenty of computing power. It was preferred over the Nvidia Jetson TX2 as the Xavier NX is smaller, 15x more powerful, and the chip-wide bottom connector combined with the 4 mounting holes provides for a much sturdier and secure fit. The flight controller type that is selected is a micro controller (mass below 10g and surface below 40x40 mm) with an F7 processor and with an efficiently vibration isolated IMU. This provides a significant amount of functionality in a minimal and efficient form factor.

The philosophy is that having less instruments means having less components that can break. This concept will have a camera as only sensor (the e-CAM CUANANO produced by e-con systems).

#### Structure

With durability in mind, propeller guards are an obvious choice. Not only do they protect the propellers in case of light impacts, they also act as dampener for sensitive electronics in case of hard impacts. With optimal durability in mind, full circular propeller guards that surround the whole propeller are chosen. The propellor guards will have a secondary function as ducted fans, which increase propeller efficiency. Another feature of the durable concept is a carbon fibre frame with increased thickness. This concept makes use of the Deadcat frame, which in this case allows for the rotors to be placed close to each other with the ducted fans for protection enclosing the entire main body.

#### Propulsion and Power

For the sizing of the power and propulsion subsystem the approach in section 7.3.6 is used. This approach yields a propulsion system mass of 153.6 g and a battery mass of 215.1 g.

### 7.2.3. SENS_C3: Sensor Focus Concept

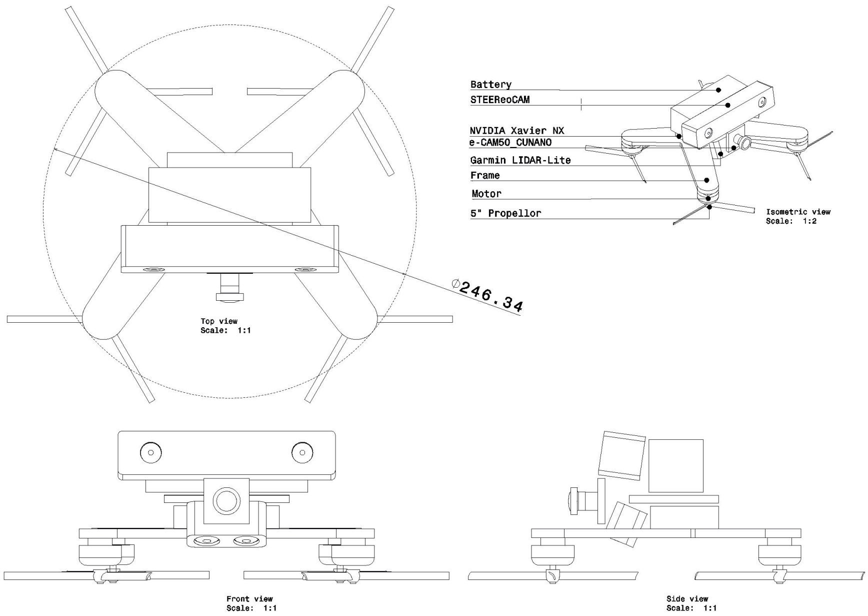



Figure 7.3: SENS_C3 CATIA drawings

#### Concept goal

This concept focus on providing the largest variety of data possible. This is achieved through a large number of different sensors being included. This would enable the drone to achieve better spatial awareness through larger and more varied inputs. A render of the concept can be seen in Figure 7.3 and an overview of the mass estimate for this concept can be found in table 7.1.

#### Payload

The SoC selected for this concept is the Nvidia Jetson Xavier NX, paired with a Quark carrier board. This allows for significant processing power to be included in a small and efficient form factor.

Furthermore, the flight controller type that is selected is a micro controller (mass below 10g and surface below 40x40 mm) with an F7 processor and with an efficiently vibration isolated IMU. This provides a significant amount of functionality in a minimal and efficient form factor.

Two different types of sensors were selected for this concept. The e-CAM CUANANO produced by e-con systems provides a good and effective baseline. Its high refresh rate and small size makes it an effective sensor for this concept. This sensor is paired with the STEEReoCAM, also by e-con systems. While only boasting a frame rate of 30 fps, this sensor provides the drone with depth information with a range of 0.95m to 8m. This concept also includes a Garmin Lidar facing the ground in order to detect if the gate has been passed properly and keeping track of the flight altitude.

#### Structure

A Deadcat frame has been selected, because it allows for a large camera field of view while still being lightweight and stiff. The frame is expected to be made out of carbon fibre.

#### Propulsion and Power

For the sizing of the power and propulsion subsystem the approach in section 7.3.6 is used. This approach yields a propulsion system mass of 153.6 g and a battery mass of 241.1 g.

### 7.2.4. LWQ_C4: Lightweight Quadrotor Concept

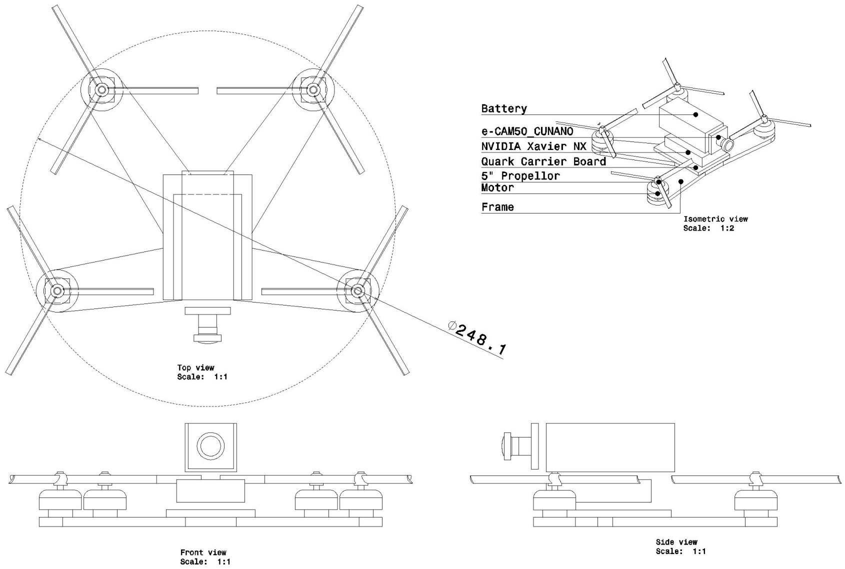



Figure 7.4: LWQ_C4 CATIA drawings

#### Concept goal

The main goal of this concept is to offer a balanced compromise between the different aspects of the drone. This allows for an efficient final layout, which boast a small footprint paired with great capabilities in terms of processing power and performance. A render of the concept can be seen in Figure 7.4 and an overview of the mass estimate for this concept can be found in table 7.1.

#### Payload

The SoC chip selected is the Nvidia Jetson Xavier NX. This chip was selected based on the balance it offers between small footprint and significant processing power. The Xavier is paired with a Quark carrier board, which again provides a good compromise of low footprint and functionality.

Furthermore, the flight controller type that is selected is a micro controller (mass below 10g and surface below 40x40 mm) with an F7 processor and with an efficiently vibration isolated IMU. This provides a significant amount of functionality in a minimal and efficient form factor.

A single sensor was selected for this concept. The e-CAM CUANANO produced by e-con systems allows for a refresh rate of up to 100 fps at hd resolutions. The cameras is connect to the board using a MIPI connector, and its small form factor makes it a good candidate for the final design.

#### Structure

The base-frame layout selected for it is the Deadcat frame made of carbon fibre. This makes for a lightweight and stiff frame while still providing a good field of view.

#### Propulsion and Power

For the sizing of the power and propulsion subsystem the approach in section 7.3.6 is used. This approach yields a propulsion system mass of 154 g and a battery mass of 177 g.

### 7.2.5. LWT_C5: Lightweight Trirotor Concept

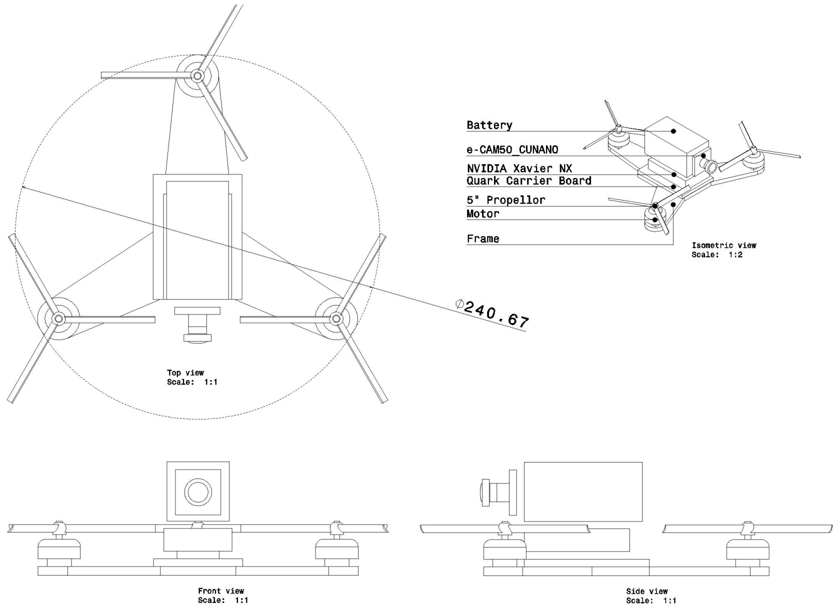



Figure 7.5: LWT_C5 CATIA drawings

#### Concept goal

This concepts follows the same goal as LWQ_C4, but with three rotors instead of four. This is do so mainly to investigate the advantages that a three-rotor configuration over four (such as lower weight and different performance characteristics). A render of the concept can be seen in Figure 7.5 and an overview of the mass estimate for this concept can be found in table 7.1.

#### Payload

The SoC chip selected is again the the Nvidia Jetson Xavier NX, paired with the Quark carrier board. This is the best processing to weight compromise and as such it is selected here too.

Furthermore, the flight controller type that is selected is a micro controller (mass below 10g and surface below 40x40 mm) with an F7 processor and with an efficiently vibration isolated IMU. This provides a significant amount of functionality in a minimal and efficient form factor.

A single sensor was selected for this concept. The e-CAM CUANANO produced by e-con systems allows for a refresh rate of up to 100 fps at hd resolutions. The cameras is connect to the board using a MIPI connector, and its small form factor makes it a well founded candidate for the final design.

#### Structure

The frame of the trirotor is a Y-frame, because it allows for the camera to have a good field of view and is less likely to break upon frontal impact with a gate or wall. The frame is expected to be made out of carbon fibre.

#### Propulsion and Power

For the sizing of the power and propulsion subsystem the approach in section 7.3.6 is used. This approach yields a propulsion system mass of 127 g and a battery mass of 204 g.

## 7.3. Concept Selection Methodology

The methodology for both structure and the propulsion elements required some more in-depth analysis, and are described bellow.

### 7.3.1. Performance

Three performance requirements have been specified by the client with identifiers: AIG-TE-HW-PF1, AIG-TE-HW-PF2 and AIG-TE-HW-PF3. By analyzing these requirements, the minimum required thrust-to-weight (T/W) ratio is calculated for each requirement, after which the critical requirement is identified.

#### Linear Acceleration

According to AIG-TE-HW-PF3, the drone shall be able to linearly accelerate at 19.61 m/s$^2$ from zero velocity. Using a simplified model of the drone, the required T/W ratio can be calculated. In this model, two assumptions are made. Firstly, drag is assumed to be negligible, since the drone is starting from zero velocity. The effect of this assumption will be that the resulting T/W ratio is an underestimation of the actual value. Secondly, horizontal, straight motion is assumed. This assumption could be made after consultation with the client about the requirement. The free body diagram can be seen in Figure 7.6a. First of all, from Newton's second law in the x-direction it is derived that,

$$T_h = m \cdot a_x = m \cdot 19.61 \tag{7.1}$$

And from equilibrium in the y-direction it is derived that,

$$T_v - W = 0 \tag{7.2}$$

Solving this linear system of equations, it is found that T/W = 2.2 and $\theta$ = 63 °.

#### Turning Performance

The other requirement with identifier AIG-TE-HW-PF2 states that the drone shall be able to make a 3 m radius arc while flying at 10 m/s. Again, a simplified model will be used to calculate the T/W ratio, which can be seen in Figure 7.6b. For this scenario, three assumptions are made. Firstly, it is assumed that there is no tangential acceleration, so the forward thrust component is equal to the drag. This assumption flows from the requirement that the drone makes the turn at a constant 10 m/s. Secondly, it is assumed that the effect of the pitch angle of the drone on the magnitude of $T_v$ and $T_h$ is negligible. The result of this assumption is that the T/W ratio is underestimated. Finally, after consultation with the client, motion is assumed to only occur in the horizontal plane. By equilibrium in the x-direction it is derived that,

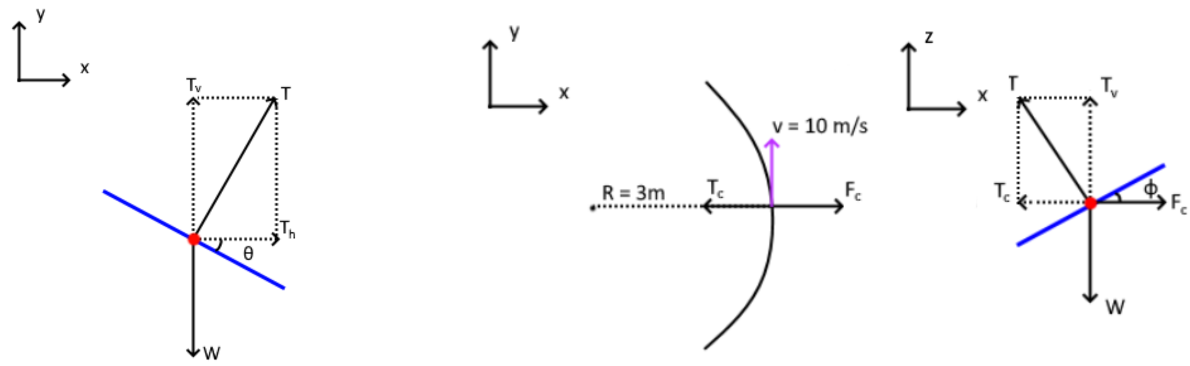
$$T_h = F_c = \frac{mv^2}{r} = \frac{100m}{3} = T \cdot \sin\phi \tag{7.3}$$

And from the assumption that motion occurs only in the horizontal plane it is derived that,

$$T_v = W = T \cdot \cos\phi \tag{7.4}$$

The solution of this system of equations is T/W = 3.5 and $\phi$ = 74 °.

Since this model predicts an underestimated T/W ratio and since it follows from a perfectly controlled drone, it is important to add a margin on the obtained T/W ratio. For preliminary estimations, it is assumed that the drone is flying at 10 m/s when entering the turn, that its camera has a frame rate of 60 fps and that there is 2 frames of delay in the initiation of the turn. Due to this delay, the drone needs to compensate by flying a turn with a radius of 2.7 $m$. Using the same approach as before, a T/W ratio of 4 and $\phi$ = 75 °is found. After more details are established on the drag characteristics of the drone, for the final design a margin will also be taken into account for the underestimation.




(a) Linear acceleration (b) Turning performance

Figure 7.6: Free body diagram of linear acceleration and turning performance

### Maximum Speed

Determining the maximum speed of the drone is necessary to confirm that it will be able to meet the requirement of flying at 30 m/s in a straight line with gates every 20 m. As will be explained later, it turns out to not be possible for any concept without disregarding other requirements such as having a weight of 1 kg and having a flight time of 5 minutes.

Three methods have been proposed to determine the maximum speed of the concepts. The first method is to use equation 7.5, which can be rewritten as equation 7.6.

$$D = C_D \frac{1}{2} \rho V^2 S \tag{7.5}$$

$$V = \sqrt{\frac{2D}{C_D \rho S}} \tag{7.6}$$

The latter can be used to calculate the maximum velocity by setting drag equal to the maximum drag, which occurs at maximum velocity. The maximum drag is set equal to the maximum forward thrust. Assuming a current thrust over weight ratio of 4, as determined in 7.3.1 and a drone weight of 1 kg, the thrust is 39 N. This can be split up in a vertical component of 9.8 N and a horizontal component of 38 N which is the maximum forward thrust. The air density is assumed to be 1.2 $\mathrm{kg/m^3}$. The surface area is determined using the Catia models for each concept. An average value of 0.03 $\mathrm{m^2}$ is used. The difficulty of this method is having an accurate prediction of the drag coefficient. Studies have been performed on the drag coefficient of several shapes [22]. The drone is assumed not to have any complex aerodynamic optimizations and therefore a drag coefficient of 0.1 is assumed for now, which is in line with the values presented in the paper. Filling in these values in equation 7.6 yields a maximum speed of 46 m/s.

The second method for determining the maximum speed uses the assumption that the drag is a linear relation of the speed for a constant mass: $D = k \cdot V \cdot m$. The value for k is picked to be 0.5 [26]. Again, assuming a weight of 1 kg and setting the drag to be equal to the maximum thrust, the maximum velocity can be approximated to be 76 m/s.

