Aigle

Baseline Report

Group 19

Technische Universiteit Delft

Aigle

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by

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Executive Overview

Project Objectives

Every year, artificial intelligence (AI) drone racing competitions are being hold like DRL and IROS, with the goal of stimulating the development of artificial intelligence in agile autonomous drone flight. Here, teams write AI software for the drone to complete a course as fast as possible, relying on full automation of their script. To make the quality of their code the deciding factor on who to win, all teams race with the same drone hardware. This baseline reports proposes design concepts for such a robotic artificial intelligence racing drone hardware. This design shall be open-source, such that all teams participating in the IROS / DRL drone racing competition can built and test their drone beforehand, also saving manufacturing costs for the organiser of this worldwide competition.

Market Analysis

AIgle aims to provide the society with the design of a racing drone piloted by artificial intelligence (AI) at no cost except the production cost. Their design aims for high agility and speed, while being controlled by AI. AIgle hopes to create a platform to test AI programs for autonomous drone applications and to further the development and understanding of artificial intelligence applied to a technical purpose.
The key partners in this project to develop, produce and fly are manifold. The first of them is the Drone Racing League (DRL). They are one of the biggest organizers of drone races, including AI competitions. They can decide whether the design concept of AIgle is good enough to be used at their competitions. Additionally the participants of the drone races are stakeholders, because they can decide whether to use their own design to test their code or the AIgle design. Besides those two key partners, the TU Delft as the initiator of the AIgle project, and the governments of the countries as the legislation makers are of importance to the AIgle project.
The current market of piloted drone races is heavily pushed by the races being broadcasted on television. The same rules for the AI races, but due to their non-human pilot are perhaps less exciting. The participants are mainly backed by educational institutions or companies. In order to fit into the races the AIgle drone design has to be more agile, faster and easier to control than current AI drones (RacerAI from the DRL), but they should also not be too expensive. Just above 400 competitors applied to the AI drone races of DRL in 2019, which allows to estimate a total production of AIgle drones of about 500 per year including hobbyists.
Currently the largest competitor to the AIgle drone would be the already existing RacerAI drone of DRL, which is not available to buy at the moment and is known to be a less optimum drone design with the main focus on aesthetics. The absolute maximum cost of the AIgle drone design to build will not exceed 2500€ including manufacturing costs. It should be mentioned, that the aim is to provide the drone design at no cost to the producer, but the AIgle team does have no further information on how the TU Delft knowledge properties will apply.
Lastly a SWOT analysis has revealed the inner strengths and weaknesses and the external opportunities and threats that might present themselves to the AIgle drone design. The main strength of the AIgle drone will be, that it will be developed by a team of engineers specialized in aerospace, while one of the larger weaknesses can be that the design has not been proven yet by being built and tested. One of the biggest opportunities that the AIgle drone might achieve is that it increases the research on artificial intelligence, while the biggest threat might be that AI drone races are much less popular than directly piloted drone races removing the market share of AI drone races. For more information a detailed SWOT analysis is mad in Table 7.1.

Sustainability Development Strategy

An approach to sustainable development was conceived to make sure environmental, social and economic aspects are considered. This is accomplished by first conducting a life cycle assessment of the drone, where various phases of the product's life are analyzed in relation to the race drone, from material acquisition to the end-of-life phase. The assessment results in a fourteen aims which should be achieved as much as possible to result in a more sustainable solution. These aims are then transformed into ten sustainability criteria which will be used to score design concepts. The criteria are split into two groups. The first group of criteria are to be used during the evaluation of concept selection; and the second group is used for evaluation during a much later detailed component selection phase. Each sustainability criterion is given a weight factor based on the affect is has on sustainability; as well as how the criteria are scored. It should be noted that the creation of this sustainability evaluation approach has its inaccuracies, and therefore should only be used a guide to help making certain decisions. It does not provide a definitive indication on a design's sustainability level.

Functional Analysis

By performing a functional analysis, the functions of the system, which refers to the drone, were established. Two tools used in this process are the functional flow diagram and the functional breakdown structure. When generating the functional flow diagram first, the functions were defined and grouped based on time sequence. Functions on the top-level include designing the drone, distributing the design, producing the drone, operating the drone after which the drone shall be ultimately disposed. Those top-level functions were broken down in lower levels, describing those functions more in-depth. As an example: operating the drone involves initiation, take-off, performing the autonomous flight mission and landing.
Secondly, a functional breakdown structure was established, breaking down the functions in an AND tree format. Whereas it does not show the time sequence, it provides deeper level actions compared to the functional flow diagram and groups the tasks based on the type of action that is performed.

Requirements

The drone hardware design is driven by requirements, either given by the customer, determined by regulators or specified per subsystem. The requirements were grouped and a requirement discovery tree was made. This way, the requirements were split in two categories: namely technical en non-technical requirements. Technical requirements address hardware characteristics, aesthetics; also referring to visibility, production and the engineering budget. Non-technical requirements were set on sustainability, the financial budget, user safety, regulations and resources.
Each requirement was classified as to which extent it drives the design, and its importance to the customer. Killer requirements drive the design to an unacceptable extent, which are in contradiction with other requirements to be met. The only killer requirement defined is that the drone shall be able to continue flying in case one motor loses operational functionality during flight.
Then driving requirements drive the design more than average, and are usually harder to meet than normal requirements. Driving requirements were set on damage tolerance, linear and rotational acceleration performance, the presence of at least one on-board camera, RAM, mass and dimensions and modularity.
The last category, key requirements, refers to requirements which are of primary importance to the customer. This also includes requirements on damage tolerance, RAM memory and linear and rotational acceleration, in addition to requirements on control modes, camera characteristics, remote communication range, computational power, and engineering budgets. Lastly, the stakeholders involved were specified for every requirement. Four different stakeholders were defined, namely users, competition spectators, the race organisation and the environment. It should be noted that the users

are involved in most of the requirements set.

Design Options

From the functional analysis the design options were derived by asking the question for every function: "What design option can perform this function?" In order to not reject any possible solution, all design options were considered initially and placed into a design option tree. The design option tree has four main branches, configuration, electronics, structures and the propulsion system unit. These branches are split up again into subbranches and those subbranches have at least one decision level, some even have a second decision level.
The next step is to eliminated all the non-feasible design options by critically looking if the design option can fulfill not only the function, but the set requirements as well. Every design option that could certainly not meet the requirements were eliminated, leaving only the possibly feasible ones.
Due to the lack of in depth knowledge about every design option a lot of the options survived the initial cut, for the sake of not rejecting a solution. The surviving design options were then analysed and the known advantages and disadvantages were stated.
Next, some concepts are proposed for further analysis. Again, to ensure that all solutions are considered there are 6 overarching concepts with a different focus: AI/processing power focus, Sensor focus, Modularity focus, "Physical performance" focus, Durability focus and Novel Technology focus. All stated with the advantages and disadvantages.
Lastly a technical budget plan is introduced. The technical budget plan assigns a Mass, Power and Cost budget to every department where the department has to stay within in order to meet the budget requirements set.

Technical Risk Management

If the system requirements are not met due to the influence of certain events it can badly influence the outcome of the mission and even results in failure. To prevent mission failure a technical risk management plan was written. In the technical risk management a few possible events are identified. Also the probability and impact of the events is estimated and based on that a mitigation plan is written. The parts causing the most risk, even after mitigation, are the structural and electrical subsystem when the drone crashes. A lot of research still needs to be done in order to reduce the risk even further. Besides these measures, during the further design of the system there will be closely looked at how these risks will develop and if new risks will occur.

Contents

1 Introduction

The first autonomous drone race dates back to the IROS autonomous drone race in 2016 [11]. In these races, participating teams have to design software to make their drones race autonomously. These races have become an annual event, with as main question whether autonomous drones would be able to fly faster than drones controlled by human pilots [10]. In 2019, an autonomous drone race called Artificial Robotic Racing circuit (AIRR) was held by the Drone Race League (DRL) [7]. To make the race fair, identical hardware was used by all teams, which was provided by DRL. This meant that teams were not able to properly test their software beforehand, which resulted in a significant number of drone crashes during the race. Furthermore, the drones were found to have poor controllability, poor aerodynamic characteristics and a high weight. To solve these problems, group 19 of the TU Delft DSE 2019-2020 aims to design an open-source hardware drone design for autonomous racing purposes.

The aim of this report is to provide an overview of proposed design concepts and to document the analyses performed. More specifically, a market and sustainability analyses were conducted, after which the functional, requirements, and risk analyses were executed. Of course, many of these run in parallel, as iteration is often required.

This report consists of a number of sections. First of all, an executive overview is provided in chapter . Secondly, the market analysis is described in chapter 2. Furthermore, the sustainability analysis is performed and documented in chapter 3. After this, the functional analysis and requirement analysis are described in chapter 4 and chapter 5, respectively. In chapter 6, the design option tree is created and concepts are proposed. Finally, in chapter 7 the technical risk assessment and mitigation is described.

2
Market Analysis

In this chaper a market analysis was conducted for the AIgle racing drone. Section 2.1 introduces the goals of the AIgle AI racing drone project and section 2.2 identifies the key stakeholders. Then section 2.3 explains what the market demands are and section 2.4 analyses the expected market volume. After that, possible competitors to this design are identified in section 2.5 and elaborated upon. Lastly the target cost is explained in section 2.6 followed by the SWOT analysis in section 2.7.

2.1. Value Proposition

AIgle aims to provide society with the design of a racing drone piloted by artificial intelligence at no cost except the production cost. This design will be worked out with the focus on its appliance within the currently existing AI drone races and is therefore trimmed for speed and agility, pushing the hardware and the software to its limits.
It is AIgle's ambition to create a platform to test AI programs for autonomous drone applications and with that to further the development and understanding of artificial intelligence applied to a technical purpose.

2.2. Stakeholders

The project relies on multiple principal partners. First of all, one of these partners is the Drone Racing League (DRL), which will hopefully welcome this drone design and integrate it within their competitions. Furthermore, the participants to the AI drone races are important to this concept, because they will decide whether to develop their own drone or whether to use the existing design of the AIgle team. Also it is expected that the participants will have access to the required hardware, including the manufacturing capabilities, as stakeholder.
Besides those three, the legislation of each country will also have to be respected by the drone pilots. Lastly, the Technical University of Delft has created the environment for the design team AIgle to develop the autonomous drone development project. This team includes eleven students together with their three tutors for guidance.
The resources that will be tapped on for this project are minimised. The design team consists of engineering students who will publish the design for free (based on current status, TU Delft policies apply), and is therefore at no cost to the producer of the drone. Most of the hardware can be directly purchased and assembled at home. Some of the hardware needs to custom made on specialized machines, such as a 2D mill, 3D printer or PCB printing machine.

2.3. Demands from the Market

Drone races with pilots steering the drone have started to appear in 'late 2013 and early 2014' in Australia [13]. Those races have become increasingly more difficult, approaching speeds of up to 100 [mph] and more [12]. The large drone races are now mainly organised by the Drone Racing League (DRL) [9] and include broadcasting on television worldwide.

Then, in 2018, the DRL introduced the Artificial Intelligence Robot Racing (AIRR) league, which had its first race in 2019. For the sake of this competition, the DRL designed the RacerAI. Unfortunately, this drone is not available to the programmers before the actual competition. The programming pilots have to upload their code onto the drone and test it within a limited time frame before the race. Of course, this setting makes it more difficult for the competitors to test their program properly.

It can be understood from this background that this concept can be improved by making one drone design available to the public. This design will have to be more agile and faster than the RacerAI, but also it will need to be cost effective and easy to produce by one own.

The design of AIgle can combine just this and more, allowing for a high speed, high agility drone, combined with AI and the design available at no cost (TU Delft policies apply).

