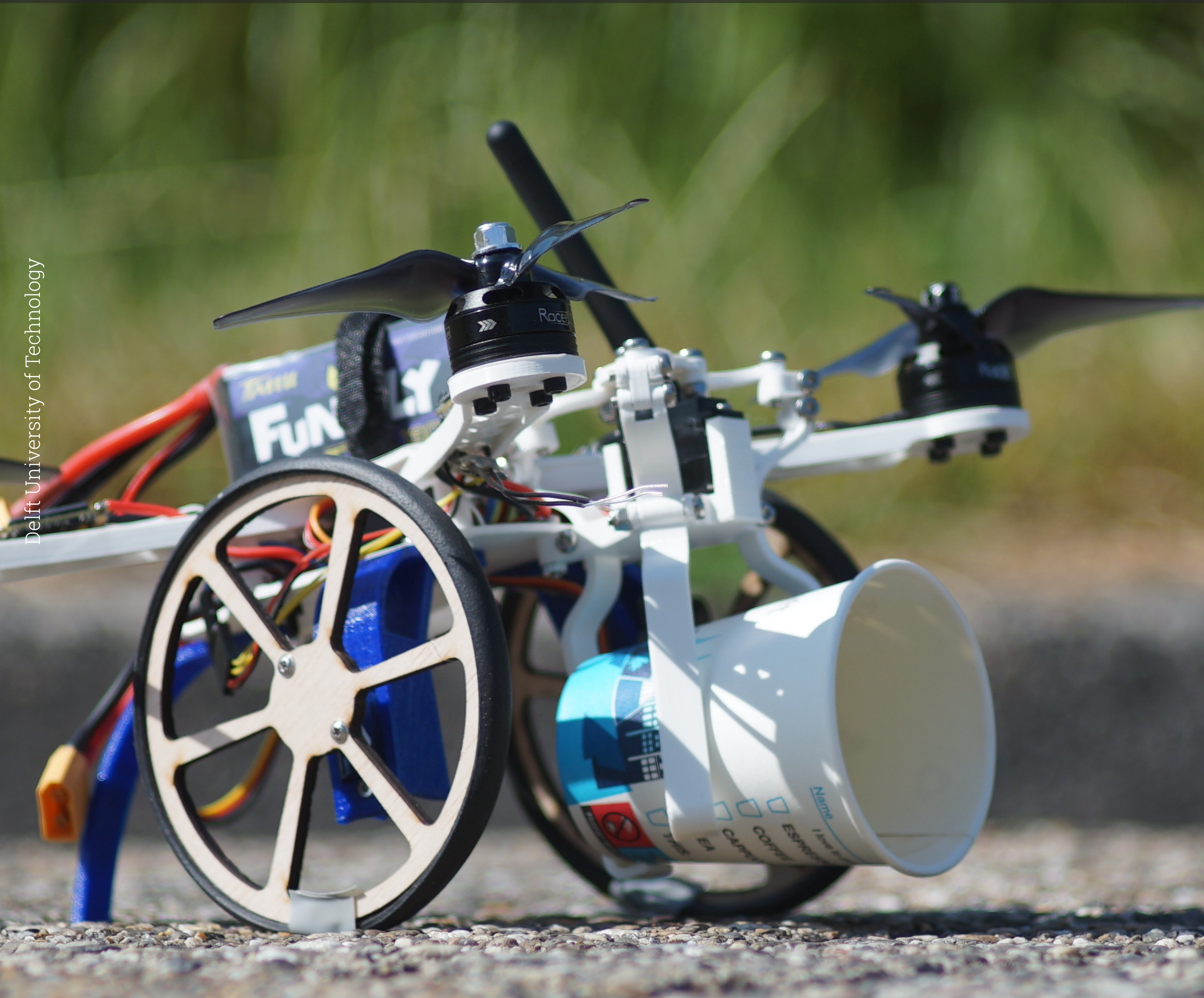
ADIOS

The Final Report

AE3200: Design Synthesis Exercise

Group 17



Delft University of Technology

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ADIOS

The Final Report

by

Group 17

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Project Duration:	April - June 2023
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Nomenclature

Abbreviation	Definition
ADIOS	Autonomous Drones Integrated Operational cleaning System
AI	Artificial Intelligence
BVLOS	Beyond Visual Line-Of-Sight
CAGR	Compound Annual Growth Rate
COG	Centre of Gravity
EPS	Electrical Power Supply
ESC	Electronic Speed Controller
FBS	Functional Breakdown Structure
FFD	Functional Flow Diagram
FPV	First Person View
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input/Output
GPU	Graphics Processing Unit
GS	Ground Station
LiPo	Lithium-Polymer
LQI	Linear Quadratic-Integral Regulator
LQR	Linear Quadratic Regulator
OSD	On-Screen Display
PDB	Power Distribution Board
RAMS	Reliability, Availability, Maintainability and Safety
RPM	Revolutions Per Minute
SPL	Sound Pressure Level
SWOT	Strengths, Weaknesses, Opportunities and Threats
TT&C	Telemetry, Tracking and Command
UART	Universal Asynchronous Receiver-Transmitter
UAV	Unmanned Aerial Vehicle

Symbol	Definition	Unit
A	Area	[m^2]
b	Propeller thrust coefficient	[Ns^2]
B	Number of Blades	[-]
c	Speed of sound	[m/s]
C_{Ah}	Battery Capacity	[Ah]
d	Diameter	[m]
f	Frequency	[Hz]
FPS	Frames Per Second	[1/s]
g	Gravitational acceleration on Earth	[m/s^2]
i_d	Disc Incidence Angle	[deg]
I	Area moment of inertia	[m^4]
I_{xx}	Mass moment of inertia around x-axis	[kgm^2]
I_{yy}	Mass moment of inertia around y-axis	[kgm^2]
I_{zz}	Moment of inertia around z-axis	[kgm^2]
k	Propeller moment coefficient	[Nms^2]
L	Length	[m]
m	Mass	[kg]

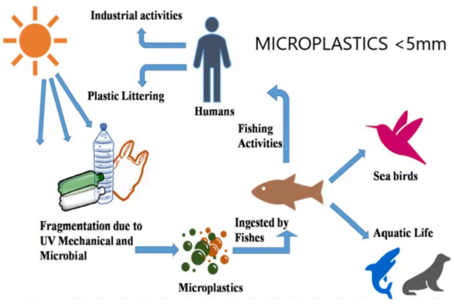
Symbol	Definition	Unit
M	Rotational Mach Number	[-]
M_f	Flight Mach Number	[-]
M_e	Effective Rotational Mach Number	[-]
n	Radial Velocity	[rad/s]
n_{bats}	number of drone batteries	[-]
P	Power	[W]
P_{charge}	Power draw of drone batteries during charging	[W]
P_{GS}	Ground station power	[W]
r	Range	[ft]
R	Radius	[ft]
t_{hour}	Time	[h]
t_s	Time	[s]
tp	true positive	[-]
fn	false negative	[-]
T	Thrust	[N]
U	Voltage	[V]
V	Velocity	[m/s]
x	X-position	[m]
y	Y-position	[m]
z	Z-position	[m]
α	angle of impact	[°]
ϵ	Angle between flight direction and the line joining the rotor and field point [deg]	
ρ	Density	[kg/m^3]
θ	Angle between rotor plane and line	[deg]
θ	Pitch angle	[rad]
μ_{bat}	Battery Charging Efficiency	[-]
μ_{grid}	Charing from Grid Efficiency	[-]
ϕ	Roll angle	[rad]
ψ	Yaw angle	[rad]

Executive overview

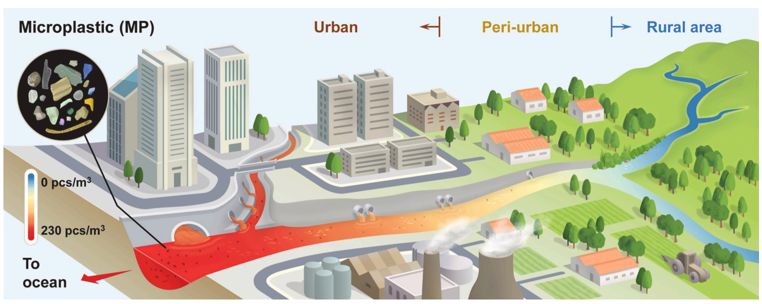
The Autonomous Drones Integrated Operational Cleaning System (ADIOS) is the Design Synthesis Exercise of Group 17, a team of ten Aerospace Engineering students from Delft University of Technology. The project aims to design a system that is capable of cleaning litter in a fast, energy-efficient, and autonomous manner by utilising drones. This chapter begins by addressing the problem after which it will go into describing the project. Afterwards, a summary of the design of the system is described, followed by the operation of the system. Next, important performance parameters are showcased and a brief financial analysis is given. After this, the production of the system is described, along with the sustainability measures incorporated. Finally, an overview of the prototype developed during the project is depicted in and the future development of the system is summarised.

Problem statement

Littering in urban areas poses a serious threat across the globe. With an increasing human population, the amount of waste escalates as well, having an impact on the environment, biodiversity and human health. Litter pieces such as soda cans or plastic bags left in animal habitats destroy nature by, for example, polluting water or contaminating soil. Litter from urban areas can be washed away towards the sea (Figure 1b), leaving not only birds but also fish to ingest these pieces. Animals consume these non-digestible pieces of litter, either killing them or passing microplastics to their consumer, which often happen to be humans (Figure 1a). These microplastics have adverse effects on human health due to their toxicity, leading to many health risks [71] [111]. In light of these reasons, there is a need for a rapid and flexible litter cleanup system.



(a) Microplastics entering the food chain[70]



(b) Microplastics being washed away toward ocean[107]

Traditionally, the cleanup of litter in urban areas is done manually by people with picking tools, grabbers or brooms. While more often innovative ideas are introduced, such as mobile machines, most of the methods are still time-consuming, costly and require large amounts of manual labour. They also tend to be ineffective or unable to operate in hard-to-reach areas, such as narrow alleys or steep slopes. These constraints all rely on manoeuvrability and mobility, which could be fixed when using drones.
With the advancing technology of drones, they are increasingly introduced for commercial purposes [90]. When considering the cleanup of litter, they could be useful in view of the fact that they have high accessibility. Their ability to avoid obstacles, like fences, poles and waterways, makes them practical and efficient for picking up litter in urban areas. Additionally, to make the system autonomous, artificial intelligence (AI) could be used for litter detection. Image detection is an AI feature that enables the understanding to interpret visual information in computers. It is already used in a wide range of applications, from landmine detection to cancer detection purposes [31] [84]. Additionally, image detection allows for categorisation of litter types. This can play a role in determining which grabbing system should be used for litter pieces with various dimensions and weights. With this, it is helpful for sorting the litter as well, facilitating recycling possibilities.
The drones require transport, docking and a communication system, which can be provided by an

installable ground station system. This is an electric van driven by the operator of the system. A ground station is needed to control the operations with commands, where the driver intervenes when any kind of failure occurs. This ensures safety and security, which entirely relies on durable energy sources.
The ADIOS covers all these capabilities. It is a flexible, sustainable and fast way of cleaning up large areas of litter. Due to automation, it has the potential to be extremely scalable, reducing labour and costs globally. Designing for this requires accurate systems engineering and project management, which are two key aspects throughout the entire process. Considering this, risk analyses and risk mitigation are performed in multiple stages to account for all kinds of failures. To conclude, ADIOS will be a multidisciplinary attempt to clean up the world.

Project objective

This project symbolises the Design Synthesis Exercise (DSE) of Group 17. Ten aerospace engineering students from the Delft University of Technology aim to design ADIOS by combining their aerospace expertise, experience and knowledge with obtained skills in the bachelor's programme.
One crucial aspect of the ADIOS project is that the team does not aim for a design only. At the end of the DSE, the team should have established a product that should be market-ready in three years. To establish this product, it is essential that a need statement is formulated. In this case, the need statement is as follows:

"Litter must be removed from the environment".

This statement is held quite general because the system should be applicable in a wide range of possibilities. It ensures adaptability to changing circumstances, which makes it a flexible base.

To ensure that the product is ready for the market, one main objective is to win the symposium. In order to accomplish that, the team makes use of the uniqueness of the ADIOS principle by making a proof of concept. This way, the team works towards a demonstration to show the practicability of ADIOS drones. Along with the design goals, the project objective statement is as follows:

"The objective is to design an autonomous drone system to pick out litter from the environment and win the symposium with a proof of concept demonstration".

With this ambitious goal set, the team distinguishes a theoretical as well as a practical side of the project. While it may seem that this extra effort does not support the project hours, the proof of concept actually improves the quality of the design process. More specifically, building a proof of concept provides new insights; it can even serve as a validation method, to check whether the team is building the right product.
Aiming to design ADIOS, the team has to make a lot of considerations for the variety of litter, the use of multiple drones and the operational characteristics. The detailed design of the ADIOS system is the focal point of this report. The operation of the system is also extremely important, as even a stellar design can operate ineffectively if the logistics are not well considered.

Project approach

A 10-week project requires immense planning and effort in order to be successful. The project began in the first week by acquainting the task on hand and structuring the organisation of the group for the following 9 weeks. After this, market research into the field was performed. This included finding any current or previous attempts in automated drone-based cleaning systems as well as current litter cleaning methods and a literature review of automated drone systems. It was found that the concept had been conceived and attempted but was abandoned at the concept phase due to a lack of funding [49]. Studies into the distribution of litter and the types of litter were also performed to understand the optimal methods to pick up litter and operate the system. The research was carried out simultaneously to the derivation of the requirements from the stakeholder analysis. Key stakeholders were identified and their respective requirements were formulated. The main issues/requirements that were of concern were the safety, effectiveness, sustainability and autonomy of the system. The requirements formed the guidelines and basis for the design of the system as these had to be complied with in order to satisfy the stakeholders.

Figure 2: Visual representation of the drone with the grabber pick-up mechanism

ADIOS design

To start off the design, some brainstorming sessions were held. All types of propulsion, pick-up systems, drone configurations, control systems, etc. were written down. Then, all options were structured in design option trees. For each subsystem, feasible candidates were selected to advance to the trade-offs. In these trade-offs, all major decisions were made regarding the design. It was decided to go for a swarm of hexacopters that operate from a ground station that can be installed in a van or trailer. The litter pick-up system was decided to be modular, such that an operator can change the type of pick-up mechanism depending on the types of litter present in the area.

One day before the midterm deadline, the team made a shocking discovery. It was found that when a drone approaches litter to pick it up, the rotor wake is so strong that it blows away all trash it is trying to approach. The effect is so severe that approaching litter while flying is no longer a feasible option. Consequently, the next day, a new brainstorming session was held to collect some creative ideas on working around this problem. In the end, the group opted for putting wheels under the drone. This way, the drone can land at a small distance of a few meters from a litter piece, and then drive up to it before picking it up without the wake hindering the pick-up ability. This one of the major benefits of developing a prototype. It enabled the team to make discoveries which may not have been clear in theory and provides a platform to test new ideas to ensure their feasibility.

Drone Structure

The drone utilises a hexacopter configuration with a central hub under which the wheels and pick-up system are found. The central hub consists of a housing containing the central nervous system of the drone comprising of the sensors, controllers, battery, power distribution board, and safety components. The housing of the structure is made of biodegradable PLA and is required to shield the internal components as well as provide a more sleek and aerodynamic appearance. It is designed such that the battery can be easily removed and swapped with another reducing down time when the nominal battery is empty. The pick-up systems are attached below the centre of the housing using the modular design system. Six carbon fibre arms extend from the six corners of the hexagonal base on which the motors, propellers and propeller guards are placed. The wheels are placed below the drone and connected via suspension composed of TPU plastic.

Pick-Up System

After performing research into litter distributions, it was found that litter comes in various shapes and sizes and thus one pick-up mechanism would not suffice. Numerous different pick-up mechanisms were considered and traded-off based on their effectiveness for small and large litter pieces. Small litter pieces such as cigarette butts and plastic chips make 64% of the litter distribution [83]. In order to collect these, the trade off showed that a brush mechanism is the optimal design. The brush mechanism for the final design consists of a bucket attached to the base of the drone via a hinge arm with a servo brush at the mouth of the bucket. The hinge arm allows the bucket to rotate and is placed on the bucket such that the bucket is vertical in flight and rotates horizontally after landing to enable pick-up. During pick-up, the servo connected to the brush is switched on in turn sweeping up the litter into the bucket. The litter is expelled via the same method, except the bucket is now upside down relative to pick-up.

For large litter pieces such as plastic bottles and cans, a litter picker was selected from the trade-off. This works by driving over the litter and activating the servos to close the grips and compress the litter from above to keep it stable during the flight. Both mechanisms were tested using a prototype model and were successful in collecting litter. The ADIOS system consists of 6 drones of which 2 have brush mechanisms and 4 have litter picker mechanisms. However, the system is modular meaning if litter distribution in a certain area requires more brushes or litter pickers, the mechanisms can be quickly swapped using the bayonet mounting.

Computer vision

To be able to detect litter while conducting surveillance and approach litter autonomously and avoid collisions, the utilization of imaging devices is essential. The imaging data acquired using these devices must consequently be processed using a computer algorithm. An ideal candidate for this purpose is deep learning, with recent advancements facilitating the detection of objects with minimal computational costs at high accuracy. Moreover, deep learning offers the advantage of automatic feature detection, eliminating the need for manual engineering of feature extraction techniques.

As a solution, the YOLOv8 model family is chosen for object detection, as it provides high accuracy at a low computational cost. Among the available model sizes, the smallest variant, YOLOv8n, is preferred as the marginal increase in accuracy does not justify the additional computational cost. However, to achieve a more substantial improvement in accuracy, a higher model resolution of 960p is chosen. This increase in resolution justifies the associated increase in computational cost, unlike the effect observed with increased model size. Consequently, the chosen model for the task is YOLOv8n with a resolution of 960p.

Propulsion

One of the notable features of the ADIOS is the use of toroidal propellers in the propulsion system. In late 2022, MIT published a paper investigating the performance of the propellers stating that they reduce noise whilst maintaining thrust levels [79]. Insufficient data and literature exists surrounding this matter hence it was decided to test these for ourselves. A 4 inch conventional triblade propeller and a triloop toroidal propeller were 3D printed and connected to a test bench to measure thrust and electrical power usage. A sound meter was also placed by the testbench to measure the noise throughout the experiment. The results pointed in favour of the toroidal propellers as they produced a thrust efficiency of 1.29gf/W (grams of thrust per Watt) and a maximum noise of 94.6dBA (decibels A-weighted) compared to the conventional triblade's 1.00gf/W and 98.1dBA.

A hexacopter configuration was selected to account for the case of motor failure as motor failure for a hexacopter is not detrimental to flight ability, unlike for a quadcopter. The toroidal propellers were sized to be 10 inches such that each rotor produces 1.17kgf thrust at 110W, which is the nominal flight case, and a maximum thrust-to-weight ratio of 5:1. At this setting, it is expected the drone will produce a maximum of 50dBA at a distance of 5 m away. Furthermore, spinning propellers are inherently dangerous thus propeller guards were designed to prevent any potential harmful situations.

Control System

From the trade-off in the midterm report [19], the PID angle controller was chosen. However, further research showed that a controller named the Linear Quadratic Regulator was far superior. It has as much functionality as a PID position controller, but is far easier to implement and tune. On top of that, the LQR controller also guarantees a large stability margin. For a SISO (Single input, single output) system, LQR guarantees a gain margin of 0.5 on the lower bound, infinity on the upper bound and phase margins of +/- 60 degrees. Thus, it was decided to change to this controller type. A schematic of the controller is shown in Figure 3. The drone itself is represented by the state space system (the big block on the right). The controller is represented by the feedback loop and feedback matrix K.

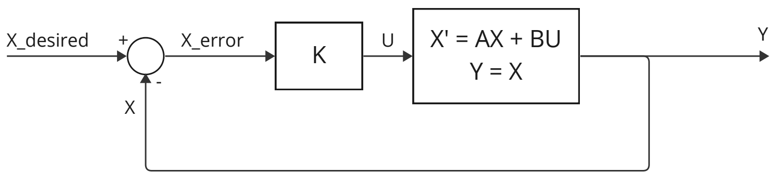


Figure 3: Schematic of the LQR controller

Material choice

Material choice is a compromise between performance, mass, cost, and sustainability. Only parts with high-performance requirements such as the propellers and drone arms are made of carbon fibre. Carbon fibre is light and strong but it is expensive and its recyclability is currently limited in comparison to other materials. Therefore, its use is minimized. TPU plastic is used in the suspension of the wheels as it is a flexible material but again its recycling is limited. The brushes in the brush pick-up mechanism are made of bamboo fibres which are cheap, strong, renewable, and can be sourced sustainably. The rest of the hardware is made of PLA plastic which is composed of organic materials and is biodegradable, which gives it great end-of-life opportunities, and it is lightweight and durable.

Ground Station

The clean-up operation of the ADIOS drones will be initiated from a ground station. This ground station will be mobile and will have several functions. One of these functions is to act as transportation of the drones and the litter between the ADIOS facilities and the operation site. Furthermore, the ground station can be used by the operator to monitor the drones during their autonomous operation. This will be done using live video data, a map with drone locations and general data of the drones like battery life. The ground station will also be a base station for drone maintenance in case a drone gets damaged, hence spare parts will be stored as well. Furthermore, to charge spare drone batteries and power the electronic equipment in the ground station, a power supply will be used inside the ground station. Finally, the ground station is essential to manage the safety of the drone operation, for which monitoring the drones plays an important role.
In order to fulfil all the functions mentioned above, several components are required, like a storage cabinet to transport the drones, garbage bins to transport the litter, a workbench for drone maintenance and more. In total, these components add up to a weight of approximately 405 kg.
To verify the installability of the ground station components, they were installed inside a sample van, namely the 2020 model of the Mercedes-Benz Sprinter. A render of the ground station with the van made transparent is shown in Figure 4.

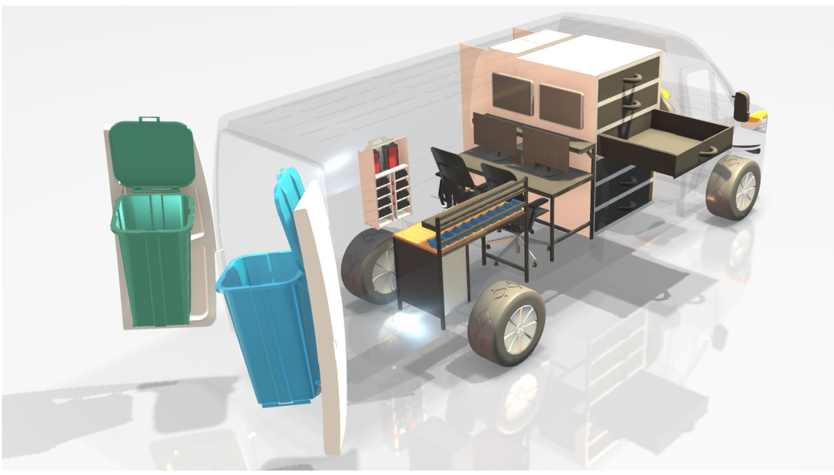


Figure 4: Render of the ground station with transparent van body

The installed ground station shown in Figure 4 is designed for minimal operational load, i.e. the number of required actions from the operation before initiating litter clean-up. The drone storage cabinet is motorised so the drones can take off and land autonomously, and the garbage bins are attached to the door for easy litter drop-off.

ADIOS operations

To design the total operation of the ADIOS system, a simulation is built. This simulation contains all important processes for the sizing of the ADIOS system: drones which can drive, the ground station where litter can be dropped off, a physical simulation of the drone, keeping track of the battery life of the drones and pathplanning and obstacle avoidance. with all these components combined, in combination with a range of experiments, the total number of drones in the ADIOS system can be determined to meet the requirements. In total, there will be six drones, of which two are equipped with brushes and four are equipped with the grabber. In some cases, it is needed to have one drone with brushes and five drones with a grabber. This can easily be switched because the grabbing mechanism is designed to be modular. For the reconnaissance of the litter pieces, some drones will be equipped with better-resolution cameras to be able to spot the litter from a higher distance. When the reconnaissance is performed, these drones will continue grabbing litter.

Another use for the simulation is to test the pathplanning strategy. This is performed by using the A* algorithm for finding the shortest path to all litter pieces and by using a minimum snap function to find which paths the drones should fly. These methods have been implemented successfully and are included in the simulation

The current design of the ADIOS system has batteries that were designed to be able to operate for 20 minutes. However, from the simulation, it can be concluded that the batteries last way longer. This is the case, because the drones also drive, which uses less power and a more accurate power calculation is used in the simulation. Therefore, the operation time for the ADIOS drones is 45 minutes before the batteries need to be recharged.

Performance Analysis

Table 3: Overview of all performance parameters of the drone

Variable	**Symbol [unit]**	**Value**
Inertial properties		
Mass	$m\ [kg]$	4.4
Moment of inertia around x	$I_{xx}\ [kgm^2]$	0.0506
Moment of inertia around y	$I_{yy}\ [kgm^2]$	0.0577
Moment of inertia around z	$I_{zz}\ [kgm^2]$	0.1058
Endurance		
Battery capacity	$Q\ [mAh]$	16000
Battery energy	$E\ [kJ]$	1278.72
Single battery operation time	$t_op\ [min]$	45
Single battery flight time	$t_{fl}\ [min]$	35
Propulsion		
Thrust-to-weight ratio	$T/W\ [-]$	5:1
Maximum thrust	$T\ [kgf]$	20
Nominal propulsive power	$P_{prop}\ [W]$	523
Maximum flight speed in operation	$V_op\ [m/s]$	10
Noise		
Noise @ 5m distance	$-\ [dBA]$	50
Ground station		
Total computer & monitor power	$P_{GS}\ [W]$	900
Total drone charging power	$P_charging\ [W]$	4,300
Total battery energy	$E\ [kWh]$	33.8
Mass	$m\ [kg]$	405.2

Figure 5: Monthly profit vs number of working systems for several prices

With the design of the system complete and the operations explained, a final performance analysis with key performance characteristics can be computed and is shown in Table 3.

Financial Analysis

The ADIOS was compared in function to an equivalent number of full-time workers picking up litter. This was done through fieldwork by the group. It was found that the ADIOS can pick up the equivalent of 9 people's pieces of litter per hour. When these people receive minimum wage the ADIOS must be priced at €630,- per day to be 10% more economical than minimum wage workers picking up litter.

The R&D cost required for developing the ADIOS was compared to other autonomous drone companies. The development cost of the ADIOS was found to be approximately €35.4 Million.

The operating costs of the system were analyzed. The costs include the replacement of the components, having maintenance checks, the salaries of the operator, the cost of leasing a van, and the cost of electricity to run the system resulting in a monthly cost per system of approximately €9300,- per month.

It was found that a system should be priced at approximately €1000,- per day to make a profit when it is operating 200 systems. The company then makes a profit of €224K per month. After 91 months the company has broken even. In Figure 5 the monthly profit of the company can be seen vs the number of working systems in use at different price points.

Production of System

For full functionality and safety, ADIOS requires numerous components and parts, from motors to on-board computers, which are ordered from commercial suppliers. Custom components, such as the propellers and the housing structure, are outsourced for production at 3D printing companies. An ADIOS assembly warehouse is required, where all components and parts will arrive ready for assembly. The assembly of the system is simple as it only requires the screwing together of components following the production plan, much like an IKEA set, along with the soldering of the electrical equipment in the drone. For the total assembly of a system involving six drones and a ground station, it is estimated to take 130 work-hours, which between a 10 person workforce takes 13 hours, or roughly 2 working days.

Sustainability

Sustainability is an ever-growing consideration in design procedures and operations and varies from environmental to economical to social sustainability. The ADIOS system takes all variations of sustainability into account to ensure the system is sustainable without hindering the performance of the system.

Simply put, project ADIOS is designed to enhance the environmental sustainability of the planet. Removing litter from the environment has many environmental benefits for the plants, animals and humans as previously mentioned. However, it must be ensured that the system does not aggravate the current environmental issues, for example by emitting greenhouse gases during operation or by generating litter with hardware components. As a result, the ADIOS has many environmental sustainability aspect incorporated into the design. For example, the whole system runs purely on electricity which can be generated from renewable sources. Furthermore, the system utilises off-the-shelf components where applicable and incorporates sustainable materials for custom parts such as PLA which is biodegradable and recyclable. The modular design of the pick-up system also enables quick and easy repairs and does not require a whole new drone if broken.