The third method to determine the maximum velocity is based on statistics. Racing drones and consumer drones were considered for which the thrust to weight ratio is known and the top speed had been measured and verified (by GPS,timer or a radar). With the use of internet, eighteen drones were found with the necessary information. The maximum velocity is plotted against the thrust to weight ratio, as can be seen in figure 7.7. There appears to be a exponential relation between these parameters. Applying this relation to our drone means that a thrust to weight ratio of 6.5 is needed in order to satisfy the maximum velocity requirement.

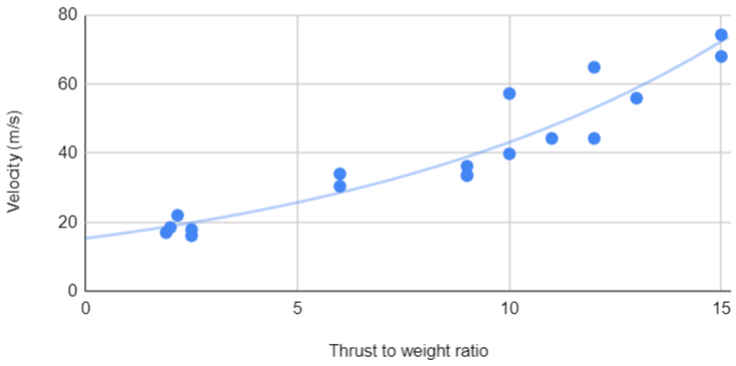



Figure 7.7: Thrust to weight ratio versus maximum velocity

To conclude, the results of these three methods are very different. The second method can be discarded because the assumption of drag being a linear relation of velocity is only true for slow speeds. The first method is also uncertain due to the difficulty in accurately predicting the drag coefficient. Therefore, the statistical approach will be considered for this preliminary analysis.

### Load Factor, T/W

Having a higher load factor will result in the drone being heavier. The reason for this is that there is a requirement of flying 1 minute at maximum thrust. A more powerful drone will require more energy and thus a larger (heavier) battery to fly. The same is true for a longer flight time, which will also cause the battery to be larger (and heavier). The relation between flight time and weight at different load factors can be seen in Figure 7.8. This graph is based on the model explained in Section 8.2.1. The load factor of 4 is to achieve the 3m turning radius at 10 m/s requirement, however it only results in a top speed of 23 m/s. The load factor of 6.5 is to meet the velocity of 30 m/s requirement. As can be seen from the graph, the load factor does not influence the weight much if the flight time requirements are low. However, as the flight time requirement increases, the higher load factor curves slope upwards much sooner than for a lower load factor. It should be noted that the statistical data used creation of Figure 7.8 is not valid for the large mass range indicated, however, it is a valid conclusion to say that a higher load factor leads to earlier weight growth with increasing flight time requirements. The lower load factor similarly has large growth, but at a much higher flight time requirement. Therefore, a load factor of 4 is used by all concepts, as it has results in a substantial amount of weight reduction, while still maintaining a reasonable maximum velocity value. This was agreed upon by the customer as mentioned in section 5.1

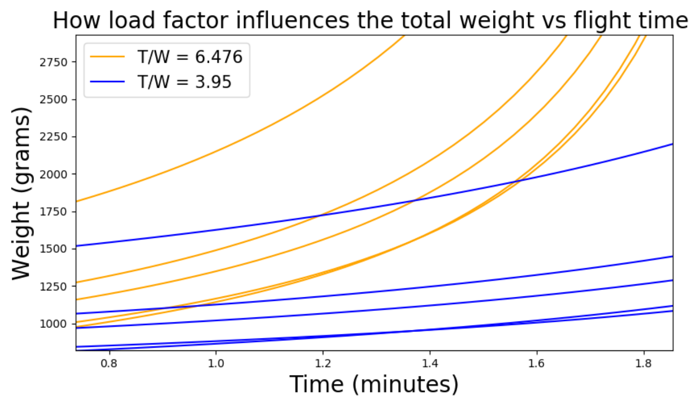



Figure 7.8: Influence of the load factor on the weight of the concepts. Each line corresponds to one concept at a specific load factor.

## 7.3.2. Structure

### Manufacturing Processes

The requirements allow for only a few standard manufacturing techniques. This includes 2D milling, 3D printing and standard PCB assembly techniques.

2D milling is a form of subtractive manufacturing, where chips are removed from a block of material within the requirements constraint of only 2D milling. This process can be accomplished by hand, but is more easily done with a CNC (Computer Numerical Control) router. In general any material that can be worked on with subtractive manufacturing techniques can be used in this process. It is important to note that different cutting tools are required for different materials. In general the availability of shops that can 2D mill is sufficient [45]. Yet, milling is expensive with costs of around 120 Euro/hour.

3D printing is in contrast to 2D milling an additive manufacturing (AM) process. This means that the part is generated by adding layer upon layer of material, building up the product. Multiple processes are defined as additive manufacturing. Material extrusion is being used in the Fused Deposition Modelling (FDM) process (also called Fused Filament Fabrication), in which the "object is built by selectively depositing melted material in a pre-determined path layer-by-layer" [41]. Another AM technique is photopolymerization used in stereolithography (SLA), where the "is created by selectively curing a polymer resin layer-by-layer using an ultraviolet laser beam" [41]. Powder bed fusion is a process in which "a laser selectively sinters the particles of a polymer/metal/ceramic powder, fusing them together and building" the object layer-by-layer [41] as done in Selective Laser Melting (SLM) and Selective Laser Sintering (SLS). Another AM option is binder jetting where a glue, called binder, is deposited on a powder bed. Material jetting is using a print head that "dispenses droplets of a photosensitive material that solidifies under ultraviolet light" [41]. The direct energy deposition method focusses thermal energy to fuse powder in the bed together. During sheet lamination sheets of material are cut out in the right shape and then glued on top of each other. In general all these AM techniques could be used for the drone manufacturing. For now mainly FDM and SLA are being considered, because it is much less complicated than for example powder bed fusion and more readily available [45]. As the drone is planned to be build by the owner it should be designed to be manufactured with minimum knowledge of productions. Yet, if at a later stage another method than those two is found to have a higher efficiency it can still be considered. The materials that can be used in FDM are such as PLA (PolyLactic Acid), ABS (Acrylonitrile butadiene styrene), Nylon, PC (Polycarbonate Thermoplastic), ASA (Acrylic Styrene Acrylonitrile). A detailed description of different materials that can be used can be found at [47]. The cost of printing can be low at just below 3 Euros/hour plus the cost of the filament [49]. SLA usually uses printer brand specific resins and therefore vary in composition.

The frame can be 2D milled or 3D printed, as the shape will probably not be complex allowing for the simpler 2D milling as well. If it is to be made with high carbon fibre content, 2D milling will be the only option. It should be noted that there also exist carbon fibre reinforced FDM filaments, which might be strong and lightweight as well. The aerodynamic shell will likely be a more complex shape, which requires a 3D manufacturing process leaving only 3D printing. The manufacturing technique does probably not differ per concept. Perhaps only for the durability concept a more ruggedized version is needed changing the material and the process.

PCB (printed circuit board) assembly might follow later in the detailed design phase and will be part of the electronics design.

### Materials

The materials for the drone concept will have to be most importantly lightweight. Additionally the material used should be stiff enough to provide structural integrity and strong enough to withstand crashes from at least 3 m height section 5.2. Furthermore the materials should be manufacturable as specified in the previous section and leaves a couple of main groups for materials, which are composites, light metals and plastics (considered apart from composites).

Table 7.2: Representable materials for building the drone structure

| Material | Ultimate Tensile Strength [MPa] | Tensile Yield Strength [MPa] | Youngs Modulus [GPa] | Density [kg/m$^3$] | Cost [Euro/kg] | Description & Source |
|---|---|---|---|---|---|---|
| **3D Printing PLA** | $\approx 50$ | $\approx 45$ | $\approx 3$ | $\approx 1240$ | $\approx 20$ | 11% infill 45 degree pattern [9] [16] |
| **3D Printing ABS** | $22-57$ | $13-65$ | $1-2.7$ | $1010-1200$ | $\approx 26$ | [48] [30] |
| **Carbon Fibre** | 1500 | – | 135 | 1600 | $\approx 136$ | [28] [25] |
| **Carbon Fibre Fabric (0°=90°)** | 600 | – | 70 | 1600 | $\approx 136$ | [28] [25] |
| **Carbon Fibre Fabric (45°)** | 110 | – | 17 | 1600 | $\approx 136$ | [28] [25] |
| **7068 Aluminium Alloy** | 683 | 655 | 73.1 | 2850 | $\approx 2.8$ | [53] [46] |
| **Titanium Carbide** | 258 | – | 449 | 4940 | $\approx 45$ | [33] [23] |
| **9260 Steel** | $\approx 1147$ | $\approx 790$ | 200 | 7850 | 2.3 | [32] [51] |
| **Balsa Wood** | 75 | 25 | 1.1 | 130 | $\approx 4$ | [8][43] |
| **Birch Wood** | 134 | – | 11 | 730 | $\approx 0.7$ | [29][31] |

This comparison of these in Table 7.2 shows the strong lead of carbon fibre for being highly lightweight yet strong. Other materials might be considered as well, as for example 3D printing PLA, which allows for highly optimized shapes. This has the potential of making lightweight frames and might compete with carbon fibre or similar composites. The final product might include also composite frames such as a carbon fibre frame encasing foam, which allows for a higher moment of inertia, while still remaining lightweight. Disadvantages of a carbon fibre frame are that it blocks telemetry signals, requiring the antenna to stick out of the casing. Also it is hard to manufacture and is electrically conductive, which could lead to short circuits.

### Structural Considerations

First of all structures needs to provide a base frame, on which all components need to be mounted on. This base frame needs to be stiff enough to not deform under full acceleration and strong enough to not break due to potential crashes. It will consist of the body frame, which is the main support for all the electronics and other subsystems, and the arms, which will connect the motors and propellers to the body frame. The body frame consists of bottom plate, top plate and so called standoffs, which are the side plates in between the bottom and top to hold those together.

Furthermore structures will provide the aerodynamic shell, that is designed to ensure good aerodynamic flow around the drone to reduce the drag.

Lastly the structures will have to provide sufficient protection to the on-board systems. This can be achieved by having a strong frame and electronics configuration, but the on-board systems will likely need extra protection. This can be achieved by having an additional shock absorbing structure around endangered components. These protective structures might be for example in the form of foam, micro lattice structures, cork or sandwich structures that serve this purpose.

For racing drones in general it is important to be lightweight and crash resistant. A lightweight drone can fly faster, has a higher agility, a lower mass moment of inertia upon impact with obstacles and can also provide longer flight times. A crash resistant drone translated into having a rigid base frame, where a high stiffness to weight ratio is important for crashes and the frame rigidity benefits the stability and flight performance.

### Drone Frame Shapes

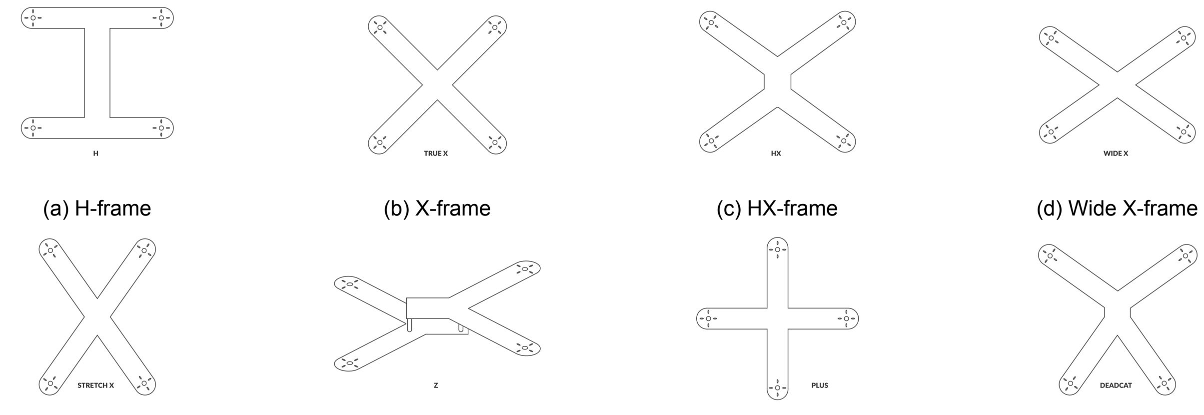
Now the many base frame shapes that are common to use for racing drones will be considered. For each frame option the advantages and disadvantages will be quickly discussed.

The **X-frame** Figure 7.9b is a lightweight frame, because of its direct connections between the components. Moreover due to the short body frame, the mass of the drone is more centralized having a

lower mass moment of inertia and thus allowing for a more agile drone. Also the same perpendicular distance between center of each motor results equal stability around all its axis. Disadvantages are, that the drone is a little more difficult to build than for example the H-frame and that the on-board systems need to be stacked on top of each other in the center of the X. The X configuration has long arms in relation to its size and is subject to high bending loads on its arms due to acceleration or crashes. Lastly the propellers might appear within the camera field of view, which could be resolved by having pusher propellers or hanging the camera beneath the frame, which in both cases requires landing gear adding extra weight.
The **H-frame** shown in Figure 7.9a leaves a lot of space to mount the on-board systems and is easy to build due to its simple shape. Furthermore it is optimal for mounting a forward facing camera, which can be mounted on top of the frame requiring no landing gear. Also its rather short arms allow for higher durability during crashes.
On the other hand it is the one of the heaviest frame shapes due to its large body size. The shape might have problems with torsional stiffness, because the front of the quadrotor rotates with respect to the rear during flight, which would require extra stiffening elements increasing the mass. Lastly it is less agile than for example the X-frame, because of its lower moment of inertia on its pitch axis as the weight is more spread out and not so much centered at the middle as in the X-frame.
A hybrid of those first two configurations would be the **HX-frame** Figure 7.9c. It can combine the advantages and disadvantages of both frames depending on the exact dimensions, but has most likely a similar mass distribution as the H-frame resulting in lower agility. A 60 % shorter body frame would mean a roughly 60 % lighter frame than the H-frame while also being 60 % stiffer.
A Square frame is similar to the H-frame, just with another set of beams connecting the forward and aft motors to each other. This of course increases the weight and the cross-sectional area, increasing aerodynamic drag and thus decreasing the flight performance. On the positive side it is much tougher than the original H-frame.
A **Plus frame** Figure 7.9g is beneficial for minimum rotor interference, because the forward and most aft propeller are further apart. Also this design has finer control as each motor only adds thrust along one axis. Two disadvantages of this concept are that the front facing arm and motor are obstructing the forward facing camera view and this front facing arm is the only part taking up the loads during a frontal crash, which needs to be accounted for by adding material and thus mass.
The **Deadcat frame** Figure 7.9h is a X-frame with wider front facing arms. This allows the camera to have a less obstructed view. The other advantages and disadvantages are close to the hybrid HX-frame.
A **Z-frame** Figure 7.9f is similar to the HX-frame, but the aft part of the frame is mounted higher. This serves the sole purpose of the back rotor being less affected by the induced downwash of the front rotors.
Besides the already mentioned frames variations of those configurations can be made to change some of its properties.
Therefore a **Wide X-frame** Figure 7.9d allows for a better field of view of the camera. Or a **Stretch X-frame** Figure 7.9e can reduce the front to aft rotor downwash disturbance and can make the drone more stable in pitch allowing for an improved high speed flight at the cost of lower roll control and higher weight.
Of course there are many other shapes that could be considered, but the basic shapes have been covered so far and therefore allow for a good concept selection and trade off.

For a possible concept of a tricopter there are two options to choose from. Those are the Y-frame Figure 7.10a and the Reverse Y-frame Figure 7.10b. They are both highly lightweight, because only three instead of four arms are required. Also the concentrate their on.board systems at the intersection point like the X-frame and therefore have a high agility. On the other hand the camera view might partially be obstructed in the Y-frame configuration and completely blocked in the Reverse Y-frame configuration.

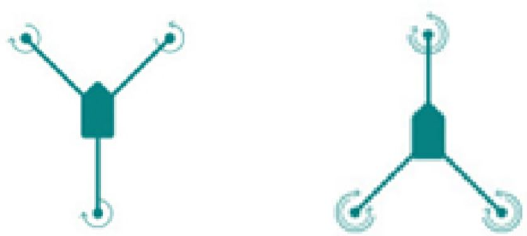
For all frames it can be considered whether the arms shall be placed horizontally or vertically. If the




(a) H-frame (b) X-frame (c) HX-frame (d) Wide X-frame

(e) Stretch X-frame (f) Z-frame (g) Plus frame (h) Deadcat frame

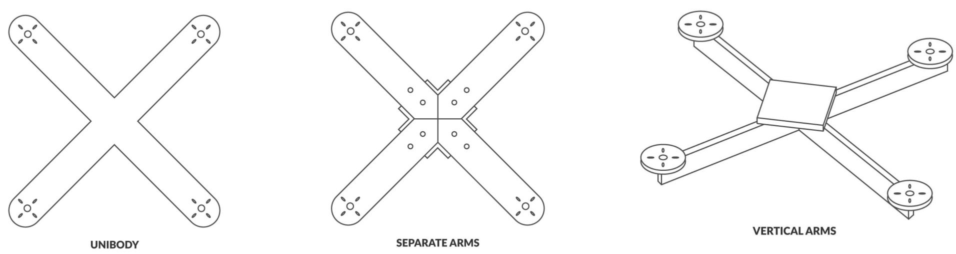
Figure 7.9: Different quadcopter frame types for visualisation [17]



(a) Y-frame (b) Reverse Y-frame

Figure 7.10: Different tricopter frame types for visualisation

arms are of **vertical shape** Figure 7.11c it reduces the crosssectional area during forward pitched flight. On the other hand this design is more susceptible to horizontal bending and a little bit more complex to build.
Another possibility during assembly of the selected frame is choosing a **unibody** Figure 7.11a or separate arms Figure 7.11b. Separate arms have the advantage of modularity and replaceability. Also they can allow for easier customization as for example a thinner arm than baseplate allowing for reduced mass and less cost, because less waste is produced when cutting four arms out of one sheet instead of the whole drone.
Furthermore the arms can be designed to have dihedral and the edges of the structure could be chamfered, which prevents the delamination of carbon fibre, prevents sharp edges from cutting components or harming the environment and looks better at the cost of increased manufacturing complexity.