2.4. Volume of the Market

The market of the directly piloted drone races is quite open. No specific beforehand knowledge such as programming is required and also the races itself are being broadcasted on the television allowing those races to be profitable. This has lead to the races being driven by the entertainment sector with the goal to be as exciting as possible for the spectators.

The AI races are dominated mainly by technological companies and universities as participants who both have the resources to put a team together to succeed piloting a drone autonomously through a course. Those resources include specific knowledge about how a drone is being flown and how this knowledge can be programmed on the drone. On top of that, financial resources are required to build and test a drone, which will be needed to test the program written by the participating team.

The number of participants might increase with increasing popularity. The first AI drone race has attracted 424 teams (2300 people from more than 80 countries), of which 9 teams were selected after a series of programming tests [9]. Considering that the design of AIgle will be accessible to everyone, it will probably, and hopefully, be used by many more teams. It would be expected, that at least those 424 teams, wishing to participate in the race, could then use the design of AIgle to prepare for the races. On top of that, it will be expected that the threshold to design such an autonomous AI drone will be lowered significantly, allowing hobby drone flyers and programmers to enter this niche, together with the teams backed by larger institutions or companies.

Concluding, this means that there is an estimated potential for about 500 productions of the AIgle drone design within one year. Technological companies and university will likely be responsible for the biggest share of those 500 productions.

2.5. Competitor Analysis

Currently, the largest possible competitor would be the RacerAI drone of DRL itself. However, at the moment, they do not sell this drone yet. It will be difficult to predict the reaction of DRL, when AIgle proposes its concept to be the next AI drone for the DRL competition. If it is not used at the AIRR competitions, it could at least give the teams a basis, on which their code could be tested on. The modularity of the AIgle concept will also allow for quick repairs and if chosen, allow for design changes as well, making it possible to adjust to the rules of the AI competitions. Furthermore it will be of large advantage, that the AIgle designer team consists of unpaid students, allowing to have no or minimum development costs. This allows the design to be offered at no cost (TU Delft policies apply), except the actual parts of the drone to the pilot.

2.6. Target Cost

The current target cost of the drone to be built will be at most 2500€. This cost covers the entire production, including manufacturing methods and materials or commonly available hardware. The price range of directly piloted drones top off at about 500€, excluding the goggle kits [3]. This would suggest that the price for the AI drone is much too high. On the other hand, the market for piloted drones is much larger, allowing the companies to offer lower prices. In addition, the customers are very different. For a company or a university, a cost of 2500€ is very much acceptable and can possibly be even dragged down, by using workshops of their own. It should be mentioned that this project is made possible through the TU Delft and currently intended to be at no cost for the user of the design. Yet, the TU Delft policies will apply to this project as well, which could lead to restrictions on the usage of the free content. The AIgle team has no information on how the publication of the design with TU Delft's policies will be handled.

2.7. SWOT Analysis

In order to better understand the market capabilities of the AIgle project, the SWOT analysis can help. On one side the internal strengths and weaknesses will be investigated, and on the other hand the external threats and opportunities are shown. This diagram allows the design team of AIgle to know and mitigate their own weaknesses and their project's susceptibility to external threats.

The strengths come from the advantages that the AIgle concept has over competitors, while the opportunities include areas with room for improvement. Thus, an example of a strength is that the design will be offered at no cost (TU Delft policies apply), while an opportunity is the application of the AIgle drone for other purposes. Similarly, the weaknesses are describing the disadvantages, that the team may have on the market, such as the need of the team to build the drone, and the threats would include possible situations, which would harm the target market of the AIgle drone, such as rising material costs.

Table 2.1: SWOT analysis for project organisation and execution based on the market analysis

Strengths	**Weaknesses**
Modularity of AIgle drone allows for quick repairs	Need of the team to build the drone themselves
AIgle team includes specialized engineering knowledge and tools	No proven technology yet, but just a design
High speed and high agility of AIgle drone	Lack of marketing techniques/experience to increase popularity of AIgle design
AIgle design including sensor(s) for high accuracy path detection	Aesthetics might not be convincing enough - no prior art experiences in team
AIgle design will be published openly accessible (TU Delft policies apply)	
Opportunities	**Threats**
TU Delft's reputation helping the AIgle project gain traction	Rising cost of materials and hardware for production
Increasing the research on AI piloted drones significantly	Development of AI Drone races - they might not be as profitable on television as piloted drone races
Application of the AIgle drone design as base for other purposes than drone races	Rising competition of other 'for-free' AI drone designers
Better accessibility of drone technology	New legislation forbidding free use of AI drones
Allowing hobbyists to enter the AI drone market	Not enough working hours on the AIgle team due to sickness, especially the corona-virus
Development and application of easy manufacturing principles to create a complex product might drive the manufacturing cost down	Acceptance of the AIgle drone design by the racing competitions, such as the DRL

3 Sustainability

This chapter introduces the sustainability approach of the project with regards to the technical aspects of the design in section 3.1.

3.1. Sustainable Development Strategy

The UN World Commission on Environment and Development states that [6]: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Sustainability is about supporting environmental, social and economic health, and often requires trade-offs between them to make sure all three aspects are satisfied.

Sustainability is mainly focused on minimizing waste and emissions during the entire life of the product, which is beneficial to both environmental and social well-being. Economic well-being is satisfied by producing the product itself and providing value to consumers.

3.1.1. Life Cycle Assessment

A common method to analyze the sustainability of a design is to conduct a life cycle assessment, which looks at all the phases of a products life and looks for ways in which it can be improved. The phases of the drones product life are:

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

These aspects will be briefly analyzed at varying levels of detail depending on the importance for the design of the race drone. During the assessment, several aims will be derived. These are to be kept in mind throughout the project by all group members and will also be used to define certain sustainability criteria. Each sustainability criterion is used to rate a design from 0 (not sustainable) to 4 (very sustainable). Additionally, since some criteria provide better indication of the product's overall sustainability than others, each criterion will be given a weight factor to account for their importance. The sum of all criteria scores with applied weightings will give the overall sustainability score for a particular design, which can be used to compare to other designs.

The most important phases that can have most influence on the drone design are the product consumption and end-of-life phases, which will be discussed later. Raw material acquisition, material manufacture, and product manufacture of components are not factors that the design has much control over. This is because the drone will largely consist of electronic components, and therefore there is hardly anything that can be done in terms of material choice or production methods. The main decision that can be taken during the design is to select components that are supplied by more sustainable suppliers. Such suppliers should have good production practices such as using lean production methods to minimize waste. They should have above-average environmental and social ratings. Secondly, components should as much as possible be made using sustainably harvested resources using fair methods. Renewable resources are beneficial, however are not necessarily sustainably harvested. Two aims have been mentioned so far:

- **Aim 1:** Components should be selected from sustainable suppliers, with good environmental and social ratings.
- **Aim 2:** Components should be produced using sustainably harvested resources that have been obtained using fair methods.

Final product manufacture, which is done by the consumer, contributes a small part to the overall sustainability of the product, but will still be considered here. Firstly, it is important to minimize the amount of energy required for certain processes such as machining and soldering. Secondly, waste material and emissions should be reduced. Lastly, the transportation of components from the supplier to the consumer should be minimized. This can be done by selecting components which are manufactured in multiple regions around the world. This leads to the following aims:

- **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.

The drone's product consumption phase is really influenced by the design as the energy it uses can be linked to CO2 emissions. A simple CO2 analysis can be conducted by considering the amount of energy in a battery, and the amount of CO2 emission to produce that amount of energy. However, battery size does not necessarily lead to a more sustainable drone. A smaller battery could take less energy to charge; however it could also mean less flight time. This could result in the user flying the drone more often, requiring more battery charges, and therefore not decreasing the total energy usage. Therefore, a more important aim is to increase the energy usage for a fixed duration of flight time. One way this can be accomplished is by minimizing the weight of the drone, such that the motors require less power to maneuver the drone. Secondly, computational requirements should be reduced as much as possible such that the main processor aboard the drone consumes less energy, and additionally a lower weight of the processor will be required. Thirdly, all other systems aboard the drone should have a minimized power requirement. This can be accomplished by only adding necessary components to the drone and choosing less power intensive solutions. These aims to reduce the mass, computational power and electrical power requirements of other systems will be greatly conflicting with the performance requirements and hence trade-offs must be made. The following aims have been discussed:

- **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.

The final product phase is the end-of-life phase and is also very influenced by the design and therefore much attention should be made in this phase. The EU waste hierarchy [5] introduced in the waste framework directive will be considered in this section. It ranks the following five levels with regards to minimizing waste:

1. Prevention
2. Reuse
3. Recycle
4. Other recovery (eg: recovering energy by incineration)
5. Disposal (eg: landfill)

The levels gradually increase the amount of waste produced.
The first level is to prevent waste altogether. One way prevention of waste can be achieved is by reducing material volume of the drone. Another way to prevent waste is by increasing the lifespan of the whole drone, as well as individual components. This way the drone can be used for longer periods of time, and avoids the consumer having to buy another drone or drone components. Additionally, a durable design with a protective structure will also reduce waste by preventing damage to components.

Reuse is very important since the race drone consists of many components that are still able to perform their function after the drone's life. This would apply to many electronic components and the frame of the drone. Since the users of the drone buy the individual components themselves and perform the final manufacturing of the drone, reuse is very likely as the user will have a great understanding of the individual parts, what they are used for, and perhaps use these parts in other electronics projects. A way to promote the reuse of these components is to design the drone such that the assembling joints are temporary. This way if a component breaks, it can easily be replaced, or if the drone reaches the end of its life, working components can be reused in other projects.

The rest of the points on the waste hierarchy – recycle, other recovery, and disposal - are very dependent on external systems. These waste solutions require the connection of the waste product to the end-of-life industry. Consumers must actively send their waste components either back to the supplier or other organizations to recycle or dispose of the components properly. This requires effort on the consumer side, and the ease of doing this depends on the available end-of-life systems within a country or region. For example, it is a lot easier for a consumer to send back waste components if the supplier has a take-back system in place which rewards customers. Similarly to the 'reuse' level, the 'recycle' level also benefits from using temporary joints in the assembly, such that the different materials can be separated.

For the 'other recovery' and 'disposal' levels in the waste hierarchy, biodegradability of the design is an important factor such that the materials are broken down into natural resources in a short time, and no harmful chemicals are released.

The aims for the end-of-life phase of the product are as follows:

- **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.

3.1.2. Sustainability Criteria

Table 3.1 shows the sustainability criteria, including the sustainability aims from which they were derived, and the weight factor associated with each criterion. An explanation is given for each criterion on how a design can obtain the scores of 0 and 4, and intermediate values can be obtained by fulfilling conditions in between. 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 a much later component selection phase. The weight factor was applied by considering the importance of each criterion to the sustainability of the drone, and how each criterion is assessed with the 0 to 4 score. Some examples are given to how the weighting factors are given. Criterion 8 is given the highest rating factor as most of the production is done by the suppliers. Hence, a lot of waste material and emissions can be produced in this stage, as well as possibilities of bad factory worker treatment. Criterion 1 is also given a high weight factor as a lot of energy is used during the entire usage phase of the drone, which can last for an extended period of time. Criteria related to the final manufacturing phase are given a very low weighting, as this phase is a very small part of the entire life cycle.