During the building of the prototype, economical sustainability was ensured by reusing drones and components available in the MAVLab, and this ideology will be implemented in the final design where second-hand parts will be used where possible. In order for the company to remain economically sustainable, initial financial analysis estimated that ADIOS will charge a fee of €1000 for an 8 hour working day. This figure is higher than desired however this will likely reduce as the system design is iterated and further optimised for reduced costs.

The ADIOS is also extremely safe and thus socially sustainable. Its AI vision is able to detect people in order to avoid any collisions. It is equipped with ultrasonic speakers to deter any nearby animals and LED lights to alert civilians close by preventing any interference. Its toroidal propellers, which in-house testing proved to be 29% more efficient than traditional propellers reducing power consumption, are inherently dangerous and thus are covered by custom-made propeller guards to ensure any contact with the propellers is mitigated.

Prototype

The main reason why ADIOS could be designed in such a short time was the possibility to test propose solutions, without elaborate theoretical simulations. Multiple prototypes were developed throughout the past 10 weeks. They can be categorised into 3 main branches: pick-up mechanism, Computer Vision and drone configuration. Thanks to this modular approach all subsystems could be tested, without risking too big delays caused by complicated system integration into one product.

For these branches, the obtained results can be summarised as 3 different pick-up mechanisms were developed and tested for the collection of 15 different litter types. The most successful one was shown in the final design render. The proposed computer vision algorithm for the autonomous flight was implemented on Bebop 2 drone and proved to work correctly in a controlled environment. For the last branch, designed drone configuration consisting of wheels, a trash collection mechanism and 4 rotors were assembled and tested.

Future Development

The ADIOS is a service which can be employed by any corporation or organisation at an hourly fee. Before the ADIOS can be launched, several issues were encountered and resulting in recommendations for future development. For example, a quadcopter drone with counter-rotating propellers at each rotor could be beneficial for noise reduction and efficiency increases. Implementing phase-synchronised rotors could further reduce noise as studies have shown. Furthermore, initial financial analysis renders the service of the ADIOS more expensive than human labour which will reduce the number of potential clients greatly. Further iterations of the design of the system must be performed to obtain a more economical design and operation.

A development plan for the future of ADIOS has been developed with the goal of launching in 2026. The development plan begins with founding a business and performing further market analysis to perhaps diversify the service for other clients. The system design is then enhanced and the production and assembly can begin. Marketing must be performed in order to gain brand recognition and to attract clients to which we provide the ADIOS service to. By adhering to the development plan, ADIOS hopes to reach clients around globe with the hopes we can, as a planet, ’say goodbye to litter’.

Contents

1
Introduction

The increasing human population leaves its traces, and one of these is the growing issue of litter on the streets. Leaving an alarming amount of non-degradable pieces of litter in ecosystems influences the environment, biodiversity and wildlife, with implications for climate change as well. Animals, such as birds and fish, ingest non-digestible plastic pieces and consequently introduce micro-plastics into the human food chain, ultimately posing a serious threat to people's health. In light of these reasons, it is crucial to find an innovative solution for rapidly and feasibly cleaning up litter.

ADIOS (Autonomous Drones Integrated Operational cleaning System) combines aerospace disciplines to tackle this problem. Drones not only offer high manoeuvrability, they are also able to cover hard-to-reach areas and fly over any obstruction. Using a ground station for efficient communication, they function as a fast, convenient and sustainable system that can clean large areas without supervision. Utilising artificial intelligence to identify litter pieces allows for sorting the garbage and effortless recycling, while an electric ground station provides docking as well as recharging. Overall, ADIOS has the potential to pick out litter from urban areas faster than any other system.

This is the Final Report of the ADIOS project. To gain an insight in the demand from the market, a market analysis is performed in chapter 2. Subsequently, the requirements that follow from these analyses are set up in chapter 3, along with all system requirements. The design of ADIOS is built upon fundamental design options from the Baseline Report. Therefore, a summary of these and their trade-off can be found in chapter 4. The final design of the drones and Ground Station are described in chapter 5 and chapter 6, respectively. The operations of the ADIOS are reported in chapter 7, together with an accurate simulation. After that, the overall performance of the system is analysed in chapter 8, and the risk analysis is performed in chapter 9. To have a clear understanding about the profits of the system, the finances are researched in chapter 10. Then, a sustainable development strategy is established in chapter 11. Verification and validation is performed in chapter 13 After this, chapter 12 visualises the realism of ADIOS, as here an actual prototype is created and the RAMS characteristics are described in chapter 14. The report ends with the production plan in chapter 15, the future recommendations in chapter 16 and the conclusion in chapter 17. In Figure 17, the Gantt chart, Functional Flow Diagram and Function Breakdown Structure can be reviewed. Next to this, in Appendix B, Appendix C and Appendix D, the compliance matrix, requirements and rotor noise levels, respectively, can be found.

2 Market Analysis

Before entering the design, a market analysis must be performed to analyse the potential demand for the product or service and the competition in the market. The market analysis also serves as an indication of how well the product or service will perform on the market. In this chapter, the market analysis for the ADIOS is presented. First, in section 2.1, the objective of ADIOS is described and its value is compared to other existing systems. Subsequently, section 2.2 analyses potential stakeholders of the system. Then, in section 2.3, the proposed business model for ADIOS is described, including estimations with regards to the target market. Finally, in section 2.4, some potential partners for ADIOS are mentioned and described.

2.1. Objective and Value Proposition

The objective of the company ADIOS is to fill a niche in litter retrieval. The main purpose of the system is to eliminate human labour and clean in areas which are hard to reach. This is where the main value of the system can be obtained compared to existing systems. It is important to note that the system cannot outperform other existing systems in very littered environments. Instead, the system excels in cases where single pieces of litter are hard to reach which can be picked up one by one by a drone. However, it must be noted that there are limits on the size and weight of the litter that can be picked up, see section 5.1.

2.1.1. Comparable Systems

The ADIOS is the first system that is being developed using flying drones to autonomously pick up litter. However, there is a small market of comparable systems which are analysed and compared in this subsection.

To build an autonomous garbage cleaning system, it is inevitable to use artificial intelligence for image recognition and path planning. The field of artificial intelligence has made significant progress the last few years. This has created a lot of opportunities for autonomous drone systems.

Seagull Robotics

As these developments are recent, autonomous drone cleanup systems are very rare. Only one UAV cleaning system project was found, called Seagull Robotics [49]. However, this project has been abandoned due to a lack of funding. This was probably caused due to a lack of information on the system details. Apart from the crowdfunding page with a small pitch, no further information can be found. Investors might have been hesitant to invest for this very reason.

WasteShark

However, there are some projects on autonomous cleaning systems without aerial vehicles. For example, WasteShark, shown in Figure 2.1 [119].

Figure 2.1: Picture of the WasteShark ASV in action [119]

WasteShark is an autonomous surface vessel (ASV), which cleans waters collecting up to 500kg of debris per day. It 'swims' through the water and is designed to collect all litter in its path, as shown in Figure 2.1. It has collision avoidance, but it does not have any trash-detecting software, as it just swims and collects everything in its path. This could however impose a danger to animals such as small ducks, as they are possibly not considered by the collision avoidance.

Project.BB

An equivalent system that operates on land is Project.BB [102]. This system is designed to clean litter on beaches, as shown in Figure 2.2. This system makes use of a litter detection system with the aid of artificial intelligence. Furthermore, Project.BB is based in the Netherlands and is definitely a competitor of ADIOS which should therefore be followed closely during and after the development and launch of ADIOS.

Figure 2.2: Project.BB in action on a beach [102]

DustBot

Lastly, another robot cleaning system is the DustBot [47], shown in Figure 2.3. This is a system that does not clean autonomously, but works as an on demand waste collection system. The drone can be requested to navigate to a certain location. It will travel autonomously, with the use of collision avoidance. Once arrived, the applicant can place their waste inside a hatch in the drone. Afterwards the drone will dispatch of the waste in the proper location.

Figure 2.3: DustBot in the streets [47]

This robot does not share a lot of similarities with what is required from the ADIOS system. However, it is noteworthy that this robot is explicitly designed to look friendly. This is important since the robot operates close to pedestrians. Of course, these pedestrians should feel safe when the robot is in their vicinity. The ADIOS system shall also operate in urban areas, close to pedestrians. So preferably, this system should also have a friendly appearance to pedestrians.

2.1.2. Concluding Remarks

One of the weaknesses that the comparable systems described in subsection 2.1.1 have in common is that these systems are all limited to the environment that they operate in. Systems that operate on land like Project.BB are limited to environments with continuous and relatively flat pieces of land, and are easily obstructed by constructions like buildings or bodies of water like ponds. Similarly, systems that operate on water like the WasteShark are limited to bodies of water only. This is the very aspect where the drone system beats any other system. For drones, the sky is the limit, quite literally, as they can simply fly over almost any obstruction that they encounter. This unique strength of drones allows for a very efficient way of trash collection that cannot be replicated by any other system.

2.2. Identifying stakeholders

In this section, all stakeholders of the ADIOS project are identified. Different categories of stakeholders have been established and each stakeholder has been allocated to the category that it belongs to, including the relation between the stakeholder and the project and the stakeholder need(s).

- General public
  - ST-GP1: People living in the operating area

    Relation: The drone system will operate in selected areas and therefore affect the people living in these areas. Concerns like privacy, noise and potential damage have to be taken into account.

    Needs: Privacy should be maintained and no damage should be done to buildings and objects.
  - ST-GP2: People in public

    Relation: The drone system will operate in public places and will therefore likely encounter people in public, both pedestrians/bystanders and people using transportation devices like cars and bikes. These people have to be taken into account by the drone system in order to avoid dangerous or disturbing situations. Additionally, people in public are positively affected by the lack of litter on the streets.

Needs: No physical damage may be done to humans and transportation devices, nor may they be blocked, obstructed, or interfered with. Also, people in public need to have a litter-free environment.

- Environment
  - ST-E1: Fauna

    Relation: The drone system will operate outside and may therefore encounter animals, i.e. fauna. The animals need to be taken into account in order to disturb these animals as little as possible. Additionally, the drone system will improve the habitat of the animals since litter will be removed.

    Needs: No physical damage may be done to animals nor may the animals be disturbed. As much litter as possible needs to be removed in order to improve the habitat of the animals.
  - ST-E2: Flora

    Relation: The drone system will operate outside and may therefore encounter trees, plants and flowers, i.e. flora. These organisms need to be taken into account since the flora in the operating area needs to be preserved. The drone system will also potentially improve the flora in the operating area as litter will be removed.

    Needs: The flora may not be harmed more than conventional cleanup methods during the operation of the drone system.
- Business
  - ST-B1: Project tutor

    Relation: The project tutor initiated the project and set the general guidelines for the project. He also determines the time budget for the project.

    Needs: The design project needs to be finished within 10 weeks by 10 students. The final drone system design also needs to be such that it can be produced within the next 3 years.
  - ST-B2: Municipalities

    Relation: The municipalities are responsible for litter within the municipality and are therefore likely interested in project ADIOS. They are therefore potential customers of the project and are interested in the cost and effectiveness of the drone system.

    Needs: The project needs to be as cheap as possible and needs to be more profitable and efficient than current litter clean-up systems in the targeted urban areas in which the system will operate.
  - ST-B3: Potential employees

    Relation: The drone system will eventually need human operators and therefore there are potential employees. The complexity of the operation of the drone system will determine the employees that are applicable for the job or how much training they require and are therefore affected by the design of the drone system.

    Needs: The operators should require as little training as possible and a Car Driving License B should be sufficient for the driver of the mobile van.
  - ST-B4: Recycling companies

    Relation: The drone system does not only need to pick up litter but also sort it correctly. Recycling companies specify how litter should be recycled and therefore directly affect the design of the drone system.

    Needs: The drone system needs to sort the litter in the correct categories specified by the recycling company.
- Government
  - ST-GO1: Ministry of Infrastructure and Water Management

    Relation: The regulators for drone regulations, garbage processing and noise disturbance. There are European regulations on drones and the Ministry of infrastructure and water management has an inspection department (ILT) that ensures those rules are followed.

Needs: The developed drones must adhere to the existing European regulations on drones and Dutch regulations on noise and garbage.

- ST-GO2: Ministry of Economic Affairs and Climate Policy

  Relation: The regulators on climate policy. There is a goal to decrease a substantial amount of greenhouse gasses emitted before 2030. Therefore, the mitigation of greenhouse gasses is important for this ministry.
  Needs: For future systems it is very important to not have a serious impact on the climate.

- ST-GO3: Dutch Data Protection Authority (AP)

  Relation: The regulators of privacy policy.
  Needs: The drone system shall adhere to the privacy regulations in the Netherlands.

With the identification of these stakeholders, requirements can be set up, which are described in chapter 3.

2.3. Business Model

Before any new product or service enters a market, it is very important to develop a proper business model for the company. Especially for ADIOS, this is an essential step since the product that is being developed is very innovative. The business model will describe the product or service that will be sold, the target market for the product or service, an outlook and prediction on the market, the growth strategy for future company development, and the expected type of expenses of the company.

2.3.1. Products and Services

Before analysing the market that ADIOS will be targeting, it is essential to have a clear description of the product or service that ADIOS will be providing. ADIOS is a system of drones rather than a simple product, which will be utilising a mobile ground station as the base of its operations. Although the drone system will be autonomous, a trained operator is still required to operate the mobile ground station, but also the drones in emergency cases. As the drone system that will be developed by ADIOS is rather complex, the best option for ADIOS is to provide a service to the client. This means that ADIOS will own the complete drone system, and provide a litter clean-up service to clients that own the urban areas that require a clean-up. In this way, in case any problems occur with the drone system, it can be solved quickly by the ADIOS company itself. In case the drone system would be sold to the client as a whole, much more consultancy would be required to train the client, which introduces costs. Another benefit of providing a service is that ADIOS can serve more than one client with only one drone system, which reduces the cost for ADIOS. A reduction of cost leads to a reduction in price of the service, which makes the service more attractive to clients.

2.3.2. Target Market

For ADIOS, the variety of potential clients is quite small. Since the purpose of ADIOS is to clean up litter in the urban environment, its potential clients are limited to organisations that want their area to be cleaned up. Therefore, the target market of ADIOS will be municipalities. Municipalities are interested to be as green as possible, which also involves getting rid of litter in the municipality. It must be noted however, that some municipalities might be more interested to become greener than others. For example, in the Netherlands, municipalities that are more politically left orientated will likely be more interested in ADIOS than politically right orientated municipalities.

2.3.3. Market Outlook and Prediction

Now that the target market for ADIOS has been established, the market for ADIOS will be analysed to make estimates about the market that ADIOS will be entering. This includes an analysis of existing comparable markets, after which the market volume for ADIOS will be estimated. The expected share in this market will then be determined.

Comparable Markets

The ADIOS system will be an innovative service that will target a completely new market. However, it is still important to analyse comparable markets from which estimations for the target market can be derived.

The ADIOS system will utilise autonomous drones. The market size of the global autonomous drone market is roughly $\$15.6$ billion, while the market size of the global drone market is roughly $\$33.9$ billion [74]. Hence, the autonomous drone market covers roughly half of the complete drone market. Furthermore, the global autonomous drone market also accounted for almost 46% of the sales in the complete drone market at the end of 2022 [74]. It is also important to note that the autonomous drone market has a CAGR (Compound Annual Growth Rate) of 19.3% and the complete drone market has a CAGR of 17.6%. For a high-risk company like ADIOS, a CAGR between 15% to 25% is desired, hence these CAGRs are very promising [136]. All these numbers clearly show the high potential and promising future of autonomous drones and drones in general.

Market Size

The market size refers to the amount of potential clients interested in the clean-up service that ADIOS will be providing. Indirectly, it also relates to the amount of litter that is present in the urban environment that ADIOS will be operating in and how long it takes to clean up that litter. To make an estimate of this, the following assumptions will be used:

- The drone system of ADIOS will be able to pick up 1000 pieces of litter within one hour.
- ADIOS will be operating in urban environments only.
- ADIOS will be operating in the Netherlands.
- The total amount of urban area in the Netherlands is $12\,803\,\text{km}^2$ (31% of the total area of the Netherlands) [132].
- The drones will only pick up fine litter, which is litter bigger than $1\,\text{cm}$ and smaller than or equal to $10\,\text{cm}$, excluding chewing gum [26].
- In the Netherlands there are 7.39 pieces of fine litter per $100\,\text{m}^2$. This was calculated using interpolation, as the average score in the Netherlands is 3.71, where a score of 3 refers to one 1 piece of litter per $1\,\text{m}^2$ and a score of 4 refers to 10 pieces of litter per $100\,\text{m}^2$ [26].
- The operational time per day is 8 hours.

With the assumptions stated above, it can be determined that the total amount of fine litter in urban areas in the Netherlands is roughly 950 million. This means that it takes a single ADIOS drone system roughly 950,000 hours to clean up all the fine litter in the Netherlands. With 8 hours of operational time per day, this means that it would take more than 118,000 days, which is more than 324 years. However, ADIOS will not be cleaning up the Netherlands with only one drone system, hence it can be done much quicker if, for example, every municipality has one ADIOS drone system. However, it must be noted that this only takes the current litter into account, and not new litter that is deposited into the environment.

Since the target market is municipalities, it is also important to analyse the performance of ADIOS in a single municipality. For example, the total land area of Delft is $22.65\,\text{km}^2$, which means that there are almost 1.7 million pieces of fine litter in Delft [35]. It would therefore take approximately 1674 hours to clean Delft from all fine litter using one ADIOS drone system, which is more than 209 working days.

In general, the market size for ADIOS is extremely large, as litter is a global problem. However, it is unreasonable to expect global clients right from the start after ADIOS is launched into the market. Therefore, the company ADIOS will first aim for clients within the Netherlands. Nonetheless, ADIOS is ambitious and aims to target clients all over the world in the future, which will be discussed in subsection 2.3.4. Since there are 342 municipalities in the Netherlands, this means that the starting market size for ADIOS is 342 [50]. However, this number is subject to change, as there may be more unexpected demand for ADIOS from different types of land-owners in the urban environment in the Netherlands. If every municipality in the Netherlands would have an ADIOS drone system operating 8 hours every single day, it would take less than a year to clean up the Netherlands from all current fine litter.

Market Share

As mentioned before, ADIOS will launch its service into a completely new market, since no other similar systems exist yet. Although entering a completely new market introduces high risks, it is also a major advantage since ADIOS will likely be first to market. This advantage is the so-called ”First-mover advantage” (FMA) [117]. This first-mover advantage gives ADIOS a competitive advantage compared to other companies that follow with a similar design, since it allows ADIOS to build a strong name in the new market. Additionally, the first customers and suppliers will likely be loyal to the company and ignore products that follow from the copy-cat companies. Although being first to market brings a lot of benefits, the drawbacks should also be taken into account. One of the big drawbacks is that other companies can improve upon the ADIOS product, which might result in a loss of share in the market. It is therefore extremely important to have a solid design that has been iterated several times before being launched into the market.

Although it is hard to predict the actual size of the completely new market that ADIOS will be targeting, it is possible to estimate the share of ADIOS in the market. For revolutionary products, often more than half of the market is owned by the first-mover. As an example, when Apple launched the revolutionary iPod in October 2001, they still possessed 70% of the market for digital music player with hard drives a year after launch [114]. Although this product is obviously vastly different from the product that ADIOS will be putting on the market, it still gives a great indication of what the market share of ADIOS could be. Similarly, drone company DJI was one of the first companies to enter the commercial drone market after the FAA started releasing commercial drone permits in 2006 [100]. On this day in 2023, DJI owns around 70% of the global drone market [36]. Again, this shows the importance of being one of the first companies in a new market.

2.3.4. Growth Strategy

As mentioned in subsection 2.3.2, the target market of ADIOS will be municipalities. However, as a new business, chances are slim that there will be a lot of demand right from the start. Generally, a product or service follows the product life cycle as shown in Figure 2.4, although often new products do not even reach the second stage [124].

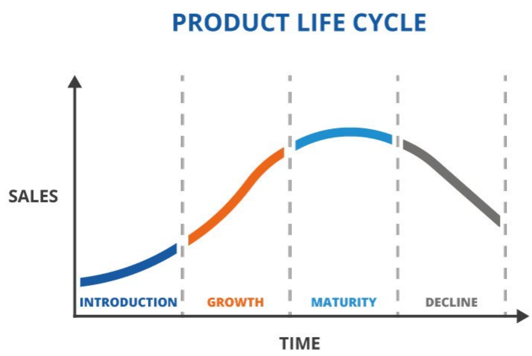


Figure 2.4: The four different stages of a product's life cycle [124]

Note that the width of the stages is not to scale, as some products stay within some stages for much longer than in other stages. The ADIOS service will first enter the introduction stage, where it is introduced to the market. It is very important that a lot of marketing will be done in the beginning to make potential clients aware of the ADIOS service.

The demand for ADIOS is then expected to increase exponentially during the growth stage. During this stage, ADIOS might have to deal with competitors, so it is important to keep improving the service throughout its life cycle to maintain customer loyalty.

Eventually ADIOS might reach the maturity stage, when the company's name is well-known in the market. It will then be important to maintain the position in the market for as long as possible before reaching a decline in sales. However, this will most likely be very far in the future.

Nonetheless, it is wise to think about a growth strategy for ADIOS. Since ADIOS is based in Delft, it is best to stay within the Netherlands at first, and then try to expand the business internationally. The municipality Rijswijk, which is right next to Delft, was voted to be the greenest municipality in the "Groene Stad Challenge" (translation "Green City Challenge") in 2021, and second greenest in 2022. Delft was placed second in 2021 and third in 2022 [42]. Hence, both municipalities show great potential for being the first clients of ADIOS.

Once the ADIOS drone system has shown its potential while operating in Delft or Rijswijk, chances are high that more municipalities in the Netherlands become interested in ADIOS. Although dependent on the demand, ADIOS is planning to expand to all municipalities in the Haaglanden region, followed by the province South-Holland, then the Netherlands, and eventually worldwide. That is the plan of ADIOS, because litter in the environment is a global problem, not just locally. All of this supports the vision of ADIOS, which is to contribute to a more sustainable world.

2.3.5. Expenses

Finally, the expenses of the company ADIOS will be analysed. Relating to the product life cycle shown in Figure 2.4, the cash flow from a new product or service usually looks like the graph shown in Figure 2.5.

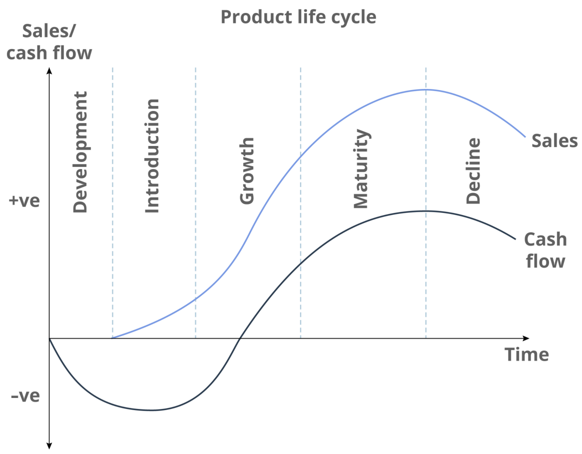


Figure 2.5: The cumulative cash flow of a product during its life cycle [66]

As can be seen in Figure 2.5, before the product is launched into the market, the company has a negative cash flow since there is no cash entering the company yet and only costs are generated. The main sources of these costs are usually research, development, production and overhead costs. For the ADIOS system, these accumulated costs before launching ADIOS into the market are estimated to be roughly €35.4 Million. With a price per day of €1000 for the ADIOS service, the company would break even after 91 months assuming 200 functioning ADIOS systems. A detailed analysis of these costs and pricing is described in section 10.1. Furthermore, Figure 2.5 also shows the importance of finding investors or getting loans to rely on, since cash flow is negative during the first stages of a product's life cycle.

2.4. Potential Partners

In addition to finding investors to rely on, ADIOS also aims to establish partnerships with other companies. Establishing partnerships with other companies is very important for the growth of any company, since it allows valuable knowledge, skills and resources to be exchanged. Furthermore, it can significantly help a company to establish a business identity, especially when brand new companies like ADIOS partner up with larger well-established companies. So far, there are a few potential partners that could work well with ADIOS.

2.4.1. KPN Drone Connect

One of the potential partners is KPN. The drones that ADIOS need to be able to communicate both with each other as with the ground stations, hence a communication link is required between them. Via this link, video, control and other data need to be transferred. KPN has its own drone-service called KPN Drone Connect which is part of KPN Internet of Things (IoT): a business-to-business service provided by KPN. With KPN Drone Connect, they allow any company to connect drones to their mobile 4G or 5G network. The only thing that is required is a KPN IoT SIM card. An example of a drone partnered with KPN Drone Connect is shown in Figure 2.6.

Figure 2.6: A drone working with KPN Drone Connect, covered with a KPN wrapping [77]

This partnership would bring many advantages for ADIOS. One of these advantages is that a 4G or 5G connection allows for Beyond Visual Line-Of-Sight (BVLOS) remote control, which is ideal for the autonomous drones that ADIOS is developing. Furthermore, the connection is very secure, as KPN has developed the security of their network with hackers for many years [77].

This partnership would not only bring benefits for ADIOS, but also for KPN. Since ADIOS is a very sustainable system, the partnership will give KPN a greener and more sustainable image, which is very beneficial especially nowadays where sustainability is highly appreciated.

2.4.2. Supporter van Schoon

Another potential partner for ADIOS is Supporter van Schoon (translated Supporter of Clean). Supporter van Schoon, formerly Nederland Schoon, is an organisation that aims to clean the Netherlands from litter and is part of the ”afvalbeheerstructuur” (translated ”waste management structure”): a partnership between several organisations that aims to create a circular economy with regards to packaging material. Supporter van Schoon is also co-founder of the Clean Europe Network, which is a European network where organisations share knowledge about litter prevention [115].

Partnering up with Supporter van Schoon will be a wise decision for ADIOS as they can provide a lot of useful knowledge about litter. Additionally, the partnership can allow for other partnerships to arise, since Supporter van Schoon is already working together with many other big companies like the Plastic Soup Foundation, the Wereld Natuur Fonds (Dutch part of the World Wide Fund for nature) and many more [116]. In case ADIOS decides to partner up with Supporter van Schoon, they will join a big network focused on litter prevention, which is ideal for the growth of the company.

3 Requirements

This chapter serves to show the requirement of ADIOS. In order to derive these in a proper and concise manner, a requirements discovery tree method was first formulated. It begins with top-level requirements from which system and subsystem requirements are derived. Furthermore, each top-level requirement is given a code and each low-level is given a number. These codes and numbers are then used to derive the requirements codes, such that they follow the hierarchy of the tree. All requirements are preceded by SYS and appended with the following codes:

Code	Definition
TE	Technically
CON	Constraints
QN	Quantity
QL	Quality
TI	Timely
PR	Privacy
RE	Reliability
SU	Sustainability
COS	Cost
SCH	Schedule
LE	Legal
REL	Reliability
SA	Safety

For example, the requirements on the amount of drones are in the output quantity branch (QN), and are the first entry. Then, the corresponding code becomes SYS-QN-1. The first subrequirement will then be SYS-QN-1-1. The final set of requirements can be reviewed in Appendix C.

Some requirements were additionally assigned a type, which can be one of the following:

- Key - a requirement which is of primary importance for the customer.
- Driving - a requirement that drives the design more than average.
- Killer - a requirement that drives the design to an unacceptable extent.

These types will be then used to identify which requirements should be taken into account more carefully and which should be revised in order to ensure the design can be accomplished. The requirements will be referred to throughout the project to provide reasoning for design choices.

4 Design Options Trade-off

In this chapter, the start of the design is shown given the stated requirements. The purpose of this chapter is to illustrate the steps taken before the detailed design was initialised. The steps taken include the design options considered for the final design and the trade-off decisions made to develop the detailed design. In section 4.1 a large design choice encountered through testing is explained. In section 4.2 a summary table of the trade-offs made during the designing of the report is shown.

4.1. Wheel Choice

Initially, a plain drone with a pick-up mechanism was considered. The drone would simply approach the trash during the flight. However, this strategy proved to be infeasible due to the wake effect of the propellers and pick-up instability, resulting in noncompliance with SYS-TE-QL-3. This section addresses these problems.

The requirement that the wake the drones produce should not disrupt its ability to pick up litter could not be fulfilled after testing with a Bebop 2 drone was done. It was demonstrated that during the approach the wake of the drone was blowing the trash away rendering the drone unable to approach it. This effect was significant from around 2 meters away. The weight of the ADIOS drones would be higher than the weight of the Bebop 2 drone and therefore the effect of the wake would also increase.