(a) Unibody frame (b) Separate arms (c) Vertical arms

Figure 7.11: Options on frame assembly [17]

### 7.3.3. Computing

The choice of SoC often had to be done early as its significant size and weight usually drives the overall design. To correctly establish and evaluate the different design options, a detailed option was first performed. The goal was to establish a database containing all potential options and their respective characteristics. This include chips footprint, power/current requirements, processing capability, and general compatibility. Once established, the different chips where sorted into different categories, and the best compromise of footprint-to-processing-power was selected. Two main chips came on top as the best options for their respective categories:

- **Small-footprint Soc: Nvidia Jetson Xavier NX**: In the ”minimal footprint” category, the Nvidia Jetson Xavier NX SoC came out as the clear optimal option. The compromise of processing power (up to 21 TOPs) packed in a compact form factor (dimensions: 69.6mm x 45mm x 15mm, SoC weight: 24g, total module weight: 175g) makes it to clearly stand out from the other options available. This allows for a lightweight and efficient on-the-edge solution, which lend itself well to AI drone racing applications. The price tag and large compatibility of the chip with common tools and libraries make it a particularly well fitting option for the task at hand.
- **Large processing power: Nvidia Jetson Xavier AGX**: The Nvidia Jetson Xavier AGX comes out as the clear winner in the category of sheer raw processing power. It’s 31 TOPs make it the most powerful at-the-edge option available. This however comes at a cost, with the Xavier AGX also being the heaviest and largest option available (dimensions: 105mm x 105mm x 65mm, total module weight: 650g). This less efficient form factor (especially when compared to the Xavier NX) is mainly resulting from the chip being older. It still however remains the main option if processing power is the main priority.

A number of carrier board for the above chips were considered, and the final carrier board selection was based mainly on footprint and IO (Input-Output). The developer kit packages along with third party solutions where considered, and the following were finally selected:

- **Jetson Xavier NX board: Quark Carrier**: For the Jetson Xavier NX SoC, the Quark carrier board produced by Connect Tech presents a combination of low footprint and large enough IO selection. This allows for the entire assembly to remain small and lightweight while not limiting functionality.
- **Jetson Xavier AGX: Nvidia Xavier AGX Dev kit**: For the Jetson Xavier AGX, the already relatively efficient carrier board solution provided with the Nvidia Xavier AGX dev kit proved good enough to be considered as a good solution. The extensive IO paired with a limited footprint makes it an effective solution.

### 7.3.4. Sensors

It is critical that the choice of sensors for an autonomous drone is done correctly, as without proper data of its surroundings, the drone will be much less effective. For this reason, various types of sensors have been considered such as mono and stereo cameras, lidar, GPS, ultrasound, IMU and optical flow sensors. A number of characteristics are important for a good sensor, the most critical of which are the sensor delay, its frame rate, resolution and field of view. Cost and mass of the sensor should also be considered. The delay is important because it is desirable to have the most up-to-date data as possible, and every millisecond delay adds to the inaccuracy of the navigation, and thus to slower results. Similarly, the frame rate is important because determines the interval between images, and thus the possible inaccuracy of navigation and state determination. Some of the most appealing options for cameras are:

- **e-CAM50_CUNANO - 5.0 MP**: Boasting a 139 degree field of view and high framerates at even higher resolutions, this camera is certainly sufficient. Adding to the fact that its small weight, power consumption and size make this an even better option [15].
- **e-CAM130_CUXVR**: This multi-camera system is capable of providing multiple synchronised images at 60 frames per second with good resolution. This allows methods such as visual-inertial odometry to be used which allows for accurate state estimation. Furthermore, this camera system is designed to work well together with the Nvidia Jetson AGX Xavier allowing for easy integration, giving this option a clear edge - though this comes at the drawback of a higher price and power consumption [14].
- **STEEReoCAM™ - 2MP Stereo Camera for NVIDIA® Jetson Nano™/AGX Xavier™/TX2**: Providing stereo cameras ideal for state estimation at a low price, the STEEReoCAM™ is an option worth considering. Its integration with numerous platforms only aids this furhter. However,

the main drawbacks of this option are its wide size, significant 161 g of weight and low framerate which means it will need to be supplemented with another, higher framerate camera [13].

A number of IMUs have also been considered, though since these are typically already in the flight controller, adding another seperate one has little benefits. Another component that is considered is a lider. The accurate estimates of the surroundings provide many benefits. Some of the main considered lidars are:

- **Garmin LIDAR-Lite v4 LED**: Using little power, weight or space and providing high frequency readings at up to 10 m range with single-centimeter accuracy it is self-explanatory why the Garmin LIDAR-Lite v4 LED is a prime option for a lidar.
- **Hokuyo URG-04LX-UG01**: Providing measurements in a 240 degree FoV at 30 mm accuracy and offering enhanced impact resistance, this lidar has obvious benefits. However, this comes with drawbacks such as a price exceeding 1000$, 160 g weight and a slow USB connection which make this option a less appealing solution.

Options like GPS, ultrasound and optical flow sensors have been considered, but other options were favoured due to more appealing characteristics. For example GPS has longer delays and lower accuracy than options like mono or stereo cameras and does not work as well in unknown or indoors environments.

### 7.3.5. Flight Controllers

The choice of the flight controller has a major influence on the drone design, as their dimensions range from a few cm to sizes comparable to those of the companion computers. Naturally, the size of the flight controller affects the overall drone weight and thus, the propulsion system design. In order to choose the most suitable model, research has been conducted into flight controller types and functions. The following flight controller aspects have been found:

- Processor type. The fastest processors are F4, F7 and H7. They differ in the clock speed, number of channels and the flash memory. The fastest processor is H7 however, it has less flash memory than F4 and F7 and generally, it is a new technology and not many flight controllers use it. The second best clock speed, together with good flash memory, is found in the F7 processors and this is the only type that is considered for the design.
- Number and type of channels for connecting devices like the companion computer and the communication module. The type should be compatible with the devices that will be connected to the flight controller. Generally, flight controllers with processors of type F7 have multiple channels that are sufficient for the purposes of this project.
- The flight control firmware that the controller supports. The firmware that is used in this project is BetaFlight and thus, only flight controllers that support it can be considered.
- Whether the required input voltage matches the one provided by the battery. Most flight controllers can have an input of 2-4S LiPo or higher with a capacitor, which is the same range as the batteries chosen for the design. Therefore, most flight controllers have the appropriate input voltage so this requirement does not constrict the possible options.
- Whether the flight controller can perform the function of power distribution. Some flight controllers are so-called all-in-one (AIO) boards that are both flight controllers and power distribution boards. This type is not necessary for this project though, as the flight computer can perform that function, and since AIO boards are heavier, it is not desirable to choose this type.
- Whether the flight controller has a communication module. This could be a useful feature however, it is not necessary, as a separate communication module can be easily connected to the flight controller.
- The instruments the flight controller includes and whether it has effective vibration damping for them. Not many instruments are required, however, a set of well isolated and coordinated IMUs is desirable.
- The size and weight of the flight controller. Naturally, the smaller the better as long as the flight controller has good processor speed and instruments. There exist multiple F7 controllers that are only 2cm or 3cm wide, which is an optimal size for this design. This size means a mass of only a few grams (3-10g).

- Whether the flight controller can be soft mounted. This is an important feature if the IMUs are not isolated directly on the board.

There are multiple flight controllers that adhere to all the above requirements. Therefore, the flight controller model will be chosen in the final design phase. At the moment, the flight controller receives a space budget of 40x40x15mm, a mass budget of 10g and an energy budget of 1A, based on typical flight controller models [7] [3] [4] [5] [6] [2] [1]. These average values are sufficient to create a conceptual design.

### 7.3.6. Power and Propulsion

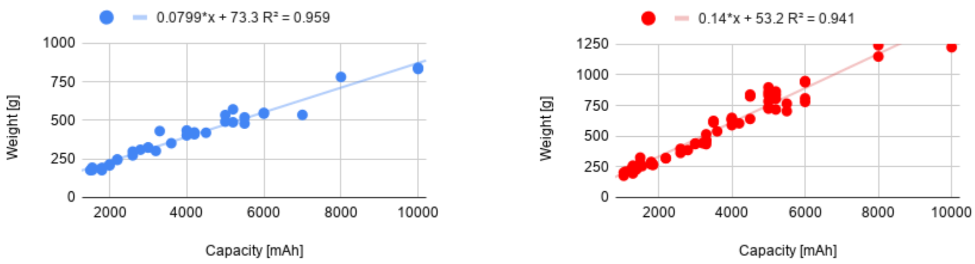
After the dry mass has been determined, the propulsion elements can be sized. This is a simultaneous sizing process for the battery and motors, since they are heavily dependent on each other. To obtain properties such as mass or capacity, average values or statistical relationships were used, which are derived from databases.

#### Power

The choice and sizing of the battery has a large effect on the entire system, since this component by itself is a large part of the drone's mass. As mass is a crucial factor, a battery with high specific energy is desired. From the many types of batteries that are available, the lithium-ion battery is most often used for drone racing, which has a high specific energy compared to other types. More specifically, the lithium-ion polymer or LiPo battery is often used, which uses a polymer electrolyte. These batteries have an even higher specific energy [44] and specific power compared to other batteries based on lithium-ion technology. Therefore, the scope has been limited to these batteries for the trade-off. The sizing of the battery involves the following key parameters: Capacity, c-rate, nominal voltage, mass and cost.
The nominal voltage is often defined in the amount of cells, which are defined by the number of cells, followed by the letter S (e.g. 4S). Each of these cells provide a nominal voltage of 3.7V. After the first preliminary design, it was seen that the motors that could provide enough thrust, were rated for 4S-6S batteries. To accommodate the sizing process, a database was created using off-the-shelf 4S, 5S and 6S batteries from online retailers, containing the formerly stated parameters. From this database, linear regression was performed for the capacity versus mass for the 4S battery and 6S battery separately, which can be seen in Figure 7.12a and Figure 7.12b respectively. 35 datapoints were obtained for 4S batteries, 44 datapoints for 5S batteries and 64 datapoints for 6S batteries. The 5S batteries are not used in the sizing since a significant majority of the motors in the database were tested using 4S and 6S voltages. As seen from the figures, there is a clear linear relationship between capacity and mass, which is used in the design optimization process with the motor to obtain the same T/W ratio for each design concept for comparability.
Additionally, linear regression was performed for the capacity versus cost for the same batteries, which can be seen in Figure 7.13a and Figure 7.13b respectively. Here, the residuals are a lot larger, mainly due to the many other factors that affect cost, such as supply and demand, brand reputation and quality. However, for initial sizing it can provide a good enough estimate of the cost, and since the same relation is used for each design concept, fairness in comparability is achieved.
Resulting from this process, the battery mass, capacity and cost has been determined for each design concept for 1 minute flight time at 100% throttle. In the meantime, it was noticed that the 4S batteries always resulted in a lower total mass, which is why these were used in the trade-off for all concepts. The estimated battery masses can be found in Table 7.1.

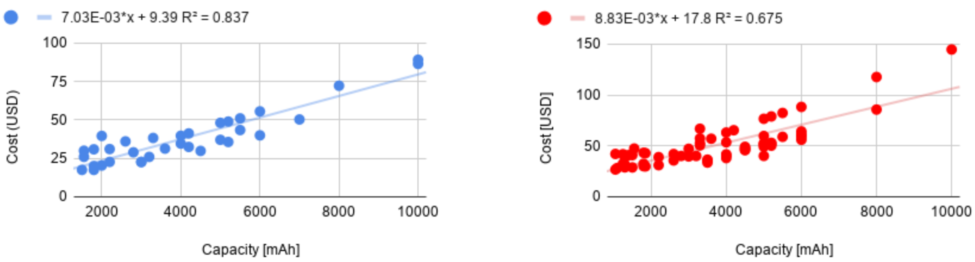
#### Propulsion

To size the propulsion system the mass and cost of the following elements have to be known: the electronic motor, the electronic speed controller (ESC) and the propeller.
At this stage a motor database for tested motors producing a thrust between 900 to 2000 g at 100% power was set up using [21]. After this database was completed it is analysed for relationships between parameters. To ensure comparison is possible, similar propellers were used with 3 blades. Furthermore, generally the same ESC was used during testing: the Hobbywing XROTOR Micro 4in1




(a) 4S LiPo (b) 6S LiPo

Figure 7.12: Mass versus capacity relationship for 4S and 6S LiPo batteries in the database, root mean square error is 36.




(a) 4S Batteries (b) 6S Batteries

Figure 7.13: Cost versus capacity relationship for 4S and 6S LiPo batteries in the database, root mean square error is 8.

40 A [21]. This database includes information on the following motor properties: Mass, Price, Voltage class (either 4S or 6S), Power, Max average current, Thrust at 100% power, Dimensions and the Propeller type & mass used during testing,
Only 4S and 6S motors are included in the database since thrust testing was done at these voltage levels. The ESC used has a mass of 12 g. In addition, to estimate the cost of the propeller, the price of a HQ v1s 5x4.3x3PC propeller is used since this was used most frequently in the database. Analysis of the motor database shows no great differences in cost or mass between different motors. Therefore, in further calculations the average cost and mass of the motor is used. The propulsion system mass and cost estimates for tri- and quad-copter configurations are given in table 7.3 and table 7.4 respectively. At this stage, the concept design, the propulsion system only differs whenever a different volt class motor is used or a different configuration. Thus, it does not differ for different concepts if they have the same volt class motor and configuration.

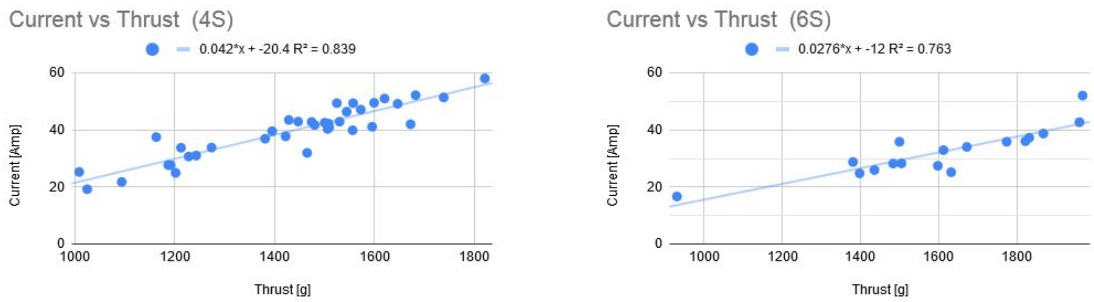
Table 7.3: Mass estimate of propulsion system mass for tri- and quad-copter configurations. (PS = propulsion system)

| **Component** | **Tri-copter (4S)** | **Tri-copter (6S)** | **Quad-copter (4S)** | **Quad-copter (6S)** |
|---|---|---|---|---|
| Motor $[g]$ | 3x30.8 | 3x30.9 | 4x30.8 | 4x30.9 |
| ESC $[g]$ | 1x12 | 1x12 | 1x12 | 1x12 |
| Propeller $[g]$ | 3x4.5 | 3x4.5 | 4x4.5 | 4x4.5 |
| Servo motor $[g]$ | 1x9 | 1x9 | N/A | N/A |
| PS Total $[g]$ | 127.2 | 127.4 | 153.6 | 153.8 |

Table 7.4: Cost estimate of the propulsion system for tri- and quad-copter configurations. (PS = propulsion system)

| **Component** | **Tri-copter (4S)** | **Tri-copter (6S)** | **Quad-copter (4S)** | **Quad-copter (6S)** |
|---|---|---|---|---|
| Motor $[Euro]$ | 3x20.93 | 3x16.59 | 4x20.93 | 4x16.59 |
| Propeller $[Euro]$ | 3x2.85 | 3x2.85 | 4x2.85 | 4x2.85 |
| ESC $[Euro]$ | 1x61.28 | 1x61.28 | 1x61.28 | 1x61.28 |
| Servo motor $[Euro]$ | 1x2.54 | 1x2.54 | N/A | N/A |
| PS Total $[Euro]$ | 135.16 | 122.14 | 156.40 | 139.04 |

Besides performing an analysis on parameters and their relationship to motor mass another analysis is performed on the relationship between the thrust generated and power related parameters such as current. This provides a clear and linear relationship between the thrust generated and the current needed. This relationship is an important finding for further steps to size the power and propulsion system since it is used to translate the thrust into current; an important parameter required for battery sizing. The results of this analysis for 4S and 6S motors is given in Figure 7.14.