Table 3.1: 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 factor
Criteria group A: for evaluation during concept selection phase		
6, 7, 8	**Criterion 1:** Estimated power consumption per unit of flight time 0 = High power consumption 4 = Low power consumption	7
11	**Criterion 2:** Volume of solid material: 0 = High volume of solid material 4 = Low volume of solid material	4
10	**Criterion 3:** Durability of design: 0 = There is hardly any protection for the hardware, and the drone's structure can break easily. 4 = The drone is very durable and able to withstand many hard crashes without damaging the hardware or structure.	6
3	**Criterion 4:** Estimation of energy usage of processes during final manufacturing phase: 0 = At least 3 power tools required (drill, circular saw, grinder, hot glue gun, soldering iron) 4 = No power tools required	2
4	**Criterion 5:** Material waste during final manufacture phase: 0 = Over 20% volume of final product material waste 4 = No material waste or emissions	2
12	**Criterion 6:** Types of joints used for assembly: 0 = Only permanent joints used (eg: adhesives) 4 = Temporary joints between all components (eg: nuts and bolts)	5
14	**Criterion 7:** Volume percentage of biodegradable material 0 = No biodegradable material 4 = Over 50% of total drone volume contains biodegradable material	5
Criteria group B: for evaluation during detailed component selection phase		
1, 2, 13	**Criterion 8:** Sustainability of suppliers: 0 = Most suppliers have bad environmental and social ratings. They obtain raw materials from unsustainable sources. No end-of-life systems in place. 4 = Most suppliers have good environmental and social ratings. They obtain raw materials from sustainable sources. End-of-life systems in place and working.	10
5	**Criterion 9:** Location of manufactured components 0 = Most components are manufactured in only 1 location in the world. 4 = Most components are manufactured in at least every continent.	2
9	**Criterion 10:** Lifespan of components: 0 = Most components of the drone have a lifespan rating of less than one year. 4 = All components of the drone have a lifespan rating of over two years.	5

Some criteria are scored in a quantitative way making them more verifiable and accurate. Alternatively, some criteria are scored qualitatively as they are not possible to describe quantitatively. Another reason for qualitative scoring is because not enough knowledge is known about specific values at this early stage of the design process. For example, for criteria 1 the design is scored qualitatively as the standard power consumption per unit of flight time is not known. The same goes for criteria 2. Therefore, for now simple scoring conditions will be set, such as 'High power consumption', and when more information is known at later stages, the conditions can be modified and made more specific.

3.1.3. Accuracy of the Sustainability Evaluation Approach

The sustainability evaluation approach described above does have it's limitations, due to the inaccuracies in creating the sustainability criterion scoring and weight factors. 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.

During sustainability evaluations, if it is found that certain criteria cannot be scored due to the lack of obtainable information, then they should be disregarded. This could be expected for criterion 8, where the environmental and social ratings for component suppliers are not indicated, and the way they obtain their raw materials are unknown.

3.2. Sustainability Requirements

Although a set of sustainability aims have already been identified, they are not hard requirements that have to be met for the design to succeed. This section will identify some of these requirements such that the design is steered to a sustainable result, starting early in the design process. Unlike the sustainability aims, the requirements only contain verifiable statements. Only three sustainability requirements have been set as adding too many constraints could limit the design options to a too large extent. Therefore, only requirements with minimal affect on performance have been set.

AIG-NT-S1: The rated lifespan of components shall be at least 2 years.

AIG-NT-S2: The components of the drone shall be interconnected using temporary joints.

AIG-NT-S3: The amount of waste material during the final production phase shall not exceed <tbd>.

4
Functional Analysis

In this chapter, the functional analysis is described. The goal of functional analysis is to gain insight in the relations of the system architecture by creating a functional architecture [8]. Two tools that accommodate this process are the functional flow diagram, as generated in section 4.1, and the functional breakdown diagram in section 4.2. First of all, a description is given of both diagrams. Secondly, the diagrams are provided.

4.1. Functional Flow Diagram

The functional flow diagram relates the functions to each other in sequential manner. In this diagram, "the top-level functions should cover the complete span of life cycle functions anticipated from initial set-up and check-out through disposal." [8] (p. 5-4), whereas the lower-level functions expand upon the high-level functions and provide more detailed information about the process. The diagram can be found in Figure 4.1 and Figure 4.2.
Elaborating on the diagram in Figure 4.1, the top-level functions span from designing the drone, to distributing the open-source hardware, production, operation, and finally, disposal. For the processes regarding the design of the drone, a reference is made to the work flow diagram in the project plan [4].
The top-level functions are expanded in more detail in the green blocks, which are further expanded in yellow blocks. Again, the yellow blocks are further expanded into orange blocks. Emphasis is put on the operation of the drone, where functional information should be provided in sufficient detail to accommodate the generation of requirements.

4.2. Functional Breakdown Structure

After having completed the functional analysis and functional flow diagram the functional breakdown structure is set up. This diagram hierarchically categorizes all the functions the system must perform during its life phases in an AND tree format. It is time independent and provides additional/deeper level actions with respect to the functional flow diagram. However, in this report the functional breakdown diagram still provides the functions at a relatively high level. Thus, in general it does not include actions of specific subsystems. Its life phases have been defined as the design (distribution), production, operation and disposal phase. All functions mentioned in the flow diagram have been implemented with consistent numbering into the breakdown diagram. Whenever a box misses numbers this means it goes deeper than the functional flow diagram or categorizes a group of functions. The diagram can be found in figure 4.3.