After consultations with internal experts from the Aerospace Engineering faculty and a literature study, it was found that pick-up operation in flight poses a significant challenge [23]. First of all, the drone experiences the ground effect, which introduces aerodynamic interference, which is problematic for the flight controller to account for. This can be solved by attempting to model the ground effect and account for it within the control algorithm. However, up to date, no controllers have been proposed to mitigate this effect for dynamics grasping of objects [23]. Furthermore, in order to approach the object detected by the vision algorithm it would be necessary to implement state estimation. However, this may lead to a critical failure of the drone in case state estimation fails [53].

Furthermore, diverting the wake increases the complexity of the system and the feasibility of such options could not be tested by the team. The distance between the drone and the ground was deemed too high to utilise any mechanism that drops to the ground to attempt to pick up the trash while the drone is still in flight. It was therefore chosen to have the drone land in the vicinity of the litter. Close enough to not have the wake influence the position of the litter. The drone would then need a method to approach and then grab the litter. It was chosen that wheels were the right option. A set of two wheels delivers enough manoeuvrability and adds limited weight.

4.2. Summary Table

This section serves to give the design summary table for all the design options chosen to enter the final design. The trade-off table shown in Table 4.1 illustrates the trade-offs made to enter the final design as well as the rationale for the trade-off made. Each rationale briefly summarises the most important criteria that were taken into account, as well as justifies the most optimal design choice.

Table 4.1: Trade-off summary table

Trade-off	Result	Rationale
Pick-up Mechanism	Litter picker & brush	Litter picker & brush exhibit high efficiency while consuming little power and being relatively safe. They are also lightweight and cost less than other options that were considered.
Collision Avoidance	Binocular (stereo) camera & radar	Binocular camera & radar combine well, as the former has high resolution while operating at a small range, while the latter has low resolution but can operate at much larger distances.
Object Detection	YOLOv8n	YOLO is a state-of-the-art model YOLOv8n exhibits sufficient accuracy and is the fastest model from the YOLO family
Drone Handling	VTOL on landing pad	VTOL on landing pad exhibits low cost, allows for easy battery swapping, has low volume, acceptable sustainability and acceptable operator action
Ground Station	Installable system	Installable system exhibits low cost, acceptable complexity, good flexibility and acceptable required consultancy.
TT&C	Cellular, centralised	Cellular is widely available and cheap enough to use in the system
Control	PID angle controller	PID angle controller requires low computational power, exhibits low complexity and sufficient performance in terms of dynamics handling
Propulsion	Closed propellers	Closed propellers provide much higher safety levels as they protect the propeller blades
Operations	Only aerial drones	Depositing litter at the ground station requires less effort and is easier to design than a ground drone alongside the aerial drones.
Modular pick-up system	Interchangeable pick-up system	A modular pick-up system allows for pick-up where litter differs between areas.
Component Acquisition	Off-the-shelf components	Off-the-shelf components can be replaced more easily when maintenance is required.

5
Detailed Drone Design

From the trade-offs performed it was chosen that ADIOS system will utilise aerial drones that are capable of landing and driving in order to pick up the litter. The drones must designed in detail to ensure they are effective and efficient whilst complying with the requirements discussed in chapter 3. This chapter begins with discussing the pick-up systems in section 5.1 before discussing the computer vision in section 5.2. The hardware of the drone is covered in section 5.3, section 5.4, section 5.5, section 5.6. Finally, the control system is discussed in section 5.7 before a sensitivity analysis is performed in section 5.8.

5.1. Pick-up System

The pick-up system is a vital component of the mission. It must be capable of picking litter in a lot of different sizes, shapes, and masses. Additionally, it must hold on to the litter until the drop-off location. In order to design such a pick-up system, the first step was to perform an analysis of the litter that can be found in the environment, as seen in subsection 5.1.1. Secondly, all possible pick-up solutions were collected and the best option was traded off, as can be seen in subsection 5.1.2. Lastly, the chosen option was designed. This design was also created in real life and tested in order to verify and validate the design, which in turn optimises the design, seen in subsection 5.1.3.

5.1.1. Litter Analysis

In order to define what types of litter the pick-up system needs to pick up an analysis must be performed. This analysis can give information about what type of litter is most common and give estimates on parameters such as mass and volume. Using this the main goal and dimensions of the pick-up system can be defined. At first, the group went out to collect litter around the TU Delft. An area of around $20\,000\,\mathrm{m}^2$ was covered and around 650 pieces were collected. This gave a lot of insight into how litter is distributed in the environment and what type of litter to expect. A picture of the activity can be seen in Figure 5.1. Additionally, an analysis was performed using the Litter Data Explorer and Litter AI from *Litterati* [83].

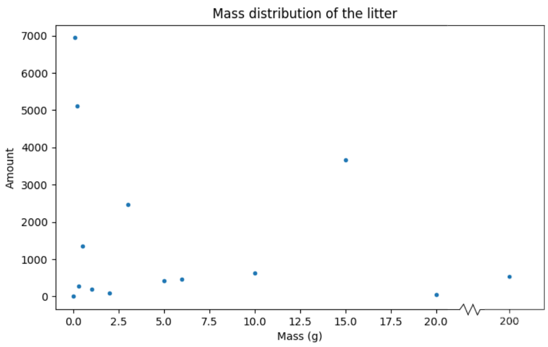
Litterati lets people take photos of litter and gives back useful information such as the type and dimensions of litter. All this data is saved in a dataset that you can explore with the Litter Data Explorer. The Litter AI can estimate parameters about the litter such as mass and volume. it must be noted however that the data can be biased or has discrepancies. First of all, as the photos are taken by people, some areas might contain no litter data as people there have no knowledge of Litterati. Additionally, the parameters of the litter are AI-generated and thus have possible discrepancies.

Table 5.1: Litter Parameters from the Litter Data Explorer and Litter AI [83] in an area selected in Rotterdam, here std stands for Standard Deviation

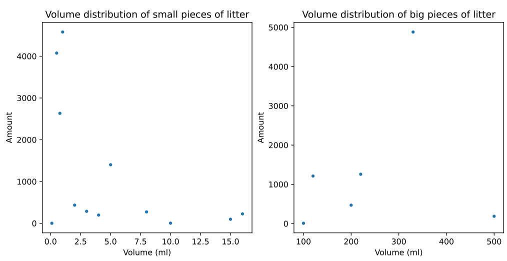
Mass (min) [g]	Mass (max) [g]	Mass (mean) [g]	Mass (std) [g]	Volume (min) [ml]	Volume (max) [ml]	Volume (mean) [ml]	Volume (std) [ml]
0	200.0	3.0	124	0.0	500.0	72.0	13

Figure 5.1: Litter Picking Activity performed for litter analysis

For the current research, an area covering Rotterdam was selected including more than 10000 pieces of trash. This data was extracted and the parameters of the litter were analyzed. The results can be found in Table 5.1. Additionally, an area in Den Haag was chosen for more data. From this data it was found that 64% of litter was smaller than 16 ml. Distributions of the litter can be found in Figure 5.2.



(a) Distribution of the volume of the litter, the x-axis shows the volume in millilitres and the y-axis the number of litter pieces with this volume.



(b) Distribution of the mass of the litter, the x-axis shows the mass in grams and the y-axis the number of litter pieces with this volume.

Figure 5.2: Distributions of the parameters of the litter

Besides these values, the litter was also divided into two categories: Small and Large litter. This was done as the way these two categories must be picked up differs significantly. For example, for a bottle, a claw might be the best solution, which might not work with cigarette buds. Here small pieces are considered until 16 ml in volume, such as cigarette butts, candy wrappers or bottle caps, and large pieces above this, such as cans, bottles, or cups.

The total mass and volume that is required to be stored in some manner are then equal to the number of litter pieces collected per hour n_{lit} multiplied by the average volume of litter pieces $V_{lit_{avg}}$ and the time that the system is operation T, see Equation 5.1. A factor of S is added to deal with the extra size of the litter when it is stacked and different types of litter being encountered when cleaning different areas.

$$V = n_{lit} * V_{lit_{avg}} * T * S \tag{5.1}$$

The size of the factor S is determined from a worst-case scenario this is assumed to be 1 standard deviation from the mean volume of the litter as gathered from the Rotterdam litter data set. From the values seen in Table 5.1, the parameter S was found to be 1.18.

5.1.2. Pick-up Design Options

Now that it has been defined what types of litter need to be picked up, the possible mechanism options can be analyzed. Like the litter, the pick-up options have also been split into these two categories. These options can be found below:

Large Objects

- **MIP Gripper**: Hsiao et al. [64] created a lightweight, unpowered mechanism which can pick up an object using a pad which pushes against it in turn pushing pads around the object. The object is released when it is placed on the floor relieving the tension within the mechanism. This mechanism is optimal for rod-like structures which it can hook onto
- **Tendon Grasper**: This mechanism picks up an object by pulling on 'tendons' to grasp an object, much like a hand. This mechanism requires a power source to provide the pulling force on the tendons. This mechanism is based on research performed by Fishman et al. [53] and McLaren et al. [88].
- **Mantis Claw**: An unpowered claw opens by itself when it is placed on the ground and encloses again when it is lifted off the ground, enclosing the material within. For safety concerns, the mantis claw would be equipped with a motor and spool to reel the claw in to prevent it from swinging low below the drone
- **Active Suction Cups**: Suction cups are accompanied by a vacuum pump enabling it to attach to an object and lift. This mechanism requires power during pick-up and flight to retain the object. This option is from the research done by Kessens et al. [75]. They show a wide variety of objects that can be grasped.
- **Passive Suction Cups**: Suction cups are forced onto an object causing it to stick. This would be a flexible array of smaller suction cups to pick up multiple objects and improve the success rate by having more suction points. The mechanism must include a power source either to push the object off or to open it up internally to relieve the pressure differential, in turn dropping the object at the correct location.
- **Litter Picker**: Based on a traditional litter picker, this mechanism requires a force to grasp the object before being released at the correct location. The mechanism will require a power source to provide the force.

Small Objects

- **Brushes**: Based on current street cleaning technology, a brush will spin in turn sweeping up small objects which are disposed of in an adjacent compartment. This mechanism requires a power source to spin the brush
- **Array Active Suction**: At first the idea was to perform active suction by adding an adapted vacuum cleaner option. However, after preliminary calculations, it was found that this would not be feasible as it was too heavy and required too much power. Therefore an array of suction pens was chosen. This array would hover approach smaller objects which would then stick to the pens.

Table 5.2: Winners from the trade-off and sensitivity analysis of the pick-up mechanisms

Type	Winner
Small Pieces	Brushes
Big Pieces	Litter Picker/Mantis Claw

Lighter objects, like thin sheets of paper or plastic, would be able to be easily picked up with this type of system.

- **Double Scoop**: Based on a hand-held "Pooper Scooper", this mechanism requires a force to enable the two scoops to be brought together, enclosing the material within. The force will have to be provided with a power source to converge and diverge the scoops during the pick-up and drop-off of litter

Using all these pick-up design options a trade-off was performed considering the criteria: effectiveness, safety, power, mass, cost, and design complexity. This trade-off was done for both the small and large object pick-up solutions. Additionally, sensitivity analysis was performed. The winners of the trade of were the litter picker/mantis claw for the big objects and the brushes for the small litter pieces, also see Table 5.2. Both the mantis claw and the litter picker were considered for the final design, including the possibility for adaptation or combination.

5.1.3. Final Pick-up Design

After trading-off all options for the pick-up mechanism, two were selected for the detailed design. This includes a brush mechanism for small litter pieces and litter picker for larger pieces. Having two mechanisms complies with requirements SYS-TE-QN-1-2, SYS-TE-QL-6-1-(1,2) & SYS-TE-QL-6-2-(1,2).

Pick-up for small pieces of litter: Brushes

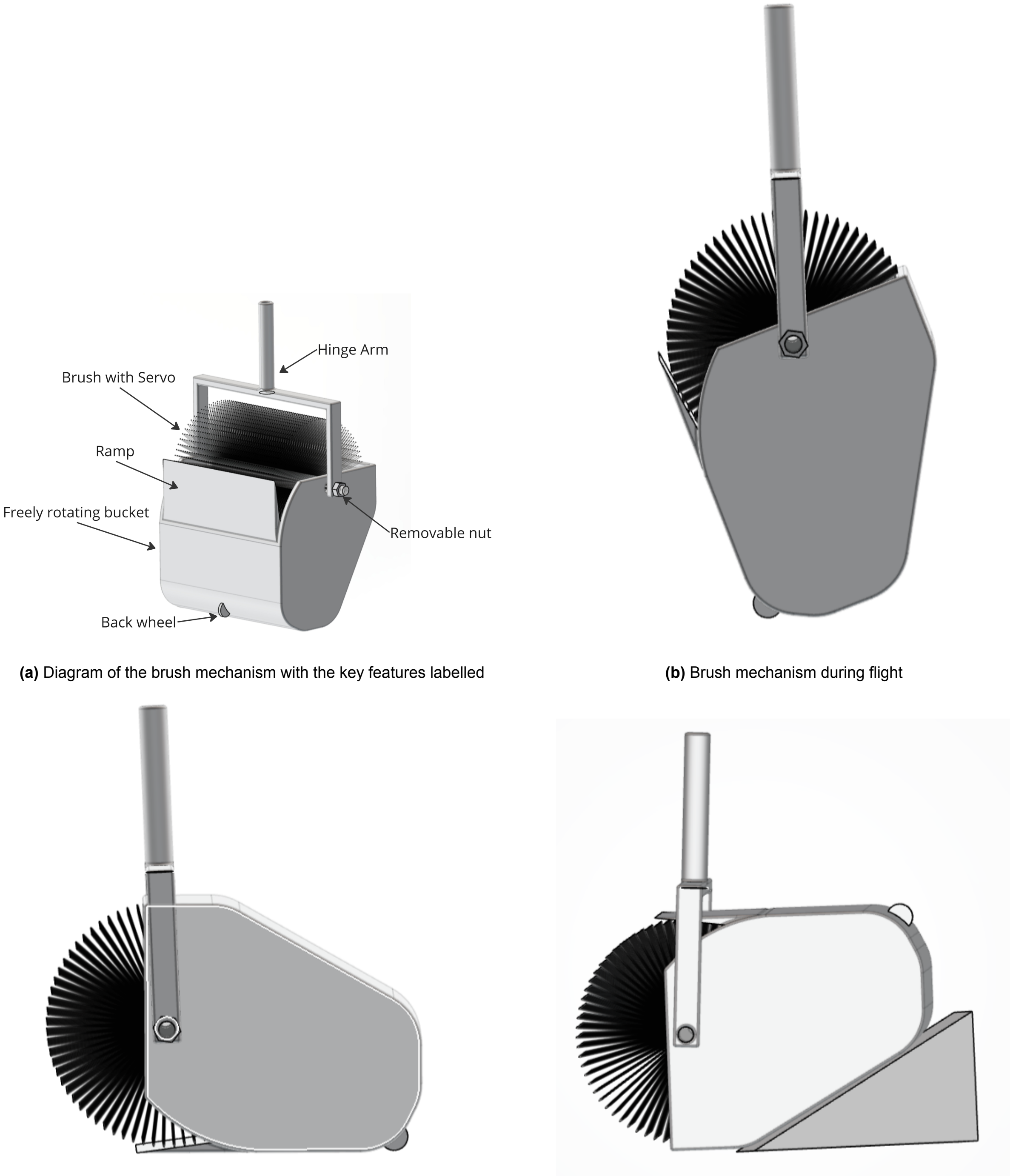
Small pieces of litter, such as cigarette butts and pieces of plastic, are scattered all around urban areas and make up 64% of litter [83]. To pick it up using some sort of grabbing mechanism would require immense precision which is unreasonable and inefficient. As a result, a brush mechanism is much more effective as it can sweep small pieces of litter into a container.

The design of the brush pick-up mechanism can be seen in Figure 5.3. It consists of a brush in a bucket, which is connected to a hinge arm. This hinge arm allows the bucket to rotate freely, allowing the bucket to be horizontal when on the ground to enable pick-up and vertical during flight to prevent litter from escaping. The bucket and hinge are designed such that the centre of gravity, at z=40mm, is forward of the hinge connection, at z=45mm, meaning the bucket hangs with its front tilted slightly forward and its back slightly backwards (with z measured from the centre of the tip of the ramp), as seen in Figure 5.3b. This, along with its rounded bottom, allows the bucket to easily and naturally rotate from its vertical position to its horizontal position when the normal force of the ground is applied during landing, as seen in Figure 5.3c.

The brush is designed such that it covers the entire mouth of the bucket, preventing any litter from escaping, complying with SYS-TE-QL-6-5. This could be a problem during takeoff when the bucket is still horizontal and there is a large wake effect of the propellers present. This is also mitigated by having the bucket beneath the drone such that it is shielded by the body of the drone.

The brush mechanism function is summarised as follows:

1. The drone lands on the ground causing the bucket to rotate to its horizontal position
2. The drone drives up to the litter - the rear-wheel prevents scraping of the bucket on the ground
3. The brush servo is switched on sweeping the litter into the bucket - this is aided by the ramp at the front of the bucket
4. The drone takes off and the bucket falls back to its vertical position
5. Steps 1-4 are repeated until the bin is full or at maximum weight capacity
6. The drone returns to the ground station landing on the ramp 'reversed' as depicted in Figure 5.3d
7. The brush servo is turned on and the litter is swept out of the bucket into bin - the steep nature of the back side of the bucket causes the litter to fall to the mouth of the bucket
8. Repeat steps 1-7



(a) Diagram of the brush mechanism with the key features labelled

(b) Brush mechanism during flight

(c) Brush mechanism during pick-up

(d) Brush mechanism during drop-off with the ramp

Figure 5.3: The brush mechanism in its various configurations

The material choice is important for the brush mechanism as it must be durable yet lightweight. The cost and sustainability of the materials is also an extremely important consideration. After researching various materials and comparing their relative performances with regard to the aforementioned criteria, it was decided the bucket and hinge are to be made of biodegradable PLA plastic and the brush is to be made of bamboo fibres. PLA plastic is chosen because it is composed of renewable and organic sources and it has many end-of-life options such as recycling and composting, which ties in with the Sustainable Development Strategy (see chapter 11). Furthermore, it is durable and lightweight and can be used in 3D printing. Similarly, bamboo fibre is also an organic material which is both strong and lightweight and can be sourced from greenhouses in the Netherlands and is biodegradable. The mouth of the bucket has a height of 70 mm and a width of 110 mm and the bucket extends for 100 mm with a 4 mm thickness, totalling a volume of $1.474 * 10^{-4} m^3$ with exact geometries considered. With a PLA density of $1200 kg/m^3$, this gives the mass of the bucket to be 177 grams. The hinge consists of a 60 mm hollow tube to connect to the drone. This allows the bucket to be flat on the ground during pick-up. The hinge extends 120 mm across and 60 mm down from the tube totalling a volume of $1.437 * 10^{-5} m^3$, resulting in a mass of 17.24 grams when using PLA. The brushes consist of 3,285 bamboo fibres all 0.5 mm in diameter and 40 mm in length connected to a circular tube, totalling a mass of 15 grams for a bamboo fibre density of $500 kg/m^3$. This gives the brush pick-up mechanism a total mass of 209 grams with the bucket having a litter capacity of 500ml.

In order to test that this mechanism works, a simple model made of thin plywood and a brush was created, as seen in Figure 5.4. The model worked by placing the mouth of the box by the litter pieces and manually spinning the brush using the nuts outside the box at the end of the brush piece. This model was extremely helpful for verifying the effectiveness of the mechanism and optimizing the design for the final design. During testing, it was fairly successful in collecting small pieces of litter, however, it was noticed that some pieces got stuck at the base of, or even under, the box and thus were not able to be collected. As a result, it was decided to add a ramp to the final design to aid the litter collection and mitigate this effect. Furthermore, having the hinge arms inside the box constricted the rotational degree of freedom, hence in the final design they are placed outside the bucket.

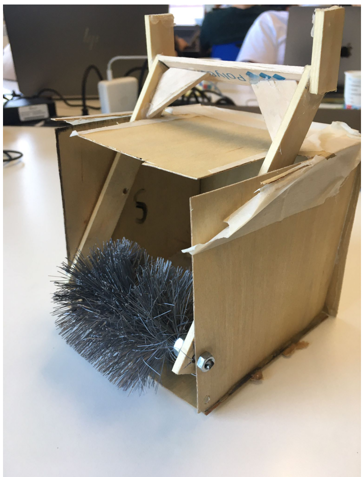
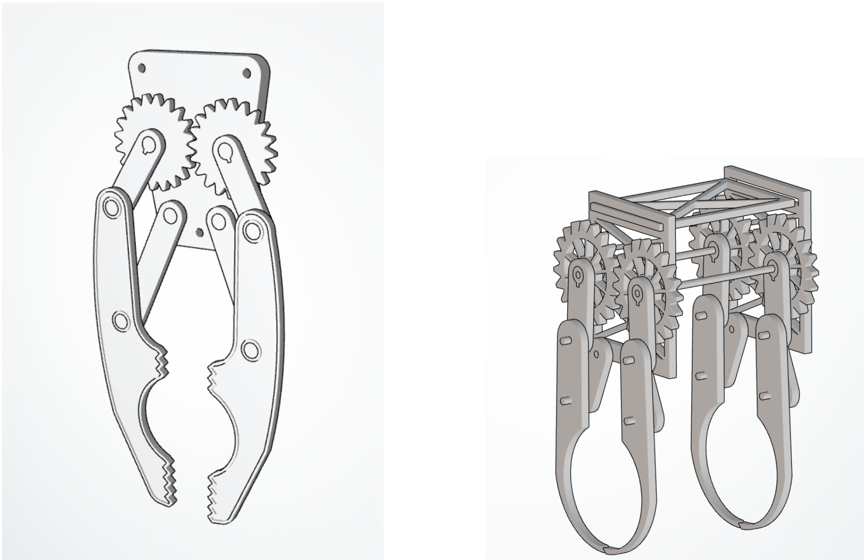


Figure 5.4: Prototype model of the brush mechanism

Pick-up for bigger pieces of litter: Grabber

As described earlier for the detailed design the litter picker was chosen with possible combinations or adaptations of the mantis claw were considered. However, the mantis claw requires a significant amount of space to open and move towards the object. As the drone is driving, this requires very big wheels which makes it not feasible anymore. Therefore only the litter picker was considered. In the beginning, a design of a litter picker claw made by Waqas Ayyaz [24] was adapted, the original design can be found in Figure 5.5. This design is slim and therefore light and small. Additionally, when constraints are added in CATIA and the mechanism is moved it could be seen that this mechanism snaps into place when closed and moves in a scooping motion instead of closing in a circular motion. This benefits the picking ability as the mechanism can quickly scoop underneath the object. In order to optimize the claw for pick-up several adaptations were performed. First of all, the top part of the claw was removed in order to create more space for various different objects. Secondly, in order to comply with SYS-TE-TI-1-1-1, the radius of the arcs seen in the arm of the claws was increased to 3.5 centimetres, which fits around bottles and cans [97] [98]. Lastly, the ends of the claw were decreased in height in order to grab underneath the trash.



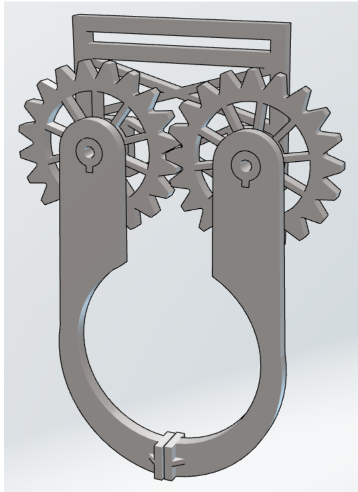
(a) CAD model of the original design of litter claw by Waqas Ayyaz [24]

(b) First iteration of the pick-up system claw design, adapted from Ayyaz [24]

Figure 5.5: First iteration of the design and the original CAD model by Waqas Ayyaz [24]

The first iteration of the whole design consisted of three of these claws, arranged in series and connected together using one shaft. To this shaft a servo is attached that can turn all three claws simultaneously. However, when the volume of this whole system was measured it turned out that the option of three claws was quite heavy, in the order of 400 grams. Therefore the number of claws was lowered to two, more closely spaced, with a distance of ten centimetres in between. This design can be seen in Figure 5.6.

(a) 3D printed prototype of the pick-up system, the green grabbing mechanism represents the first iteration, while the orange one represents the final iteration



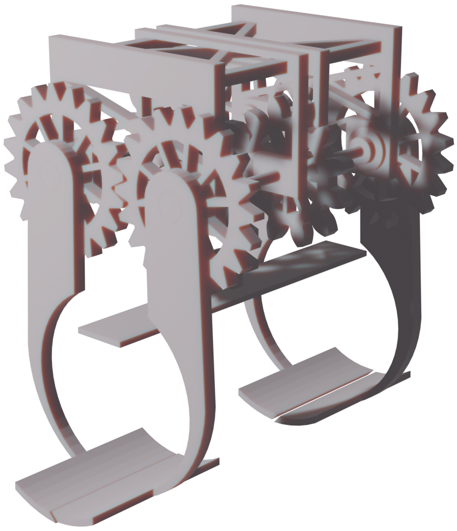
(b) Another type of possible pick-up claw that can be used for litter that requires pinching

Figure 5.6: CAD model of the final grabbing pick-up design

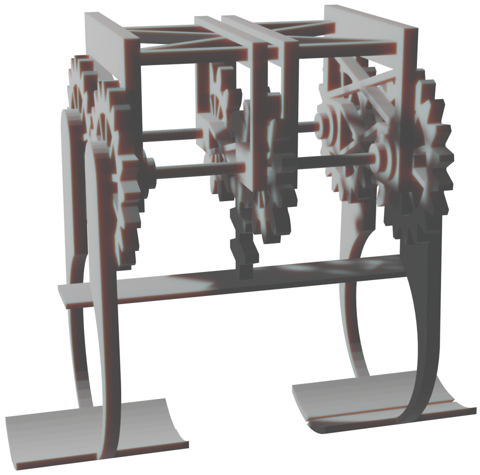
In order to validate and test this claw design, the CAD model was 3D printed and tested. The print was performed on an Ultimaker 3 using PLA material. The arms were connected using an M4 aluminium shaft and glue. Additionally, washers were added to keep the arms in place and add spacing where needed. A visual representation can be seen in Figure 5.5. After testing it it was quickly found that the claws needed an extension at the tips in order to hold items better. For this, the ends of the claws were extruded around two centimetres in both directions.

Next to this, it was also found that even though the scooping-like behaviour of the mechanism is beneficial, it takes quite some force to close, and sometimes the mechanism blocked and did not close properly. This has both advantages and disadvantages, as the system stays closed properly but it requires a stronger motor to close and it is more prone to failure in case the system blocks. The hypothesis was that this was either due to mistakes in production and that the offset of the arms need to be perfect or that there was a mistake in the design. In order to mitigate this issue, the choice was made to directly attach the claws to the gears, and have the closing be controlled by a servo, that can hold the mechanism into place. This change reduces the complexity of the system and makes the system significantly lighter by having no additional arms and a smaller back plate.

Lastly, in order to keep the picked-up litter in place an additional plate is pushed from above. It will incorporate a spring in order to add flexibility and adaptation to different sizes of litter pieces. This mechanism adds additional stability and grabbing capabilities to the pick-up mechanism, complying with SYS-TE-QL-6-5. Additionally, an additional type of arm was made, that can be used for a piece of litter that can be better picked up using pinching, see Figure 5.6. This can be combined together with the claw or maybe there is a drone that carries two of these grabbers. The final design of the pick-up system can be seen in Figure 5.7. The pick-up system will be 3D printed using NonOilen Biodegradable PLA material [52]. Additionally, rubber will be added to the claw surface in order to increase friction with the litter.



(a) Front render of the final grabbing pick-up design



(b) Side render of the final grabbing pick-up design

Figure 5.7: CAD model of the final grabbing pick-up design

Modular Design

It was decided that the pick-up mechanisms should be modular meaning the brushes can be swapped for a litter picker (and vice versa) depending on the litter distribution in a given area. This requires the pick-up mechanisms to have an attachment mechanism to the drone, which should be both reliable and quick to detach and reattach. After researching and trading-off various options, it was decided that a bayonet mount would be a suitable option. The pick-up mechanisms have a male pin which slots into a female receptor on the drone and it is rotated and drops into a position where it is locked. To remove the pick-up mechanism, it must be lifted and rotated out of the slot. The bayonet mount is shown in Figure 5.8 for the case of the brush pick-up mechanism. The tube is hollow, which not only reduces mass but also presents a safe pathway for the electrical wires to connect the pick-up servos to the drone. The wires can be connected from the pick-up system to the drone using a pin connector, like the xt60.