(a) 4S Batteries (b) 6S Batteries

Figure 7.14: Current vs Thrust relationship for 4S and 6S motors (trend-line equation included)

### Sizing

After the databases for batteries and motors have been established, as well as their respective statistical relationships, it is time to perform the sizing. Before the sizing can be performed, a few parameters need to be obtained. First of all, the dry mass of the system is needed, which is the total mass excluding the ESC's, motors, propellers and battery. Secondly, the dry current is needed, which is the current required for the part of the system as described before. Finally, the flight time, the amount of battery cells, and the depth of discharge has to be specified.

The dry mass has been estimated, which can be found in Table 7.1. The dry current also has been estimated based on selected components. Furthermore, the initial flight time of 5 minutes resulted in exceeding the mass requirement of 1 kg by a large amount. Therefore, after discussion with the client, the flight time at 100% throttle has been set at 1 minute. In addition, the amount of battery cells that are considered are 4 and 6, as explained in subsection 7.3.6. The depth of discharge (DoD) is set at 80% for each concept, since there is a drop-off in voltage when the battery is nearly depleted [52]. For now, this is deemed to be a reasonable percentage, although for the detailed design this will be further investigated. Please note that the battery energy efficiency, which is between 90-95% for lithium-ion batteries [38], has been left out of the equation. The reason for this, is that it was assumed that the specified capacity in the battery database are the actual discharge capacities and that the wire efficiency is negligible.

The actual sizing process is described as follows. By selecting the thrust, the motor current can be estimated using the thrust-current relationship. Knowing this, the dry current, the DoD and the flight time, the battery capacity can be calculated with Equation 7.7.

$$\mathrm{C} = \frac{(\text{number of motors} \cdot I_{motor} + I_{dry}) \cdot \mathrm{t}}{60} \cdot \frac{1000}{\mathrm{DoD}} \tag{7.7}$$

Using the capacity-mass relationship, the battery mass can be estimated. Having estimated the dry mass before, and the motor, propeller and ESC mass in propulsion subsection, the total mass can be calculated, as well as the T/W ratio. Since the minimum required T/W ratio has been determined in subsection 7.3.1, the thrust can be solved for a certain T/W ratio using this process.

Comparison of the concept mass with regard to either 4S or 6S volt classes shows a that using a 4S system consistently provides a lighter concept, which is why the 4S is used in the trade-off. An overview of the mass estimates can be found in Table 7.1. The estimated costs for each concept can be found in Table 11.10. Important to note is that these are the values which will be used in the eventual trade-off process.

# 8

# Verification and Validation Procedures

Verification and validation plays a role in two different ways. First of all, any software or simulations used have to be verified and validated (Simulations). Secondly, verification and validation has to check requirements compliance and system compliance with its intended purpose (Product). Furthermore, verification and validation on this report's computations was also done. Those procedures and all obtained results/conclusions will be discussed in the following sections.

## 8.1. Simulations

### 8.1.1. Verification

In case a numerical model or software is used, these need to be verified and validated. The verification consists of two parts, namely code verification and calculation verification [35]. In code verification, which applies to self-developed models, the model is tested for implementation errors in the form of bugs. Integrated development environments (IDEs) will be used for this, which offer many debugging tools, including breakpoints and variable value inspection.
In calculation verification, it will be checked whether the numerical model is correct. The testing will be performed on different levels to make error tracing possible. The lowest level test is the unit test, in which individual functions or small blocks of code are tested. Secondly, there is an integration test to make sure that the integration of units and interdependencies are working correctly. Lastly, a system test is performed. Higher level tests shall only be performed after enough confidence has been established from lower level tests, in order to make error tracing possible.

For these tests, a few different checks are performed [50].

1. The output is checked to be in the expected range and order of magnitude.
2. The output does not change in an unexpected way when changing the input.
3. The output is compared to analytical solutions (if possible) and the error will be quantified.

### 8.1.2. Validation

In the more detailed design phase there are two scenarios for validation. Since there will not be any opportunity to test the system in real life, validation will have to be conducted through analysis. The two approaches are as follows:
In the first scenario, the designers will create with their own numerical models. Once the numerical model has been verified, validation can be done by comparison with a validated simulator or existing data. In the second scenario, the designers will use existing software tools. Preferably, validated software is used, in which case its validness for certain scenario's has to be assessed. If the software is not validated, similar procedures have to be followed as for self-developed models.

## 8.2. Midterm Report: Results

### 8.2.1. Verification of Sizing Calculations

The propulsion and power system was sized using spreadsheet calculations. Various parameters were input into the model, including the dry mass, and the statistical data related to the batteries and motors. Within the model, the total maximum thrust of the motors were changed such that the load factor (T/W ratio) would equal to 4/0. For example, increasing the thrust would require higher current motors, leading to a battery with higher capacity, and a higher mass. This then leads to either a higher or lower T/W ratio.
The unit functions in this spreadsheet consists only of simple operations, such as addition and multiplication, and tests (1), (2) and (3) have been performed on these units by inspection. Due to the simplicity of the units and for the sake of brevity, the results are omitted in the report.

Instead, the system test that is performed and its results are discussed. The system test is performed by comparison with another model. This model consists of formulating two equations.

The following equation states that the total mass is equal to the dry mass (without propulsion system and battery) plus the propulsion and battery mass.

$$m_{total} = m_{dry} + m_{p+b} \tag{8.1}$$

The next equation is used to determine the total drone mass and is based on the statistical relations where A and B are the coefficients of the linear regression line for the motors. Y and Z are the coefficients for the battery regression line. These coefficients change depending on whether 4S or 6S batteries are considered. All other symbols are shown in the nomenclature.

$$m_{total} = \frac{R}{n}\left[\frac{A}{R}\left(\frac{60 \cdot DoD}{1000 \cdot t}\left(Y\left[m_{p+b} - m_{prop}\right] + Z\right) - I_{dry}\right) + B\right] \tag{8.2}$$

Equation 8.1 and Equation 8.2 are both equated together to result in an implicit equation, and solved for the unknown, $W_{p+b}$, using an equation solver. The total mass can then be found by adding the solution to the dry mass, $W_{dry}$. This equation has been solved for each of the concepts and compared to the results from the spreadsheet calculations. Table 8.1 shows the comparison of results for both methods for for the durability concept for a flight time of 1 minute. It can be seen that the difference between the two are negligible, and likely due to differences in rounding the input parameters.

Table 8.1: Sizing calculations for the DUR_C2 concept

| | $m_{dry}$ [g] | $m_{p+b}$ [g] | $m_{tot}$ [g] |
|---|---|---|---|
| Sheet Calculation | 608.5 | 369.013 | 977.513 |
| Equation Solution | 608.5 | 368.784 | 977.284 |
| $\epsilon$ [%] | 0 | $6.21 \cdot 10^{-2}$ | $2.34 \cdot 10^{-2}$ |

### 8.2.2. Validation of Sizing Calculations

The validation process is done as follows: Data is collected from the autonomous drone designed by the University of Pennsylvania (UoP) [34]. From their paper, mass and battery information, and the flight time is known (5 minutes). The UoP drone has a 6S battery with a capacity of 99.9 Wh. A 6S battery translates to a voltage of 3.7∗6 = 22.2 V. Using the Wh and the flight time it can be calculated that total current supplied by the battery is 54 A. Assuming that 5 A is the UoP drone's dry current, based on the fact that the concepts dry current range from 4.7 to 5.5 A (excluding COMP_C1), since this is an obvious outlier). Furthermore, to compare the own data to the UoP's data the same thrust setting will be used; the drone will be hovering (T/W ≈1) for a duration of 5 minutes. All in all, the UoP drone data will be used as validation tool for the two obtained statistical relationships. First validation of the motor thrust-ampere relationship will be evaluated. Afterwards the same will be done for the battery capacity-mass relationship.

As mentioned in subsection 7.3.6 the statistical thrust-ampere relationship is governed by the motors efficiency of thrust generated and power used. The current allocated per motor by the battery is 12.25 A (= (54-5)/4). This value is obtained prior to any energy losses. [34] mentions a efficiency from battery to mechanical output 60 %, called the propulsion system efficiency. In the approach of translating thrust to ampere mentioned in this report, efficiency is based on the mechanical power outputted to the energy supplied [to the motor] during testing. It is assumed for this report's own approach that other efficiencies [than motor] (e.g. wire losses) are negligible. In order to allow for comparability during validation it is thus assumed that 60 % of the supplied power of [34] generates the required thrust. Consequently, this means that for a 6S system, an effective current of 0.6 · 12.25 = 7.35 A is obtained when translated from power into current (thus, accounting for energy losses). The results in are given in table 8.2.

For the second relationship (battery capacity-mass), the average total current of 54 A is used to calculate the battery's capacity. The process is the same as in Figure 7.3.6, except that the thrust is not used. Using the relationship to obtain the battery's mass yields a mass of 841 g. For the UoP's battery capacity of 99.9 Wh the actual battery mass is 740 g based on a specific energy of 135 Wh/kg [34]. The results in are given in table 8.2.

Table 8.2: Comparison of intermediary values of validation data & this report's data w.r.t. propulsion & power system
* = not applicable since have to be set equal to allow for validation. a = Includes energy losses. b= Excludes energy losses. c = Thrust-ampere relationship used. d = Battery capacity-mass relationship used.

| | Thrust [g] | Computed current per motor$^a$ [A] | Current per motor$^b$ [A] | Battery mass [g] |
|---|---|---|---|---|
| Sheet calculations | 717.5 | 7.80$^c$ | 12.25 | 841$^d$ |
| Validation data | 717.5 | 7.35 | 12.25 | 740 |
| $\epsilon$ [%] | N/A* | + 6.2 | N/A* | + 13.6 |

Evaluating the table shows a current per motor difference of + 6.2 percent which will overestimate the battery mass. With regard to the actual battery's mass, the battery mass using the sheet calculation is also overestimated in this case.
It can be seen in the table that both computed current per motor and the battery mass are in the same order of magnitude. Furthermore, the error percentage of the current is 6.2%, which is deemed to be in the acceptable range. For the battery mass a larger error is seen of 13.6%. This can be explained by the fact that the method by UoP differs fundamentally from the method in Figure 7.3.6. In their method [34], the average power to hover, the specific energy, and the total efficiency is used. All in all, both (over)estimations do not seem detrimental at this design stage.

## 8.3. Product

### 8.3.1. Verification

For the drone itself, verification has to be performed to confirm compliance with the requirements. Generally speaking, there are a few ways to do verification. These are, inspection, testing, analysis and demonstration. In this early design stage, resources for testing, inspection and demonstration are not available, and all work is done remotely. Therefore, the only viable verification method is analysis. Although mathematically supported analysis is desired, this is not always possible. In that case, analysis will be performed by comparison and review of design.
For analysis, it is important to note that research will be conducted to determine to what extent the validated simulators are valid for this particular design scenario. Multiple simulators will be used to verify different subsystems. All in all, it seems to be most cost and time efficient to use existing validated software, since it incorporates all relevant phenomena into the design process from the start. By using self-developed models, there is a higher probability of excluding certain phenomena due to negligence or ignorance. Simulators which might be used for verification procedures and their relevant subsystems are as follows: Ecalc for propulsion, EasyEDA for electronics, Abaqus for structures, OpenFOAM for aerodynamics, AirSim for software.

### 8.3.2. Validation

Product validation will not be possible during or at the end of the final design phase. More specifically, the hardware components will not be able to be validated due to the fact that this project does not conclude in a product testable in a real life environment. With regard to software, the processing environment could only be simulated because of the lack of the actual on-board processors to test upon. Whenever an actual product would be produced, post-DSE, conventional product validation methods can be applied to allow for complete validation.
These validation methods are as follows [19]:

1. End-to-End Information System Testing: Showing compatibility of information systems
2. Mission Scenario Tests: Showing that the system is able to execute the actual flight mission
3. Operation Readiness Test: Showing that the combination of all system elements, including telemetry and manual control can accomplish their purpose.
4. Stress-Testing: Demonstrating the robustness of the system.

# 8.4. Final Design: Results

## 8.4.1. Mass Requirement: Contingency Management

In the mid-term phase a preliminary verification is done on the mass requirement. In order to provide an estimate for contingency management of the mass requirement, additional computations are done with altered relationships. These alterations are done by computing the root-mean squared error and adding this to obtained statistical relationships (ampere-thrust and mass-capacity). Essentially, this introduces two design factors. The first is introduced in the statistical current-thrust relationship of the motors, resulting in a higher current required to power the system. The second is introduced in the statistical mass-capacity relationship of the battery and increases mass. Ultimately, this increases the mass estimate of the battery and, consequently, the total wet mass. The mass estimates computed with these additional design factors are given in table 8.3. It is important to note that the actual values in this table will not be used in the final trade-off, instead it is used to shed light on the susceptibility of concept mass estimate. As seen in the table, by taking into the contingency into account, the mass requirement is violated by three out of five concepts for 1 minute flight time at 100% throttle. Therefore, for these concepts it is likely that the mass requirement of 1 kg will not be met.

Table 8.3: Total & subsystem mass estimates of concepts computed with additional design factors (at T/W ≈4 & flight time of 1 minute)

| **Property** | **COMP_C1** | **DUR_C2** | **SENS_C3** | **LWQ_C4** | **LWT_C5** |
|---|---|---|---|---|---|
| Volt class | 4S | 4S | 4S | 4S | 4S |
| Configuration | Quad-rotor | Quad-rotor | Quad-rotor | Quad-rotor | Tri-rotor |
| Total dry mass [g] | 1075.0 | 608.5 | 671.1 | 507.5 | 481.5 |
| Propulsion system [g] | 153.6 | 153.6 | 153.6 | 153.6 | 127.2 |
| Battery [g] | 486.6 | 308.8 | 332.5 | 270.2 | 279.4 |
| **Total wet mass [g]** | 1715.3 | 1070.9 | 1157.3 | 931.3 | 888.1 |

## 8.4.2. Flight Time Requirement: Effect on Mass Estimate

The initial flight time requirement stated that the drone shall be able to fly for 5 minutes. Figure 8.1 shows how the total mass of the drone increases with an increasing flight time requirement, caused by increasing battery size. This graph is based on the model used for verification explained in Section 8.2.1. It assumes the critical case, namely the drone continuously flying at 100% throttle. It is clear for this critical case that the mass of the drone concepts increases exponentially with flight time, making it clear that the initial requirements of 5 minutes flight time and total mass of under 1 kg is not possible. The two lightweight concepts can be seen to have the lightest weight of all the concepts. They both have equal masses for a flight time of about 1.3 minutes (78 sec), where the quad becomes lighter than the tri-copter after this time, and vise versa.

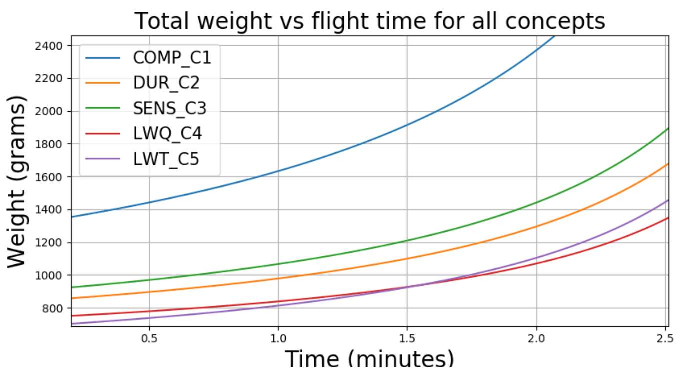


Figure 8.1: Flight time vs. mass estimate for all five concepts

# 9 Technical Risk Assessment

When designing it is important to be aware of events that can have a negative impact. It is important to analyse what can go wrong, and how this can be prevented or how to design in such a way the consequences will not heavily influence the mission. Therefore a risk analysis is done in this chapter. Firstly, an identification of the different risks will be given in section 9.1, followed by the strategies to mitigate these risks in section 9.2.