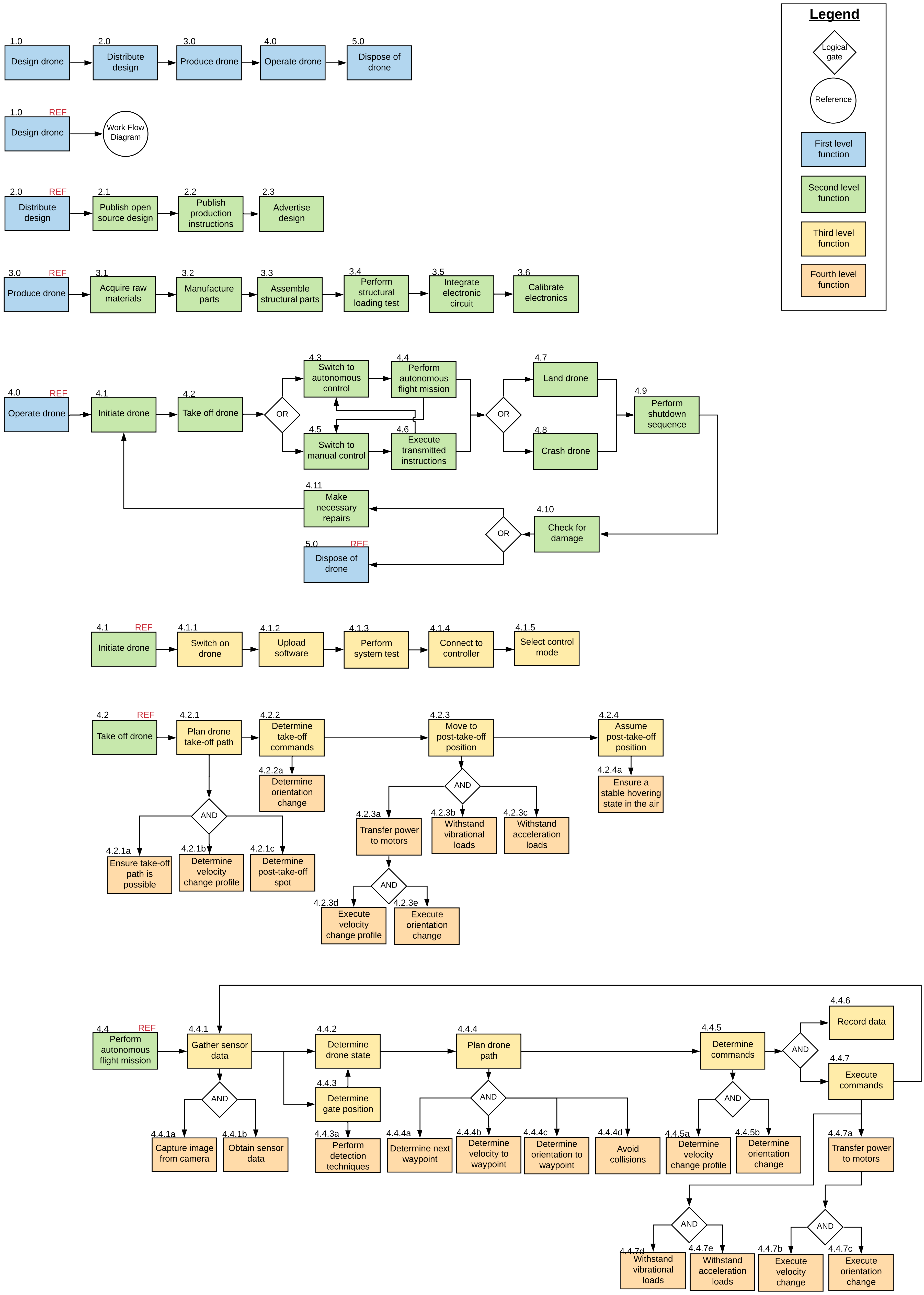

Figure 4.1: The first part of the Functional Flow Diagram

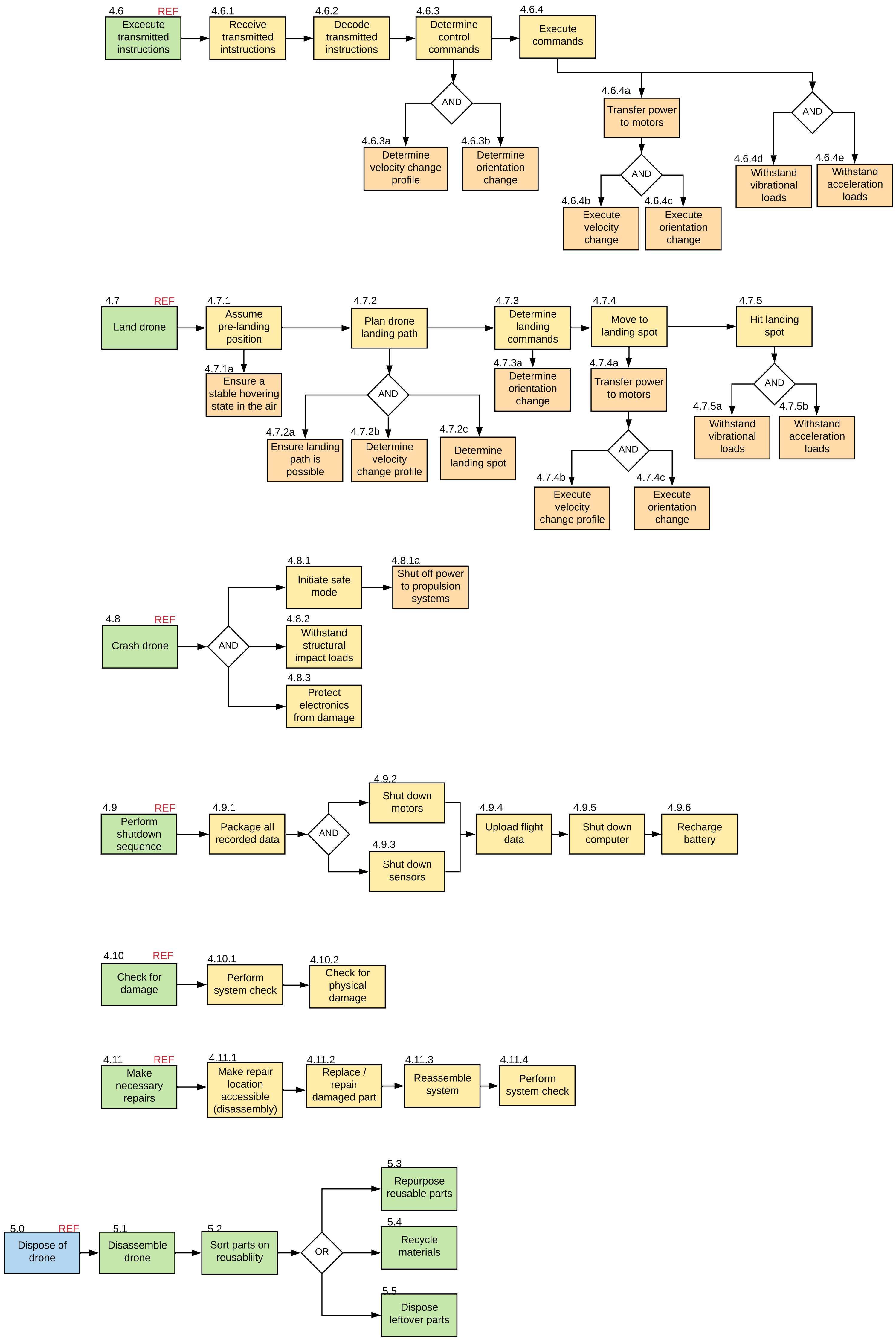

Figure 4.2: The second part of the Functional Flow Diagram

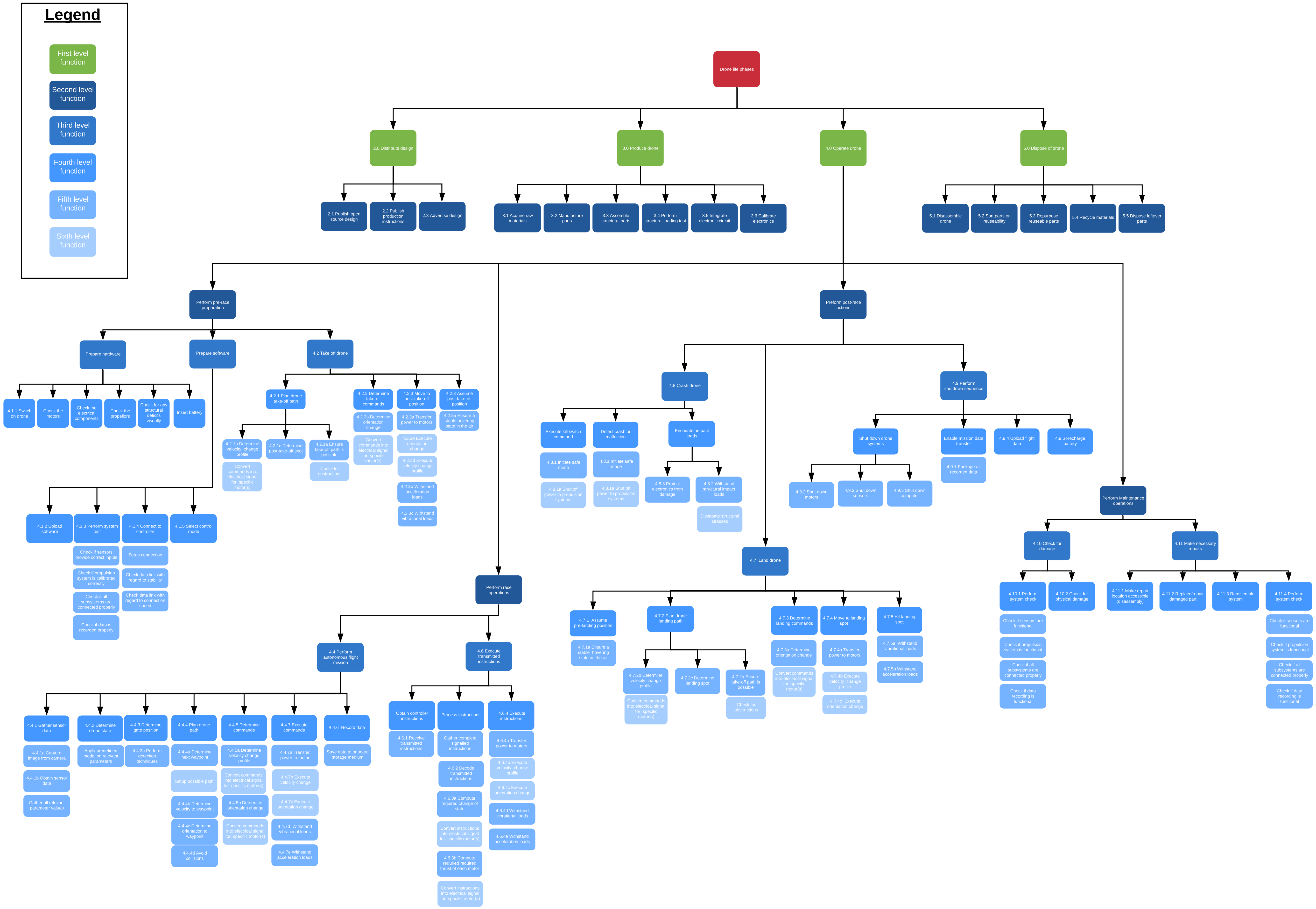

Figure 4.3: The Functional Breakdown Diagram

5 Requirements

This chapter describes various requirements that will guide the design of the drone. A tool used to do so is the requirement discovery tree, as presented in section 5.1. The requirements have been split into multiple branches to clearly organise and easily trace the requirement. Furthermore, each requirement has a unique indicator that can be used to refer to them easier.
Certain requirements have also been marked as Killer, Driving or Key Requirements. Killer Requirements are requirements that cannot be met while also fulfilling all other requirements. The only Killer Requirement states that the drone shall be able to continue flying when one of the motors fails. This is considered infeasible for a drone that only has a small number of engines without severely overdesigning the drone, leading to conflicts with requirements that limit, among others, cost and mass. Driving Requirements are requirements that influence the design more than normal requirements. These requirements are for example implementing modularity in the design, which will clearly impact the final design. Finally, Key Requirements are the most important requirements that must be met. These are for example constraints given by the client. It is furthermore indicated which stakeholders are connected to each requirement. A quick overview of the stakeholders is:

- Users: The people on the teams that use the drones for races.
- Environment: A healthy global environment/climate and the people who care about the environment/climate.
- Spectators: The people watching drone races, both locally in-person and remotely.
- Organisation: The organizers of drone races, who also have to produce a large number of the drones.

All requirements are listed in section 5.1 where they are sorted by the different branches. They can also be seen in the Requirement Discovery Tree, figures 5.1, 5.2 and 5.3.