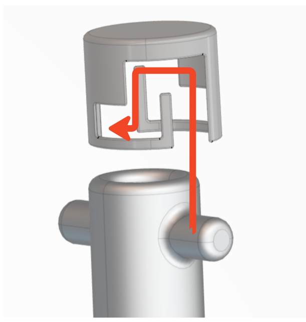


Figure 5.8: CAD model of the bayonet mount for pick-up system enabling the modular design. The arrow depicts the motion of the pin to lock

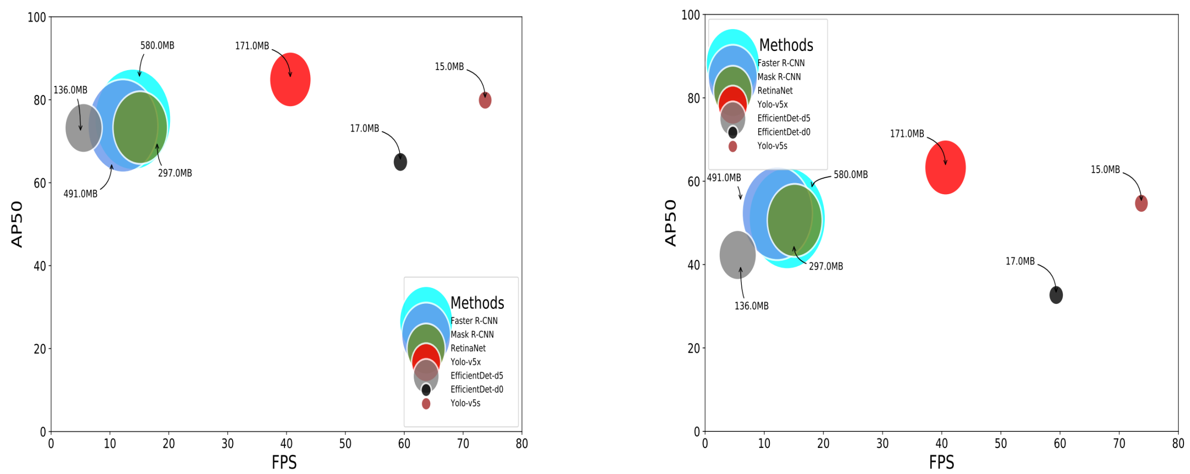
5.2. Computer Vision

To be able to detect litter while conducting reconnaissance, as required by SYS-TE-QL-8-1-2-1, and approach litter autonomously and avoid collisions, the utilisation of imaging devices is essential, as required by SYS-TE-QL-8-1-2-4. The imaging data acquired using these devices must consequently be processed using a computer algorithm, as required by SYS-TE-QL-8-1-2-3. An ideal candidate for this purpose is deep learning, with recent advancements facilitating the detection of objects with minimal computational costs at high accuracy. Moreover, deep learning offers the advantage of automatic feature detection, eliminating the need for manual engineering of feature extraction techniques. In the following subsection, the model employed for data processing and its performance on the UAVVaste dataset will be presented, which is specifically designed for litter detection from drones. Additionally, an algorithm for mapping litter using surveillance drones will be introduced. Lastly, the remarkable capabilities of combining state-of-the-art deep learning techniques and classical control theory in autonomously approaching litter will be showcased.

5.2.1. Object Detection

In this era of rapid advancements in AI, numerous deep learning solutions have emerged to address the challenge of object detection. In the subsequent subsection, the selection process of a suitable model will be examined, beginning from a high-level perspective by selecting a model family, and gradually narrowing down to the low-level considerations, such as selecting an appropriate model resolution.

Selecting Model Family



(a) Comparison between models on the PlastOPol dataset

(b) Comparison between models on the TACO dataset

Figure 5.9: Comparison between models on litter-related datasets . AP50 is the precision of the object detection model at a recall of 50%, where recall $= \frac{tp}{tp+fn}$, where tp is true positives and fn is false negatives. FPS is the number of images the model can infer per second. Image taken from [40].

To tackle the task of selecting a model family from the vast array of existing solutions, a comparative study of litter detection algorithms was conducted by Córdova et al. Figure 5.9 illustrates the key findings of the study, where the authors compare the computational cost of different models with their corresponding performance on the dataset. Specifically, it shows a comparison between the model size, FPS and accuracy expressed in terms of AP50, which is the average precision of the object detection model at a recall of 50%, with the recall R being described by the following equation:

$$R = \frac{tp}{tp + fn} \tag{5.2}$$

where tp is the number of true positives and fn is the number of false negatives in the context of object detection. The figure clearly demonstrates that the YOLO model family exhibits comparable performance to other model families while requiring significantly lower computational resources, including memory utilisation and FPS. Based on these findings, the decision to select the YOLO model as our preferred choice for litter detection was made.

Selecting YOLO Model version

Considering the advancements in deep learning technology, it is natural to assume that choosing the latest version of the YOLO model would yield the best results. In Figure 5.10, it becomes evident that the performance, both in terms of computational efficiency and accuracy on the dataset, improved with each subsequent version of the YOLO model [125]. Hence, the superior performance demonstrated by the later versions in these figures serves to validate the initial assumption that the latest version shows superior performance. Consequently, YOLOv8 is chosen as the model version for litter detection.

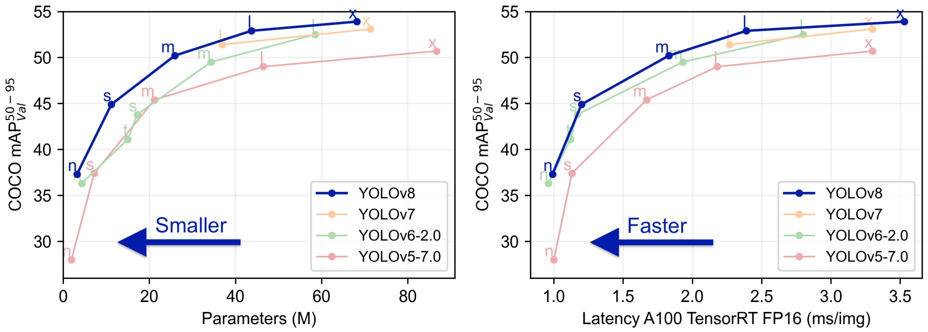


Figure 5.10: Comparison between YOLO model family models. Image taken from [125].

Training Model

The chosen YOLOv8 model family has several versions based on the model size. The model sizes range from nano (n), small (s), medium (m), large (l) and extra large (x). Moreover, the resolution of the input images can be arbitrarily chosen. Consequently, the model size and resolution shall be chosen to balance computational efficiency and precision.

In order to make these important choices, first a dataset shall be chosen to evaluate the performance. Three main datasets exist for litter detection: Plastopol [40], UAVVaste [78] and TACO [101]. While the Plastopol dataset solely offers detection capabilities, the UAVVaste dataset extends its offerings to include segmentation, albeit in a rudimentary form. On the other hand, the TACO dataset stands out as it has the most detailed labels: detection, extensive segmentation, and classification. Then again, the UAVVaste dataset is unique in its focus on providing litter detection specifically for drone images, while the other datasets encompass a broader range of images that are not directly relevant to our intended purpose.

Furthermore, initial tests have revealed that although the Plastopol and TACO datasets demonstrated reasonable performance in terms of metrics, the majority of the objects depicted in their images were already litter. Consequently, this led to a notable number of false positives when non-litter objects were encountered in real-world scenarios, which were simulated using a webcam. Furthermore, as depicted in Figure 5.11, it can be observed that the litter objects in the UAVVaste dataset generally occupy a considerably smaller area compared to the TACO dataset. This characteristic aligns more closely with real-world scenarios, such as litter mapping using surveillance drones. Following these observations, the UAVVaste dataset was consequently selected for evaluating model performance, as it does not exhibit the aforementioned issues. However, future endeavours will involve labelling the UAVVaste dataset with classification labels and possibly extending this dataset with our own images, enabling the deployment of a drone equipped with a suitable pick-up mechanism based on the litter class.

The accuracy of several model sizes and resolutions on the UAVVaste dataset is determined by training the model in Pytorch on an RTX4080 16GB GPU. The model has been trained with the SGD optimizer, with a momentum of 0.937, a linear warmup of 5 epochs and an exponential learning rate decay, with a peak learning rate of 0.01. The batch size was chosen to be 16, which was constrained to larger numbers due to memory limitations.

Model Size Selection

In order to determine the appropriate model size, training was conducted for all available sizes, followed by an assessment of the corresponding inference time. The resulting relationship between inference time and model accuracy is illustrated in Figure 5.12. Additionally, to gain a visual understanding of the model's accuracy, the object detection results on a chosen validation image are displayed in Figure 5.13.

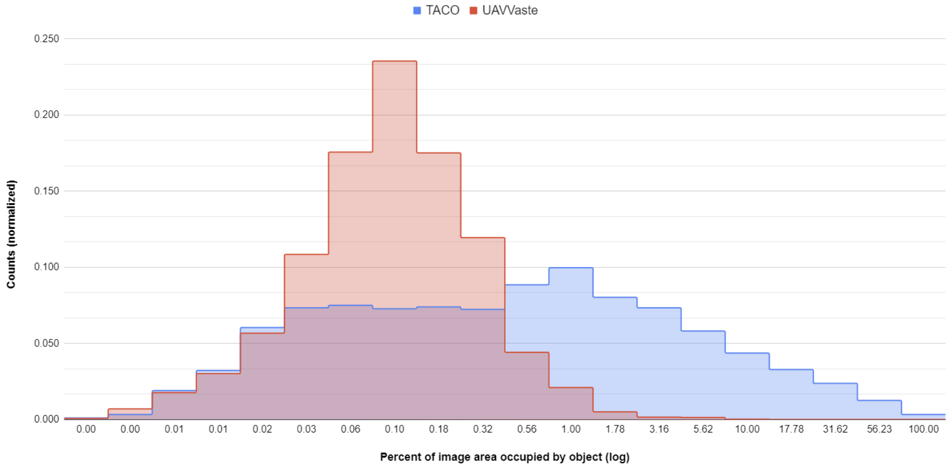
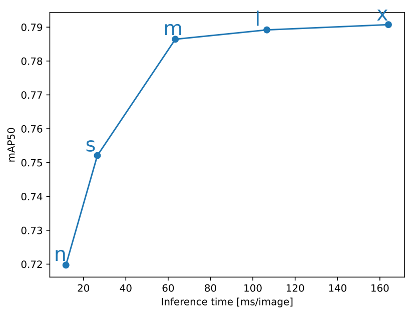
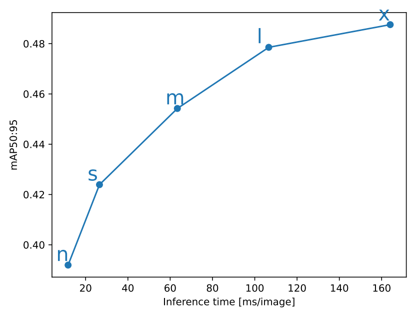


Figure 5.11: 'Comparison of relative object size distributions in the TACO and UAVVwaste datasets—Normalized counts versus percent of image occupied by objects. Please note the log-scale on the horizontal axis', [78]. TACO has a similar distribution compared to Plastopol [40]. Image taken from [78].



(a) Inference time versus mAP50 accuracy for YOLOv8 model trained on UAVVaste dataset.



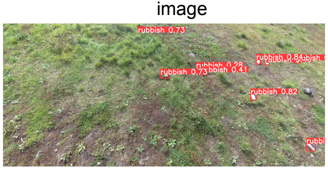
(b) Inference time versus mAP50:95 accuracy for YOLOv8 model trained on UAVVaste dataset.

Figure 5.12: Inference time versus accuracy for YOLOv8 model trained on UAVVaste dataset. The annotations indicate the standard size of the model (nano, small, medium, large, and extra large respectively). The parameters used to train this model on this dataset can be found

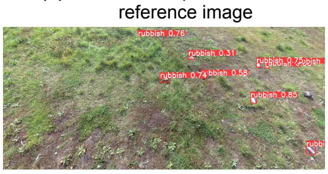
(a) Ground truth of the chosen reference image

(b) YOLOv8n output on the chosen reference image

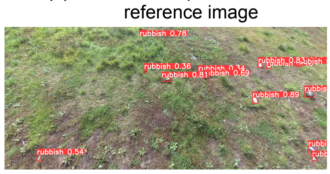
(c) YOLOv8s output on the chosen reference image



(d) YOLOv8m output on the chosen reference image



(e) YOLOv8l output on the chosen reference image



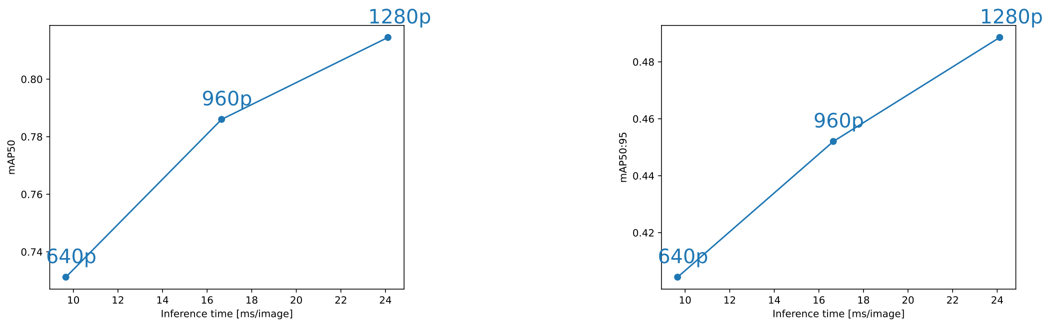
(f) YOLOv8x output on the chosen reference image

Figure 5.13: Model outputs and ground truth of 3 chosen reference images from the UAVVaste validation dataset for all YOLOv8 model sizes. The numbers next to the predicted class indicate in the red box indicate the confidence of the prediction.

In Figure 5.12, there is a noticeable increase in inference time as the model size is increased. However, both Figure 5.12 and Figure 5.13 illustrate that this increase in computational performance is only marginally reflected in the model's accuracy. Considering that the model needs to be executed onboard a drone with hardware that, while power-efficient, may not be particularly fast, it becomes evident that the significant decrease in computational performance does not justify the incremental gain in accuracy. Hence, YOLOv8n, the smallest model size, is chosen as the preferred model.

Selecting Model Resolution

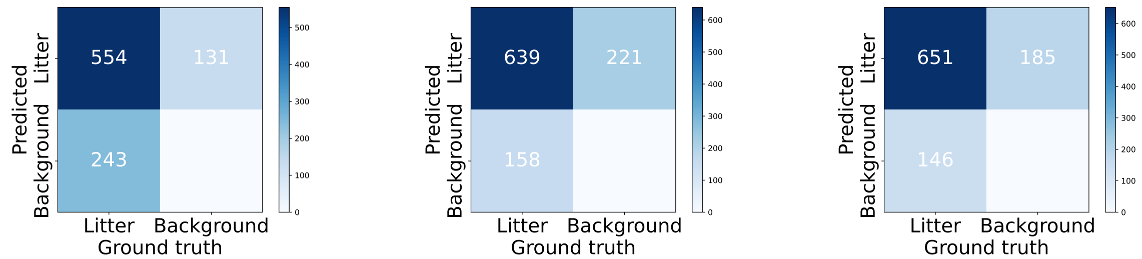
In order to determine the most suitable model resolution, a similar approach to selecting the model size is followed. The model is trained at different resolutions, and consequently the inference times are evaluated. To facilitate a fair comparison between resolutions, the relationship between inference time and accuracy is depicted in Figure 5.14. Additionally, to provide a more intuitive assessment of the model performances, a confusion matrix can be found in Figure 5.15.



(a) Inference time versus mAP50 accuracy for YOLOv8n model trained on UAVVaste dataset.

(b) Inference time versus mAP50:95 accuracy for YOLOv8n model trained on UAVVaste dataset.

Figure 5.14: Inference time versus accuracy for YOLOv8n model trained on UAVVaste dataset. The annotations indicate the resolution of the model: 640p x 640p, 960p x 960p and 1280p x 1280p respectively.



(a) Confusion matrix for YOLOv8n with 640p x 640p resolution.

(b) Confusion matrix for YOLOv8n with 960p x 960p resolution.

(c) Confusion matrix for YOLOv8n with 1280p x 1280p resolution.

Figure 5.15: Confusion matrices for YOLOv8n model trained on UAVVaste dataset.

Upon comparing Figure 5.12 and Figure 5.14, it becomes evident that scaling the resolution has a more pronounced impact than scaling the actual model. Remarkably, the yolov8n model with a 960p resolution achieves nearly identical performance to the yolov8x model with a 640p resolution. These observations further justify the choice for the smallest model size, namely yolov8n. Analysis of Figure 5.15 reveals a substantial increase in true positives and a notable decrease in false negatives when transitioning from 640p to 960p resolution. However, the same pattern of improvement does not persist when moving from 960p to 1280p. Consequently, it can be concluded that the resolution increase from 640p to 960p offers justifiable benefits, while further increments do not yield significant performance enhancements for the corresponding reduction in computational demands. Hence, a resolution of 960p is selected as the optimal choice.

Finally, Figure 5.16 presents a collection of reference images extracted from the UAVVaste validation dataset, overlayed with the ground truth and the output of the chosen model YOLOv8n 960p. Notably, it is evident that the model demonstrates a high level of accuracy in identifying the majority of litter instances with a notable level of confidence ranging from 70% to 100%. Additionally, the model exhibits robustness against distracting objects such as stones, as it avoids misidentifying these as litter.

To conclude, the YOLOv8 model family is chosen for object detection, as it provides high accuracy at a low computational cost. Among the available model sizes, the smallest variant, YOLOv8n, is preferred

(a) Ground truth of the chosen reference image 1
(b) YOLOv8n 960p output on reference image 1
(c) Ground truth of the chosen reference image 2
(d) YOLOv8n 960p output on reference image 2
(e) Ground truth of the chosen reference image 3
(f) YOLOv8n 960p output on reference image 3

Figure 5.16: Model outputs and ground truth of 3 chosen reference images from the UAVVaste validation dataset for the YOLOv8n model with a model resolution of 960p. The numbers next to the predicted class indicate in the red box indicate the confidence of the prediction.

as the marginal increase in accuracy does not justify the additional computational cost. However, to achieve a more substantial improvement in accuracy, a higher model resolution of 960p is chosen. This increase in resolution justifies the associated increase in computational cost, unlike the effect observed with increased model size. Consequently, the chosen model for the task is YOLOv8n with a resolution of 960p.

5.2.2. Collision Avoidance

The collision avoidance system is a crucial part of the entire system. It ensures that drones can operate safely in an urban environment by avoiding obstacles. It is especially important in the context of this project, as the system has special requirements regarding the avoidance of humans and vehicles, which poses an additional challenge for the collision avoidance subsystem.

It is a common practice to use several types of sensors in parallel to ensure a more robust system that can serve in a variety of environmental and operational conditions. In particular, it is beneficial to use a combination of sensors where one guarantees high resolution for short distances and another that covers larger distances with lower resolution [20]. Therefore, it is decided to go with a combination of radar and binocular vision. The former will ensure a coverage of up to 250 m and be insensitive to poor lighting and weather conditions. The latter will ensure high resolution at smaller distances [20].

One binocular vision sensor will be installed at the front of the drone to ensure that obstacles can be detected and avoided in the anticipated path of the drone. However, for the other sides of the drone, it is not that crucial to achieve a high level of resolution. Therefore, to rely entirely on the radar to cover other sides of the drone.

5.2.3. On-board Computer Vision Inference

In order to accommodate performing computer vision tasks on board the drones, a dedicated computational unit needs to be added, as required by SYS-TE-QL-8-1-2-3. The drones need to be able to recognise humans, vehicles and objects in real-time, in order to ensure that collisions with them can be effectively avoided thus ensuring the safety of the system. Moreover, trash has to be detected using surveillance to ensure optimal use of all drones. Initially, sending video feed from the drones to the ground station was considered, such that images from all drones could be analysed centrally on one computational unit. That would reduce the computational load handled by individual drones and redistribute it to the ground station, which has better access to power and is not constrained by weight so heavily. However, there are notable drawbacks to this centralized approach. It would introduce significant latency due to video transmission and analysis, which could impair real-time decision-making. Moreover, privacy concerns arise from transmitting video data, as it may include sensitive information. Additionally, relying solely on a ground station for analysis raises safety concerns in case of loss of contact, as the drones would lose the ability to autonomously process visual information. Therefore, onboard computational capabilities are crucial for efficient and secure real-time computer vision tasks. A state-of-the-art solution is the NVIDIA Jetson, which uses little power, is lightweight and offers easy machine learning integration [3, 4].

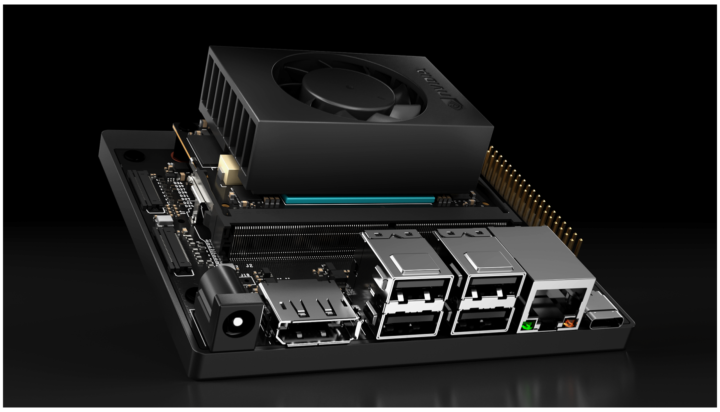


Figure 5.17: Nvidia Jetson Orin NX 8GB. Image taken from [2].

NVIDIA provides a wide spectrum of Jetson modules that can be used for that application. Initially, the NVIDIA Jetson Nano was considered. However, more research revealed that it has insufficient computational capabilities to perform inference on the YOLOv8n. Therefore, the Orin NX 8 GB was chosen, since it was the next cheapest and lightest option that was able to provide inference at a reasonable speed. According to Ultralytics documentation, Orin NX 8 GB should achieve around 61 FPS at 960p running YOLOv8n [5], which is sufficient for this application.

5.3. Propulsion

The propulsion subsystem is a pivotal part of a drone as insufficient design would render the drone flightless. As a result, the propulsion system must be carefully designed such that it provides the required thrust for flight and manoeuvres. Design option trees and trade-offs of the options were formulated in order to find the optimal solution.

5.3.1. Open or Closed Rotors

A design option tree for the propulsion subsystem was created to explore the various possible options for the design. The outcome was that the only feasible option for propulsion was to utilise electric motors with rotors. A key design choice was whether the rotors should be open or closed. Researched was conducted into the various options and a trade-off was completed, which can be found in [19]. This resulted in combining propeller guards with ducts around the rotors, ultimately choosing closed rotors. The ducts and propeller guards were consistently the highest scorers in the trade-off and it was decided to combine them to fuse their superior performances in varying categories. The propeller guards greatly increase the safety of the drone as they prevent objects from becoming entangled in the rotors, which would either break the rotors or damage the object. Adding propeller guards is the most effective design choice that can be made to avoid this and considerably increases safety. Considering that the drone will be operating in urban conditions surrounded by animals, plants and humans, this is a logical step in preventing any potential detrimental situations. Furthermore, ducts have proven to increase thrust performance by 7% even in a basic configuration where there is a one large duct surrounding all rotors in a multi-rotor drone [82]. Consequently, a duct-guard was selected and designed for the rotors, which will also be made of biodegradable PLA. This complies with SYS-CON-SA-3-1-1 & SYS-CON-SA-2-1.

5.3.2. Propeller Type

Over the past century, drones have typically utilised straight blade propellers to provide the thrust. They have been optimised over this time to improve performance and efficiency. However, recent innovations in propeller design has produced some concepts which suggest an increase in thrust, efficiency and noise performance.

Many variations of the blade propellers exist and some concepts are still being conceived, such as Prandtl-D propellers. This design incorporates wing tips and blade twist to supposedly improve efficiency. However, there is limited data and literature available investigating the performance of this design. Furthermore, in late 2022, a paper was released by MIT investigating the use of the toroidal propellers, particularly with respect to the noise performance. Toriodal propellers are closed-loop, which reduces tip vortices as they are spread over the whole blade loop. Tip vortices are known to be a major contributor to the noise produced by a propeller so reducing them implies the noise shall be reduced. As the vortices are smaller, they should also dissipate faster into the surrounding flow. Therefore, the MIT paper states that the toroidal propellers reduce noise, particularly at the frequencies humans are most sensitive to, whilst maintaining thrust performance [79]. However, this innovation is extremely novel and there is insufficient peer-reviewed professional data and literature that surround the toroidal propeller design.

Due to the lack of information with regards to the various propeller types, the team 3D printed and tested the propellers to gain first-hand data to aid the decision process. 4-inch toroidal, Prandtl-D and straight blade propellers were 3D-printed using Bambu Lab X1 Carbon 3D printer with Carbon-reinforced PET as the material. Unfortunately, the printing of the Prandtl-D turned out improper and was not suitable to test. The toroidal and straight-blade propellers were tested using a Racestar BR2205 motor connected to a Tyto Series 1580 testbench. The setup is shown in Figure 5.18a along with the toroidal propeller and blade propeller and their masses that were tested, shown in Figure 5.18b and Figure 5.18c, respectively. The testbench was able to measure the thrust and the electrical power usage of the motor among other less relevant parameters. A real propeller was also tested as a control. The motor setting was steadily increased up to its highest setting and the data was measured for each propeller individually. Furthermore, a sound meter was placed 20cm below the propeller to measure the noise during the tests.

(a) Test setup with the Tyto Series 1580 testbench

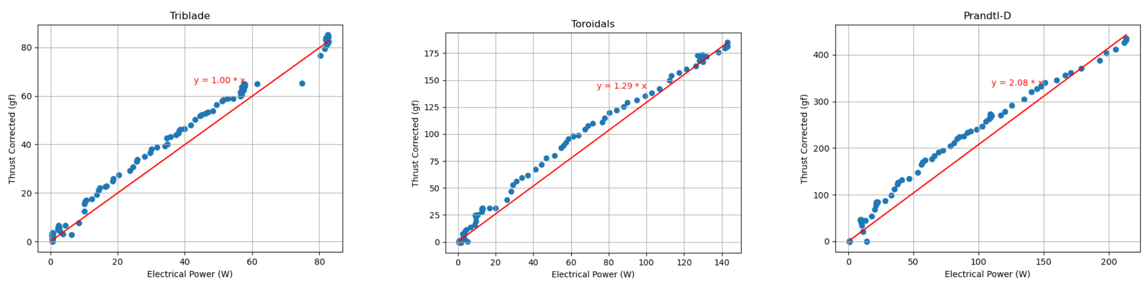
(b) Blade Propeller used in testing with its mass

(c) Toroidal propeller used in testing with its mass

Figure 5.18: Propeller testing setup with the propellers

Graphs depicting the data for the test can be found in Figure 5.19. Figure 5.19a depicts the thrust and power consumption of the blade propeller and Figure 5.19b showcases the same for the toroidal propeller. The power consumption is given as electrical power provided because the same motor is used so the efficiency of the conversion of electrical power to mechanical power is the same for both. The results are very interesting as the data shows that the toroidal propeller is actually more efficient as it produces an average of 1.29gf/W, whereas the blade only produces an average of 1.00gf/W. This implies that the toroidal propeller is 29% more efficient than the blade propeller, meaning it can produce 29% more thrust for the same amount of the power as the blade propeller. It must be noted that the thrust produced by the triblade and toroidal propellers are much lower (roughly 50%) than the real propeller, shown in Figure 5.19c. This is due to poor printing quality and material of the propellers. The propellers had many rough edges and were not very rigid. It would therefore be advised to repeat this experiment using better quality propellers. Nevertheless, as both propellers were printed using the same method and material, the results can still provide a fair insight into the relative performance of the propellers.

Furthermore, at full throttle the blade propeller produced a maximum noise of 98.1dBA whereas the toroidal produced a maximum noise of only 94.6dBA. On the other hand, the toroidal propeller was 80% heavier in relation to the blade propeller. This may appear as a concerning figure, however propellers generally weigh around the 10g mark, therefore an 80% increase in propeller weight relative to a 4kg drone is minimal and will not greatly impact the performance of the drone. Therefore, it can be concluded from the tests that the toroidal propeller is the optimal choice as it is both more efficient in thrust and quieter than the standard blade propellers. The toroidal propeller will hence be utilised in the drone design.