## 9.1. Risk Overview

Risk contains a certain probability and impact, the higher the probability and impact are, the higher the risk is. The probabilities for each risk are ranked based on [37] and rewritten to how many flights it takes for an event to occur. The impact is based on [20] and are ranked not only based on the direct influence an event has on the mission, but also the resources that have to be spent when the event occurs like time and money (i.e. replacing an expensive, hard to reach, computer has a bigger impact on the mission than replacing a cheap, easy to reach motor, while the drone cannot fly if either of them is broken). The explanation for each rank of probability and impact can be seen in the table below.

| Rank | Probability | | Impact | |
|---|---|---|---|---|
| **1** | Very low | Over $10^6$ flights | Negligible | Small inconvenience, no direct influence on technical performance. |
| **2** | Low | Between 1000-$10^6$ flights | Marginal | Little impact, small reduction in technical performance. |
| **3** | Moderate | Between 100-1000 flights | Significant | Mission success is harder, reduction in technical performance. |
| **4** | High | Between 10-100 flights | Critical | Mission success questionable, big reduction in technical performance. |
| **5** | Very high | Every 10 flights | Catastrophic | Mission failure, technical performance fully compromised. |

Every event that is thought of at this point is described in table 9.1, including the drivers behind it, the rank of probability ”P”, the impact it has on the project, and the rank of impact ”I”. The risks are mainly based on experiences from prior Autonomous racing drone competitions provided by the tutor. For a good overview the risk are displayed in a risk map as can be seen in Table 9.3. There are four sections in the risk map: ”red”, ”orange”, ”yellow”, ”green” which indicate very high to low risk respectively. Many events that might bring along risk, as depicted in Table 9.1, are acknowledged in these graphs with it’s corresponding symbol and risk characteristics. Based on the color actions are to be taken. Red - avoid if possible, orange - mitigation needed, yellow - mitigation preferred, green - accepted.

## 9.2. Risk Mitigation Strategy

Naturally, the risks described in section 9.1 should be minimized. Particularly those with the highest probability and impact should be mitigated as much as possible. An overview of all the risks and the strategy to mitigate them is shown in table 9.2 including the effect the mitigation strategy will have on the impact and the probability. A new ranking for the probability and impact is given as ”PM” and ”IM”, probability mitigated and impact mitigated. This will lead to a new risk map as can be seen in Table 9.4. It is clear that with the mitigation strategy the risk are definitely lower. However, there are only a few risks that are already acceptable. The risks in the ”yellow” section of the risk map should be watched closely in case the risk develops. For the risks in the ”orange” section there should be done some research to find a way to lower that risk even further. It can be noticed that the risks in the ”orange” section are mostly common when crashing, which is hard to avoid.

Table 9.1: Identification of the probability and impact of Risks

| ID | Event | Cause | P | Impact | I |
|---|---|---|---|---|---|
| | | **Risks regarding the Structure** | | | |
| ST1 | Body failure (Where the electronics are attached) | Crash into a gate or the ground | 3 | Drone cannot perform mission. Whole frame needs to be replaced. Possible damage to the electronics. | 5 |
| ST2 | Arm failure | Crash into a gate or the ground | 3 | Drone cannot perform mission. Arm needs to be replaced. Possible damage to the motor, propeller and body. | 4 |
| | | **Risks regarding the Electrical Subsystem** | | | |
| ES1 | Computer failure | Overheating, damage due to a crash | 4 | Drone cannot perform mission. Computer needs to be replaced. | 5 |
| ES2 | System catching fire | Puncturing of the battery, battery over or under charged, short circuit | 4 | Causes a dangerous situation. Drone cannot perform mission. Might be needed to rebuild the whole system. | 5 |
| ES3 | Camera failure | Crash into a gate or the ground | 5 | Drone cannot use computer vision anymore. Drone cannot perform mission. Camera needs to be replaced. | 4 |
| ES4 | ESC Failure | Overheating, Damage due to a crash, short circuit | 4 | Motor stops working. Drone cannot perform the mission. ESC needs to be replaced. | 3 |
| ES5 | Flight controller failure | Crash into a gate or the ground, overheating, short circuit | 3 | Drone cannot perform mission. Flight controller needs to be replaced. | 4 |
| ES6 | Computer malfunction | A bug in the software | 4 | Drone cannot properly perform mission. Software needs to be debugged. | 2 |
| ES7 | Battery degradation | Depth of Discharge (DoD) is too high | 3 | Drone cannot perform mission properly. Might be needed to replace the battery. | 3 |
| ES8 | Battery depleted too much before start | Power used for processing when the drone stands by for the race | 4 | Drone cannot properly perform mission. | 2 |
| | | **Risks regarding the Propulsion subsystem** | | | |
| PR1 | Motor failure | Crash into a gate or the ground, overheating, short circuit | 4 | Drone cannot perform the mission. Motor needs to be replaced | 3 |
| PR2 | Propeller failure | Crash into a gate or the ground, too high RPM | 5 | Drone cannot properly perform mission. Propeller needs to be replaced | 2 |
| | | **Risks regarding the Control and Stability** | | | |
| CS1 | Pilot not able to control the drone after take-over. | Transmitter or receiver malfunction, a bug in the software | 2 | Drone will be uncontrollable. Can cause a dangerous situation | 5 |
| | | **Risks regarding the Computer vision and Navigation** | | | |
| CVN1 | Drone not able to find the gate | Gate out of FOV or out of range, broken camera, blocked view | 4 | Drone cannot properly perform the mission. Camera might be needed to be replaced. | 3 |
| CVN2 | Blurry vision at high speeds | Too high speeds. Computing power not sufficient | 4 | Drone cannot properly perform the mission. | 3 |
| CVN3 | Path planning too slow for high speeds | Computing power not sufficient | 4 | Drone cannot properly perform the mission. | 3 |
| | | **General risks** | | | |
| GE1 | Technology used gets outdated | Technological progress | 3 | The drone will not be used when there is a better alternative. | 2 |

Table 9.2: Mitigation strategy including the effect on the risk

| ID | Event | Mitigation strategy | PM | IM |
|---|---|---|---|---|
| | | **Risks regarding the Structure** | | |
| ST1 | Body failure | Make the body easily replacable. Reduction in impact. | 3 | 3 |
| ST2 | Arm failure | Make the arms easily replacable. Reduction in impact. | 3 | 2 |
| | | **Risks regarding the Electrical Subsystem** | | |
| ES1 | Computer failure | Extra cooling and protection. Reduction in probability. | 3 | 5 |
| ES2 | System catching fire | Protect the battery in case of a crash. Reduction in probability. Implement a LiPo battery protection board to protect against over/undercharging and short circuit. Reduction in probability. | 3 | 5 |
| ES3 | Camera failure | Extra protection for the camera. Reduction in probability | 4 | 4 |
| ES4 | ESC failure | Make the ESC easily replacable. Reduction in impact. | 3 | 3 |
| ES5 | Flight contoller failure | Extra protection for the flight controller. Reduction in probability. | 2 | 4 |
| ES6 | Computer malfunction | Good verification of the software. Reduction in probability. | 3 | 2 |
| ES7 | Battery degradation | Set a DoD limit using the computer module to extend lifetime. Reduction in probability and impact. | 2 | 2 |
| ES8 | Battery depleted too much before start | Use a 10% safety margin on the battery design. Reduction in probability | 3 | 2 |
| | | **Risks regarding the Propulsion subsystem** | | |
| PR1 | Motor failure | Make the motors easy and cheap to replace. Reduction in impact. | 4 | 2 |
| PR2 | Propeller failure | Make the propellers easy and cheap to replace. Reduction in impact. | 5 | 1 |
| | | **Risks regarding the Control and Stability** | | |
| CS1 | Pilot not able to control the drone after take-over. | Implement a killswitch which works at a different frequency and overrules every other input. Large reduction in impact. | 2 | 2 |
| | | **Risks regarding the Computer vision and Navigation** | | |
| CVN1 | Drone not able to find the gate | Pre-race camera check for malfunctions. Reduction in probability. Use highest quality camera supported by the computer. Reduction in probability. | 3 | 3 |
| CVN2 | Blurry vision at high speeds | Feedback loop to reduce the speed when computer vision is not supported so the drone can still perform the mission. Reduction in probability and impact. | 3 | 2 |
| CVN3 | Path planning too slow for high speeds | Invest in a high performance computer module. Reduction in probability. | 3 | 3 |
| | | **General risks** | | |
| GE1 | Technology used gets outdated | Making electrical components modular so drone can be updated. Reduction in probability. | 2 | 2 |

Table 9.3: Technical risk map before mitigation

| Impact \ Probability | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 5 | | CS1 | ST1 | ES1,ES2 | |
| 4 | | | ST2, ES5 | | ES3 |
| 3 | | | ES7 | ES4, PR1 CVN1, CVN2 CVN3 | |
| 2 | | | GE1 | ES6, ES8 | PR2 |
| 1 | | | | | |

Table 9.4: Technical risk map after mitigation

| Impact \ Probability | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 5 | | | ES1, ES2 | | |
| 4 | | ES5 | | ES3 | |
| 3 | | | ST1, ES4 CVN1, CVN3 | | |
| 2 | | ES7, CS1 GE1 | ST2, ES6 ES8, CVN2 | PR1 | |
| 1 | | | | | PR2 |

| | |
|---|---|
| Red | Very high risk |
| Orange | High risk |
| Yellow | Medium risk |
| Green | Low Risk |

# 10 Sustainable Development Strategy

This chapter explains the sustainability development strategy, which consists of the identification of sustainability criteria by conducting a life cycle assessment of the race drone. The sustainability criteria is used to score the sustainability of each concept, and will be considered in the trade-off the the concepts.

## 10.1. Life Cycle Assessment

A life cycle assessment of the race drone has been conducted, which is thoroughly explained in the baseline report [11]. The life cycle assessment analyses various ways in which the sustainability of the drone is affected in each phase of its life. The drone's phases are shown below:

1. Raw material acquisition
2. Material manufacture
3. Product component manufacture
4. Final product manufacture and assembly (done by the consumer)
5. Product consumption
6. End-of-life phase

The life cycle assessment from the baseline report [11] identified the following fourteen sustainability aims, which indicate ways in which the drone design can improve its sustainability. These aims are used to formulate sustainability criteria to be used to compare concepts with one another during the design of the drone.

- **Aim 1:** Components should be selected from sustainable suppliers, with good environmental and social ratings.
- **Aim 2:** Components should be produced using sustainability harvested resources that have been obtained using fair methods.
- **Aim 3:** The design should allow for minimal energy usage for processes during the final manufacturing phase.
- **Aim 4:** The design should minimize the waste material and emissions during the final manufacturing phase.
- **Aim 5:** The design should use components which are manufactured in as many areas of the world as possible.
- **Aim 6:** The weight of the drone should be reduced as much as possible.
- **Aim 7:** The computational requirements should be as low as possible such that the processor power consumption is minimized.
- **Aim 8:** All systems aboard the drone should have as low power consumption as possible.
- **Aim 9:** The rated lifetime of components should be as long as possible.
- **Aim 10:** The design should be as durable as possible and protect all components during collisions.
- **Aim 11:** The volume of material should be minimized.
- **Aim 12:** The design should contain temporary joints.
- **Aim 13:** Suppliers of components should have proper disposal and recyclability systems in place.
- **Aim 14:** The drone should be designed as much as possible using biodegradable materials.

## 10.2. Sustainability Criteria

Table 10.1 shows the sustainability criteria and from which sustainability aims they were derived. Some changes were made from the original criteria in the baseline report [11]. The sustainability criteria are split into two groups: group A is for evaluating the sustainability of designs during the concept selection phase; and group B is for evaluating the sustainability during future sustainability assessments when more information about the design is known.
Only three sustainability criteria are used during the concept trade-off. This is because the other criteria in group B require information about each concept which is not yet known. The final manufacturing phase has not yet been characterized, ruling out the use of criteria 4 and 5 from the trade-off. The difference in assembly of components for each design has not been decided, requiring the omission of criterion 6. Specific material types have not yet been defined for each concept, ruling out criterion 7. Criteria 8, 9 and 10 are omitted as the exact components of each concept have not yet been chosen. The three sustainability criteria have been given a weight factor based on the importance of each criterion on the sustainability of the drone design. Criterion 1 is given a high weight factor as the energy consumption will accumulate throughout the entire usage phase of the drone's life. Criterion 2 is given a lower weighting than criterion 1, as the volume of the drone influences sustainability mainly during the end-of-life phase. This happens only once, and is not a continuous process as with the energy consumption for criterion 1. Criterion 3 is also given a high weight factor, like criterion 1. Durability of the design is important to sustainability as it greatly determines the time till end-of-life of the drone, and the amount of waste that results over a long term, considering the user continuously replaces parts within the drone when it breaks. Both criterion 1 and 3 are given the same weight factor, as they seem to have similar contributions to waste, however, it is difficult to measure this. More details on exactly how each criteria is scored is shown in the trade-off section, subsection 11.1.3.

Table 10.1: List of sustainability criteria and how they are assessed with a score from 0 to 4. The left column indicates from which aims the each criterion was derived. The right column indicates the weighting factor applied to each criterion.

| Derived from aim no. | Sustainability Criterion | Weight |
|---|---|---|
| **Criteria group A: for evaluation during concept selection phase** | | |
| 6, 7, 8 | **Criterion 1:** Estimated power consumption<br>0 = High power consumption, 5 = Low power consumption | 40% |
| 11 | **Criterion 2:** Volume of solid material:<br>0 = High volume of solid material, 5 = Low volume of solid material | 20% |
| 10 | **Criterion 3:** Durability of design:<br>0 = The drone's structure can break easily.<br>5 = The drone is very durable | 40% |
| **Criteria group B: for future sustainability assessments** | | |
| 3 | **Criterion 4:** Estimation of energy usage of processes during final manufacturing phase | |
| 4 | **Criterion 5:** Material waste during final manufacture phase | |
| 12 | **Criterion 6:** Types of joints used for assembly | |
| 14 | **Criterion 7:** Volume percentage of biodegradable material | |
| 1, 2, 13 | **Criterion 8:** Sustainability of suppliers | |
| 5 | **Criterion 9:** Location of manufactured components | |
| 9 | **Criterion 10:** Lifespan of components | |

The sustainability evaluation approach does have it's limitations, due to the inaccuracies in creating the sustainability criterion scoring and weight factors. For example, the difference between how waste material impacts the sustainability of the drone and how its energy usage affects sustainability is difficult to determine. Therefore this sustainability evaluation approach does not provide a definitive measure of a design's sustainability, but should be used as a rough measure to help compare designs.

# 11 Trade-off

Now that five possible concepts have been proposed as possible candidates for the final design, the winning concept has to be chosen. In order to choose the concept that suits the project objective best, certain trade criteria and weights are proposed in section 11.1. The trade-off is then performed and shown in section 11.2. Finally, the sensitivity analysis is performed in section 11.3. The goal of this chapter is to decide which concept will be considered for the final design, and to provide reasoning on how the optimal design is selected.

## 11.1. Trade Method

The trade off will be performed based on criteria. Each of these criteria will be weighted. Intentionally, only the most important and influential criteria were selected. The amount of criteria should be limited in order to simplify the trade off. Another benefit of selecting few criteria is that these criteria can than be evaluated in more detail for each concept, considering that there is only limited time available for analysis.

To evaluate and compare all concepts with each other, several trade-off criteria were defined. The design criteria along with their weight, and evaluation method are presented in Table 11.1. The weights of the trade-off criteria were based on the AHP (Analytical Hierarchy Process) method where the relative importance of two criteria were set with respect to each other, after which the scores were slightly modified after discussion with the team and the client.

Table 11.1: Trade-off criteria with their respective weights and estimation methods.

| Criterion | Weight | Estimation Method |
|---|---|---|
| Autonomous Navigation Performance | 35 % | Quantitative and Qualitative |
| Flight Performance | 20 % | Quantitative and Qualitative |
| Risk | 20 % | Qualitative |
| Sustainability | 10 % | Qualitative |
| Mass | 10 % | Quantitative |
| Cost | 5 % | Quantitative |

The Autonomous Navigation Performance receives the highest weight of 35% as the project mission statement is to facilitate AI development. This criterion should be a driving one but it should not overshadow other important criteria too much. The second most important criteria are the Flight Performance and Risk, both with a weight of 20%. As the project goal is to design a racing drone, the speed and agility of the concept are highly important. At the same time, the drone should not pose any significant risks of damage upon impact as it would mean a higher down time to repair it. Then, the Sustainability and Mass criteria are both given a weight of 10%. It is a goal of the project to maintain a sustainable development strategy, which, regarding the design itself concerns mostly reducing material and component waste and recharging the batteries. The mass criterion on the other hand, is relevant as lighter drones fit better through the gates and are generally easier to control. Finally, the Cost criterion is given the lowest weight of 5%. It is considered an important criterion by the customer, however, it should not have much influence, given the customer requirement is met, as it is considered significantly less relevant than the other criteria.

As can be seen in Table 11.1, the trade-off criteria are scored either quantitatively or qualitatively. When quantitative analysis is possible, usually a linear scale is used, which is explained in detail in the criteria elaboration below. However, when only a qualitative estimation method is possible, scores are given according to Table 11.2.

Table 11.2: Scoring method for criteria scored qualitatively.

| Score | Quality |
|---|---|
| 5 | Excellent |
| 3 - 4 | Good |
| 1 - 2 | Marginal |
| 0 | Unacceptable |

It should be noted that the durability of the design impacts both the risk and sustainability criterion scores, however for different reasons. For the risk criterion, durability should be improved to reduce downtime during races. Alternatively, for the sustainability criterion, durability should be improved to reduce the waste produced. This dual benefit of durability is the reason it is counted twice in the trade-off.