5.1. Requirements Discovery Tree

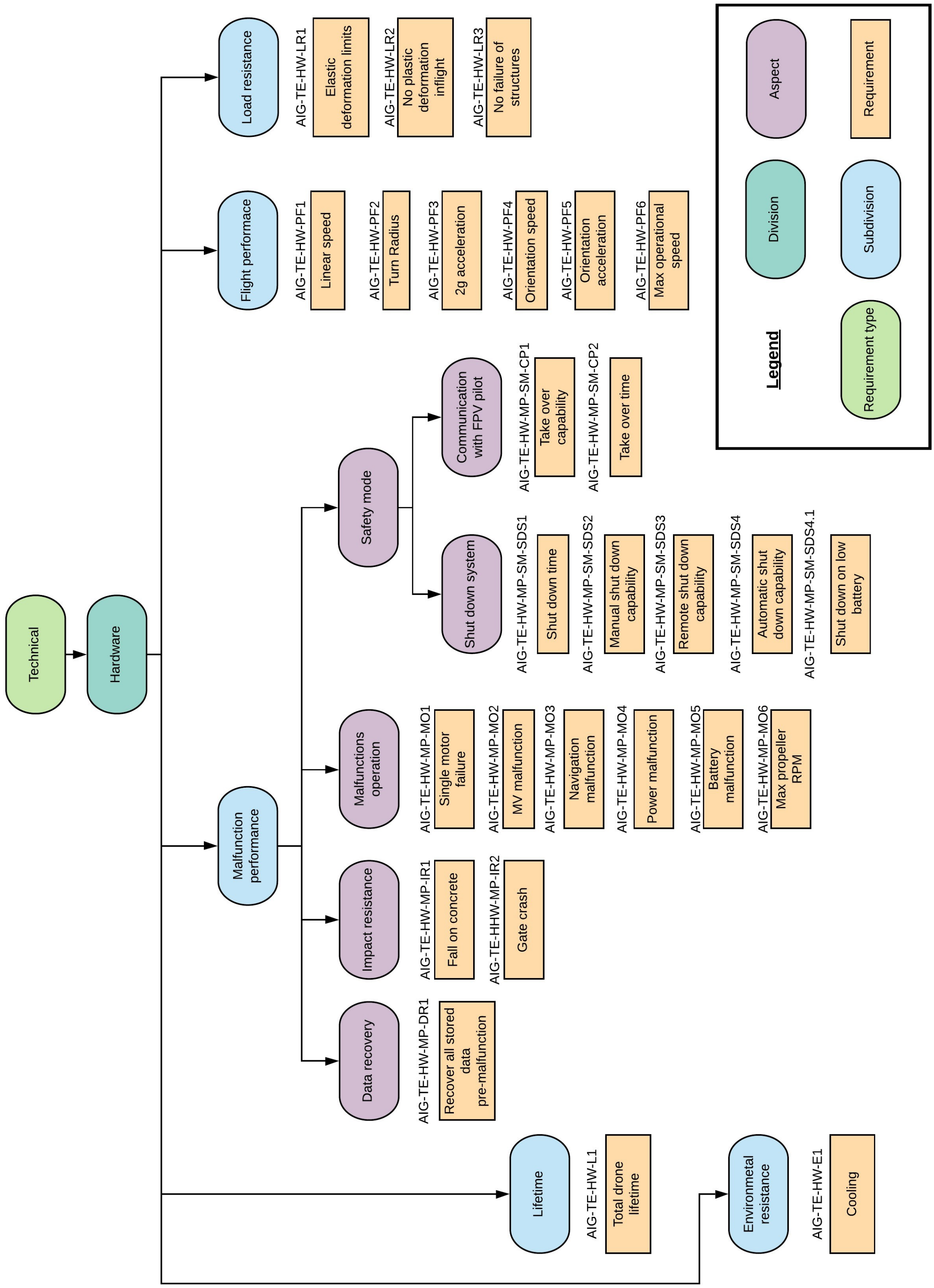

Figure 5.1: The Requirement Discovery Tree, part 1

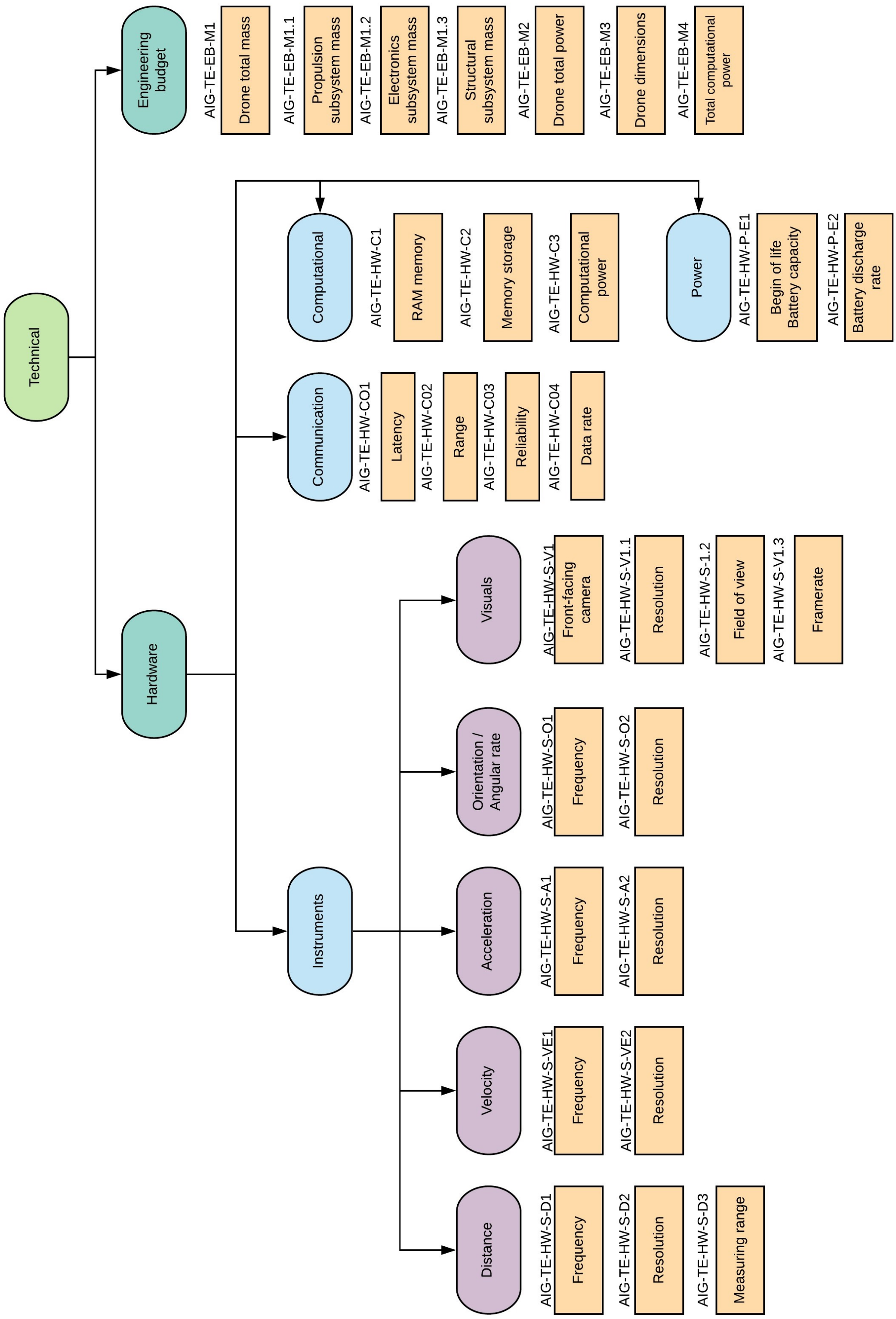

Figure 5.2: The Requirement Discovery Tree, part 2

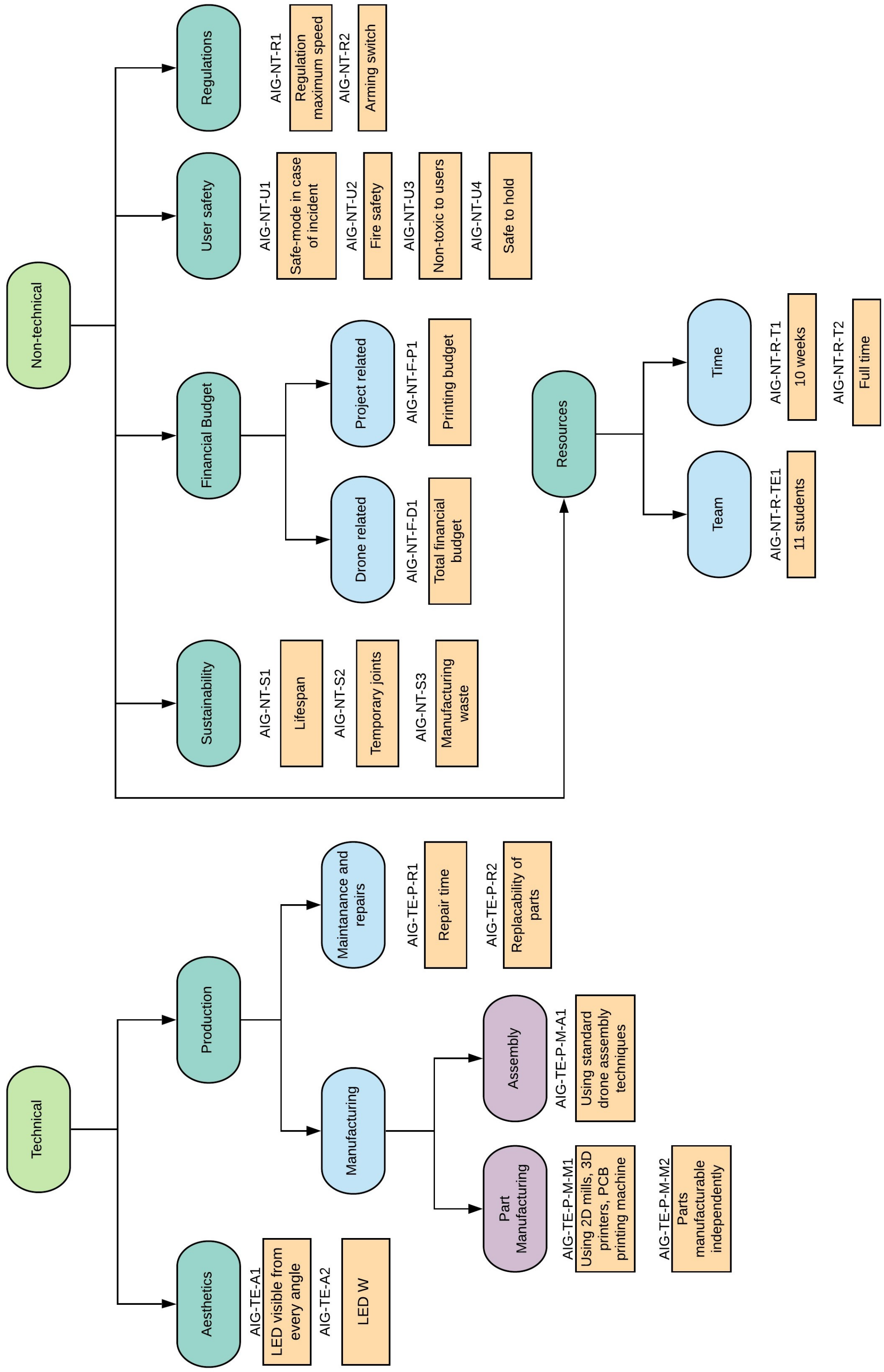

Figure 5.3: The Requirement Discovery Tree, part 3

5.1.1. Technical Requirements

Hardware

Table 5.1: Hardware requirements.

ID: AIG-TE-HW-	Requirement	Stakeholders	Classification
-E1	The drone shall be outfitted with a cooling system that prevents any component from being heated to temperatures higher than their respective operational limit.	Users	
-L1	The drone shall be able to be used for <tbd> flight hours total before a component needs to be replaced, excluding replacement of components damaged due to accidents.	Users, Environment	
-MP-DR1	All data stored on the drone before a malfunction occurs shall be recoverable.	Users	
-MP-IR1	The drone shall suffer no damage to on-board systems or structure if the drone is dropped from 3 meters onto a concrete floor.	Users	Key, Driving
-MP-IR2	The drone shall suffer no fracture, plastic deformation or loss of electronic function if the drone flies into a gate at maximum normal flight speed.	Users	Key, Driving
-MP-MO1	The drone shall be able to continue flying in the case one motor loses operational functionality during flight.	Users	Killer
-MP-MO2	If the Machine Vision subsystem loses (partial) functionality, the drone shall automatically switch to safety mode within <tbd> seconds.	Users, Spectators	
-MP-MO3	If the Navigation subsystem loses (partial) functionality, the drone shall automatically switch to safety mode within <tbd> seconds.	Users, Spectators	
-MP-MO4	If the Power subsystem loses (partial) functionality, the drone shall automatically switch to safety mode within <tbd> seconds.	Users, Spectators	
-MP-MO5	If the Battery loses (partial) functionality, the drone shall automatically switch to safety mode within <tbd> seconds.	Users, Spectators	
-MP-MO6	During normal operations, the RPM of the propellers shall not exceed <tbd>.	Users, Spectators	
-MP-SM-SDS1	The system shall be able to shut down within <tbd> seconds of being ordered to shut down.	Users, Spectators	
-MP-SM-SDS2	The system shall be able to be turned off manually.	Users, Spectators	
-MP-SM-SDS3	The system shall be able to be turned off remotely while within <tbd> meters.	Users, Spectators	
-MP-SM-SDS4	The system shall turn itself off within <tbd> seconds of detecting a malfunction.	Users, Spectators	

-MP-SM-SDS4.1	If the system detects the batteries contain less than <tbd> Joules, it shall turn itself off within <tbd> seconds.	Users	
-MP-SM-CP1	The drone shall be able to switch from the autopilot mode to the manual control mode within <tbd> meters.	Users, Spectators	Key
-MP-SM-CP2	The drone shall be switched from autopilot mode to manual control within <tbd> seconds from the order to switch being given.	Users, Spectators	
-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 meters.	Users	Key
-PF2	The drone shall be able to make a 3 meter radius arc while flying at 10 m/s.	Users	Key, Driving
-PF3	The drone shall be able to linearly accelerate at 19.61 m/s^2 from zero velocity.	Users	Key, Driving
-PF4	The drone shall be able to reach a rotational velocity of <tbd> rad/s about any of its own axis while hovering.	Users	Key
-PF5	The drone shall be able to reach a rotational acceleration of <tbd> rad/s^2 about any of its own axis while hovering.	Users	Key, Driving
-PF6	The maximum operational speed of the drone shall be at least <tbd> m/s	Users, Organisation, Spectators	Key, Driving
-LR1	The elastic deformation strain during normal flight conditions shall not exceed <tbd>.	Users	
-LR2	No plastic deformation of the drone shall occur during normal flight conditions.	Users, Environment	
-LR3	No failure of the structural components of the drone shall occur during normal flight conditions.	Users, Environment	
-S-D1	The distance to the environment shall be measured at least <tbd> times per second.	Users	
-S-D2	The resolution of the distance measurements shall be at most <tbd> meters.	Users	
-S-D3	The distance from the drone to its environment shall be measured for distances up to <tbd> meters.	Users	
-S-VE1	The velocity of the drone shall be measured <tbd> times per second.	Users	
-S-VE2	The resolution of the velocity measurements shall be at most <tbd> m/s.	Users	
-S-A1	The acceleration of the drone shall be measured <tbd> times per second.	Users	
-S-A2	The resolution of the acceleration measurements shall be at most <tbd> m/s^2.	Users	
-S-O1	The angular rate of the drone shall be measured <tbd> times per second.	Users	
-S-O2	The resolution of the angular rate measurements shall be at most <tbd> radials.	Users	

-S-V1	At least one front facing camera shall be present.	Users	Key, Driving
-S-V1.1	The resolution of the front-facing camera shall be at least <tbd> megapixel.	Users	Key
-S-V1.2	The field-of-view of the front-facing camera shall be at least <tbd> degrees.	Users	Key
-S-V1.3	The front-facing camera shall capture images at 60 Hz or greater.	Users	Key
-P-E1	The battery shall have a begin-of-life capacity of at least <tbd> Joules.	Users	Key
-P-E2	The maximum battery discharge rate shall be at least <tbd> Watt.	Users	
-CO1	The latency of communications between the drone system and remote computers shall be no greater than <tbd> milliseconds.	Users	
-CO2	The range of remote communications to the drone shall be at least <tbd> meters.	Users	Key
-CO3	The packet loss rate of remote communications shall be no greater than <tbd> % during normal flight conditions.	Users	Key
-CO4	The rate of data sent from the drone to remote computers shall be at least <tbd> kB/s during normal flight conditions.	Users	
-C1	The RAM of the drone system shall be at least <tbd> MB.	Users	Key, Driving
-C2	The memory storage of the drone system shall be at least <tbd> GB.	Users	Key
-C3	The computational power of the drone shall be at least <tbd>.	Users	Key

Engineering Budget

Table 5.2: Requirements due to the engineering budget.