(a) Triblade propeller **(b)** Toroidal propeller **(c)** Real propeller for control

Figure 5.19: Graphs to show the thrust vs electrical power consumption of the tested propellers

5.3.3. Motor Selection & Propeller Design

Multicopter drones employ at least 4 rotors to provide the thrust and controllability. Most small multicopter drones are quadcopters, utilising 4 rotors in a square configuration. However, as safety is such a key concern for the design as the drones will be operating in urban environments surrounded by civilians and public property, it was decided that a hexacopter configuration would be more appropriate. This offers motor redundancy in case of failure as the drone will still be able to fly with 5 operational motors. In case of a quadcopter, motor failure would be detrimental to the controllability of the drone and could be potentially harmful to its surrounding environment. Therefore, this design choice complies requirement SYS-TE-QL-9-4(-1,2).

Furthermore, there was also an option of utilising coaxial or counter-rotating propellers as these exhibit a greater thrust efficiency and produce less noise [41]. These were deemed inappropriate for the hexacopter design as this would require six extra motors which would increase the mass and cost of the system greatly. It could, however, in future be considered for a quadcopter design, see chapter 16.

In chapter 8, the mass of the drone is shown to be 4kg. The drone is designed with the idea of having a maximum thrust-to-weight ratio of at least 2.5, providing a significant margin to allow for manoeuvrability of the drone. Therefore, the propellers must be sized with a compatible motor such that hexacopter drone is able to provide a maximum of 10kgf of thrust, meaning each rotor should be able to provide 1.7kgf, with an average value of 1kgf taken for flight. A top level estimate shows current drones use approximately 170W to provide 1kgf of thrust [96]. These values will be used to estimate the propeller dimensions and propulsion subsystem design.

Various off-the-shelf motors were researched which have a maximum thrust capacity of roughly 1.7kgf and are able to provide 1 kgf of thrust using less than 170W when paired with propellers. Different motors were compared and placed in a trade-off and the ECX 42 Flat UAV brushless motor developed by Maxon Group was the best choice, which has an efficiency of 91.6% and a mass of only 88.6g with the cables included [86]. It must be noted that this model is not yet commercially available but it is expected to be ready by Autumn 2023. When paired with a 14x4.5 double blade propeller, it is capable of producing a maximum of 2222gf of thrust and 1004gf at 110W and 5000RPM, complying with SYS-TE-QN-3-1-2. The motor choice also complies with requirement SYS-TE-QL-9-5.

The power, P, in Watts of a single rotor helicopter in hover, can be calculated using using Equation 5.3 with the thrust T in Newtons, density of air, ρ, in kg/m^3, and the area, A, of the spinning blade disc in m^2 [44] . This equation will be used to calculate the area of the spinning propeller disc from which the propeller diameter can be found. For this calculation, the top level estimate value of the power to provide 1kgf of thrust, hence it is assumed that $T = 9.81N$. The toroidal propellers were proven to be 29% more efficient, the motor has an efficiency of 91.6%, and the ducts are taken to provide an extra 7% of thrust, hence P = 111W instead of the 170W which was previously estimated. Plugging in these values and rearranging for A gives a disc area of $0.0312m^2$, meaning a diameter of 0.199m, or roughly 7.9 inches. This initial value seemed relatively small, particularly as the motor selected uses 14-inch propellers to provide 1kgf of thrust at 110W. Hence, an engineering decision was made, also considering the structure and layout of the drone, to increase the propeller diameter to 10 inches. This gives a thrust of 1.17kgf at 111W, which is similar to what the motor data gives for 14-inch propeller. This adds a safety margin and also allows for a better comparison between the propeller data given for the motor and what ADIOS design can expect, as the propellers are closer in size. A larger diameter requires less RPM to produce thrust and also reduces noise [92]. Furthermore, it was chosen to use a 3 loop toroidal propeller, instead of 2, as more blades produce less noise [92], which is another key requirement to be met. The material chosen for the propellers is carbon fibre as this is commonly used in drone propellers and is a strong and durable material, which is necessary as the propellers are subject to extremely high accelerations. These design choices enables the compliance with requirements SYS-TE-QL-9-3(-1).

$$P = \frac{T^{3/2}}{\sqrt{2 \cdot \rho \cdot A}} \tag{5.3}$$

Noise estimations can be made using semi-empirical methods that exist for rotors or propellers, however none such exist specifically for drones yet, especially for toroidal propellers. Traditionally, noise generated by propellers consists of rotational and vortex components [85]. Methods exist for the Generalised Rotor-Noise Estimating Procedure presented in A Review of Aerodynamic Noise From Propellers, Rotors, and Lift Fans (1970) [85]. It presents a method to estimate the rotor rotational noise as well as rotor vortex noise to an accuracy of $\pm 8dB$. The requirements state that the drone shall produce less than 70dB on the facade of houses so this is a goal that must be complied with.

To calculate the rotational noise spectrum occurring instantaneously at any point P, relative to the rotor centre and its direction of motion, the following steps can be performed. For the case of interest, the point P is chosen to be 5m in lateral distance away from the rotor (x = 16.4ft) and the drone is assumed to be flying at 10m/s (V = 32.8ft/s) velocity with three (B=3) 10inch (d = 0.83ft) propellers operating at 5000RPM (n = 523 rad/s) , producing 6kgf (13.2lbs) of thrust, meaning 1kgf thrust per rotor (T = 2.2lbs). The following equations are calculated in imperial units with C = 1117ft/s, representing the speed of sound.

1. Calculate the range: $r = \sqrt{x^2 + y^2 + z^2} = 16.4ft$
2. Calculate the rotational Mach number: $M = 0.8 \cdot \frac{nR}{c} = 0.8 \cdot \frac{523 \cdot 0.417}{1117} = 0.156$
3. Calculate the flight Mach number: $M_f = \frac{V}{C} = \frac{32.8}{1117} = 0.0294$
4. Calculate the angle ϵ between the flight direction and the line joining the rotor and the field point: $\epsilon = \cos^{-1}\left(\frac{x}{r}\right) = 0.0deg$
5. Calculate the effective rotational Mach number: $M_e = \frac{M}{1 - M \cdot \cos\epsilon'} = 0.161$
6. Calculate the angle θ between the rotor plane and the line r. If the disc incidence is $i_d = 0$, this is given by: $\theta = \tan^{-1}\left(\frac{z}{\sqrt{x^2+y^2}}\right) - i_d \cdot \tan^{-1}\left(\frac{x}{\sqrt{x^2+y^2}}\right) = 0.0deg$

7. Using the values of M_e and θ, see the appropriate sheet in Appendix D to obtain values of the harmonic sound pressure level I_N, for $N = 2, 3, 4, 6, 8, 10, 12, 16, 20, 30, 40$, and 60. Given that the calculated $M_e = 0.161$, the values will follow for $M_e = 0.2$ as this is the closest value. This gives $I_N = [76, 70, 66, 60, 57, 55, 52, 47, 45, 40, 35, 30]$
8. Calculate the rotor area: $A = \pi \cdot \dfrac{d}{2}^2 = 0.54ft^2$
9. Correct the values obtained for thrust, disc loading, and distances according to: $SPL = I_N + 11 + 10\log_{10}(\frac{T}{r^2}\frac{T}{A}) = [72, 66, 62, 56, 53, 51, 48, 43, 41, 36, 31, 26]$ dB re 0.0002 dyne/cm^2
10. The fundamental frequency is $\frac{nB}{2T(1-MF\cdot\cos\epsilon')} = 257$ Hz, where B is the number of blades.

The rotor vortex noise follows from the same report and the procedure for calculating the sound pressure level of vortex noise from a rotor under conditions of uniform inflow is shown below.

1. Calculate the linear velocity: $V_{0.7} = 0.7\dfrac{n \cdot \pi \cdot d}{60} = 153ft/s$
2. Calculate the total blade area, where a is the chord length, a, is taken to be 20mm (0.066ft): $A_b = B \cdot \dfrac{d}{2} \cdot a = 0.082$
3. Use Schlegel's equation to calculate overall vortex noise at 300ft at 70° F: $SPL_{300} = 10(2 \cdot \log V_{0.7} + 2\log T - \log A_b - 3.57) = 25dB$
4. Calculate SPL at the specified distance r: $SPL_r = SPL_{300} - 20 \cdot \log 10\dfrac{r}{300} = 50.9dB$

Given that there are 6 rotors, the accumulation of the noised produced by K=6 rotors can be estimated using Equation 5.4 to find the extra noise produced by 6 rotors.

$$SPL_{total} = 10\log_{10}(K) = 7.8dB \tag{5.4}$$

Therefore, the total maximum noise generated by the propellers can be estimated to a sum of the maximum rotational noise plus the vortex noise plus the noise accounting for the total number of rotors. This gives a total maximum noise of $72 + 51 + 7.8 = 130 \pm 8dB$. This can be converted to A-weighted decibels, which accounts for the relative loudness perceived by human ears. As the rotational noise is the majority contributor to the noise, the frequency will be taken to be the fundamental frequency of the rotational noise, namely 257Hz. Given a frequency f, the A-weighted decibel difference can calculated using Equation 5.5 and Equation 5.6, totalling -8.42dB. Therefore, the total noise can be said to be equal to 120dBA. From initial inspection, this value is extremely high as it is comparable to a jet taking off. This value was still the case after verifying the methods and calculations. The method was also used to calculate the noise for a 4 inch propeller (scaled down by 2.5x), the size used in the tests. This gave a total noise of 150dBA, which is 50dBA more than the test measurements despite being much further away and is roughly 18 times louder than the calculated value for the 10 inch propellers. Reasons for such a high value could be due to the fact that this method is tailored for larger rotorcraft such as helicopters and that an M_e value of 0.2 was used for the graphs in the rotational noise calculations when the actual value was only 0.16.

$$A(f) = 20\log 10(R_A(f)) + 2.00 \tag{5.5}$$

$$R_A(f) = \frac{12194^2 f^4}{(f^2 + 20.6^2)\ \sqrt{(f^2 + 107.7^2)\,(f^2 + 737.9^2)}\ (f^2 + 12194^2)} \tag{5.6}$$

The noise can also be estimated using the experimental data obtained during the propeller testing. The noise was measured using a sound meter approximately 20cm below the propeller, perpendicular to the flow. For the toroidal propeller, it measured a maximum noise of 94.6dBA. The noise generated by 6 of these propellers totals 102.4dBA using Equation 5.4. The noise attenuation for a distance of 5m away can be estimated using Equation 5.7. Attenuation of 28dBA results in a final noise of 74.4dBA, which seems much more reasonable. It was previously found that the 10 inch propellers were approximately 18 times quieter than the 4 inch propellers using the Generalised Rotor-Noise Estimating Procedure. Therefore, seeing as the tested propellers were 4 inches in size but the propellers are 10 inches in actuality, one can say that the noise value for the 10 inch propellers can be scaled down to be 18 times quieter than the measured value for the 4 inch test propellers. This gives a final noise estimate value of 50dBA. This would comply with requirements SYS-CON-SA-1-2-1, SYS-CON-LE-2-1-1 and SYS-CON-LE-2-1-2.

$$dL = 20\log 10(r_2/r_1) = 20\log 10(5/0.2) = 28.0dBA \tag{5.7}$$

It must be noted however, the experiments were performed with propellers of incorrect material and incorrect motor and the Generalised Rotor-Noise Estimating Procedure gives inaccurate noise values, as its method outputs noises which are much louder than the experimental data. Therefore, the value found is not entirely reliable. Printing with a finer material should improve the noise characteristics as using a finer material would mitigate rough edges from interfering with the flow causing turbulence, which contributes to the noise production. The calculated value above is purely an estimate for the noise emissions but it gives a preliminary indication into the expected noise value. The most appropriate way to accurately and reliably find the noise emissions would be to test the real propellers on a drone and measure the noise levels.

5.4. Telemetry, Tracking and Command

To ensure the safety of drones and bystanders, the ADIOS system needs proper communication for various purposes such as transmitting video and state data, while receiving commands from the ground station. It is common to have a separate link for video transmission, as it requires far more output than other communication purposes [134] [93]. Initially, the communication had been divided into two links: one for video transmission and the other for control and non-payload communication (CNPC). However, after making a proper trade-off for the separate links, cellular communication resulted in being the most feasible option for both of them. Therefore, cellular communication is used for all TT&C functions of ADIOS.

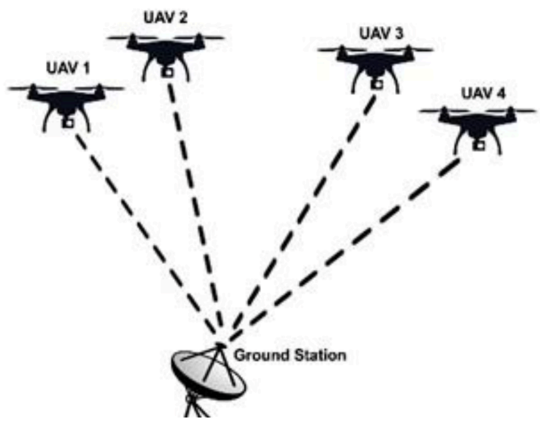


Figure 5.20: Centralized architecture [76]

Cellular communication relies on mobile towers that create coverage areas into cells. The applicability of this type of communication follows from a high data rate, and ensuring stable connection Beyond Visual Line-Of-Sight (BVLOS) [54], which is the requirement SYS-TE-QL-8-1-1. While the high data rate is required for the video transmission from the drones to the GS, the BVLOS performance is crucial for being able to operate autonomously while being behind buildings or other obstructs.

Furthermore, the architecture opted for is a centralised architecture. This choice was made mainly due to its reliability and simplicity. It means that all drones will have a direct communication link with the ground station and indirect inter-drone communication, as can be seen in Figure 5.20.

The main component of the TT&C subsystem is a 4G modem, which has a built-in receiver and transmitter. 4G was chosen since it provides widespread coverage in all kinds of areas. Newer technologies like 5G tend to have limited coverage, while 4G is often cheaper and more reliable. The specific modem that was chosen is a SIM7600G-H Module for Jetson Nano, which is the onboard computer of ADIOS drones. This modem supports 4G communication as well as GNSS positioning. It as a maximum uplink and downlink data rate of 50 and 150 Mbs, respectively, over which all video transmission and telemetry data shall be sent. A more detailed overview of the components and their data flows is shown in Figure 5.21:

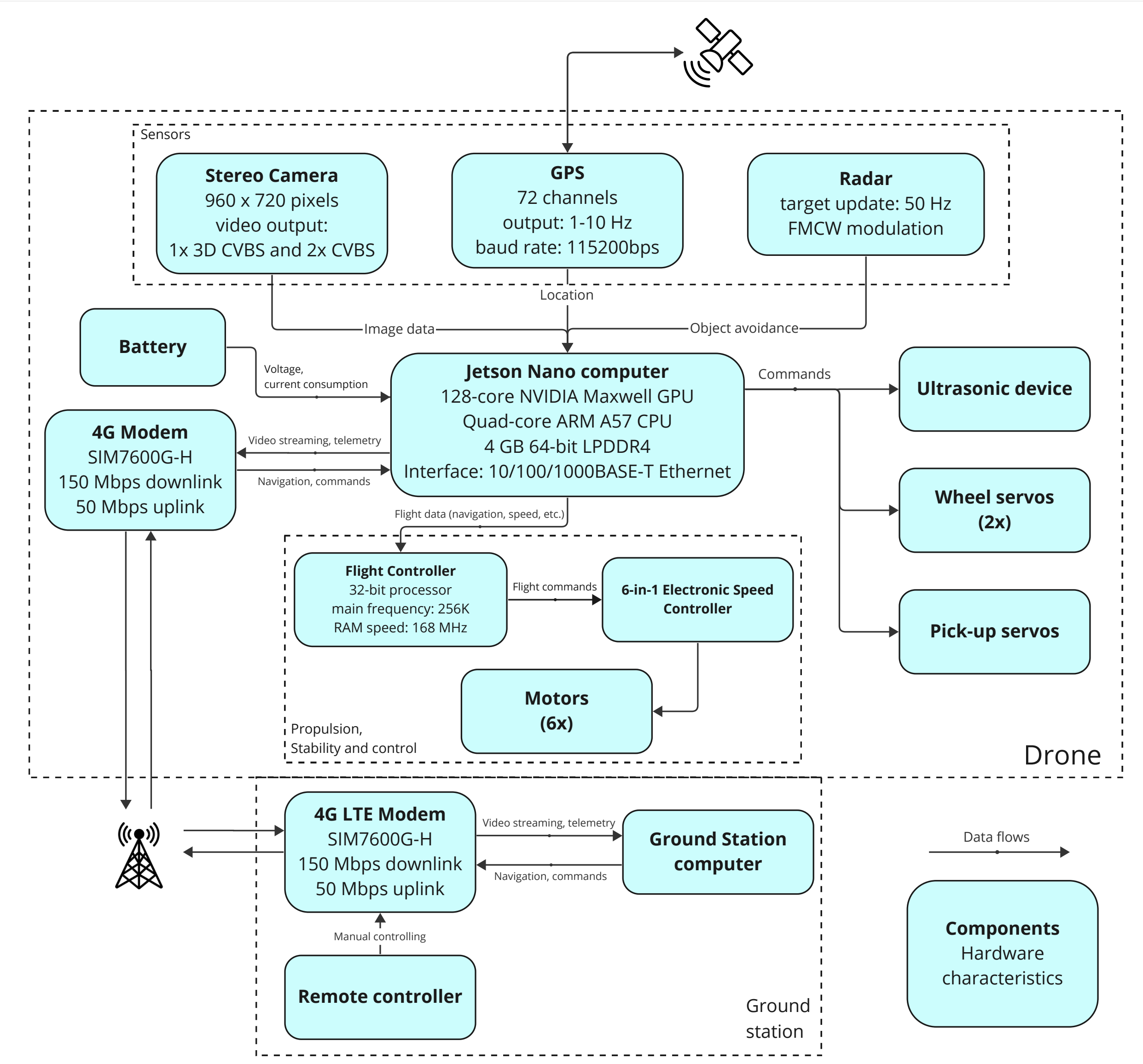


Figure 5.21: Data Handling Block Diagram

In this block diagram, the blue boxes represent the components that share data flows. Furthermore, it is clear that all data is firstly processed in the computers, after which it can be communicated with the 4G modem. Furthermore, a communication flow diagram is shown in Figure 5.22. It illustrates the flow of data through the system and to and from its environment.

5.5. Electrical Power Supply

The Electrical Power Supply subsystem (EPS) of the ADIOS drones provides and distributes energy to all electrical components on board. The energy storage takes place in a Lithium-Polymer (LiPo) battery. This type is commonly used in UAVs because they offer high energy density while being relatively small and lightweight in comparison to other rechargeable types. Another lithium-based battery often

Figure 5.23: The Tattu battery used in ADIOS drones

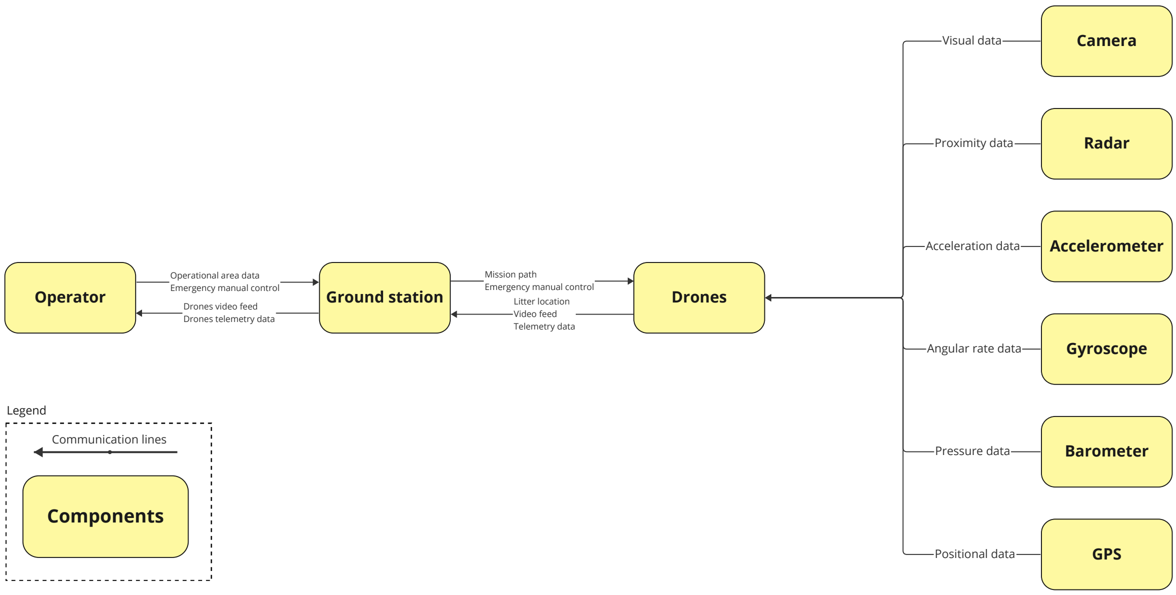


Figure 5.22: Communication flow diagram

used for energy supply in drones is Lithium-Ion batteries. However, LiPo batteries generally hold more power and are thus more applicable for ADIOS [120].

The specific battery that the ADIOS drones carry is a Tattu 16000 mAh 22.2V 30C 6S1P LiPo battery with an XT-90 connector (Figure 5.23). The discharge rate being 30C indicates that the discharge current of the battery can be at most 480 A. Furthermore, the configuration 6S1P means that six cells are connected in series.

Next to the power supply, a power distributor is required. This distributor is built in the 13A 6-in-1 ESC, which distributes the available power to all six motors for propulsion. Moreover, this component distributes power to all components: the sensors, servos, and even communication components. A clear overview is shown in Figure 5.24:

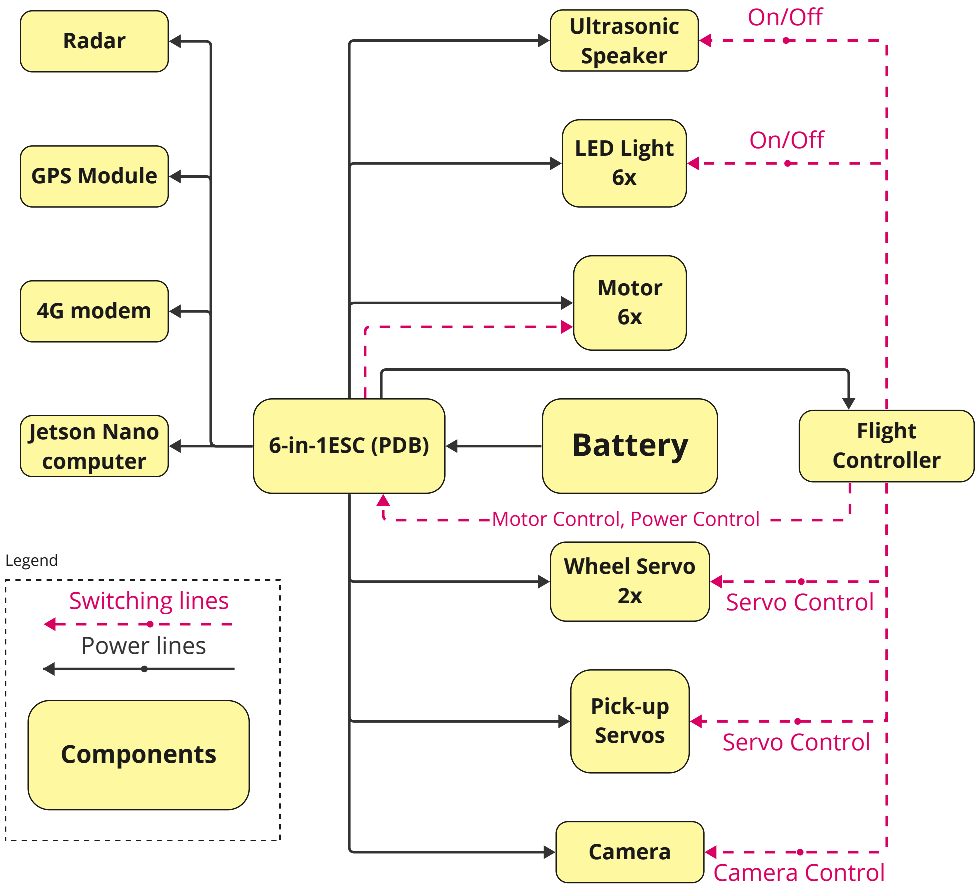


Figure 5.24: Electrical Block Diagram of an ADIOS drone

In this block diagram, the black arrows represent the power flows through the drone and the dotted red arrows indicate the switching line, representing a signal that is used to switch or control the operations. It can be seen that the PDB component gathers all power from the battery, and distributes it over the electrical components. Furthermore, the flight controller primarily transmits signals to the components responsible for flight operations.

5.6. Configuration

As all subsystems have been designed, they can be integrated together with each other to create the final configuration of the drone. This final configuration includes the design of some structural components of the drone, an assembly of all the components, and a layout configuration of the electronic units inside the drone housing.

5.6.1. Hardware Structure

In order to combine the subsystems together, a hardware structure is required. It was chosen to have all components and subsystems at the centre of the drone except for the propulsion and pick-up systems. In order to protect these components and also provide a more appealing design, the central components are encapsulated by a housing structure. The housing structure is designed with a hexagonal base as it is a hexacopter, with a rounded top to give it a more sleek and aerodynamic design. The housing structure has ports for the cameras and radar to protrude through and to allow easy exchange of the battery. The pick-up systems are attached below the centre of the housing using the modular design system discussed in subsection 5.1.3. It was decided to use biodegradable PLA for the material for the same reasons explained in subsection 5.1.3.

The propulsion subsystem extends out from the housing to ensure the wake of the propellers is clear of the central housing. To accommodate for this, arms protrude from each corner of the hexagonal base with the propulsion units fixed to the end. They are designed to be 150 mm long to ensure sufficient clearance between the propellers and the housing. The arms are subject to high loads and stresses due to the upward lift force provided by the propellers at the end of the arm. Therefore, the arms are made of carbon fibre which is an extremely strong material and can withstand high loads and stresses. For further structural analysis of the arms, please see section 8.1.

As discussed in chapter 4, the drones must be equipped with wheels to enable a ground approach of the drone as the wake effect is too strong and cannot be effectively mitigated. As a result, two wheels are placed below the housing at the outermost points with a rear stabiliser to ensure stability during driving. The wheels are sized to be 250 mm in diameter to compromise between the mass of the wheels and the power required to rotate them whilst also ensuring sufficient clearance between the wheels and the main drone structure. The wheels are again made of biodegradable PLA plastic. The wheels are connected to the drone via suspension to provide support, particularly during landing as it is assumed that the maximum landing height will be from 0.5 m. As a result, the suspension is composed of TPU plastic as it is a very flexible material to absorb the landing loads without breaking. For further analysis of the landing loads, please refer to section 8.1.

5.6.2. Assembly

The ADIOS drone is built out of many different components. While some of these components are custom-designed, others are simply existing drone components, like the Jetson Orin NX 8 GB onboard computer that was discussed in subsection 5.2.3. One of the components that was custom-designed is the pick-up mechanism. As explained in subsection 5.1.3, the drones can be attached with two different pick-up mechanisms for different purposes. A technical assembly drawing of a drone with the grabber mechanism is shown in Figure 5.25.