### 11.1.1. Autonomous Navigation Performance (ANP)

Since the mission need statement of the project is to facilitate development of artificial intelligence systems, the autonomous navigation performance of the chosen drone concept is of utmost importance. The autonomous navigation performance is influenced by two aspects - the computational power of the on-board computer and the data gathering capabilities of the on-board sensors. The computational power is considered to be a slightly more important criterion as a good computer with somewhat lacking data gathering capabilities can still perform fine when good algorithms are used, whereas a system with excellent data gathering capabilities but a sub-optimal computer might not even be able to process the gathered data. The two criteria should still have a similar importance though. For this reason, the computational power criterion is given a weight of 60% and the data gathering criterion is given a weight of 40%, as can be seen in Table 11.3. The table also shows the scores for each criteria, which is elaborated on below.

Computational performance can be quantified in various ways but the aspect that is taken into account in this trade-off is the number of operations per unit time described by the TOPs unit (tera operations per second) This aspect is directly related to how fast the processor is and thus, how complex the applied algorithms can be. The considered concepts use either the NVIDIA Jetson Xavier NX with 21 TOPs or the NVIDIA Jetson Xavier AGX with 32 TOPs. The latter one is a state of the art computer and therefore, the concept that uses it receives the highest score - 5. The processor speed of the NX model is about 65% of the speed of the AGX model and thus, concepts with the NX model receive a score of 3.3, which is equivalent to 65% of the maximum score of 5.

The data gathering capabilities cannot be scored quantitatively as various types of sensors cannot be easily compared. All concepts include a low latency and high frame rate and high resolution camera, as well as a vibration damped IMU. This set of sensors is sufficient for decent data gathering that, together with a powerful computer and efficient algorithms, allows for good autonomous navigation. For this reason, concepts with only these two basic sensors receive a good score of 3. On the other hand, having only these two sensors poses a challenge for the machine vision algorithm. It is certainly very useful to gather more types of data such as depth measurements like the SENS_C3 does. On top of the primary camera and an IMU, it has a stereo camera system capable of mapping the surroundings in 3D and a LIDAR capable of measuring the altitude. For this reason, this concept receives an maximum score of 5.

Table 11.3: Autonomous navigation performance trade-off table.

| | COMP_C1 | DUR_C2 | SENS_C3 | LWQ_C4 | LWT_C5 |
|---|---|---|---|---|---|
| Computational performance (60%) | 5 | 3.3 | 3.3 | 3.3 | 3.3 |
| Data gathering (40%) | 3 | 3 | 5 | 3 | 3 |
| **Total** | **4.2** | **3.2** | **4.0** | **3.2** | **3.2** |

### 11.1.2. Flight Performance (FP)

The flight performance criterion characterises the drones agility, indicating the drones ability to accelerate quickly and to make sharp turns. It is dependent first on the drone size, a smaller drone will obtain a higher score as it fits more easily through the gate, and it has a smaller frontal surface area lowering the aerodynamic drag. This parameter was measured with the drone's wheelbase, which is the largest diameter that can be drawn around the drone frame. Its value was derived from the Catia drawings for every concept, and a score was defined with the ranges following Table 11.4. Secondly, the frame type was taken into account when evaluating the flight performance. Due to the placement of the yaw control at the tail of the trirotor Y-frame, a trirotor is more agile and has better stability performance than the quadrotor. Also with fewer motors, it has a higher flight efficiency [27] [24].

In addition, the more centralised the drone mass, the lower the drone its moment of inertia (MMOI) allowing for more agile flight conditions. A preliminary estimation of the mass moment of inertia in all roll, pitch and yaw direction was made from the 3D configuration drawings with the Catia software. Here the computer, carrier board and battery were modelled as solid blocks, and the cameras, sensors, motors and propellers were made on scale with their dimensions. A density of 1000 kg/m$^3$ was assumed for every component. This does of course not represent the reality, but it is used only for comparison and as it is applied to each concept it is a fair assumption. A range for the scoring was defined in Table 11.4, and the scores per concept are given in Table 11.5.

The drone flight performance is also affected by the location of the battery. When there is enough space on top of the frame, it is always preferred to place the battery on top of the frame. Then the center of mass lies closer to the center of thrust located on the propeller level plane, allowing for a higher thrust efficiency and a sharper response. Since all concepts have their battery located on top of the frame, this parameter was not taken into account as a criteria [39]. There is also a difference between pusher and puller propellers, where a pusher propeller has a slightly higher propulsive efficiency compared the puller propeller, approximately 3 % higher [10]. Therefore, a + was given to the sensors concept, which is the only concept that uses push propellers at this moment. However, since this is a design choice that still needs to be evaluated in the detailed design, the criteria weight was set to zero.

The same holds for the fans, where ducted fans have a higher propulsive efficiency as they reduce vortices. However, this is an aspect that has to be re-evaluated in the detailed design for the winning concept, thus the weight was set to zero as well.

Lastly, the flight performance criterion is dependent on the shape of the aerodynamic shell, that smoothens the airflow reducing the aerodynamic drag. However, this parameter will be optimised in the detailed design phase for the selected concept, and was therefore not evaluated yet.

The weights of all five criteria were set as follows. First all weights were evenly distributed, every criteria got a weight of 20 %. Then it was realised that the mass moment of inertia and wheelbase are somewhat connected, as a drone with a larger size both has a larger wheelbase and a larger mass moment of inertia. For this reason the weight of the wheelbase criterion was lowered by 5 %, and the weight of the frame type was increased by this amount. This leads to the criteria weights and scores as defined in table Table 11.5. Then the scores per criterion were defined, and the total score was computed by multiplying all scores with the weights. The pluses and minuses were also considered in the rounding of the scores. The durability and sensors concept both had a plus on ducted fans and push propellers respectively. Relative to the lightweight quad concept, which had a higher average score, it was then decided that it would be fair to have all concepts the same rounded flight performance score.

### 11.1.3. Sustainability (Sust)

The following section explains how the three sustainability criteria from Chapter 10.2 are scored. A set of three sustainability criteria and their weights have been established, and each concept is graded based on these in Table 11.7. The concept characteristics used to perform the trade-off are shown in Table 11.6.

Table 11.4: Flight performance score definition.

| Score | Frame Type | Wheelbase [mm] | MMOI [kg/m$^2$] · $10^3$ |
|---|---|---|---|
| **5** | Y | < 220 | < 1 |
| **4** | DC, X, + | 220 - 250 | 1 - 1.5 |
| **3** | HX | 250 - 280 | 1.5 - 2 |
| **2** | H | 280 - 310 | 2 - 2.5 |
| **1** | n.a. | > 310 | > 2.5 |

Table 11.5: Flight performance trade-off table.

| | COMP _C1 | | DUR _C2 | | SENS _C3 | | LWQ_C4 | | LWT_C5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Frame type (25%) | HX | 3 | DC | 4 | DC | 4 | DC | 4 | Y | 5 |
| Wheelbase [mm] (15%) | 361 | 1 | 245 | 4 | 246 | 4 | 248 | 4 | 241 | 4 |
| MMOI xx (roll) [km$^2$] $*10^{-3}$ (20%) | 3.10 | 1 | 1.10 | 4 | 1.17 | 4 | 0.73 | 5 | 0.55 | 5 |
| MMOI yy (pitch) [kg/m$^2$] $*10^{-3}$ (20%) | 3.29 | 1 | 1.01 | 4 | 0.89 | 5 | 0.68 | 5 | 0.65 | 5 |
| MMOI zz (yaw) [kg/m$^2$] $*10^{-3}$ (20%) | 5.40 | 1 | 1.71 | 3 | 1.47 | 4 | 1.14 | 4 | 0.83 | 5 |
| Propeller Configuration (0%) | Pull | - | Pull | - | Push | + | Pull | - | Pull | - |
| Fans (0%) | Non-ducted | - | Ducted | + | Non-ducted | - | Non-ducted | - | Non-ducted | - |
| **Total** | **1.5** | | **3.8** | | **4.2** | | **4.4** | | **4.9** | |

Table 11.6: Estimated current and volume of each concept to be used for sustainability trade-off scoring.

| | COMP_C1 | DUR_C2 | SENS_C3 | LWQ_C4 | LWT_C5 |
|---|---|---|---|---|---|
| **Current (A)** | 197 | 92 | 111 | 69 | 87 |
| **Volume (· $10^6$ mm$^3$)** | 1.17 | 0.38 | 0.48 | 0.31 | 0.31 |

Table 11.7: Sustainability trade-off of the five concepts based on three sustainability criteria.

| | COMP_C1 | DUR_C2 | SENS_C3 | LWQ_C4 | LWT_C5 |
|---|---|---|---|---|---|
| Power (40%) | 1 | 3 | 3 | 4 | 4 |
| Volume (20%) | 1 | 4 | 4 | 4 | 4 |
| Durability (40%) | 1 | 5 | 2 | 3 | 2 |
| **Total** | **1.0** | **4.0** | **2.8** | **3.6** | **3.2** |

The power criterion is scored based on current draw of the battery, as current is proportional to the power. A current draw of less than 50A corresponds to the highest score of 5; while less than 200A corresponds to the lowest score of 1. Above 200A results in a score of 0. The scoring boundaries increase in a linear fashion from 50A to 200A. The volume criterion is based on the total volume of the drone as estimated from the chosen components used for each concept. A high score of 5 is obtained by having a volume less than $0.25 \cdot 10^6$ mm$^3$, with the score decreasing as the volume increases linearly to $1.25 \cdot 10^6$ mm$^3$. The durability criterion is based on the following qualitative reasoning. COMP_C1 was scored very low as the drone's high mass (high inertia) combined with lack of protective structure would make it fragile. However, it is not given a score of zero, as this problem can be solved by adding extra protection. DUR_C2 is given a high score, as it includes a very protective structure. SENS_C3 is given a fairly low score as it has multiple cameras which can get damaged and it has a relatively high weight, but not as high as COMP_C1. LWQ_C4 is given an average score as it is fairly lightweight, however doesn't contain a very protective structure. LWT_C5 is given a low score, as it is similar to the lightweight quad, however it contains a rotatable arm, which adds extra fragility to the design. The resulting sustainability scores are used in the final trade-off of the concepts.

### 11.1.4. Risk

When looking at the risks identified in Chapter 9, it is clear that the highest risk involves the damage to the drone after crashing into a gate or the ground. For now these risk are evaluated as structural failure (including propellers) and electrical failure on impact. Not only are the risk it brings high, it also is hard to mitigate and therefore it is rather avoided. Since the risks involving the electrical components is considerably higher than those of the structural components, the weight given to electrical risk is 50% and the weight for the structural risk is 30%. Besides those two risks there is also a risk involving the reliability of the estimations on which the concept designs are made, this will be given a weight of 20%. Every concept is scored for each risk mentioned, relatively to each other, and can be foun in Table 11.8. The higher the score the less risky a design will be.

Table 11.8: Technical risk assessment of each concept.

| | COMP_C1 | DUR_C2 | SENS_C3 | LWQ_C4 | LWT_C5 |
|---|---|---|---|---|---|
| Structural (30%) | 2 | 4 | 3 | 3 | 0 |
| Electrical (50%) | 1 | 5 | 1 | 3 | 1 |
| Design Method Reliability (20%) | 3 | 3 | 2 | 2 | 1 |
| **Total** | **1.7** | **4.3** | **1.8** | **2.8** | **0.7** |

**COMP_C1**
The high weight means that the impact forces during a crash will be very high and there is not a lot of room in the mass budget to fully protect the drone. This brings great risk when looking at the structural and electrical failure, especially when the electronics are this expensive. The estimations done for this concept are pretty reliable, due to the high availability of information.

**DUR_C2**
The durability concept is based on impact resistance and protecting the vulnerable parts of the drone. The extra weight available for protection of the electronics is a big factor in the relative low risk. Also the design factors influence this concept the least.

**SENS_C3**
The sensor concept depends on the relative high amount of sensors. This makes the electrical failure highly probable and therefore also the risk. The fact that the cameras are at a vulnerable place in the structure just increases this risk. The structure and the estimation reliability score average.

**LWQ_C4**
This concept is the lightest weight quadrotor and is basically a balanced concept. So the risks that it brings are also quite balanced. Due to the low weight the impact forces in a crash will be relatively low, but it is not as heavily protected as the durability concept. Therefore the risk involving this concept will be slightly higher than the risk of the durability concept.

**LWT_C5**
The biggest risk concerning the trirotor concept comes forth from the tail-arm. Due to the servo motor needed to control the drone, the tail-arm will be a very weak point and vulnerable to damage when a crash occurs. Therefore the structural risk is extremely high and it is extremely hard to mitigate this risk, so it is better to avoid. Since the structure is fragile the protection for the electronics is lower, especially electronics related to the tail-arm. Also, this concept is most heavily influenced by the design factors coming from the estimation reliability.

### 11.1.5. Mass

The mass of each concept has an influence on a range of design aspects. Heavier designs can be harder to control and are usually larger in size, increasing the risk of crashing into a gate. Furthermore, larger size means more necessary material for manufacturing, which decreases the level of design sustainability and increases cost. So even though the concept mass is taken into account when designing the propulsion system such that each concept has a similar thrust over weight ratio, concept mass should still be kept as low as possible. More importantly, it is a customer requirement that mass should stay below 1kg. Going over this number by a few grams is not considered a problem by the customer, as the focus should be on meeting flight performance requirements first. Nevertheless, mass should still be considered in the trade-off with a small weight.

The mass criterion is scored quantitatively on a linear scale, where the lightest concept, which in this case is LWT_C5 weighing 813g, receives a score of 5 and the other concepts receive a score according to the following relation: $\frac{813}{mass} \cdot 5$. However, concepts with masses exceeding 1kg are scored differently. If the mass exceeds 1kg by up to 10%, the concept receives a marginal score of 2, as it only exceeds the requirement by a small amount, which could be corrected in the final design phase or renegotiated with the customer. Furthermore, exceeding the requirement of 1kg by more than 10% results automatically in an unacceptable score of 0. The mass requirement is currently a hard customer requirement that has not been renegotiated and this much of a mass increase cannot be corrected for without drastically changing the entire design. Based on this discussed grading method, the concepts are scored accordingly in Table 11.9. It should be noted that the scores are rounded off to one decimal place.

Table 11.9: Concept masses and trade-off scores.

| | COMP_C1 | DUR_C2 | SENS_C3 | LWQ_C4 | LWT_C5 |
|---|---|---|---|---|---|
| **Mass [g]** | 1631 | 978 | 1066 | 838 | 813 |
| **Score** | 0.0 | 4.2 | 2.0 | 4.9 | 5.0 |

### 11.1.6. Cost

The cost of each concept is evaluated based on a quantitative analysis. Here, the cost per component is estimated based on reference open-source parts on the internet. Then all parts costs are summed up, after which the total cost per drone is defined. This criterion is given a relative low weight, since all concepts meet the requirement of having a total cost of €2500 so this would not be the limiting factor. Nevertheless, the weight estimations at this point are not precise, not all process-related costs can be estimated, like the cost of renting tools, and most importantly, the designs might change significantly during the final design phase. Thus, some margin should be left such that the final design does not go over the budget.

The cost criterion is scored quantitatively on a linear scale, where the cheapest concept, which in this case is LWT_C5 with a cost of €1103, receives a score of 5 and the other concepts receive a score according to the following relation: $\frac{1103}{cost} \cdot 5$. The estimated concept costs and the resulting trade-off scores are given in Table 11.10. It should be noted that the scores are rounded off to one decimal place.

Table 11.10: Concept costs and trade-off scores.

| | COMP_C1 | DUR_C2 | SENS_C3 | LWQ_C4 | LWT_C5 |
|---|---|---|---|---|---|
| **Cost [€]** | 1667 | 1123 | 1270 | 1120 | 1103 |
| **Score** | 3.3 | 4.9 | 4.3 | 4.9 | 5.0 |

## 11.2. Trade-off of Concepts

In order to properly compare the different concepts, a trade-off table has been made, as can be seen in Table 11.12. This table shows the various design concepts on the vertical axis, and the most important criteria to which they will be judged on the horizontal axis. Criteria with a higher weight have a proportionally higher width. Each cell contains a number ranging from 0 to 5 as well as a color. Those indicate how well the concept scores on a criterion. A legend for the colors can be seen in Table 11.11. The scores given in Sections 11.1.1 - 11.1.6 are rounded to the nearest integer, as many of them are highly uncertain and the number of significant figures should be reduced to a minimum. However when rounding to full numbers, too much data is lost. Furthermore, it should be noted that scores below 1 have been set to 0, such that unacceptable scores do not add to the final score. The total score was computed by multiplying the criterion score with each criterion weight, and summing all up. This score is given in the most right column of the table.