ID: AIG-TE-EB-	Requirement	Stakeholders	Classification
-M1	The total mass of the drone shall be no greater than 1 kg.	Users, Spectators, Organisers	Key, Driving
-M1.1	The total mass of the propulsion unit subsystem shall be no greater than <tbd> g.	Users	
-M1.2	The total mass of the electronics subsystem shall be no greater than <tbd>g.	Users	
-M1.3	The total mass of the structures subsystem shall be no greater than <tbd> g.	Users	
-M2	The drone shall be able to supply enough power to all subsystems for them to all function simultaneously.	Users	Key
-M3	The maximum drone dimension in all length, width and height, shall be smaller than 50 cm.	Users, Organisers	Key, Driving

-M4	The drone shall have enough computational power to process images at 60 Hz and calculate a flight path.	Users	

Aesthetics

Table 5.3: Aesthetics requirements.

ID: AIG-TE-	Requirement	Stakeholders	Classification
-A1	The drone shall have lights visible from every angle	Spectators	
-A2	The drone lights shall emit at least <tbd> W.	Spectators	

Production

Table 5.4: Production requirements.

ID: AIG-TE-P-	Requirement	Stakeholders	Classification
-M-M1	All parts of the drone shall be manufacturable using 2D milling, 3D printing and Printed Circuit Board printing machines.	Users, Organisers	Key, Driving
-M-M2	All parts of the drone shall be able to be manufactured independently.	Users, Organisers	
-M-A1	It shall be possible to assemble the drone using only standard drone assembly techniques.	Users, Organisers	Key, Driving
-R1	Each structural component of the drone shall be replaceable within 2 minutes.	Users, Organisers, Spectators	
-R2	Each component of the drone shall be able to be replaced individually.	Users, Organisers, Environment	

5.1.2. Non Technical Requirements

Resources

Table 5.5: Resources requirements.

ID: AIG-NT-R-	Requirement	Stakeholders	Classification
-TE1	The drone shall be designed by a team of 11 people.	Designers	
-T1	The drone shall be design in detail within 10 weeks.	Designers	
-T2	The team shall work on designing the drone full time.	Designers	

Financial Budget

Table 5.6: Requirements due to the financial budget.

ID: AIG-NT-F-	Requirement	Stakeholders	Classification
-D1	The total cost of the drone, including manufacturing, shall be no greater than 2500 euros.	Users, Organisers	Key, Driving
-P1	The total cost of printing during the design process shall be no greater than 62.50 euros [7].	Designers	

Sustainability

Table 5.7: Sustainability requirements.

ID: AIG-NT-	Requirement	Stakeholders	Classification
-S1	The rated lifespan of components shall be at least 2 years.		
-S2	The components of the drone shall be interconnected using temporary joints.	Environment	
-S3	The amount of waste material during the final production phase shall not exceed <tbd> kg.	Environment	

User Safety

Table 5.8: User safety requirements.

ID: AIG-NT-	Requirement	Stakeholders	Classification
-U1	The drone shall have a ’safety mode’, which, when activated, attempts to prevent hazards and incidents.	Users, Organisers, Spectators	
-U2	The drone should adhere to European fire safety regulations.	Users, Organisers, Spectators, Government	
-U3	All materials used in the drone shall comply with the RoHS 1 and RoHS 2 restrictions on hazardous substances.	Users, Organisers, Government	
-U4	The drone can be hand-held safely while the rotors are spinning.	Users, Organisation	

Regulations

Table 5.9: Requirements due to regulations.

ID: AIG-NT-	Requirement	Stakeholders	Classification
-R1	The maximum speed of the drone shall be lower than 44.7 m/s [1].	Users, Organisers, Government	
-R2	The drone shall have an ’arming switch’, which can be used to allow the drone to move under its own power.	Users, Organisers	Driving

6 Design Options

The analysis of all possible designs is a crucial steps in the design process. No design consideration should be left out and therefore an overview of all possible design options has to be constructed, which is done in section 6.1. The next step will be to eliminate non-feasible design options from this list, this process is described in section 6.2. The survivor options are then evaluated in section 6.3. From this, several design options, which will be further analysed in the phase, are described in section 6.4. Finally a preliminary technical budget will be constructed in section 6.5. This will include an initial estimation of how mass, power and cost will be divided between different subsystems.

6.1. Design Option Tree

All designs need to be considered in order to not reject any solution to the problem before having analysed it. In order to do so, a design option tree was used to evaluate all design options. The design option tree is an OR tree, meaning that only one of the option below the pink boxes can be selected. Since most design choices are independent from each other, a non-conventional step-procedure design option tree was chosen for. Here, every design step to be taken is specified in a pink box, and the OR-tree is shown in the green boxes where only one option shall be selected. The design option tree can be found at the end of this section in Figure 6.2.

6.2. Elimination of Design Options

Configuration

- **C.3.1.1** Single rotor: would rotate around its own axis, since there is no second rotor to counter the torque the first rotor generates.
- **C.3.2** Rocket propulsion: Infeasible, because of safety, environment and poor controllability.
- **C.3.3** Flapping: Elimination due to speed and acceleration attainable and required mismatch. Any hybrid involving flapping wings is not feasible due to the drag induced by the size of the flapping wings.
- **C.3.5** Sail: Elimination due to thrust level attainable and required mismatch cannot be overcome at this size. Any hybrid involving sails is not feasible due to the drag induced by the size of the sail.
- **C.3.6** Buoyant drone: Infeasible, due to poor performance it will not comply with speed and acceleration requirements.
- **C.3.7** Hybrid: All three part hybrids are eliminated due to their added complexity which adds weight and makes impact resistance unfeasible. For the two part hybrids:
  - Sail + any other propulsion type: Eliminated, because sail introduces drift, non-existing technology and very hard to reach required speeds, acceleration and size.

- Rockets + any other propulsion type: Eliminated, because configurations with rockets are deemed too dangerous.
- Buoyant + Rotors: Not eliminated.
- Buoyant + Flapping: Eliminated due to very high complexity, while it is still doubtful if requirements can be met.
- Buoyant + Jet: Not eliminated.
- Jet + Flapping: Very hard to make compatible, thus very high weight and complexity.
- Jet + Rotors: Not eliminated.
- Flapping + Rotors: Eliminated, due to difficulty to make compatible and therefore there it is highly complex (for future).

Electronics

- **E.1.1.2** Non-rechargeable battery: Eliminated due to very bad score regarding sustainability, especially considering the testing phase of the drone.
- **E.1.2** Mechanical energy: Infeasible, because with sufficient amount of energy, the high angular momentum would severely impact controllability. Spring energy would not be sufficient or too heavy.
- **E.1.5** Nuclear fuel: Infeasible, because of safety, environment and limits on technology.
- **E.1.6** No energy storage: Infeasible, technology limits generating enough energy mid-flight, direct energy supply would negatively impact controllability.
- **E.3.1** Measuring no quantities: Infeasible, because availability of race track information will severely decrease.

Structures

- **S.2.5** Ceramics: Too brittle, therefore not impact resistant.
- **S.4.1** No extra (electronics) protection: All on-board systems have to be protected and shall not break when falling $3\ [m]$ onto concrete, this requires extra electronics protection. This is due to the fragile nature of electronic with respect to g-loads, which propagate very easily without any extra protection.

Propulsion System Unit

- **P.2.2**: Redundant PSU (for structural protection): Adding complexity and weight, while the design aims for high speed and agility.

6.3. Survivor Design Option Evaluation

This section describes the investigation of the design options that are not eliminated and sums up the advantages and disadvantages of those survivors. This helps to decide between possible design options and find the paths leading to the final design choices.

Configuration

- **C.1.1** - Wing
  - **Pros:** Lift is not dependent on propulsion only
  - **Cons:** Heavy, slow reaction speed, very low agility
- **C.1.1.1** - Single wing

  - **Pros:** Conventional, plenty of literature available
  - **Cons:** Difficult to control if this wing is used as only control surface

- **C.1.1.2** - Multiple wings
  - **Pros:** More lift generated
  - **Cons:** Complex, heavy, large aerodynamic drag, more parts that can fail structurally

- **C.1.2** - No wing
  - **Pros:** No extra weight, no extra drag
  - **Cons:** Lift is all generated by propulsion

- **C.1.1.2.1** - Fixed wing
  - **Pros:** No extra complexity which results in less weight and less parts prone to failure
  - **Cons:** Less controllable

- **C.1.1.2.2** - Only adjustable wings
  - **Pros:** Higher controllability
  - **Cons:** A lot of extra complexity and thus more weight and parts prone to failure

- **C.1.1.2.3** - Hybrid of fixed and adjustable wing
  - **Pros:** Combination of 1.1.2.1 and 1.1.2.2
  - **Cons:** Combination of 1.1.2.1 and 1.1.2.2

- **C.2.1** - Small (max. dim. 10cm)
  - **Pros:** Less aerodynamic drag, low moment of inertia, more agile, easier to get through gate, less materials required to construct
  - **Cons:** Not able to carry a lot of hardware

- **C.2.2** - Medium (max. dim. 30cm)
  - **Pros:** Average of C.2.1 and C.2.3
  - **Cons:** Average of C.2.1 and C.2.3

- **C.2.3** - Large (max. dim. 50cm)
  - **Pros:** More room to place sensors, can carry more hardware, more room to position structural protection components like fan guards
  - **Cons:** Higher aerodynamic drag, higher weight, higher moment of inertia, less agile, more materials required to construct

- **C.3.1** - Rotors
  - **Pros:** Readily available, cheap, easily replaceable, decent thrust to weight, low structural weight
  - **Cons:** Noisy

- **C.3.1.2** - Dual rotor
  - **Pros:** More efficient energy distribution, less structural parts that can break

  - **Cons:** Unstable, at least two motor gimbles needed to make drone controllable in all degrees of freedom

- **C.3.1.3** - Triple rotor
  - **Pros:** More stable than a bi-copter design
  - **Cons:** One gimble needed to make drone controllable in all degrees of freedom
- **C.3.1.4** - Quad rotor
  - **Pros:** Good controllability
  - **Cons:** More parts
- **C.3.1.5** - 5+ rotor
  - **Pros:** Complex manoeuvres possible, high thrust possible
  - **Cons:** Complex (many parts to fail), heavy, inefficient
- **C.3.4** - Jet
  - **Pros:** High maximum velocity, high thrust
  - **Cons:** Very expensive, heavy, mediocre thrust to weight ratio, highly complex, dangerous (flammable), emits C02, has extremely hot exhaust gas.