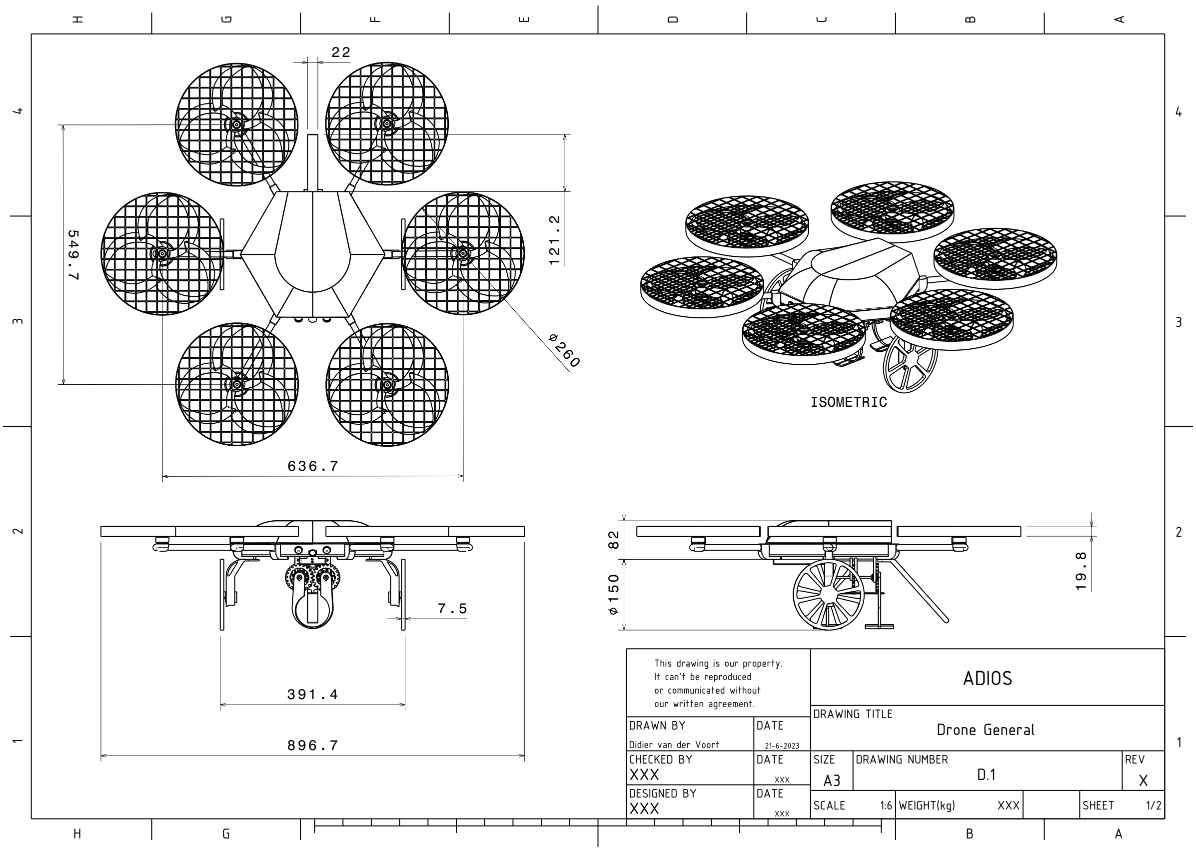


Figure 5.25: Technical drawing of the drone with the grabbing mechanism made in 3DExperience with dimensions in millimetres

The assembly for a drone with the brush mechanism is almost identical to the one with the grabber mechanism since the pick-up mechanism attachment system of the drone is modular, which means that the mechanisms can be swapped effortlessly. Furthermore, another technical assembly drawing, showing all components of the drone in an exploded view is shown in Figure 5.26. These components are numbered and listed in the Bill of Materials (BOM) at the bottom right of the figure.

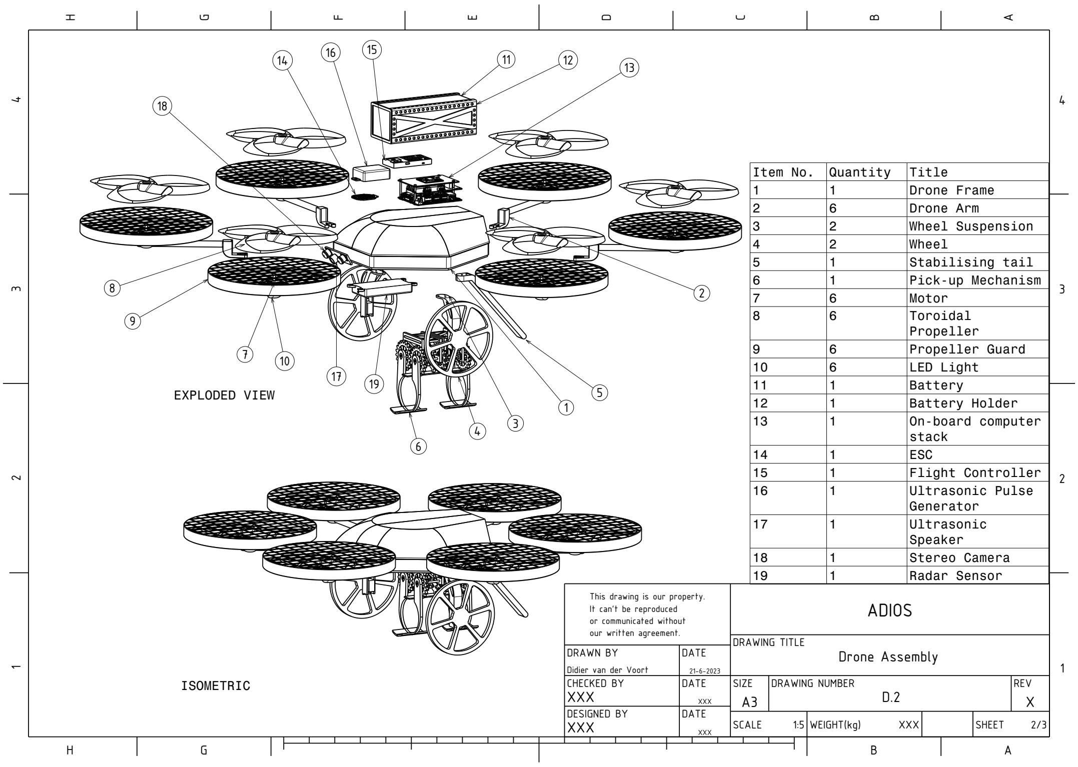


Figure 5.26: Technical drawing with an exploded view of the drone assembly made in 3DExperience

It is important to note that several of the CAD components of the drone have been imported using GrabCAD [60]. These components include the electronic units carried onboard, the motors, toroidal propellers, and the LED lights at the tip of the 6 arms of the drone. However, some of these imported components have been modified, like the toroidal propellers that have been scaled.

With the materials of all major drone components having been determined, renders of the complete ADIOS drone were created. A render of a drone with the grabber mechanism is shown in Figure 5.27, and a render of a drone with the brushes mechanism is shown in Figure 5.28.

Figure 5.27: Render of the drone with the grabbing mechanism made in 3DExperience

Figure 5.28: Render of the drone with the brushes mechanism made in 3DExperience

Although the core materials of the drone were determined, the colours of the components were not determined yet. Since most of the components will be made out of PLA, no wrapping material is required since PLA can be printed in many colours, including green and black. The wheel suspension, which is made out of TPU, does also not need wrapping material as the standard colour of TPU is often black. Finally, the arms of the drones are made out of carbon fibre, which also does not require wrapping since its standard colour is also black.

One of the requirements of the ADIOS system was that the drones shall have a friendly appearance. Therefore, the importance of selecting a fitting colour scheme should not be underestimated. As can be seen in Figure 5.27 and Figure 5.28, the two main colours of the ADIOS drone are spring green and black. The spring green colour is often associated with nature and therefore portrays the sustainability of ADIOS. The purpose of the black colour is to provide contrast, such that the drone does not blend in with grass and can still be spotted easily by the public for safety purposes. Additionally, as can be seen in Figure 5.27 and Figure 5.28, there is a flashing red LED light at the tip of every drone arm which is essential for safety as the drones will stand out more to the people in the environment.

Finally, a render of the ADIOS drone with the grabber mechanism in an urban area is shown in Figure 5.29. This shows what an ADIOS drone will look like in the environment that it will operate in.

Figure 5.29: Render of the drone with the grabber mechanism flying in an urban area made in 3DExperience

5.6.3. Electronic Units Layout

As mentioned before, the drone also houses numerous electronic units. These units are fitted onto the hexagonal base plate around which a housing is designed. Although aerodynamics are taken into consideration when designing the housing, it has not been optimised yet with regards to aerodynamics, as aerodynamics are not driving the design for drones. Nonetheless, it is recommended to perform an aerodynamic optimisation of the housing in the future. The layout of the electronic units on the base plate is shown in Figure 5.30.

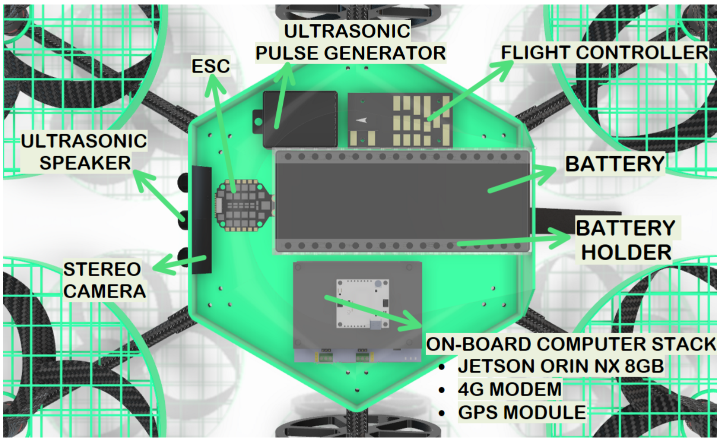


Figure 5.30: Render of the drone frame with the housing made transparent to show the electronic units layout made in 3DExperience

in Figure 5.30, some crucial electronic components can be seen. For example, the onboard computer stack is important for processing data, flying autonomously, and communicating with the ground stations. The flight controller is essential for the stability and control of the drone during operation. The 6-in-1 electronic speed controller (ESC) controls the motors of the hexacopter but also serves as a power distribution board (PDB) to distribute the power from the battery to all components. The stereo camera is used mainly for litter detection, but also for obstacle avoidance. Finally, the ultrasonic pulse generator connected to the ultrasonic speaker is capable of creating an ultrasonic sound frequency of 22 kHz which repels any animals close to the drone [105]. This is extremely important as the drones should not pose a danger to animals.

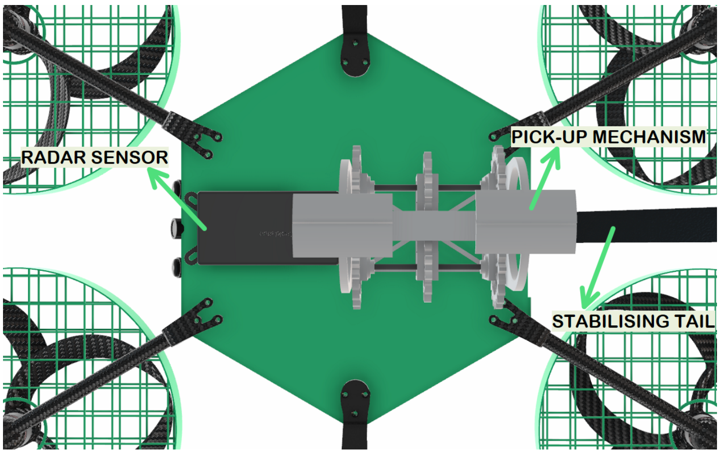


Figure 5.31: Render of the bottom of the drone frame showing the radar sensor, the pick-up mechanism and the stabilising tail made in 3DExperience

At the bottom of the drone frame, as can be seen in Figure 5.31, three components are attached. In the front, the radar sensor is attached, which can emit radio waves in all directions for obstacle avoidance. In the middle, the pick-up mechanism is attached. Note that in this view, the grabber is attached. The brush's pick-up mechanism will be attached to the same place. At the back of the frame, a stabilising tail is attached in order to provide stability while driving on the ground.

Furthermore, the layout of the electronics has been optimised with regard to space, wiring, and centre of gravity. Since the drone will be landing on the ground, it is crucial that the centre of gravity of the drone is behind the wheel axis in order to prevent it from tipping onto its nose. Therefore, the drone battery, which is almost half of the total weight of the drone, has been shifted aft slightly. This will make sure that the drone will rest on the stabilising tail while it is driving on the ground. Note however, that this will require the aft rotors to work slightly harder than the front rotors. Although this difference is not critical, it should be taken into account for drone maintenance. Furthermore, to evenly distribute the forces on the wheels, the lateral positioning of the components was also taken into account. Furthermore, wiring has also been taken into account when designing the layout. For example, the 6-in-1 electronic speed controller (ESC) which also serves as a power distribution board (PDB) is located in the middle of all components since it needs to be connected to all components. The ultrasonic pulse generator is located in the front to minimise the distance to the ultrasonic speaker. Finally, where possible, the required space was minimised as much as possible. For example, the 4G modem and the GPS module have been stacked onto the onboard computer to save space on the base plate.

5.7. Control System

In this section, the control system design of the drone is documented. In subsection 5.7.1, the trade-off done in the midterm [19] will be revisited. Then, in subsection 5.7.2, some physical drone parameters will be determined that will then be used in subsection 5.7.3 to design and tune the controller. Lastly, in subsection 5.7.4, the stability and robustness of the drone and controller will be assessed.

5.7.1. Control System Reevaluation

In [19] a trade-off was made for the control system on the drone. From this trade-off, the PID angle controller was chosen. However, after some further research, a controller named LQR controller was found [8]. This controller yields similar performance, while being far easier to implement and gain tune. As a consequence, the control system is now simpler, but at the same time more robust. Since the next step is to integrate the drone control system with a large-scale operations simulation, it makes sense to have a simple controller. For this reason, it was decided to switch to the LQR controller. The schematic of this controller is shown in Figure 5.32.

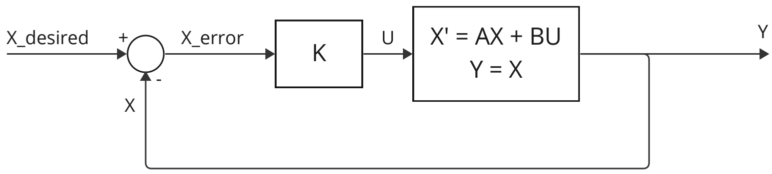


Figure 5.32: Block diagram of state space and controller

5.7.2. Physical Drone Parameters

To be able to run the control system model realistically, a number of drone properties must be specified. These properties are listed in Table 5.3. The mass, length from the centre of gravity to the propeller and the area of a spinning propeller are all results from previous sections in chapter 5. After the gain tuning and stability analysis, the drone mass increased from 4.0 kg to 4.4 kg. Thus, the gains determined in this section are not optimal. Thus, in the future these actions should be performed again.

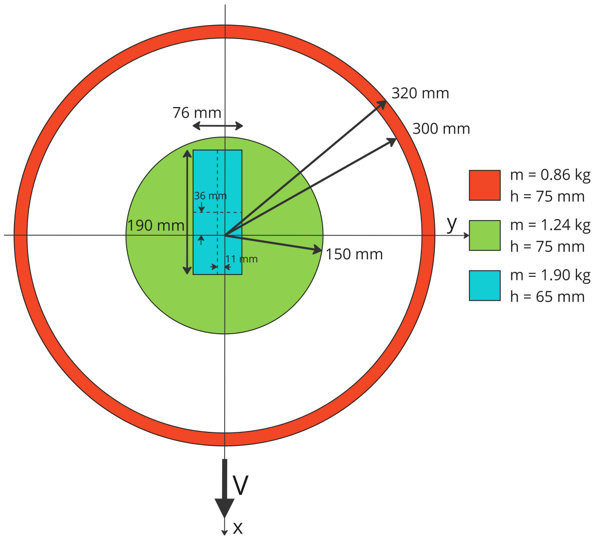


Figure 5.33: Geometry used for moment of inertia calculation

Table 5.3: Drone properties

Property [unit]	Value
Mass $[kg]$	4.0
b $[Ns^2]$	$6 \cdot 10^{-6}$
k $[Nms^2]$	$3 \cdot 10^{-8}$
Length from COG to propeller $[m]$	0.32 m
Area of spinning propeller $[m^2]$	0.0507
I_{xx} $[kgm^2]$	0.05061
I_{yy} $[kgm^2]$	0.05766
I_{zz} $[kgm^2]$	0.10577

To calculate an estimation of the moments of inertia of the drone, a simplified geometry is used, which is shown in Figure 5.33. Since the battery is the component with the highest weight and the propellers with motors are the masses furthest from the centre of gravity, these two masses are taken separately. The weight of the propellers, motors and safety guards are included in the outside ring. The radius of the ring is taken such that it is positioned at the mounting position of the propellers. The rest of the mass of the drone is put in a cylinder with a radius corresponding to the maximum distance of the housing, which is 150 mm.

It is assumed that the centre of gravity of the cylinders has the same position as the centre of the coordinate system and the centre of gravity of the battery is in its middle. Equation 5.8 and Equation 5.9 are used to calculate the moment of inertia of the cylinders [28]. For the outside ring, first, the mass is calculated when the entire cylinder was filled by keeping the same mass density. Then the moment of inertia of the ring is calculated by subtracting the moment of inertia of the inner cylinder from the total.

$$I_{xx} = I_{yy} = \frac{1}{12} m \cdot (3r^2 + h^2) \tag{5.8}$$

$$I_{zz} = \frac{1}{2} m r^2 \tag{5.9}$$

Moreover, the battery's center of gravity does not coincide with the center of gravity of the drone. Therefore, the parallel axis theorem is necessary which results in Equation 5.10 [28]. This equation is shown for the moment of inertia around the X-axis but can also be used for the other two axes.

$$I_{xx} = \frac{1}{12} m(l_y^2 + l_z^2) + m d_x^2 \tag{5.10}$$

From these calculations and summing the separate contributions, an I_{xx} of 0.0506 kgm^2, an I_{yy} of 0.0577 kgm^2 and an I_{zz} of 0.1058 kgm^2 are found.

5.7.3. LQR Controller Design

To design the control system for the hexacopter, first, an axis system must be defined. Together with this, the positions and rotational directions of the hexacopter must be specified. The definition for all of this was taken from [110], and is shown in Figure 5.34. All angles between the motor arms are 60 degrees.

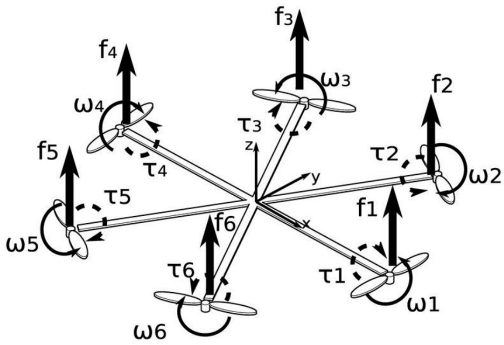


Figure 5.34: Schematic of the hexacopter axis system and motor rotation directions [110]

In Figure 5.35, a free-body diagram is made of the drone in the x-plane. Summing forces in the horizontal direction leads to the first equation in Equation 5.11. Using similar approaches, the rest of the equations in Equation 5.11 are collected.

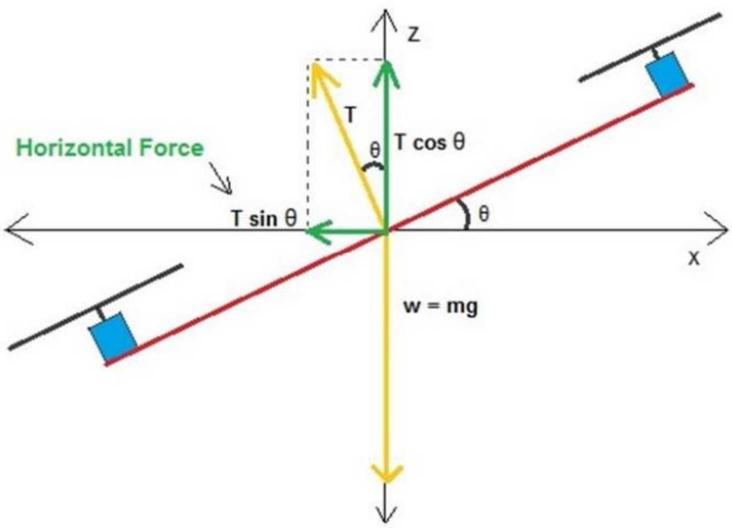


Figure 5.35: Free body diagram of the drone in the x-plane

$$\ddot{x} = -g\theta, \;\; \ddot{y} = g\phi, \;\; \ddot{z} = \frac{F_z}{m}, \;\; \ddot{\phi} = \frac{M_x}{I_{xx}}, \;\; \ddot{\theta} = \frac{M_y}{I_{yy}}, \;\; \ddot{\psi} = \frac{M_z}{I_{zz}} \tag{5.11}$$

These equations can then be grouped into a state space system, as shown in Equation 5.12.

$$A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -g & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & g & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{m} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \frac{1}{I_{xx}} & 0 & 0 \\ 0 & 0 & \frac{1}{I_{yy}} & 0 \\ 0 & 0 & 0 & \frac{1}{I_{zz}} \end{bmatrix} \tag{5.12}$$

$$X = Y = \begin{bmatrix} x & y & z & \dot{x} & \dot{y} & \dot{z} & \phi & \theta & \psi & \dot{\phi} & \dot{\theta} & \dot{\psi} \end{bmatrix}^T, \quad U = \begin{bmatrix} F_z & M_x & M_y & M_x \end{bmatrix}^T \tag{5.13}$$

$$K = \begin{bmatrix} 0 & 0 & K_3 & 0 & 0 & K_6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & K_2 & 0 & 0 & K_5 & 0 & K_7 & 0 & 0 & K_{10} & 0 & 0 \\ K_1 & 0 & 0 & K_4 & 0 & 0 & 0 & K_8 & 0 & 0 & K_{11} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_9 & 0 & 0 & K_{12} \end{bmatrix} \tag{5.14}$$

The shape of the gain matrix K is shown in Equation 5.14. Using the 'lqr(A, B, Q, R)' function from Matlab, this gain matrix K was tuned. In addition to the A and B matrices, it takes two additional matrices as parameters: Q and R. These matrices represent the importance of performance and actuator effort respectively. The value used for Q is the identity matrix of size 12 (12 state variables) with all entries multiplied by 10. For R the matrix is simply an identity matrix of size 4 (4 inputs). The identity matrices mean that the error in all states, and the effort in all input degrees of freedom are values equally. The factor 10 for Q means that performance has a higher importance than input effort. Using all these matrices, the 'lqr()' function simply minimizes a cost function that takes performance and effort into account. An overview of all values for both the state space matrices and controller gains can be found in Table 5.4.

Table 5.4: Overview of all values in the state space and feedback matrix

Parameter	$g[m/s^2]$	$m[kg]$	$I_{xx}[kgm^2]$	$I_{yy}[kgm^2]$	$I_{ZZ}[kgm^2]$	K_1	K_2	K_3
Final value	9.81	4.0	0.0506	0.0577	0.106	-3.16	3.16	3.16

Parameter	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}	K_{11}	K_{12}
Final value	-4.65	4.64	5.88	17.9	18.0	3.16	3.44	3.48	3.26

It is noteworthy that the gains K_1 and K_4 are negative. This is because these gains determine the contributions from x and θ to M_y. Due to the definition of the axis system, positive errors in x and θ need to be restored with a negative M_y. This is also visible in Equation 5.11, where the equation related to $\ddot{x}$ has a minus sign, while the equation related to $\ddot{y}$ has not.

Finally, it is important to notice that in practice, the drone is not controlled by directly manipulating its forces and moments, but by manipulating each individual rotor speed. The equations used to model how the rotor speeds generate the vertical force and attitude moments are shown in Equation 5.15. Here, b and k are the thrust and torque coefficients of the propellers respectively. These values were obtained from the midterm report [19]. The value $b = 3E-6$ was obtained by dividing the drone mass (1.2 kg at the time) by a common angular velocity value (1000 rad/s). The value $k = 3E-8$ was obtained by assuming a propeller power of 30W, dividing it by the angular velocity to get the motor torque, and then dividing it by the angular velocity squared to get the coefficient value. These values are not the most accurate. However, their only function is to scale the effect of rotor speeds: Increasing these values simply results in faster spinning rotors. Changing these values thus barely impacts the controller performance.

$$U = \begin{bmatrix} F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} b(w_1^2 + w_2^2 + w_3^2 + w_4^2 + w_5^2 + w_6^2) - mg \\ \frac{3}{4}bl(w_2^2 + w_3^2 - w_5^2 - w_6^2) \\ bl(-w_1^2 - \frac{1}{4}w2^2 + \frac{1}{4}w_3^2 + w_4^2 + \frac{1}{4}w_5^2 - \frac{1}{4}w_6^2) \\ k(-w_1^2 + w_2^2 - w_3^2 + w_4^2 - w_5^2 + w_6^2) \end{bmatrix} \tag{5.15}$$

To compute the required rotor speeds for a given control force or moment, this system must be inverted. In this case, there are infinitely many ways to create this mapping, since there are more rotor speeds than inputs. This allows for control reconfiguration in case of a rotor failure. The default control mapping was taken from [110]. These equations were put into matrix form and are shown in Equation 5.16.

$$\vec{w}^{\,2} = \begin{bmatrix} w_1^2 \\ w_2^2 \\ w_3^2 \\ w_4^2 \\ w_5^2 \\ w_6^2 \end{bmatrix} = \begin{bmatrix} \frac{1}{6b} & 0 & -\frac{2}{5bl} & -\frac{1}{10k} \\ \frac{1}{6b} & \frac{1}{3bl} & -\frac{1}{5bl} & \frac{1}{5k} \\ \frac{1}{6b} & \frac{1}{3bl} & \frac{1}{5bl} & -\frac{1}{5k} \\ \frac{1}{6b} & 0 & \frac{2}{5bl} & \frac{1}{10k} \\ \frac{1}{6b} & -\frac{1}{3bl} & \frac{1}{5bl} & -\frac{1}{5k} \\ \frac{1}{6b} & -\frac{1}{3bl} & -\frac{1}{5bl} & \frac{1}{5k} \end{bmatrix} \cdot \begin{bmatrix} F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} \tag{5.16}$$

5.7.4. Stability characteristics

In this subsection, the stability analysis is performed. It consists of two parts. First, the stability itself will be analyzed by identifying all (critical) eigenvalues and eigenvectors of the system. After that, the robustness of the controller itself will be investigated by calculating the stability margins.

Eigenvalue and eigenvector analysis

The first step to analyzing the stability of the system with controller is to perform an eigenvalue analysis. This analysis is performed using Python. Using the "control.matlab.ss()" function, a state space system is first created. Then, using the 'sys.poles()' and 'sys.zeros()' functions from the same module, the poles and zeros of the system can be found. It was found that the system does not contain any zeros. This is due to the fact that the system only contains integrators and no differentiators. Integrators multiply the denominator by s, while differentiators multiply the enumerator by s. Thus, the system does not contain any zeros. Because of all integrators present, the (closed loop) system does contain a lot of poles. These poles are shown in Figure 5.36.

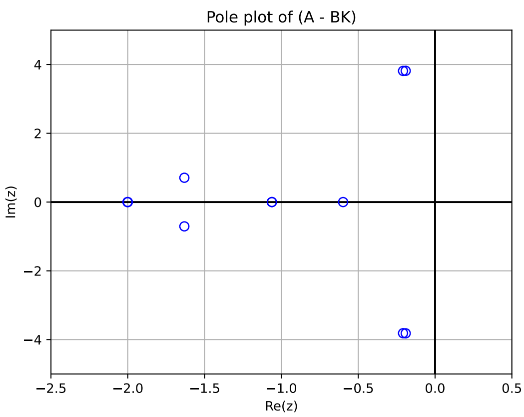


Figure 5.36: Plot of all poles of the closed loop system

All poles in Figure 5.36 are in the left half of the s-plane, which means that there are no strictly unstable eigenmodes. Most of these poles are either non-oscillatory, or slightly oscillatory. The eigenmodes associated with these poles are thus highly damped. These eigenmodes will not raise any conerns, so they will not be analyzed further. However, two pole pairs do raise some concerns, as they have high imaginary values, but real values close to zero. This indicates highly oscillatory and lightly damped behaviour. Thus, these two pole pairs need to be investigated further. The first step is to find their corresponding eigenvectors. Using 'numpy.linalg.eig(A - BK)', the eigenvectors are found. They are shown in Table 5.5.