Table 11.11: Legend for the Trade-off Table.

| Score Range | Quality | Color |
|---|---|---|
| $\geq 4.5$ | Excellent | Green |
| $2.5 \leq x < 4.5$ | Good | Blue |
| $1 \leq x < 2.5$ | Marginal | Yellow |
| 0 | Unacceptable | Red |

Table 11.12: Trade-off table.

| | ANP | FP | Risk | Sust | Mass | Cost | Score |
|---|---|---|---|---|---|---|---|
| **COMP_C1** | 4.2 | 1.5 | 2.2 | 1.0 | 0.0 | 3.3 | 2.38 |
| **DUR_C2** | 3.2 | 3.8 | 3.8 | 4.0 | 4.2 | 4.9 | 3.81 |
| **SENS_C3** | 4.0 | 4.2 | 2.0 | 2.8 | 2.0 | 4.3 | 3.30 |
| **LWQ_C4** | 3.2 | 4.4 | 2.8 | 3.6 | 4.9 | 4.9 | 3.66 |
| **LWT_C5** | 3.2 | 4.9 | 0 .0 | 3.2 | 5.0 | 5.0 | 3.17 |

The idea behind giving a score of 0 in any of the criteria is that this given design aspect is far from the customer requirements, and that it is not possible to meet those without significantly changing the entire design. Therefore, if any concept received an unacceptable score in any of the criteria, it was removed from the trade-off. Furthermore, marginal scores indicate that the design does not meet a requirement in a certain aspect by a small margin, which can be resolved in the final design phase without changing the design significantly. Thus, a yellow score means that the design does not meet the requirements yet but will likely meet them after a small redesign. Concepts with one or more marginal scores can thus be still included in the trade-off.

Looking at Table 11.12, concepts COMP_C1 and LWT_C5 were removed from the next phase of the trade-off as they received an unacceptable score in mass and risk respectively. Concept COMP_C1 has a significantly higher mass than acceptable taking into account the customer requirement, which has not been renegotiated and should thus still be met. Concept LWT_C5 is a trirotor with a very fragile gimbal at one of the rotors. This is likely to break easily upon impact, a behavior that is highly undesirable for racing drones crashing into gates usually. The remaining three concepts have scores laying close to each other. Those scores highly depend on the trade-method and the weights. Therefore, the true winning concepts was chosen after performing a sensitivity analysis.

## 11.3. Sensitivity Analysis

Performing a fair and meaningful trade-off is a difficult task, especially when concepts receive similar total scores. As can be seen in Table 11.12, the scores of concepts DUR_C2 and LWQ_C4 differ by only 0.15, which is not a sufficient margin to pick the winning concept. Therefore, a so-called sensitivity analysis was performed, which allows to determine if the winning concept would still win if the criteria weights were slightly different. It should be noted that concepts COMP_C1 and LWT_C5 have been removed and will not be assessed in this section.

The approach is to either add or subtract a certain percentage from one criterion, and evenly distribute it among the others. An example would be to add 15% to ANP, by taking 3% off every other criterion. Such approach is repeated 12 times, where each time, the extra weight added or subtracted from a certain criterion is adjusted such that the resulting weight does not differ significantly from the initial one. For example, as already mentioned, the autonomous flight performance is of utmost importance but it is debatable whether it should have a score of 20% or even 50%. A significant amount of weight can be then added or subtracted from ANP in sensitivity analysis, without affecting the expected criterion importance. However, the same amount of weight could not be added to the cost criterion for example, as it would make it go from a small importance of 5% to a large importance of 20%. Therefore, the amount of weight that is added or subtracted to a criterion per iteration depends on the initial weight of this criterion. This can be seen in Table 11.13, where the initially most relevant criteria are altered by $\pm$ 15%, the initially less relevant criteria are altered by $\pm$ 10%, and the initially least important criterion is altered by $\pm$ 5%.

Table 11.13: The criteria weights used in the sensitivity analysis.

| | **ANP** | **FP** | **Risk** | **Sust** | **Mass** | **Cost** |
|---|---|---|---|---|---|---|
| **Old weights [%]** | 35 | 20 | 20 | 10 | 10 | 5 |
| **ANP + 15% [%]** | 50 | 17 | 17 | 7 | 7 | 2 |
| **ANP - 15% [%]** | 20 | 23 | 23 | 13 | 13 | 8 |
| **FP + 15% [%]** | 32 | 35 | 17 | 7 | 7 | 2 |
| **FP - 15% [%]** | 38 | 5 | 23 | 13 | 13 | 8 |
| **Risk + 15% [%]** | 32 | 17 | 35 | 7 | 7 | 2 |
| **Risk - 15% [%]** | 38 | 23 | 5 | 13 | 13 | 8 |
| **Sust + 10% [%]** | 33 | 18 | 18 | 2 | 8 | 3 |
| **Sust - 10% [%]** | 37 | 22 | 22 | 0 | 12 | 7 |
| **Mass + 10% [%]** | 33 | 18 | 18 | 8 | 20 | 3 |
| **Mass - 10% [%]** | 37 | 22 | 22 | 12 | 0 | 7 |
| **Cost + 5% [%]** | 34 | 19 | 19 | 9 | 9 | 10 |
| **Cost - 5% [%]** | 36 | 21 | 21 | 11 | 11 | 0 |

The trade-off scores using all twelve weight distributions are shown in Table 11.14. Different weight distributions result in different winners, marked green, however, one concept wins five out of nine times, which is the durability concept.

Table 11.14: Sensitivity analysis for the trade-off. Weights used to calculate each score are specified in Table 11.13. Green cells signify the winning concept per weight distribution.

| | **Old score** | **ANP +15%** | **ANP -15%** | **FP +15%** | **FP -15%** | **Risk +15%** | **Risk -15%** | **Sust +10%** | **Sust -10%** | **Mass +10%** | **Mass -10%** | **Cost +5%** | **Cost -5%** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **DUR_C2** | 3.81 | 3.65 | 3.96 | 3.76 | 3.85 | 3.85 | 3.76 | 3.80 | 3.81 | 3.82 | 3.79 | 3.86 | 3.76 |
| **SENS_C3** | 3.30 | 3.44 | 3.15 | 3.48 | 3.11 | 3.05 | 3.54 | 3.25 | 3.34 | 3.15 | 3.44 | 3.36 | 3.23 |
| **LWQ_C4** | 3.66 | 3.52 | 3.79 | 3.73 | 3.58 | 3.45 | 3.87 | 3.61 | 3.70 | 3.77 | 3.54 | 3.71 | 3.60 |

Looking at Table 11.14, the DUR_C2 concept is the winning concept in twelve out of the thirteen iterations of the sensitivity analysis. It can be thus concluded that the durability concept DUR_C2 is the overall trade-off winner and it will be further designed in the detailed design phase. This is also in line with the team's and the customer's expectations. As long as a concept keeps a sufficient autonomous navigation and flight performance and it does not exceed the required mass, adding extra protection is highly advantageous as it decreases the down time during flying, and decreases the cost of fixing and replacing components. Less time and money spent of fixing a drone means more time to test the drone and the algorithms, which is crucial for AI advancement. Moreover, especially the electrical components in a drone are prone to failures and are very expensive to replace. Losing the flight computer would mean a cost of hundreds of euros and thus, it should be avoided as much as possible. If the electronics are well protected, a user will only have to invest in good components once and will not have to worry that a broken part can limit their testing abilities.

# 12
# Operations Logistic Concept

Having a well designed drone is useless without knowing how to acquire, operate or maintain it. Therefor a operations and logistics flow diagram was made, as can be seen in Figure 12.1. This shows the flow of all operations from the begin of life to the end of life of the drone, specifying operations, repairs, support, maintenance, logistics and disposal aspects of the drone. Each of these aspects is further divided into sub-elements as shown. Each aspect and its sub-elements is elaborated on in sections 12.1, 12.2, 12.3, 12.4, 12.5 and 12.6.

## 12.1. Operations

Operations are all actions the drone performs during normal use. These are the functions for which the drone is designed. They are specified in the following list:

- **O1: Initiate drone**: This is the entire string of actions performed before the drone starts flying. This thus entails connecting to a power source, loading and compiling code, connecting the battery and is finalized by booting the entire drone.
- **O2: Testing/learning**: This is the process where the artificial intelligence software of the drone is being trained by testing and learning procedures. The goal it to optimize the algorithm to perform well in the race.
- **O3: Racing**: This is the action where the result of the testing phase is used in a competition against other drones. The drone will fly using the trained software to achieve the fastest time.
- **O4: Shutdown**: This is the phase after the testing or racing. The drone needs to safely shut down while all relevant data is saved for evaluation and later use.
- **O5: Coupling controller and drone**: This is an action done before racing and optionally for testing. Here the controller is linked to the drone and a reliable connection is ensured.
- **O6: Controller capabilities**: The controller needs to be able to perform a number of different tasks. First of all it needs to be able to switch the drone to manual mode. In this manual mode the drone is piloted by a human instead of the AI computer. This means that second of all the controller must enable the human to control the drone in case of this manual mode. Thirdly the controller needs to be able to fully and reliably switch off the drone in case of an emergency.
- **O7: Safety mode**: This is a mode the drone enters in case a malfunction or crash is detected. The drone slows down, protects vulnerable systems and tries to land safely.

## 12.2. Repairs

Drones consist of mechanical parts that will need repairs from time to time. On top of that, they are prone to crashing and therefore having a guide on how to perform repairs is necessary.

- **R1: Repairs guide**: There will be a guide available that users can access, either online or as a printed version, that will specify how to perform a number of often occurring repairs.
- **R1.1: Propeller repairs**: The most often occurring repair that needs to be performed is replacing the propeller after it breaks due to a crash. This process should be easy and quick.
- **R1.2: Motor repairs**: The motor will need repairing or replacement after a certain flight time due to it being a mechanical part that experiences wear and tear.
- **R1.3: Computer repairs**: A sufficiently bad impact can cause the computer to break or separate from the motherboard. The repair guide will include information on how to inspect for damage and repair/replace the computer.
- **R1.4: Sensor repairs**: Sensors and other electronic equipment, just like the computer, can break due to hard impacts. There should be a description on how to replace sensors.

- **R1.5: Structural repairs**: An impact can cause the drone frame or outer shell to form cracks or in the worst case, break completely. The repair guide should specify in what case it is possible to perform repairs to the structure and how it should be done. It should also specify how to replace the whole structure and when this is necessary.
- **R2: Tooling for repair**: Certain repairs will need certain tools. There should be a list of all discussed repairs and the specific tooling needed to do this. There will be a description and/or link that allows users to obtain these tools.

## 12.3. Support

Supports consists of all actions taken by the designers and distributors of the drone to communicate with the users about the use and manufacturing of the drone.

- **S1: Design specification**: This is a document which needs to be provided and distributed by the designers. It should specify the performance and specifications of the drone.
- **S2: Construction guide**: This document needs to be provided and distributed by the designers for all persons who want to manufacture the drone themselves. It shall have the following three parts in there.
- **S2.1: Models for part manufacturing**: All parts that need to milled, 3D printed, cut or otherwise manufactured need to have detailed computer models so these actions can be easily performed. This enables to user to quickly and without any alterations manufacture parts of the drone.
- **S2.2: Tools and settings for part manufacturing**: The construction guide should also mention all tools needed for manufacturing, and the settings and capabilities these tools should have. This ensures that users can precisely and accurately reproduce the design.
- **S2.3: Construction process**: Lastly the guide should mention all steps the user needs to take to create the drone. This means describing in detail all the parts needed, the manufacturing processes for parts and the assembly process to combine these parts into a functioning drone.
- **S3: Supplier information**: A document should be provided and distributed which lists all suppliers for the required materials and parts. This ensure good reproducibility of the drone since the exact same parts are used. This can be split into the following two parts:
- **S3.1: Part suppliers information**: This gives information on parts which need to be bought. The suppliers should be able to ship worldwide, should have a large stock and should have a good reputation.
- **S3.2: Material supplier information**: This gives information on what material needs to be bought with what specifications. Also suppliers should be listed. Again, these suppliers should ship worldwide, should have a large stock and should have a good reputation.
- **S4: Support for user questions**: A communication channel should be setup where the users can ask questions and give feedback to the designers. This gives the ability for user to ask for clarification when they run into problems and for the designers to optimize the design based on problems encountered by users.
- **S5: Process and design updates**: A communication channel should be in place where the designers can update the design and communicate this to users after the initial release. This allows for a continual improvement of the design.
- **S6: User manual**: A document should be provided and distributed that explains the workings of the drone and how to properly initiate and handle the drone. It shall include a summary of all drone operations and logistics. This ensures users can easily, quickly and safely start using the drone.

## 12.4. Maintenance

All mechanical devices need proper maintenance to ensure their performance is not compromised over time. Everything that the user needs to know with regard to maintenance will be included in this section.

- **M1: Maintenance manual**: This manual will contain a detailed overview of all steps necessary for maintaining the drone

- **M1.1: Sensor calibration**: A systematic approach to (re)calibrate the sensors to ensure that all users experience good sensor accuracy.
- **M1.2: Battery maintenance**: A LiPo rechargeable battery will quickly degrade and lose performance if not treated properly. It should never be stored in locations with excessive access to sunlight. It should also not be stored in too high or too low temperatures. A detailed explanation of how the battery should be treated during and after usage will be included in the maintenance manual.
- **M1.3: Cleaning**: Excessive dirt and/or moisture in electrical and mechanical components can lead to damage. The drone should be cleaned properly so this damage is prevented.
- **M1.4: Inspect for structural damage** Structural failure can be caused by repeated use of the drone. This can sometimes be prevented by applying a good inspection method, which enables the users to make structural repairs (R1.5) if necessary.

## 12.5. Logistics

Operating an AI capable drone does not solely consist of the drone itself, but requires external equipment to operate.

- **L1: Drone storage**: The drone will need to be stored when not in use and it also needs to be possible to transport it. Therefore a storage solution for the drone is recommended. This can be a case, container or other storage options.
- **L2: Drone (dis)assembly**: When transporting the drone, storage in small space is desired. This could be achieved by having a drone that can be disassembled. Also for repairs, disassembly is sometimes required. Instructions on how to disassemble and reassemble the drone are necessary.
- **L3: Charging stations**: In order to ensure that the drone always has enough power, charging stations should be available. These need to be used to recharge batteries which have been used by the drone so there is always a charged battery available.
- **L4: Ground equipment**: When the drone is in operation, users should be able to monitor its performance. Therefore, a ground station is required which receives and processes telemetry. The ground station also is needed for evaluating, compiling and uploading the code of the drone.

## 12.6. Disposal

At end of life, the drone needs to be properly disposed of. Therefor instructions need to be provided which detail how to handle this.

- **D1: Recycling manual**: The recycling manual shall provide detailed information on the steps needed to be taken at end of life to properly dispose of the drone.
- **D1.1: Recycling processes**: A detailed description shall be given of how to disassemble the drone, separate all parts and components and how to recycle each of these.
- **D1.2: Disposal sites**: A detailed list of locations shall be given where the drone parts need to be brought to be processed and recycled.
- **D1.3: Re-use possibilities**: An explanation shall be given on which parts of the drone can be reused for other purposes and how this can most efficiently be achieved.

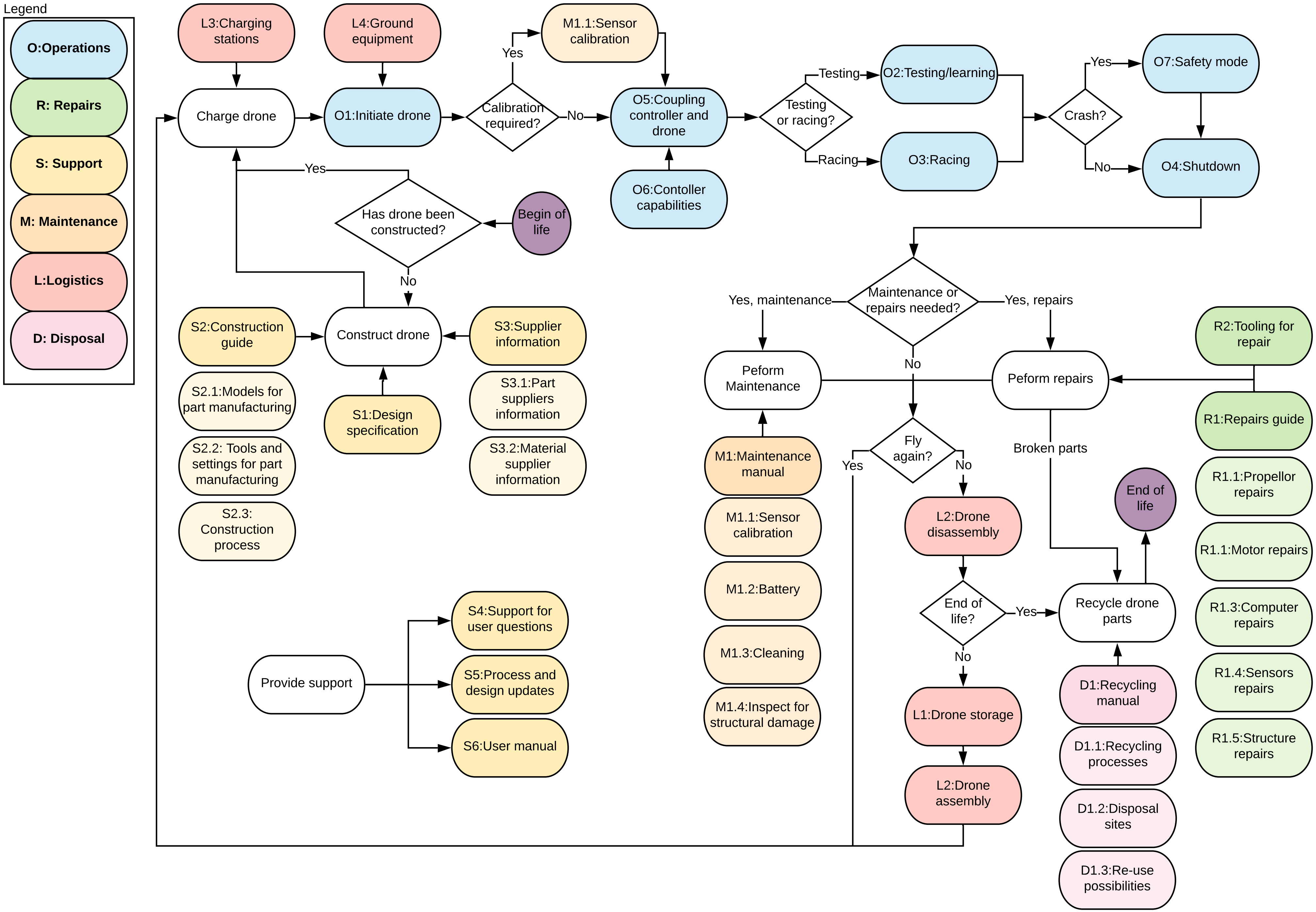



Figure 12.1: Operations and logistics flow Diagram

# 13 Conclusion

The objective of the midterm report is to provide a basis to start working from for the final report. One of the main goals is therefore to decide upon a concept that will be worked out in detail during the final phase of DSE. This report will also finalize the requirements and define preliminary subsystem relations, amongst other things.