Electronics

- **E.1.1** - Electrochemical (battery)
  - **Pros:** Inexpensive, easy to use
  - **Cons:** Not recyclable, low energy density
- **E.1.3** - Chemical (fossil fuels, biofuel, hydrogen)
  - **Pros:** High energy density
  - **Cons:** Polluting, less safe, more complex
- **E.2.1** - Minimum computational power
  - **Pros:** Lighter, inexpensive
  - **Cons:** Limited processing capabilities, limited use
- **E.2.2** - Medium computational power
  - **Pros:** More use than E.2.1, still lighter and cheaper than E.2.3
  - **Cons:** Still limited in use and capabilities
- **E.2.3** - Maximum computational power
  - **Pros:** Most processing power, most versatility
  - **Cons:** Heaviest option, most expensive option
- **E.3.2** - Few measurements
  - **Pros:** Light, cheaper overall sensor cost
  - **Cons:** Limited data available
- **E.3.3** - Many measurements
  - **Pros:** Large data quantity available for processing
  - **Cons:** More expensive overall sensor cost, heavier, more prone to damage

Structures

- **S.1.1** - PSU attached by arm
  - **Pros:** Longer moment arm for turns
  - **Cons:** Another part that may break, PSU more exposed
- **S.1.2** - PSU attached to main body
  - **Pros:** Small moment of inertia, less parts to break smaller mass
  - **Cons:** Smaller moment arm
- **S.1.3** - PSU integrated inside structure
  - **Pros:** Protected very well, less parts to break, small moment of inertia
  - **Cons:** Smaller moment arm
- **S.1.4** - Hybrid
  - **Pros:** Combination from S.1.1 - S.1.3
  - **Cons:** Combination from S.1.1 - S.1.3
- **S.2.1** - Wood
  - **Pros:** Cheap, lightweight, easy to manufacture
  - **Cons:** Low strength, splintering when breaking
- **S.2.2** - Composites
  - **Pros:** Very stiff, high impact resistance, very lightweight (many different composites)
  - **Cons:** Expensive, difficult to manufacture, splintering when breaking (many different composites)
- **S.2.3** - Metals
  - **Pros:** Cheap, rather easy to manufacture, high impact resistance, ductile
  - **Cons:** Heavy
- **S.2.4** - Polymers
  - **Pros:** Very cheap, easy to manufacture, very special shapes possible (with 3D printer), ductility possible, which can offer better protection
  - **Cons:** Lower strength, degradation
- **S.3.1** - No aerodynamic shell
  - **Pros:** Less weight
  - **Cons:** Less protection if aerodynamic shell is used for protection, more drag/less lift possible
- **S.3.2** - Aerodynamic shell
  - **Pros:** More lift/less drag possible, protection if aerodynamic shell is used for protection, good aesthetics
  - **Cons:** Heavier, more complexity
- **S.4.2** - Extra protection of electronics
  - **Pros:** Safer after crash/longer lifetime, good for aesthetics
  - **Cons:** Heavier, more complexity

Propulsion

- **P.1.1.1** - Symmetric PSU placement
  - **Pros:** Moment equilibrium while hovering, easy to control
  - **Cons:** Less flexibility in design and weight distribution
- **P.1.1.2** - Asymmetric PSU placement
  - **Pros:** More flexibility in (aerodynamic) design and weight distribution
  - **Cons:** Likely no moment equilibrium while hovering, hard to control
- **P.1.2.1** - In-plane PSU placement
  - **Pros:** Likely lighter, easier to control
  - **Cons:** Less flexibility in design
- **P.1.2.2** - Out-of-plane PSU placement
  - **Pros:** More flexibility in design e.g. staying out of the wake of other rotors.
  - **Cons:** Likely heavier due to more structural weight, harder to control
- **P.2.1** - Robuster PSU
  - **Pros:** Easy to manufacture, likely easy to repair
  - **Cons:** Likely more costly, heavier PSU, restricting in the choice of PSU, hard to verify.
- **P.2.3** - Physical protection around PSU
  - **Pros:** PSU choice not restricted, optimal PSU structural design and weight possible.
  - **Cons:** Harder to manufacture, likely harder to repair
- **P.3.1** - Variable orientation of PSU's
  - **Pros:** Quicker and more accurate response possible, good agility, optimized for both lift and thrust
  - **Cons:** Likely heavier, harder to control, higher complexity
- **P.3.2** - Fixed PSU's in flight direction
  - **Pros:** Optimized for thrust
  - **Cons:** Need for a lifting device or control mechanism, bad stability
- **P.3.3** - Fixed PSU's not in flight direction
  - **Pros:** Optimized for lift, good stability
  - **Cons:** Not optimized for thrust, need for a thrust device or control mechanism

6.4. Concepts Proposal

Several concepts will be proposed that will be further analysed in the midterm report. These concepts will be based on options that have not yet been eliminated as non-feasible.

In order to ensure that all solutions were considered, five main overarching concepts were established. The goal was to provide guidelines regarding the relative importance of the different performance components of the drone and generate designs accordingly. The resulting design would then be built around the specific concept to provide the most optimised solution accordingly.

Each concepts listed here present a particular focus which, when evaluated against the object mission and statement, offers serious potential:

1. **AI/Processing power focus:**
   The prime focus of this concept is to provide the racing teams with as much on-board processing power as possible. This would allow heavier algorithms to be run and thus offer better capabilities and versatility in terms of software. The drone would then be designed around this main target to provide the best possible performance possibles (while privileging the processing power).

2. **Sensor focus:**
   The prime focus of this concept is data variety and abundance. Having a large amount and variety of sensors, along with a large range of angles could provide teams with better possibilities and insight in the drone state. This would open up new possibilities in terms of approach, and as such also greatly impact racing performance.

3. **Modularity focus:**
   The prime focus of this concept is user freedom and tailoring of the vehicle to a specific need. Providing a system with interchangeable parts such as different sensors, different sensor layout, different amount of computing power, different structural protection etc... would allow each team to restructure their drone and allocate their technical budget according to their needs. This complies especially well with the mission objective and statement as it would enable teams to effectively choose the type of data gathered, the ”physical performances” of the drone (larger number of modules or bulkier protection = heavier and less maneuverable drone) and the characteristics of the drone at the different stages of the AI design process (a larger and heavier protection might be more adapted during the testing/training phase).

4. **”Physical performance” focus:**
   The prime focus of this concept is speed and agility. Offering a drone mainly focused on handling and speed performance for racing does make a lot of sense, and as such putting emphasis of that would provide teams with a powerful racing vehicle to base their designs on. An interesting way to achieve this would be investigating to use variable pitch rotors. Even though these rotors have existed for some years and a solid base of research exists, they have not yet been implemented in many drones. The advantages of them over fixed pitch propellers are the following: They provide orders of magnitude faster response time to thrust changes, they have the ability to generate constant thrust, they have the ability to autorotate. The first and second advantage mean that these propellers will make the drone extremely agile and greatly expand the control saturation limits. The main disadvantage is the added complexity in the mechanical design, which will need to be investigated further.

5. **Durability focus:**
   The prime focus of this concept is to make a durable drone. This design is proposed on the basis that teams would have the ability to perform more testing before the competition, without the drone becoming non-operational due to a crash. More tests could lead to more advanced/accurate and better performing algorithms.

6.5. Technical Budget Breakdown & Planning

This chapter introduces the technical budget that restricts the design of the AIgle drone. First the mass, power and cost budgets will be shown and explained and thereafter in subsection 6.5.2 the possible unexpected changes to those budgets will be investigated and a mitigating contingency plan worked out.

6.5.1. Technical Budget

The restrictions for the drone design result in the mass budget, power budget and cost budget. The detailed budget of each is shown in Figure 6.1 and takes the different systems of the drone and their subsystems for more detail into account.
From the requirements follows a maximum mass budget of 1000 $[g]$, which is split up between the subsystems with large weight on electronics budget, which will have to include the battery, one of the heaviest components on the drone. The power budget has been set at 300 $[W]$ as the highest consumption by the propulsion system, which includes the motors necessary to fly the drone. The cost budget results from another requirement set at maximum 2500 [€], which is driven by the complex and therefore expensive electronics.

	Mass Budget			Power budget			Cost Budget		
Subsystem	Budgeted Mass (%)	Possible error range (+-%)	Budgeted Mass (g)	Budgeted Power (%)	Possible error range (+-%)	Budgeted Power (W)	Budgeted Cost (%)	Possible error range (+-%)	Budgeted Cost (€)
Structure	30	-	300	-	-	-	17	-	425
Frame	25	10	250	-	-	-	15	15	375
Cover	5	10	50	-	-	-	2	10	50
Aerodynamics	-	-	-	-	-	-	-	-	-
Electronics	42	-	420	18	10	54	48	-	1.200
Battery	25	10	250	2	10	6	6	10	150
Antenna	2	10	20	1	10	3	2	10	50
Computer	15	10	150	15	20	45	40	20	1.000
Power and Propulsion	11,5	-	115	75	-	225	8	-	200
Propellor	2,5	10	25	-	-	-	2	10	50
Motor	9	20	90	75	10	50	6	10	150
Machine Vision	15	-	150	6	-	18	20	-	500
Sensors	15	10	150	6	10	18	20	10	500
Navigation	-	-	-	-	-	-	-	-	-
Control	-	-	-	-	-	-	-	-	-
Other	1	-	10	1	-	3	6,5	10	163
Production	-	-	-	-	-	-	6	10	150
Leds	1	1	10	1	1	1,00	0,5	1	13
Total	100		1000	100		300	100		2.500

Figure 6.1: Technical budget for the mass, power and cost of the AIgle drone design

6.5.2. Technical Budget Contingency Planning

The general preliminary technical budgets established during the exploration phase are generally inaccurate, and likely to be subject to significant changes and modifications as the design matures. This presents significant risks as too much deviation from the initial planned budgets could lead to a failure to fulfill certain requirements. To account for these modifications, safety margins (or uncertainty margins) are included at each phase of the design process. These margins are gradually reduced as the design progresses. Any design or design choices resulting in components falling outside of the specified margins will require iterations of the subsystem. If the resulting subsystems falls outside of the total allowed budget, a compromise needs to be found, and other subsystems might as a result be iterated over. To better illustrate this, the example of the drone frame can be taken. In the preliminary phase, a margin of +-10% of the total budget is considered. During the preliminary phase, this error margin is reduced to +-5%, to finally achieve an accuracy of +-2% during the detailed design phase.