Table 5.5: Overview of all eigenvalues and their corresponding eigenvectors of the closed loop system

Eigenvalue	Eigenvector
-0.21 + 3.81j	$\begin{bmatrix}0.023+0.14j & 0.023-0.14j & 0 & 0 & 0 & -0.41 & 0 & 0 & 0 & -0.68 & 0 & 0\end{bmatrix}^T$
-0.21 - 3.81j	$\begin{bmatrix}0 & 0 & 0.021+0.14j & 0.021-0.14j & 0 & 0 & 0 & 0 & -0.41 & 0 & 0 & -0.68\end{bmatrix}^T$
-0.19 + 3.82j	$\begin{bmatrix}0 & 0 & 0 & 0 & -0.19 & 0 & 0 & 0 & 0 & 0 & -0.86 & 0\end{bmatrix}^T$
-0.19 + 3.82j	$\begin{bmatrix}-0.54+0.058j & -0.54-0.059j & 0 & 0 & 0 & 0.83 & 0 & 0 & 0 & 0.72 & 0 & 0\end{bmatrix}^T$

To test the responses of these eigenvectors, they are given as initial conditions to the state space system model. Since for the actual physical drone system the inputs must be real, the imaginary parts of all eigenvectors were omitted when setting them as initial value. To keep it concise, only the first eigenvector response is shown, as all eigenvectors give a similar response. The response for the eigenvalue -0.21+3.81j is shown in Figure 5.37. For the left plot, the open end in the top right corner corresponds to t = 0. For the right plot, the line starts in the origin, then quickly moves straight to the left, and then goes back to the origin in an oscillatory manner.

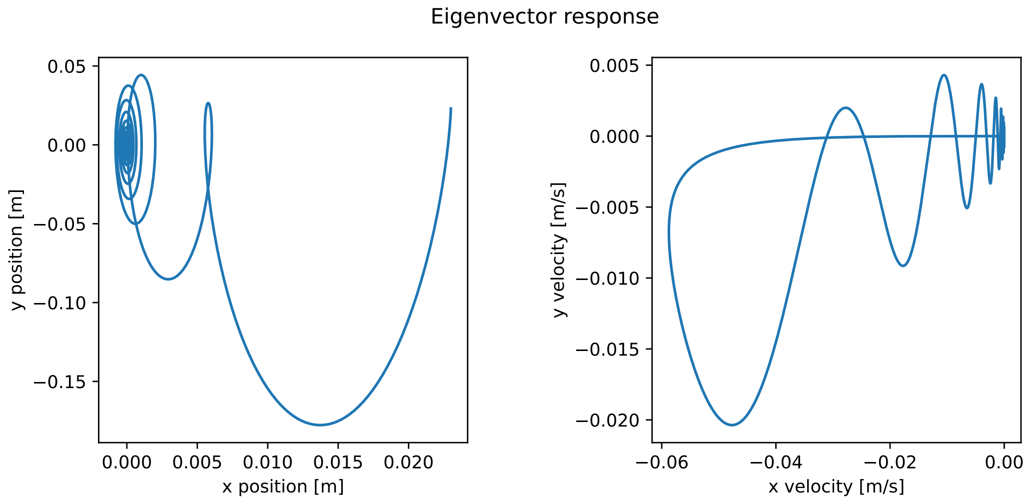


Figure 5.37: Eigenvalue analysis of the eigenvalue -0.21+3.81j

At first sight, the system looks very chaotic and uncontrolled. However, when comparing the magnitudes of the initial state and outputs, it becomes clear that this behaviour is not severe in any way: the initial velocities and rates are in the order of 0.5-1 m/s and 0.5-1 rad/s. Especially the latter is a very extreme scenario. However, the induced oscillations in space only have an amplitude of no more than 0.1 m, which is still a small deviation. Such deviations are unlikely to cause any problems. This analysis verifies that the drone complies with a few requirements, namely SYS-TE-QL-1-2-1, which states that the drone should be able to hover stationary and SYS-TE-QL-1-2-2, which states that the drones shall be able to restore to zero ground speed and zero vertical speed after a disturbance (wind, gust) within 1 second of the disturbance.

Stability margins

To assess the robustness of the controller, its stability margins will be analyzed. This was done with Matlab. First, the state space system with the controller was recreated in Simulink. The block diagram is shown in Figure 5.38.

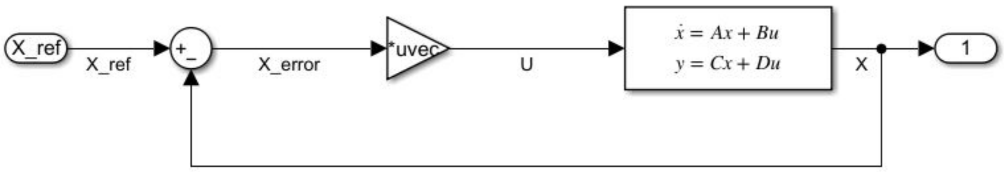


Figure 5.38: Block diagram of the state space system and controller

Using the Matlab function 'getIOtransfer()', the MIMO transfer function from 'X_error' to 'X' was obtained. Instead of regular stability margins, disk-based stability margins are used. This is because regular stability margins assess the gain and phase margin independently, while in reality there are uncertainties in both. For example, a system can have high gain margins when there are no phase perturbations and high phase margins when there are no gain perturbations, but if there are perturbations in both, it can still become unstable quickly.

Using the 'diskmargin()' function from the Matlab robust control toolbox, the disk-based stability margins were obtained. Since there are 12 inputs and outputs, there are too many possible loops to consider separately. Thus, the multiloop gain and phase margins were used. A plot showing the disk margins as a function of frequency is shown in Figure 5.39. The most critical values found for the system are shown in Table 5.6.

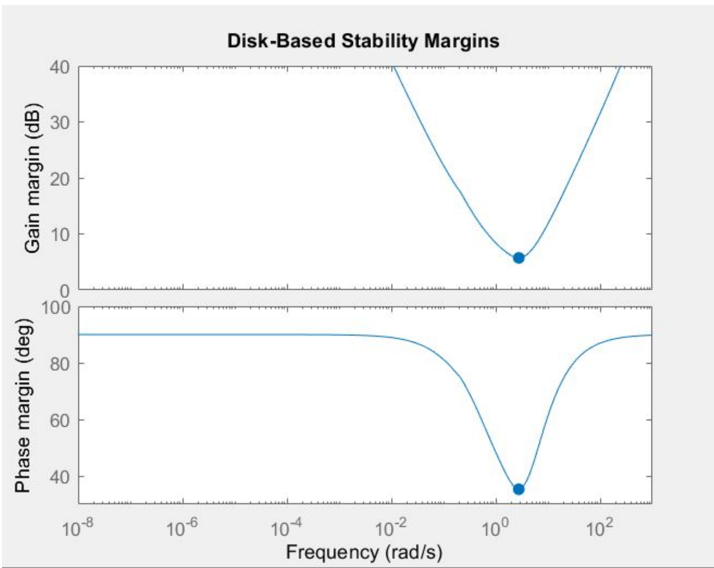


Figure 5.39: Disk margins as a function of frequency

Type	Lower bound	Upper bound	Frequency [rad/s]
Gain	0.5173	1.9331	2.7719
Phase	-35.2954	35.2954	2.7719

Table 5.6: Disk-based stability margins

Because these margins consider the system as a whole instead of single loops, they are more constraining. Thus, when the system uncertainties stay within these bounds, stability is guaranteed. Unfortunately, it is hard to obtain reference values, but critical gain margins of almost a factor two and critical phase margins of more than 35 degrees are looking promising.

It does need to be noted that due to a large number of inputs and outputs, the reliability of this analysis is not great. Thus, it is recommended to do either a more extensive analysis or do some prototype testing to properly confirm the stability.

5.8. Sensitivity

To be able to evaluate how future changes in the design will be influencing it, the sensitivity analysis was performed. The following list includes the most relevant design parameters influencing the design:

1. Mission duration
   (a) The mission duration parameter determines how long the drones can operate before needing to recharge or replace their batteries.
   (b) The drone's flight range and flight time is directly related to the battery size and thus weight and drone size.
   (c) Longer mission durations were found to positively impact the total area covered, energy consumption(less landing in the van, etc.), and collection efficiency, ensuring extended operation time and increased trash collection.
2. Number of rotors
   (a) The number of rotors directly affects the drone's stability, manoeuvrability, and payload capacity.
   (b) Different rotor configurations, including quadcopters, hexacopters, and octocopters, were evaluated. The sensitivity analysis revealed that a higher number of rotors generally improved the swarm's ability to navigate urban environments, carry larger amounts of trash, safety and perform collective tasks more efficiently. However it comes with the cost of the drone's weight increase, as more rotors means more weight and thus more power required. Hexacopters and octocopters also have more safety as the falling out of motors does not immediately lead to a crash. This is because another motor can take the load.
3. Communication system
   (a) The communication system enables coordination and control among the drones in the swarm. Various communication systems, such as Wi-Fi, radio frequency (RF), and cellular networks, were examined. The sensitivity analysis showed that communication range, bandwidth, and reliability significantly influenced the swarm's ability to avoid collisions and share information effectively. A reliable and low-latency communication system was found to be crucial for optimal swarm performance.
4. Propeller type
   (a) Different propeller types were considered, including fixed-pitch, variable-pitch, and ducted propellers. The sensitivity analysis demonstrated that propeller design had a substantial impact on flight performance, energy efficiency, manoeuvrability, and noise emissions. Careful consideration of propeller type is necessary to balance these factors and optimize the drone swarm's overall performance in urban environments.
5. Type of pick-up mechanism
   (a) The pick-up mechanism determines how the drones collect and carry trash. Various mechanisms, such as robotic arms, suction devices, and specialised collection compartments, were assessed. The sensitivity analysis revealed that different pick-up mechanisms influenced the swarm's ability to efficiently collect trash, handle various waste types, and maintain stability during pick-up operations. A well-designed pick-up mechanism is essential for maximizing collection efficiency.
6. Drivetrain/undercarriage
   (a) The drivetrain or undercarriage of the drone swarm design refers to the mechanism that supports and propels the drones on the ground, if applicable. Different configurations, such as

wheels or legs, were considered. The sensitivity analysis indicated that the drivetrain or undercarriage design had a significant impact on the swarm's ability to navigate urban terrains, traverse obstacles, and access confined spaces. The selection of an appropriate drivetrain or undercarriage is crucial for effective ground-based movement, where applicable.

7. Number of drones

    (a) The number of drones in the swarm plays a vital role in determining the overall efficiency, coverage area, and collective capabilities of the system. A comprehensive sensitivity analysis was conducted to assess the impact of varying the number of drones on the swarm's performance metrics. The analysis revealed that a larger number of drones generally led to the increased total area covered, higher collection rates, longer mission durations, and improved collaboration efficiency. However, scalability and system complexity must be carefully considered when determining the optimal number of drones.

6

Ground Station Design

One of the most crucial subsystems in the ADIOS drone system is the ground station. The ground station is a mobile vehicle that acts as a base for the ADIOS drones during operation. In this chapter, the functions of the ground station are described in section 6.1. Then, all components that are required in the ground station are described in section 6.2. Finally, a sample configuration of the ground station is presented in section 6.3 to show how the ground station could look when installed in a specific vehicle.

6.1. Functions

Although the ADIOS drone system is designed to be operating autonomously, it is still necessary to utilise a ground station. There are multiple reasons for this, which are connected to the functions of the ground station. These functions are described in the following subsections.

6.1.1. Drone and Litter Transport

One of the functions of the ground station is to act as transportation for the drones and the litter collected by the drones. Before the drones can start their litter clean-up operation, they need to be transported to the operating site. Furthermore, the drones need to be transported from operating site to operating site, and eventually back to the ADIOS facilities. The litter that is collected by the drones will be stored in garbage bins in the ground station, which will eventually enter a recycling procedure upon return to the ADIOS facilities. Note, however, that the majority of the recycling procedure will be done by recycling companies.

In chapter 7 it will be determined that one ADIOS system will utilise 6 drones. In order to avoid damage during transport, the drones must also be stored safely inside the ground station. This storage can also serve as protection for drones and other equipment in case of extreme weather conditions. The exact component that will facilitate the storage of the 6 drones will be described in section 6.2.

6.1.2. Drone Monitoring

Additionally, the ground station can be used to monitor the drones while they are operating autonomously. Therefore, several monitors are required that each show different types of data coming from the drones. The different types of data that are important for the operator to monitor at all times are listed below:

Live video: Live video data is essential for safe operation of the drone as it serves as a visual check for the operator. Although the operator should get an error message when a drone failure occurs, it is still crucial for the operator to have live video footage of the drones in order to assess the situation. Video footage can also be used to prevent problems to occur, as the operator may then be able to identify a dangerous situation and act early to prevent accidents.

Map with drone locations: To ensure that the drones stay within the operating area, it is crucial to monitor the locations of the drones on a map of the surrounding area. Again, this is important for safety as the operator can identify dangerous situations when drones are getting too close to restricted areas. Additionally, litter locations can be mapped onto this screen, so the drone operator can monitor the amount of litter left in the area.

General metrics of the drones: Finally, it is important to monitor the general metrics of the drones, like battery life, altitude, speed, rpm of each engine, and temperature. This data is important since the operator needs to know the remaining flight time of each drone before recharging is required, but also if the drones have an engine failure. Again, the main reason to monitor these metrics is for safety by means of problem prevention.

Note that four monitors are required, while only three types of data need to be monitored. This is because one of the monitors will be used for redundancy in case another monitor fails. Besides, when the operator is forced to take over control of a drone, this redundant monitor can be used to live-stream footage of the drone in question for easier and safer control.

6.1.3. Drone Maintenance

The ground station also serves as a base station for drone maintenance. Although not likely, drone parts failing or breaking can occur at any time. Instead of having to inactivate the drone and wait until the system returns to the ADIOS facilities, the drones can be repaired on-site. This requires a workbench, tools, and spare parts to enable the operator to repair the drones.

Furthermore, as described in subsection 5.1.3, the drones will utilise two different types of pick-up mechanisms, which can be attached to any drone due to the modular design of the drones. Switching between pick-up mechanisms can easily be done by the operator on the workbench.

6.1.4. Power Supply

Since the drones will be operating for several hours, their batteries will need to be swapped and recharged in order to ensure a continuous way of operation. The batteries that the drones will utilise are rather large and require a relatively large amount of energy to be charged. When the battery is low, the drones will return to the ground station to get a fresh battery. In the meantime, the depleted battery will be recharged by batteries inside the ground station.

Additionally, several electronic systems inside the ground station also draw a relatively constant amount of power continuously throughout the operation from the power supply provided by the ground station. A detailed analysis of the required power supply for the ground station is described in section 8.2.

6.1.5. Safety Management

Perhaps the most critical function of the ground station is safety management. In the Netherlands, there are certain drone regulations defined by the Human Environment and Transport Inspectorate (ILT), which is part of the Ministry of Infrastructure and Water Management. Some requirements relating to the regulations that are relevant to the ADIOS system are listed below:

- The latency between a given command from the remote pilot and the response of the drone shall be less than 3 seconds.
- The human/machine interface shall make it possible for the remote pilot to make a decision within 5 seconds when air traffic is detected.
- The drones in the system shall operate at a maximum of 120 meters from the surface.
- The remote pilot shall have the competencies to be allowed to fly drones in the 'specific' category.

Note that the first requirement listed above requires a decent control and command connection between the drones and the ground station, which was determined to be a cellular link in section 5.4. Furthermore, the second requirement requires the drone system to be able to detect air traffic, which can also be monitored at the ground station. The third requirement can be ensured by monitoring the altitude of the drones. Finally, the fourth requirement refers to competencies related to applying emergency procedures and being a skilled employee with regard to drone control. This is because the operator needs to be able to take over drones in case of emergency, or simply react to unexpected circumstances. Although these regulations are set by the government, the company ADIOS itself also values the safe conduct of the litter clean-up operation.

6.2. Components

The design choice for the ground station that resulted from the trade-off was an installable system. This means that the ground station will be a modular system of required components that can be installed inside any mobile vehicle with sufficient cargo volume. A list of all components that are necessary to ensure the proper functioning of the ground station is given in Table 6.1, including an estimate of the weight and cost of each component.

Table 6.1: All components of the ground station including an estimate of the weight and cost based on reference items

Ground station component	Mass (kg)	Cost (€)	Reference item	Source
1 Drone storage cabinet with 6 drawers	31.07	210	IKEA SMASTAD / PLATSA	[67]
1 Large additional storage cabinet	19	34	AVASCO Shelving Unit Strong	[63]
1 Computer desk	33.62	199	IKEA TROTTEN Desk sit/stand	[69]
1 Computer	8	700	AMD Ryzen 4100 RGB Gaming PC	[29]
4 Monitors including monitor stand for each	16	480	Philips 271V8LA/00	[39]
Computer peripherals	0.09	29	Logitech MK120 Keyboard and Mouse	[38]
2 Office chairs	33.78	210	IKEA FLINTAN office chair	[68]
1 Workbench with 1 cabinet and multiple storage bins	40	250	HBM 115 Cm. Workbench	[61]
2 Drone controllers	0.726	220	Radiomaster TX12 MKII	[46]
1 Power supply	144.48	4230	Sony / Murata batteries	[95]
2 Garbage bins (1 on each back door)	10.8	240	Keter Recycling Bin Split Basic	[126]
6 Landing pads	0.12	90	MMOBIEL Universal Drone Landing Pad	[30]
Total	**337.69**	**6892**		
Contingency (20%)	**67.54**	**1378.4**		
Total incl. contingency	**405.22**	**8270.4**		

Note that the power supply in the ground station will be used to charge depleted drone batteries and power the electronics inside the ground station, like the computer and monitors. The reference item for the power supply are small 3120 mAh battery cells at 3.6 V, of which 3010 are required to provide the required amount of power equal to 33.8 kWh. The calculations for this required amount of power will be described in subsection 8.2.2. Note that these batteries will be packed in a large battery pack. Theoretically, part of the vehicle battery can also be used to power components within the ground station. In that case, the number of cells in this battery pack can be reduced.

Many of the components listed in Table 6.1 are required to perform one of the functions of the ground station described in section 6.1. For example, the drone storage cabinet with 6 drawers provides storage space for the drones during transport. This drone storage cabinet is custom made since it needs to be able to fit all 6 drones while also minimizing the required space in the ground station. A CAD model of this cabinet was therefore made, of which a render is shown in Figure 6.1.

Figure 6.1: Render of the drone storage cabinet made in 3DExperience

Since this cabinet needs to be manufactured, a technical drawing has been created as well, which includes the dimensions required to manufacture the product. This technical drawing is shown in Figure 6.2.

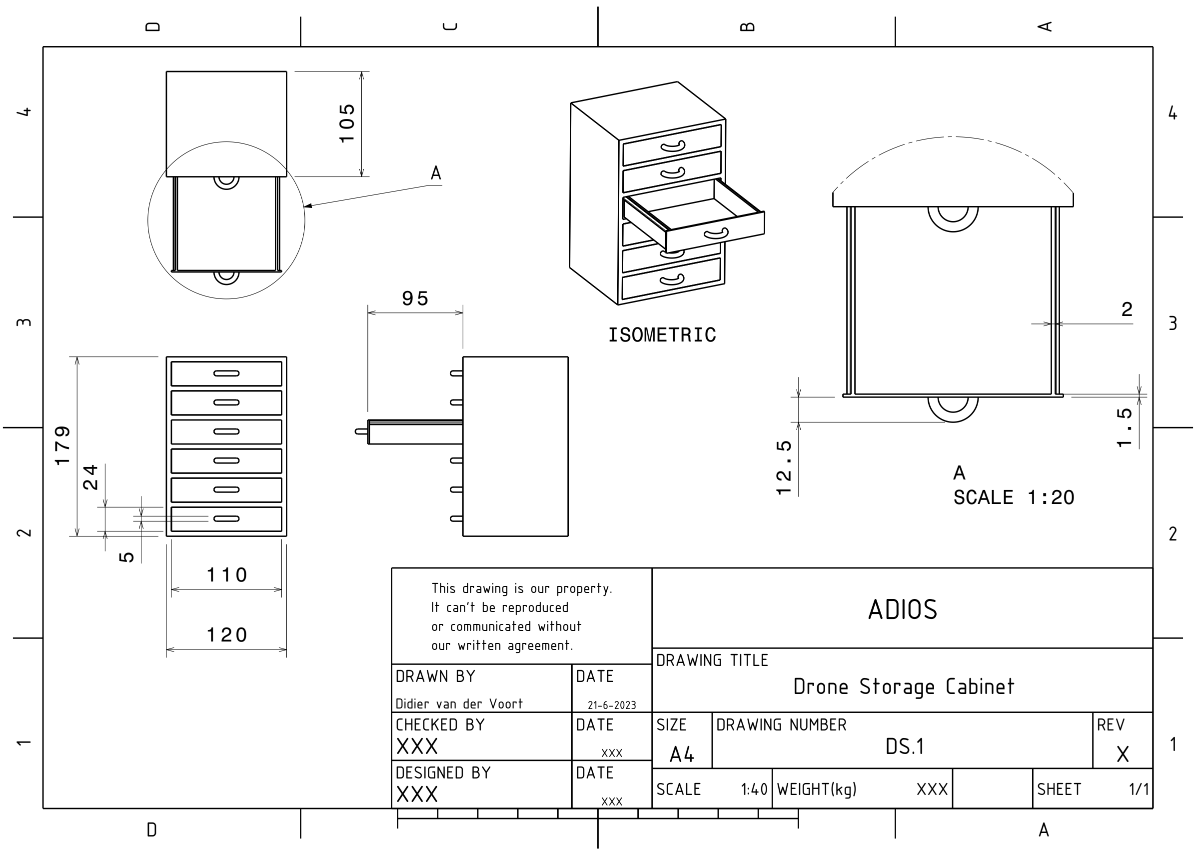


Figure 6.2: Technical drawing of the drone storage cabinet made in 3DExperiene with dimensions in centimeters

Note that the drawers from the drone storage cabinet will be motorised, so that the drawers will be drawn out and in automatically one-by-one by a single click of a button, such that each drone can take off and land autonomously. This saves the operator a significant amount of workload.

Furthermore, other components listed in Table 6.1, like the computer and monitors are required to monitor the drones during operation, which is also one of the functions of the ground station. Some components, like the large additional storage cabinet, are not directly related to the ground station functions. However, it is still an essential component to store spare parts, large equipment, and anything else that the operator wishes to bring along.

6.3. Sample configuration

Finally, to prove the installability of the ground station, the system will be installed in a sample van. This sample van will be the 2020 model of the Mercedes-Benz Sprinter. Note, however, that the system can be installed in any vehicle with sufficient dimensions and load capacity. The exact vehicle will be selected in a later stage of the ADIOS development period, after negotiations with potential partner companies have taken place. Renders of the ground station installed in the Mercedes-Benz Sprinter are shown in Figure 6.3 and Figure 6.4.

Figure 6.3: Render of the ground station made in 3DExperience

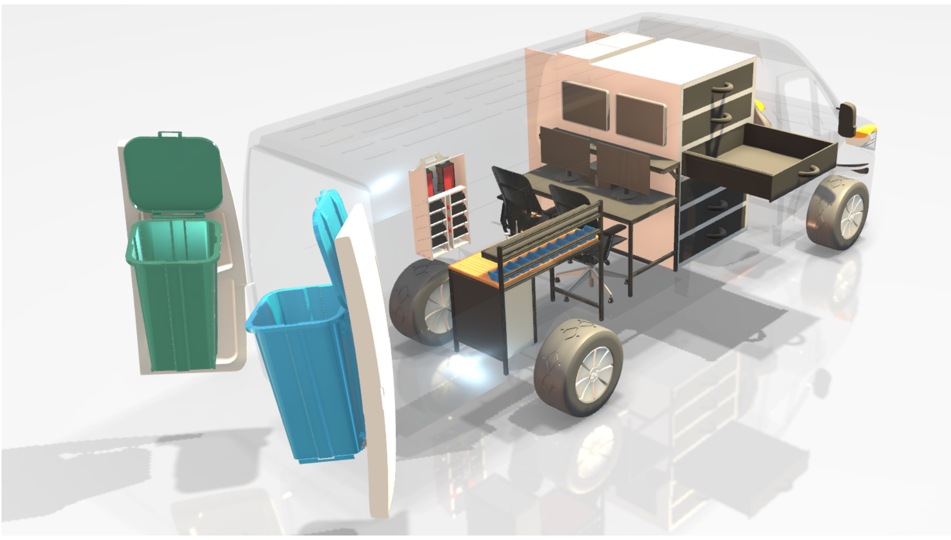


Figure 6.4: Render of the ground station with transparent van body

Furthermore, a technical drawing of the sample ground station has been made that shows the overall dimensions of the Mercedes-Benz Sprinter and a Bill of Materials (BOM) of all the components of the ground station. This technical drawing is shown in Figure 6.5.

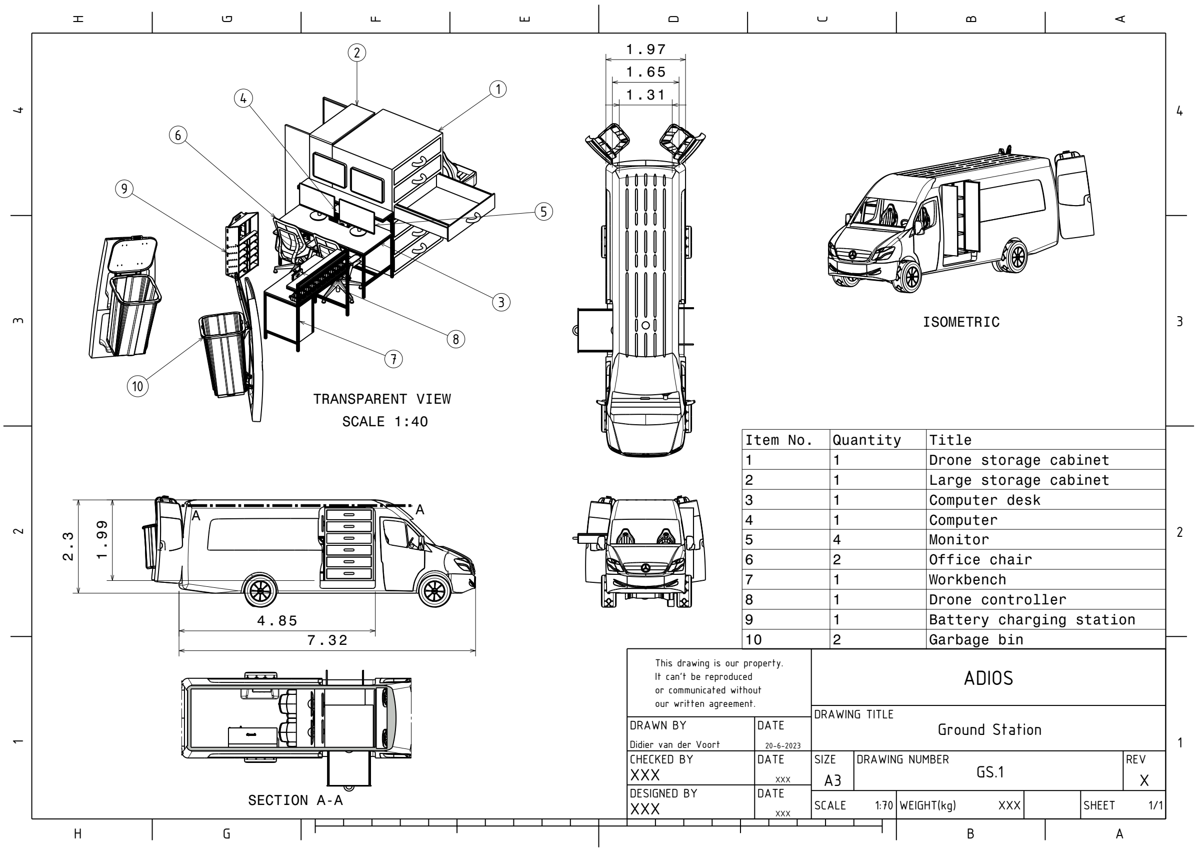


Figure 6.5: Technical drawing of the ground station made in 3DExperience with dimensions in meters

As can be seen in Figure 6.4, the ground station can house operators and house all components listed in Table 6.1. Note that the ground station is designed for minimal operational load, i.e. the number of actions the operator has to take during operation. As mentioned before, the motorised drone storage cabinet allows for autonomous take-off and landing of the drones. Furthermore, the garbage bins are attached to the back doors. Once the vehicle has been parked, the operator only needs to open these back doors to allow the drones to drop litter into these bins directly. If the back door opens, the garbage bin lids open as well, and when the doors close, the lids close too.

Note that the cargo space of the Mercedes-Benz Sprinter is $7.4\,\mathrm{m}^3$ [48]. The rest of the dimensions are shown in Figure 6.5.