Each group member has been assigned to a managerial and technical task in order to streamline work. A work flow diagram, work breakdown structure and Gantt chart have been made in order to keep a good overview of all tasks that need to be performed for the final report.

In order to make sure that proposed concepts will actually meet the design goals, a list of requirements is set up. Part of that list is directly determined from the customer requirements, but most requirements are set up by the group to ensure that there are no loopholes and the final design will meet the expectations of the customer. Three key requirements have been found to be killer requirements. This has lead to remove the maximum speed requirement such that the next limiting requirement demands the drone to have a thrust to weight ratio of at least 4. The flight time is being compromised to 1 minute of flight time and 2 minutes of standby time. The mass requirement of 1 kg is the third critical requirement, but left unchanged.

A design option tree was constructed with the goal of addressing all design possibilities, without discarding seemingly unfeasible options. All unfeasible options were removed later, and the advantages and disadvantages of all remaining options is discussed.

Five concepts were then proposed. The list of requirements and mission need statement was kept in mind to ensure that each concept would be a potentially successfully design. The first concept focuses on having an abundance of computational power allowing users to run computationally heavy algorithms. The second concept is built around having a durable drone, the advantage of which is having less downtime due to necessary repairs after crashes. This allows for more training time of the AI algorithms. The third concept is proposed with an abundance of sensor data in mind. More sensor data would allow for more flexibility in how the AI is programmed and therefore possibly better performance. Preliminary characteristics of these three concepts had been worked out which concluded that none of them could meet the 1kg weight requirement. Following this, two more concepts were proposed, namely a lightweight quadrotor and a lightweight trirotor. Both concepts are designed so they still meet the flight and computational performance requirements, but in a lighter package. All concepts have been worked out in more detail to have a preliminary weight, size and performance estimate. Results were subjected to verification and validation. On top of that more verification and validation procedures have been proposed that will be applied to later design stages.

An analysis has been performed to minimize risk in any stage of the design. For now, a risk mitigation strategy has been worked out and a method has been proposed to evaluate proposed concepts based on risk. Sustainability is another parameter in the trade off. Three sustainability criterion are proposed, each with different weights. Seven more sustainability criterion are mentioned that will be used in future sustainability assessment.

A winning concept was then picked based on a trade-off, which includes six weighted criterion. These include autonomous navigation performance (35%), flight performance (25%), risk (15%), sustainability (10%), mass (10%) and cost (5%). Each concept was graded from 1 (unacceptable) to 5 (Excellent) on each of these criterion. Based on all values and their respective weights, the concept 1 to 5 had a score of 2.85, 3.7, 3.55, 3.65, 3.35 respectively. Concept 1 has a clearly lower score and is discarded. Concept 5 has an unacceptable risk and therefore is also discarded. The three remaining concepts are subjected to a sensitivity analysis to determine the final winning concept. This turned out to be the DUR_C2 concept.

# Bibliography


[1] Airbot omninxt f7 flight controller. URL https://www.getfpv.com/airbot-omninxt-f7-flight-controller.html. Retrieved May 19, 2020.

[2] Betaflight f7 flight controller. URL https://www.getfpv.com/betaflight-f7-flight-controller.html. Retrieved May 19, 2020.

[3] Diatone mamba f722 mini 20x20 flight controller, . URL https://www.getfpv.com/diatone-mamba-f722-mini-20x20-flight-controller.html. Retrieved May 19, 2020.

[4] Diatone mamba f722s flight controller, . URL https://www.getfpv.com/diatone-mamba-f722s-flight-controller.html. Retrieved May 19, 2020.

[5] Heli-nation talon f7 v2 20x20 flight controller. URL https://www.getfpv.com/heli-nation-talon-f7-v2-20x20-flight-controller.html. Retrieved May 19, 2020.

[6] Lumenier lux mini f7 flight controller. URL https://www.getfpv.com/lumenier-lux-mini-f7-flight-controller.html. Retrieved May 19, 2020.

[7] Matek f722-mini 20x20 flight controller. URL https://www.getfpv.com/matek-f722-mini-20x20-flight-controller.html. Retrieved May 19, 2020.

[8] alibaba.com. China cheap factory price balsa wood. URL https://www.alibaba.com/product-detail/China-cheap-factory-price-balsa-wood_60723412652.html?spm=a2700.galleryofferlist.0.0.7143532dGQlFGy&s=p. Retrieved May 15, 2020.

[9] AmazonBasics. Amazonbasics 3d-drucker-filament. URL https://www.amazon.de/AmazonBasics-3D-Drucker-Filament-PETG-Kunststoff-durchscheinendes-1-kg-Spule/dp/B07T616NYT/ref=sr_1_1_sspa?__mk_de_DE=%C3%85M%C3%85%C5%BD%C3%95%C3%91&dchild=1&keywords=pla&qid=1589528080&sr=8-1-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUEyVEc5WExNRzhXVUwxJmVuY3J5cHRlZElkPUEwODM4NzEyUDMzMFk=. Retrieved May 15, 2020.

[10] P. Hendrick J. De Schutter B. Theys, G. Dimitriadis. Influence of propeller configuration on propulsion system efficiency of multi-rotor unmanned aerial vehicles. URL https://core.ac.uk/download/pdf/80797839.pdf. Retrieved May 18, 2020.

[11] D. Borstlap, F. Dam, N. Duursma, W. Dziarnowska, V. Guillet, Y. van Haaren, D. Huang, M. van Huffelen, J. Riessbacher, G. Strunck, and R. Vos. Design synthesis exercise: Baseline report. May 2020.

[12] D. Borstlap, F. Dam, N. Duursma, W. Dziarnowska, V. Guillet, Y. van Haaren, D. Huang, M. van Huffelen, J. Riessbacher, G. Strunck, and R. Vos. Design synthesis exercise: Project plan. April 2020.

[13] e-con systems. STEEReoCAM - 2MP Stereo Camera for NVIDIA Jetson Nano/AGX Xavier/TX2, . URL https://www.e-consystems.com/nvidia-cameras/jetson-agx-xavier-cameras/stereo-camera.asp. Retrieved May 20, 2020.

[14] e-con systems. e-cam130_cuxvr - multiple camera board for nvidia jetson agx xavier, . URL https://www.e-consystems.com/nvidia-cameras/jetson-agx-xavier-cameras/four-synchronized-4k-cameras.asp. Retrieved May 20, 2020.

[15] e-con systems. e-cam50_cunano - 5.0 mp nvidia jetson nano camera, . URL https://www.e-consystems.com/nvidia-cameras/jetson-nano-cameras/5mp-mipi-nano-camera.asp. Retrieved May 20, 2020.

[16] Jim Floor. Getting a grip on the ultimaker 2 tensile strength of 3d printed pla: A systematic investigation. 2015.

[17] GetFPV. All about multirotor drone fpv frames. URL https://www.getfpv.com/learn/new-to-fpv/all-about-multirotor-fpv-drone-frame/. Retrieved May 15, 2020.

[18] getfpv.com. Zeez design rgb led strip (4 pcs). URL https://www.getfpv.com/zeez-design-rgb-led-strip-4-pcs.html. Retrieved May 7, 2020.

[19] Eberhard Gill. Lecture slides: Verification and validation for the attitude and orbit control system, February 2020. AE3211-I: Systems Engineering and Aerospace Design.

[20] R.J. Hamann and M.J.L. van Tooren. Lecture notes: Systems engineering & technical management techniques part 1. September 2006.

[21] Ryan Harell. Miniquad test bench. URL https://www.miniquadtestbench.com/. Retrieved May 11, 2020.

[22] B. Ganapathisubramani J. Nedi and J. C. Vassilicos. Drag and near wake characteristics of flat plates normal to the flow with fractal edge geometries.

[23] GG Jingyan. High pure titanium carbide tic granule/power /plate /tube /sputtering target. URL https://www.alibaba.com/product-detail/High-pure-Titanium-Carbide-TiC-granule_60789260086.html?spm=a2700.galleryofferlist.0.0.373a3b68MTDsrX&bypass=true. Retrieved May 18, 2020.

[24] V Kadamatt. Tricopter vs quadcopter vs hexacopter : A comparison. URL http://www.droneybee.com/tricopter-vs-quadcopter-vs-hexacopter/. Retrieved May 18, 2020.

[25] KKmoon. Kkmoon 3k carbonfaserplatten. URL https://smile.amazon.de/KKmoon-Carbonfaserplatten-Carbonplatte-Kohlefaserplatte-gl%C3%A4nzend/dp/B07TD99S3V/ref=pd_sbs_201_2/259-7528502-4145615?_encoding=UTF8&pd_rd_i=B07TD99S3V&pd_rd_r=31ceea3e-ba32-4421-bc6c-183ed295f413&pd_rd_w=l4qCx&pd_rd_wg=L4uOS&pf_rd_p=42bf0ad8-ce6f-4127-a2f0-106727020a41&pf_rd_r=55QX1WNQAFSSV9AFNS9X&refRID=55QX1WNQAFSSV9AFNS9X&th=1. Retrieved May 15, 2020.

[26] S. Li, E. van der Horst, P. Duernay, C. de Wagter, and G.C.H.E de Croon. Visual model-predictive localization for computationally efficient autonomous racing of a 72-gram drone. 2019. arXiv:1905.10110v2 [cs.RO].

[27] Jenny List. The tri rotor drone: Why has it been overlooked? URL https://hackaday.com/2017/05/26/the-tri-rotor-drone-why-has-it-been-overlooked/. Retrieved May 18, 2020.

[28] Performance Composites Ltd. Mechanical properties of carbon fibre composite materials, fibre / epoxy resin (120°c cure). URL http://www.performance-composites.com/carbonfibre/mechanicalproperties_2.asp. Retrieved May 18, 2020.

[29] Softwood lumber. Birch wood lumber. URL https://www.alibaba.com/product-detail/Birch-Wood-lumber_62018614432.html?spm=a2700.galleryofferlist.0.0.36411e36UF8k7u&bypass=true. Retrieved May 18, 2020.

[30] MatWeb. Overview of materials for acrylonitrile butadiene styrene (abs), extruded, . URL http://www.matweb.com/search/DataSheet.aspx?MatGUID=3a8afcddac864d4b8f58d40570d2e5aa. Retrieved May 18, 2020.

[31] MatWeb. European birch wood, . URL http://www.matweb.com/search/DataSheet.aspx?MatGUID=03ffed472a044b2d9d4bf8b8636f7768. Retrieved May 18, 2020.

[32] MatWeb. Aisi 9260 steel, . URL http://www.matweb.com/search/DataSheet.aspx?MatGUID=5fea5e82829a40218c5a864bdc865422. Retrieved May 18, 2020.

[33] MatWeb. Titanium carbide, tic, . URL http://www.matweb.com/search/DataSheet.aspx?MatGUID=058d1b70edbd4b2293f298c52bbf9818. Retrieved May 18, 2020.

[34] Kartik Mohta, Michael Watterson, Yash Mulgaonkar, Sikang Liu, Chao Qu, Anurag Makineni, Kelsey Saulnier, Ke Sun, Alex Zihao Zhu, Jeffrey A. Delmerico, Konstantinos Karydis, Nikolay Atanasov, Giuseppe Loianno, Davide Scaramuzza, Kostas Daniilidis, Camillo Jose Taylor, and Vijay Kumar. Fast, autonomous flight in gps-denied and cluttered environments. *CoRR*, abs/1712.02052, 2017. URL http://arxiv.org/abs/1712.02052.

[35] E. Mooij, Z. Papp, and W. van der Wal. Simulation, verification and validation: Lecture notes. AE3212-II, February 2020.

[36] H. Moon, J. Martinez-Carranza, M. Faessler T. Cieslewski, D. Falanga, A. Simovic, D. Scaramuzza, M. Ozo S. Li, C. De Wagter, G. de Croon, S. Hwang, S. Jung, H. Shim, H. Kim,

M. Park, T. Au, , and S.J. Kim. Challenges and implemented technologies used in autonomous drone racing. *Intelligent Service Robotics*, 2019. doi: https://doi.org/10.1007/s11370-018-00271-6.

[37] Kelly D. Moses and Jr. Roy W. Malone. Development of risk assessment matrix for nasa engineering and safety center. URL https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050123548.pdf. Retrieved May 20, 2020.

[38] Noshin Omar, Mohamed Daowd, Peter Van den Bossche, Omar Hegazy, Jelle Smekens, Thierry Coosemans, and Joeri Van Mierlo. Rechargeable energy storage systems for plug-in hybrid electric vehicles—assessment of electrical characteristics. *Energies*, 5:2952–2988, December 2012. doi: 10.3390/en5082952.

[39] OscarLiang. How to choose mini quad frame – the basics and evolution. URL https://oscarliang.com/mini-quad-frame-basics/. Retrieved May 18, 2020.

[40] Landing Products Inc. APC Propellers. Apc propeller rpm limits. 2019. URL https://49u9ei2todm6vjegs45ceqp1-wpengine.netdna-ssl.com/wp-content/uploads/2019/08/APC-Propeller-RPM-Limits.pdf.

[41] Jos Sinke Reza Hedayati. Production of aerospace systems (ae3211-ii): 8. additive manufacturing. March 2020.

[42] Pedro Henrique Santos. Cover image. URL https://unsplash.com/photos/8gG1rhXJ68o. Retrieved May 20, 2020.

[43] Mike Patchus Lancaster SC. How to test balsa wood.

[44] Bruno Scrosati, K. M. Abraham, Walter A. van Schalkwijk, and Jusef Hassoun. *Lithium Batteries: Advanced Technologies and Applications*. Jon Wiley & Sons, 2013. ISBN 1118615395.

[45] Inc. ShopBot Tools. Fabbers/designers/project. URL https://100kgarages.com/map_fabber.php. Retrieved May 15, 2020.

[46] Smiths. 7068 aluminium alloy technical datasheet. 2018.

[47] Stratasys. Our materials. URL https://www.stratasys.com/materials/search. Retrieved May 15, 2020.

[48] SUNLU. Sunlu 3d printer filament abs, 1.75mm abs 3d printer filament, 3d printing filament abs for 3d printer, 1kg, black. URL https://www.amazon.de/SUNLU-Printer-Filament-1-75mm-Printing/dp/B07SYP6JMT/ref=sr_1_8?__mk_de_DE=%C3%85M%C3%85%C5%BD%C3%95%C3%91&crid=2OQP7GOGEV0TD&dchild=1&keywords=abs%2Bfilament%2B1.75&qid=1589811808&sprefix=abs%2Bfil%2Caps%2C184&sr=8-8&th=1. Retrieved May 15, 2020.

[49] Steven Mitchell Tan. Correspondence. URL https://3delft.nl/.

[50] B. van Dillen, D. Huang, A. Kadhum, A. Jadoenathmisier, S. Ramdin, and F. Vossen. Flight dynamics report - group b01. Technical report, Delft University of Technology, Faculty of Aerospace Engineering, March 2020. AE3212-II: Simulation, Verification & Validation.

[51] Xihao. Factory price aisi 9260 spring steel plate. URL https://www.alibaba.com/product-detail/Factory-Price-AISI-9260-Spring-Steel_62584226853.html?spm=a2700.galleryofferlist.0.0.152a33f5PhgSfQ&bypass=true. Retrieved May 18, 2020.

[52] Chi Zhang, Fuwu Yan, Changqing Du, Jianqiang Kang, and Richard Turkson. Evaluating the degradation mechanism and state of health of lifepo4 lithium-ion batteries in real-world plug-in hybrid electric vehicles application for different ageing paths. *Energies*, 10:110, January 2017. doi: 10.3390/en10010110.

[53] Shmily Zhang. High quality 7068 7075 t6 aluminium sheet alloy plate. URL https://www.alibaba.com/product-detail/High-quality-7068-7075-t6-aluminium_62423321551.html?spm=a2700.7724857.normalList.23.7e0b251bk8wJdW&s=p. Retrieved May 15, 2020.