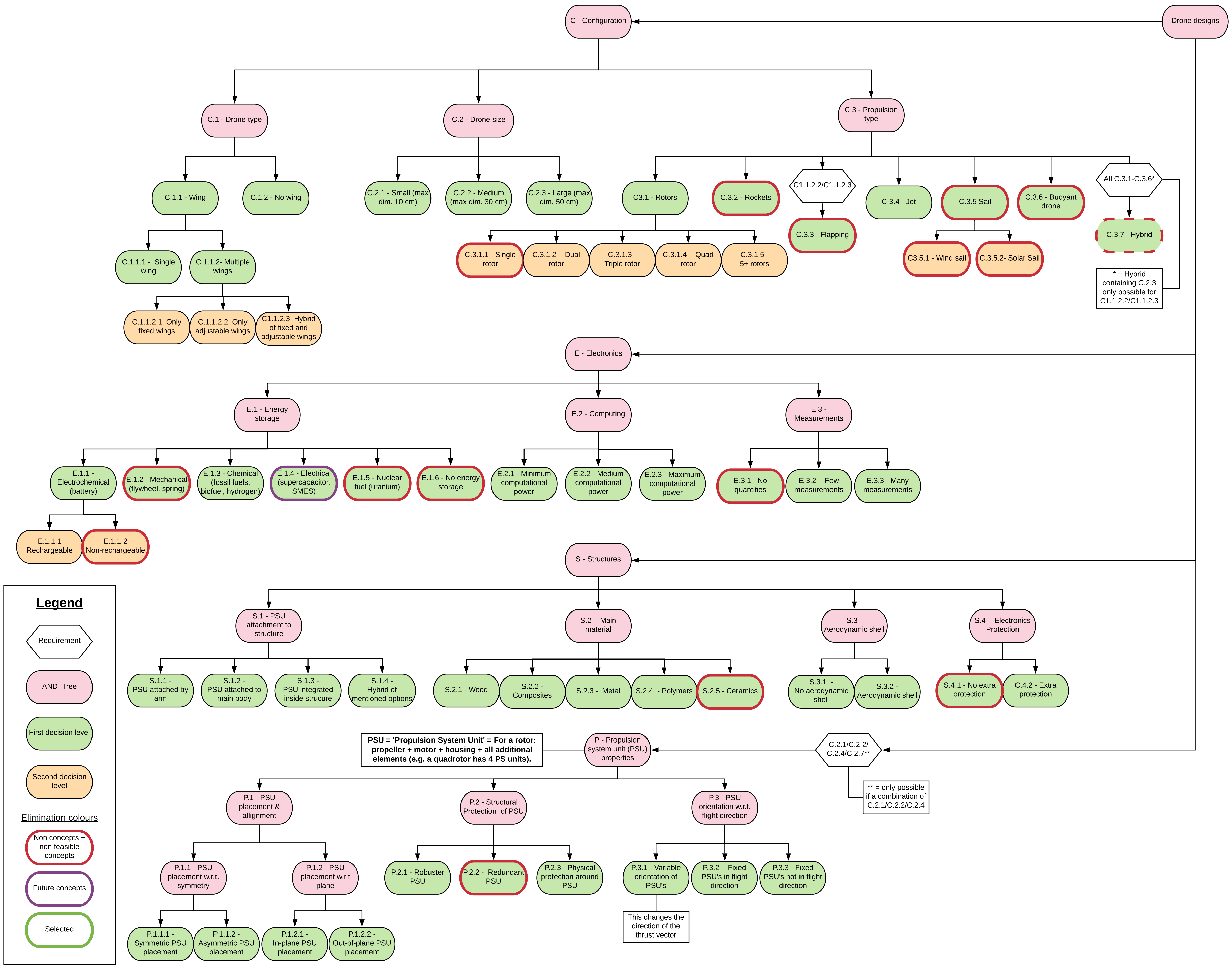

Figure 6.2: The Design Option Tree

7
Technical Risk Assessment and Mitigation

To start the Risk analysis first a technical SWOT analysis is done in Section 7.1 to identify the weaknesses and threats to the project, but also to look for strengths and opportunities that are useful to reduce the risk involved. Next, the events that can cause risks are identified and an explanation of the drivers of the risks is given in Section 7.2. Finally, a plan to mitigate the risks is given in Section 7.3.

7.1. SWOT Analysis for the Technical Risks

Table 7.1: SWOT analysis for technical risks

Strengths	**Weaknesses**
The relative low weight and small dimensions allow for high agility and performance	A crash will have larger impact at high speeds
Relative cheap design that is easily repairable allows for a lot of testing.	A lot of electronic components in a small space can cause problems like overheating or short circuit
	The vision can get blurry at high speeds
	The dimensions and weight do not allow much reinforcement
Opportunities	**Threats**
There are a lot of high strength, low density materials available	People can get hurt when the drone becomes uncontrollable
Nowadays a lot of parts can be easily and cheaply acquired	Rules and regulations limiting the drone

7.2. Risk Assessment

For the risk assessment a risk map is created with events that will bring certain risks. The drivers behind these events is explained and the probability and impact is estimated based on engineering judgement.

Structural

1. Structural failure on impact: The structure will be vulnerable since it cannot be reinforced infinitely because of the weight and size requirements. Furthermore, the impact forces when crashing will be high due to the high speeds. Therefore, the probability and the impact will be high.

Electrical

2. Electrical subsystem failure on impact: The electronics are an essential yet vulnerable part of the drone, which can easily break in a crash. Since a crash will inevitably happen at some point the probability is high and the impact as well.

3. Power loss mid-flight: This can happen due to e.g. overheating of the electrical system or short circuit. It will probably not happen often, but can cause a crash leading to a big impact.

Control and stability

4. Drone becomes uncontrollable by the pilot: Can be caused by a small crash/malfunction cutting out communication and can lead to unsafe situation for both the drone as well as the people present.
5. Singularities due to Euler angles: Since a racing drone is supposed to be agile and make very extreme maneuvers singularities can easily occur when using Euler angles for attitude control. This can make the drone uncontrollable and therefore likely to crash.

Propulsion and performance

6. Propellers breaking due to impact: Will happen often since it will probably be the weakest part of the drone and is likely to come in contact with the environment first. It might have a big impact since the is a possibility the drone cannot fly with one propeller less.
7. Motor malfunction: A motor might provide lower or no thrust. This greatly affects the control of the drone.

Navigation and computer vision

8. Computer vision being insufficient for Navigation: It is a common problem, especially with indoor races, that the vision becomes blurry at high speeds or when the drone cannot find the next gate. Could make the drone not being able to navigate and therefore uncontrollable by the AI.

General

9. Loss of data after failure: When the electrical subsystem malfunctions data might be lost, making it hard to track what went wrong. Probability will be high, the impact not necessarily high, but it is still unfortunate for improving the drone.
10. Over-designing subsystems: Probability will be reasonably high since there will be designed around uncertainties, which can lead to over-designing to stay on the save side. When, for example, the Propulsion and Computational system are over-designed the Electrical system will not be able to deliver the required power. It will then be uncertain if it can still perform the mission.
11. Under-designing subsystems: Again, since the design is based on uncertainties, there will be a good probability a subsystem will be under-designed and therefore will under-perform. Again causing uncertainty to perform the mission.

All these Events will have an impact on the technical performance and a probability at which they occur. These can be mapped in a Risk Map as shown in Table 7.2. The meaning of the indication of the impact is explained:

- **Negligible:** Very low impact causing only small inconveniences, does not directly influence the technical performance. However, if it happens often it can cause considerable risk.
- **Marginal:** Low impact, can cause a small reduction in technical performance.
- **Significant:** Medium impact making mission success harder, technical performance will be reduced.
- **Critical:** High impact leading to questionable mission success, significant reduction in technical performance.
- **Catastrophic:** Very high impact leading to mission failure, technical performance compromised heavily or not even achieved.

Table 7.2

Impact	Almost Impossible	Unlikely	Likely	Very Likely	Almost Certain
Catastrophic			3, 4		1, 2
Critical			10, 11	5, 8	6
Significant			7		
Marginal				9	
Negligible					

Probability

Very high risk, avoid if possible
High risk, action required
Medium risk, action preferred
Low risk, acceptable

7.3. Risk Mitigation

Structural

1. Structural failure on impact: By reinforcements of the structure where possible and a good material choice the probability of breaking due to a crash will be lowered. This will require a big portion of the mass and cost budget relative to other drone designs. Also lowering the impact by making it easy and cheap to replace or repair the broken parts will reduce the risk involved.

Electrical

2. Electrical subsystem failure on impact: Protecting the electrical subsystem where possible and prioritising this protection around the difficult replaceable and expensive parts to reduces the probability of breaking during a crash. Make vulnerable parts easy replaceable to reduce the impact. A good collaboration between the Electrical department and Structural department is required. Furthermore, it will also raise the mass and cost budget of the Structural department.
3. Power loss mid-flight: By retrieving mission data of the drone e.g. voltage, current and temperature malfunctions such as this one can be anticipated with more confidence. Due to this the probability and impact can be reduced.

Control and stability

4. Drone becomes uncontrollable by the pilot: Implementing a ”kill switch” which put the drone into safe mode, immediately shutting it down to reduce the impact it can have.
5. Singularities due to Euler angles: Avoid using Euler angles so the probability this event will happen is zero.

Propulsion and performance

6. Propellers breaking due to impact: Either the propellers can be protected or can be made very easily replaceable or both by protecting the propellers against certain, most common, crash angles. Both to reduce the probability and the impact for breaking a propeller.
7. Motor malfunction: High quality motors and less feedback loops for the propulsion system can reduce the probability of this event occurring. This solution will require an increase in the cost budget for the high quality motors.

Navigation and computer Vision

8. Computer vision being insufficient for Navigation: A take-over from the pilot reduces the impact this event can have. Also, making the field of vision big enough, implementing a camera able to operate at a high frame rate and implementing a computer able to handle those high frame rates will reduce the probability of this event occurring. This will require a large part of the mass, computing power and cost budget.

General

9. Loss of data after failure: The data should not only be stored in the drone, but there should be also a possibility to sent and store information outside the drone so there is always a back-up.
10. Over-designing subsystems: The System Engineers will have to pay close attention if every department stays within the technical budget and address it immediately (also to the other departments) if that is not the case, to prevent it from happening and reduce the impact as everyone will be aware.
11. Under-designing subsystems: A safety margin has to be established to account for uncertainties in the design, while staying within the technical budget. This will reduce the probability of this event occurring.

Table 7.3

Impact	Almost Impossible	Unlikely	Likely	Very Likely	Almost Certain
Catastrophic					
Critical	5	11		1, 2	
Significant		3, 7, 10	4, 8		
Marginal				6	
Negligible				9	

Probability

- Very high risk, avoid if possible
- High risk, action required
- Medium risk, action preferred
- Low risk, acceptable

As can be seen when comparing Table 7.2 and 7.3 the prediction is that with the risk mitigation plan the risk will be significantly lower. However, still not every risk is in an acceptable region. The risks in the ”Medium risk” region will have to be watched closely and more actions might have to be taken in a later stadium when there is more information available. For the ”High risk” more research has to be done in order to find possibilities to reduce the risk even further.

8 Conclusion

The aim of the Baseline Report is to conduct research on various aspects related to the project, analyse the functions of the designed drone and possible design options, in order to determine a few drone concepts that will be further investigated for the Mid-Term Report. The team started by performing a market analysis to determine the possible customers, their needs and a suitable price range. The main identified customers were AI racing drone teams created by mainly universities but also independent amateurs who will now be able to participate thanks to the open-source availability of the design. The AIgle drone will be attractive to those customers if the design is modular, affordable, and first of all, if the drone is fast and has a large computational power. However, the performance should not be the only focus of the project, as the environmental aspects are of great importance as well. To this end, a sustainability development approach was conceived by conducting a life cycle assessment. Then, sustainability criteria were identified and given a weight factor based on their influence on sustainability. These criteria will be used to help evaluate designs during concept selection, and later during detailed component selection, to ensure for the best trade-off between performance and sustainability.

After performing these analyses, a literature study on specific subsystems of the drone was conducted, resulting in the Functional Flow Diagram and the Functional Breakdown Diagram. These diagrams show all the functions that have to be performed throughout the life of a drone. The most important aspect is the operating phase of the drone, where all the relevant functions, their order and influence on each other were determined. This allowed to better understand the working principles of drones and will be immensely helpful during the preliminary and detailed design phases. This also helped to make the Requirement Discovery Tree, where high level requirements were defined for all the design aspects of the drone, with the most important aspects concerning the computational power, flight performance and impact resistance.

Moving on, after determining the most important requirements, multiple design concepts were generated and collected in a Design Option Tree. The tree was then ”pruned”, which means many concepts were already eliminated, leaving a few options to consider in the next design phase. Based on these remaining concepts, 6 design ”philosophies” were established. They each focus on optimizing a different aspect of the drone: 1. Processing power, 2. Sensor measurements, 3. Modularity, 4. Physical performance, 5. Durability, 6. Novel technology. These design concepts will be further investigated and a preliminary design will be done for each of them, in order to determine the most optimal design that will be fully developed in the detailed design phase of the project.

Finally, a crucial part of conceptual design is establishing the technical risks related to the high level, but also some lower level, technical aspects of the design. These should all be identified and a mitigation strategy developed, such that the designers realise the risks and consider them during the project. After the risk analysis, two risks remained ranked as high risk, even after the mitigation strategy. These are the risks related to the structural and electrical system failure upon impact. Throughout the project, the team will focus on minimizing these, while also keeping all the other risks low.

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