7 Operations and Simulation

Now that the design of the components of the system is performed, the operations and logistics of the ADIOS system need to be considered. First, an overview is presented regarding all the steps that need to be taken to operate the system. This is done in section 7.1. Consequently, it is also needed to choose how many drones the system should consist of to fulfil the requirements and what the eventual performance parameters of the system will be. This analysis is performed by making a simulation. This has to be a more extensive simulation as discussed in [19] since it is needed to obtain performance parameters. The goals of the simulation, the methods how these are achieved and the assumptions made will be discussed in section 7.2, section 7.3 and section 7.4, respectively. Lastly, the results of the simulation in combination with a sensitivity analysis will be performed in section 7.5. From the sensitivity analysis it will be clear up until which conditions the ADIOS system will be able to fulfil the requirements.

7.1. ADIOS Operations & Logistics

To deploy and use the ADIOS system, an extensive flow chart describing the operations and logistics has been made. It is shown in Figure 7.1.

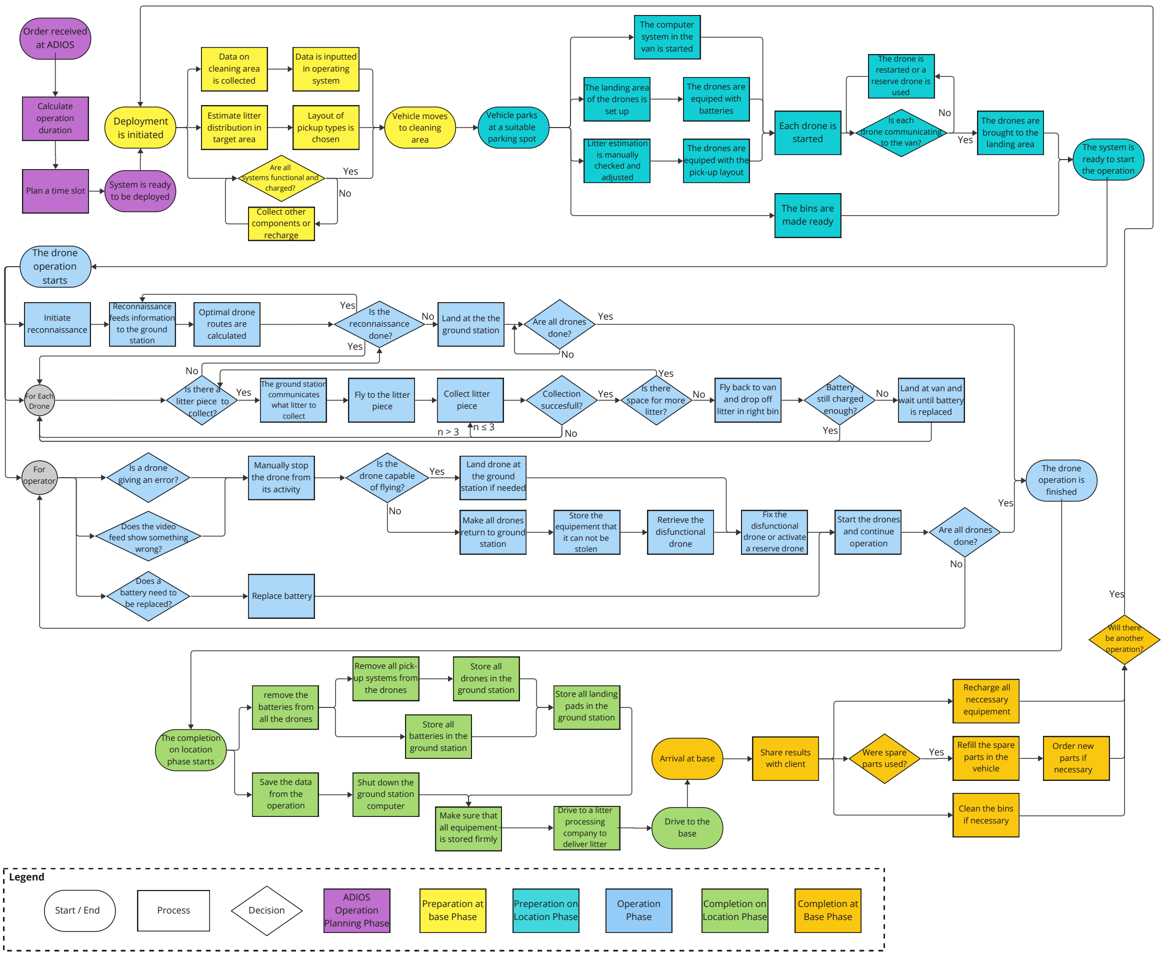


Figure 7.1: Operations and Logistics flowchart

Additionally the functions of the whole system were defined. A detailed overview of the functions of the whole drone system can be found in the functional flow diagram and function breakdown structure, found in Appendix A. First of all the drone system needs to be designed. For this

7.2. Simulation Goals

Firstly, a simulation is built to determine difficult parameters and amounts regarding the operations of the ADIOS system. These values include the number of drones necessary in the system, battery sizing and ground station positioning. Especially the number of drones is difficult to determine in an alternative manner. However, to obtain realistic values for these parameters, it is desired to include all important processes of the operations and make the simulation as realistic as possible. Secondly, the simulation can be used to experiment with the algorithms chosen for path planning and the physical model of the drone. It is impossible to test the path planning algorithm outside a simulation since during this stage of the project, the drones have not yet been built. Therefore, this is currently the best option to validate this and identify the issues that arise during the implementation.

7.3. Simulation Methods

As stated in section 7.2, it is important to make the simulation as realistic as possible to get trustworthy results. Therefore, a wide range of processes has been included. These processes have been divided into different categories: cleaning area properties, drone model, numerical integration scheme, pathplanning and minimum snap trajectory. A block diagram of the code is displayed in Figure 7.2:

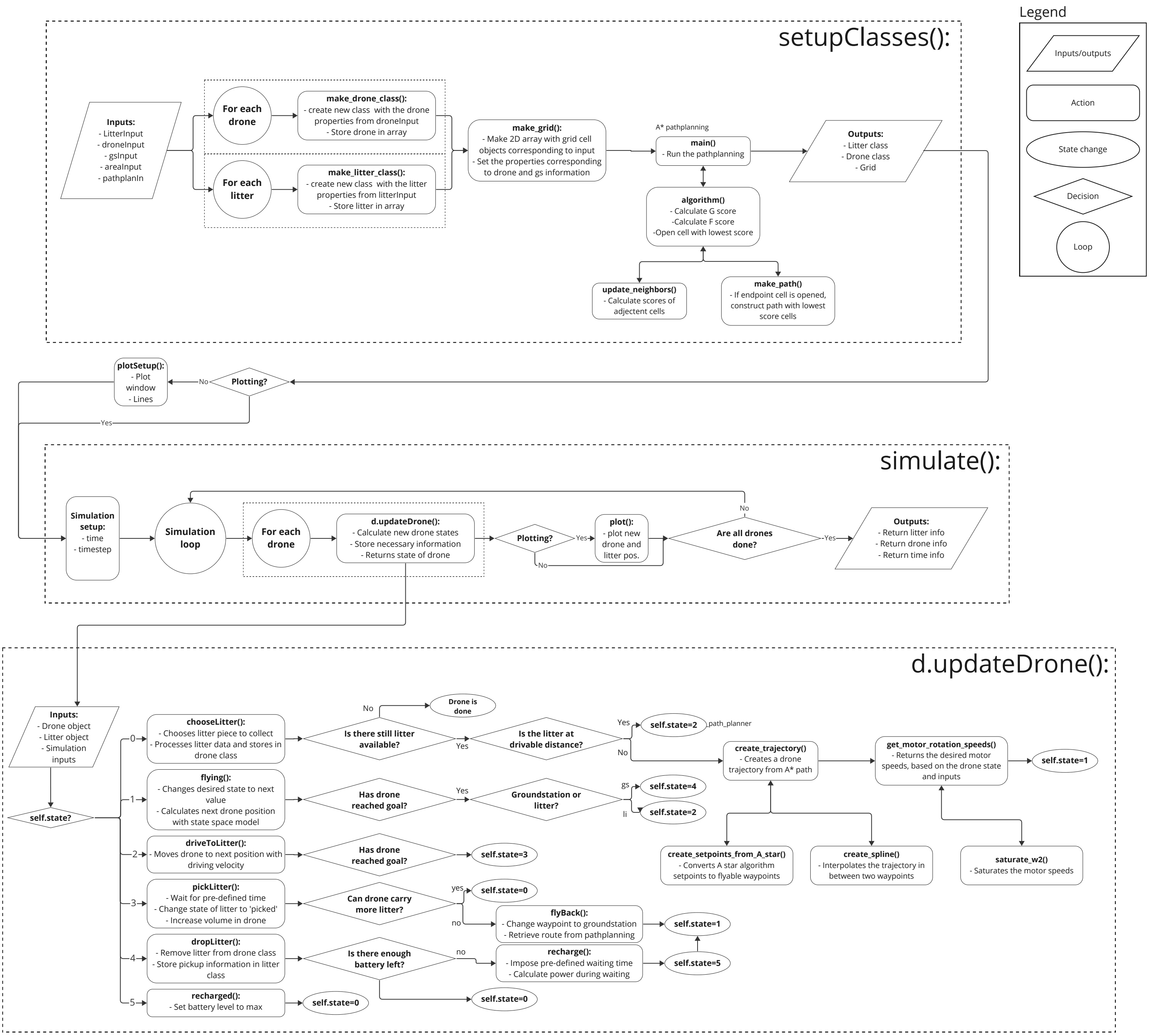


Figure 7.2: Code block diagram of the operations simulation

7.3.1. Cleaning Area Properties

In requirement SYS-TE-QN-2-1, it was stated that an area of 10.000 m^2 must be cleaned within an hour. Therefore, a square area of 100x100m is chosen for the simulation. The cleaning areas will also have obstructions that the drones have to avoid. In this model, it is assumed that the drones will rise to a preset altitude of 5 meters to avoid humans and small obstacles such as poles or small trees. To specify the location of the obstacles in the area, a grid is created with a resolution of 1 meter. Smaller obstacles do not need to be specified since the drone also will be equipped with obstacle avoidance software. Pathplanning will only be performed to choose an efficient route. The data where the obstacles are positioned can be obtained from datasets like google maps or can be inputted manually. When the obstacle detection system in the drone detects more obstacles than initially inputted, the drone can add this obstacle to the database and new routes can be calculated such that the other drones will not have to avoid the same obstacle every time. For the sizing of the ADIOS system, a typical obstruction layout is chosen with some hard-to-reach places. In Figure 7.3, an overview is shown that displays the obstacle locations chosen for the system sizing.

Within the area, the position of the ground station must be chosen where the drones depart, drop off litter and replace a battery. It is most logical to place the ground station in the centre since the average litter distance is then the shortest. This location is marked by the "loc2" label in Figure 7.3. However, during real operations, there is not always a possibility for the ground station to be positioned ideally. Moreover, the area can have a different shape than a square which also increases the average distance to the litter. Therefore, it is chosen to position the ground station in the corner of the area, at the position labelled "loc1" in Figure 7.3.

Since the ADIOS system will consist of two types of drones that clean different types of litter, it is important to know the relative occurrence of the two litter types in urban areas. From subsection 5.1.3, it was found that the drone with the brushes will be able to clean litter up to 16 ml. Using the data from subsection 5.1.1, it was found that 64% of litter in the urban area consists of this small litter. The other 36% will therefore be cleared by the grabber system. Since requirement SYS-TE-TI-1 stated that 1000 litter pieces must be cleaned within an hour, the simulation will have 640 small litter pieces and 360 larger litter pieces. The small drone has a storage space of 0.5 litres. To keep track of how full this storage space is, each litter piece also gets a random volume between 0 and 16 ml. The litter distribution generated is displayed in Figure 7.3.

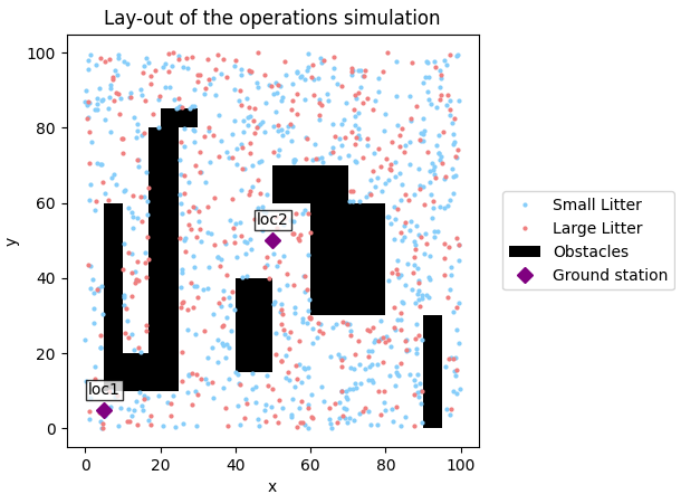


Figure 7.3: Overview of the cleaning area used in the simulation of the operation, including the obstacle positions, litter distribution and two possible ground station positions

7.3.2. Drone Model

The drones that clean the area will have different functions. Naturally, the drone has to be capable of flying. During the flight, it must be able to follow waypoints generated by the pathplanning algorithm. Moreover, the ADIOS system consists of drones that drive from a landing position towards the litter position. At the litter, the drone must be able to pick up the litter. When the drone has storage space for more litter and has enough battery left, it can continue to the next litter piece. Otherwise, it must fly back to the ground station. At the ground station, it must land and clear the litter from the internal litter storage. When the battery must be replaced or there is no more litter to clean, it lands at the ground station. Otherwise, it continues to clean. During all these processes, the power usage must be calculated and subtracted from the battery life left. There are some constant power usages that are activated in different stages of the simulation. An estimation is made for their magnitude based on the current design. The flight computer is estimated to need 10 W and the object detection 20 W of power. Driving the drones will require about 30 W of power. Lastly, the grabbing mechanism requires different amounts of power for the different payload types. The brushes will require about 20 W and the grabbing mechanism about 5 W of power. Currently, the simulation does not have any functionality towards reconnaissance. Therefore, this has to be taken into account when the results are interpreted.

Flying
For the flying stage of the simulation, the drone physics are simulated using the state space system described in subsection 5.7.3. Each drone is also controlled by the positional control system developed in subsection 5.7.3. Therefore, each drone is simulated in as much detail as is currently available. The control system requires to get a required state to which the drone will fly. It is not sufficient to only give the landing position since the drones will not avoid obstacles and it is not possible to determine at which speed the drones fly. Therefore, a pathplanning algorithm is built to determine the route the drones should fly and at which speed. This algorithm returns a list of waypoints for every timestep in the simulation. Additionally, the implementation of the control system enables the power calculation to be performed realistically. For this, Equation 5.3 is used. The control system returns how much thrust must be produced by each propeller. However, this equation is derived from an ordinary propeller with blades. As described in subsection 5.3.2, it was found that toroidal propellers require 30 % less power. Additionally, the usage of ducts reduced the power required by a further 7 %. On the other hand, there are no wind effects included in this simulation while it is expected that this can have an important impact on the power performance. In [133], it is stated that usually drones are designed to have a thrust-to-weight ratio between 1.5-2.0 to be controllable. It is assumed that this extra power is completely used to counteract the wind and disturbances, in the most limiting case. Therefore, the power usage is multiplied by a factor of 1.5, to account for these effects. This will cause the average power consumed by the propulsion, during flight, is 465 W. When the power of the separate propellers is calculated, their values are summed and the power used by the flight computer and object detection is added.

Picking Litter
When the drone has reached the landing position within 10 cm, the state of the drone is changed to driving. From the landing position, the drone moves towards the litter with a predefined velocity of 1 m/s. The power used during this state is the sum of the flight computer, object detection and driving power. It is estimated that when the drone reaches the litter piece, it takes two seconds to grab the litter. Thus, the drone will stand still for this time and consume the sum of the flight computer, object detection and grabber power. When this waiting time is over, the volume of the litter is added to the litter volume in the drone. If there is no more storage space or the battery is almost empty, the drone will follow the path retrieved from the pathplanning back to the ground station. When it is possible for the drone to retrieve more litter before returning, the closest litter piece of the right type is found and it is checked whether an obstacle is in between the litter piece and the current position. Since the pathplanning in this simulation is only performed before the operation starts, it is not possible for the drone to go to the litter when there is an obstruction in the way. Therefore, if there is no litter visible in a direct line of sight, the drone flies back to the ground station to drop off the litter and move to a new part of the area.

Ground Station
When a drone reaches the ground station, a waiting time of 20 seconds will be posed for the small drone and a waiting time of 2 seconds for the large drone will be posed to release the collected litter. These values differ because it is more difficult for the small drone to empty. During this time, the total power consumption consists of the flight computer, the object detection, the grabber and the average flight power of the last few seconds of flight. If it is necessary, the drone will land to replace the battery. On route to the ground station, the operator will be notified and can prepare a battery and the battery is designed to be easily replaceable. Therefore, a replacement time of 60 seconds is assumed. Consequently, a new litter piece from the litter database is chosen randomly to which the drone will fly. When there is no more litter known of the drone type, the drone will land. During the real operation, it can be chosen to change the grabbing mechanism on these drones or wait until new litter is detected by the reconnaissance. However, these processes have not been included in the simulation.

When all drones have landed at the ground station, the simulation is concluded. When the reconnaissance is included in a later stage, an extra condition would be that the reconnaissance also needs to be finished. During the entire operation, the energy usage of the timestep is subtracted from the battery life left. The battery chosen in section 5.5, has a voltage of 22.2 V and a capacity of 16000 mAh.

The total energy that the battery contains can be calculated with Equation 7.1, where E is energy, P is power, t_s is time in seconds, t_{hour} is time in hours and C_{Ah} is capacity in Ampère hours. This results in 1.278.720 J. It was decided in section 5.5 that the minimum and maximum battery levels shall be between 10 % and 90 %. Therefore, the total energy available in the simulation will be 1.150.848 J. Until the battery reaches a threshold of 150.000 J, it will start a new retrieval of a litter piece. Below this threshold, the drone will land for a recharge. There is an extra margin included because the drone must be able to fly back and not end up below 127.872 J in the battery.

$$E = Pt_s = UIt_s = U\frac{C_{Ah}}{t_{hour}}t_s = U\frac{3600C_{Ah}}{t_s}t_s = 3600UC_{Ah} \tag{7.1}$$

7.3.3. Numerical Integration Scheme

Initially, the forward Euler numerical integration scheme was used, due to its simplicity. The equation for this scheme is shown in Equation 7.2. The next state X_{t+1} is calculated with the derivative from the previous state (at t). The expression for $\dot{X}_t$ is described in [91].

$$X_{t+1} = X_t + \dot{X}_t \cdot dt, \quad \dot{X}_t = (A - BK)X_t + (BK)X_{desired,t} \tag{7.2}$$

For sufficiently small timesteps this scheme works fine. However, since the simulation is so computationally intensive, the time step had to be increased. This lead to an unstable scheme, where the drones would fly off to infinity in a fraction of a second. Thus, a numerical scheme had to be chosen that guarantees stability for higher time steps. It was decided to implement a backwards Euler integration instead. In this scheme, the next state X_{t+1} is calculated using the derivative in the next timestep t+1.

$$X_{t+1} = X_t + \dot{X}_{t+1} \cdot dt \tag{7.3}$$

This is an implicit scheme however, since X_{t+1} is needed to determine $\dot{X}_{t+1}$. Thus, the scheme first needs to be made explicit. This is done by first isolating the derivative term from Equation 7.3, as shown in Equation 7.4. This derivative is equated to the LQR expression for the derivate from [91].

$$\dot{X}_{t+1} = \frac{X_{t+1} - X_t}{dt} = (A - BK)X_{t+1} + (BK)X_{desired,t+1} \tag{7.4}$$

Equation 7.4 can be rewritten such that X_{t+1} is isolated. This leads to the explicit scheme shown in Equation 7.5.

$$X_{t+1} = (I + BKdt - Adt)^{-}1 \cdot (X_t + (BKdt)X_{desired,t+1}) \tag{7.5}$$

Now, $X_{desired,t+1}$ does differ from $X_{desired,t}$ in the forward scheme. However, empirical evidence shows that this difference has not much of an impact.

7.3.4. A* Pathplanning

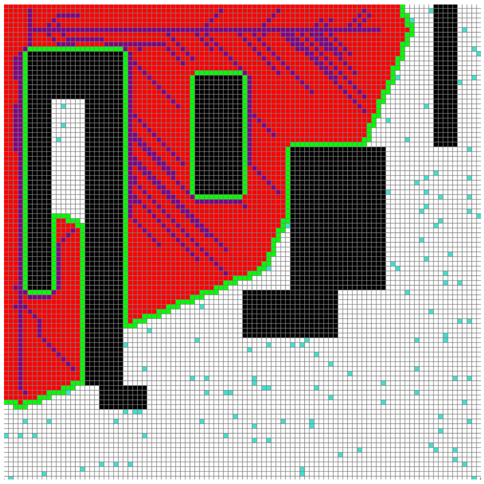


Figure 7.4: Visualization of the A* algorithm. Black squares are obstructions, white squares undiscovered area, red squared discovered area, green squares 'opened' areas, purple squares paths to the litter and blue squares litter pieces

To determine the shortest path from the GS towards the litter pieces, the A* method is used. This method relies on a grid in which a score can be assigned to each cell. The score consists of an F score and a G score; the F score represents the distance from the cell to the litter piece, whereas the G score indicates the distance from the cell to the GS. Note that in this method, the location of the GS, as well as the litter pieces, are known, as they have been detected before by a reconnaissance drone. This is done in the remaining time, as the operation itself will not take the full 60 minutes, which will be explained later.

The algorithm starts at the GS, calculating the scores of the adjacent cells. In the adjacent cells, the G scores are all the same, as they have the same distance to the GS. Then, the cell with the lowest score (which indicates the cell closest to the litter piece) 'opens', now calculating its own adjacent cells. As these steps keep repeating, the cells closer to the litter pieces keep opening. After the cell in which the litter piece is located opens, a path is constructed through the cells with the lowest score, establishing the shortest path from the GS to the litter pieces.

The code is able to make diagonal paths while keeping at least one cell (which is equal to 1 meter) between the path and the obstructs. For input, it takes the coordinates of the GS, litter pieces and obstructs, and returns one path per litter piece. The paths are used for the navigation of the drones, but to ensure that the drones do not crash into any (static or) moving object, an object collision avoidance procedure is still required on board. A visualisation of all these processes is shown in Figure 7.4

7.3.5. Minimum Snap Trajectory Planner

Now that the A* algorithm has been written, these paths need to be converted to actual controlled drone trajectories. These trajectories need to have a regulated speed and should be optimised to use the least amount of energy possible. Thus, the input force and moments as shown in Equation 5.13 should be minimised. To go from position to these inputs, a quadruple differentiation is needed. Thus, the inputs are proportional to the 4th derivative of position, called snap. Minimising the inputs thus means minimising the snap of the drone along the trajectory. Thus, a minimum snap trajectory planner will be implemented. Such a planner creates splines between setpoints, at which the position, velocity, acceleration, jerk (the first-time derivative of the acceleration) and time stamp are defined.

The first step to implementing this controller is to actually define these setpoints. Ideally, not all points from the A* algorithm should be fed through, as this still leads to a trajectory with sharp 90-degree corners. Thus, some points must be eliminated. An overview is given in Figure 7.5. For example, when the A* algorithm gives a straight line, only the points at the beginning and the end are marked. In a 90-degree corner, the corner point is left out. When making a 45-degree angle, the points marked are shown in Figure 7.5. The velocities are defined in such a way that they point straight forward, and the speed is fixed at 8 m/s. This way, the drone complies with requirement SYS-TE-TI-1-3: The drones shall be able to fly at a ground speed of at least 15 kts (7.72 m/s) for performance. At most points, the acceleration and jerk are set to 0, except for the 90-degree corners. In these corners, the acceleration is normal to the velocity pointing into the corner, its magnitude is set according to $\frac{v}{r^2}\ m/s^2$, where v is the speed in m/s and r is the corner radius in m. The yaw is set such that at each setpoint, the drone points in the direction of the velocity.

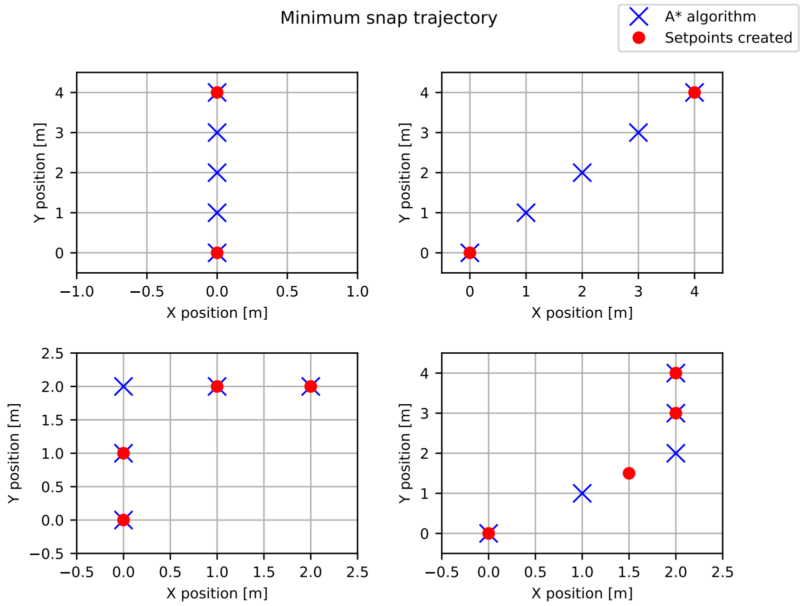


Figure 7.5: Plots showing how the setpoints are created

Now that all setpoints are defined, the next step is to create splines between these setpoints. These splines are assumed to be polynomials of time. According to [59], the snap is minimised when the 8th time derivative of the polynomials is 0. So the polynomial shall be of order 7 or less. The generic polynomial is shown in Equation 7.6. Each degree of freedom of the drone has its own polynomial.

$$\begin{bmatrix} x(t) \\ y(t) \\ z(t) \\ \psi(t) \end{bmatrix} = \vec{r}(t) = \begin{bmatrix} a_x t^7 + b_x t^6 + c_x t^5 + d_x t^4 + e_x t^3 + f_x t^2 + g_x t + h_x \\ a_y t^7 + b_y t^6 + c_y t^5 + d_y t^4 + e_y t^3 + f_y t^2 + g_y t + h_y \\ a_z t^7 + b_z t^6 + c_z t^5 + d_z t^4 + e_z t^3 + f_z t^2 + g_z t + h_z \\ a_\psi t^7 + b_\psi t^6 + c_\psi t^5 + d_\psi t^4 + e_\psi t^3 + f_\psi t^2 + g_\psi t + h_\psi \end{bmatrix} \tag{7.6}$$

Now, only these coefficients need to be calculated. This process is done separately for each degree of freedom. These equations are solved by applying the boundary conditions mentioned earlier: the position, velocity, acceleration and jerk at both ends of the spline. This leads to 8 boundary conditions, which is exactly enough to solve for the 8 unknown coefficients. Taking the nth derivative of the polynomial and matching it to the nth derivative boundary condition and grouping everything together in a matrix results in Equation 7.7. In the left matrix, called the Vandermonde matrix [130], the timestamps t_0 and t_1 must be specified. These are the timestamps at which the spline starts and ends simultaneously. In the most right vector, the boundary conditions are specified.

$$\begin{bmatrix} t_0^7 & t_0^6 & t_0^5 & t_0^4 & t_0^3 & t_0^2 & t_0 & 1 \\ 7t_0^6 & 6t_0^5 & 5t_0^4 & 4t_0^3 & 3t_0^2 & 2t_0 & 1 & 0 \\ 42t_0^5 & 30t_0^4 & 20t_0^3 & 12t_0^2 & 6t_0 & 2 & 0 & 0 \\ 210t_0^4 & 120t_0^3 & 60t_0^2 & 24t_0 & 6 & 0 & 0 & 0 \\ t_1^7 & t_1^6 & t_1^5 & t_1^4 & t_1^3 & t_1^2 & t_1 & 1 \\ 7t_1^6 & 6t_1^5 & 5t_1^4 & 4t_1^3 & 3t_1^2 & 2t_1 & 1 & 0 \\ 42t_1^5 & 30t_1^4 & 20t_1^3 & 12t_1^2 & 6t_1 & 2 & 0 & 0 \\ 210t_1^4 & 120t_1^3 & 60t_1^2 & 24t_1 & 6 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} a_x \\ b_x \\ c_x \\ d_x \\ e_x \\ f_x \\ g_x \\ h_x \end{bmatrix} = \begin{bmatrix} x_0 \\ \dot{x}_0 \\ \ddot{x}_0 \\ \dddot{x}_0 \\ x_1 \\ \dot{x}_1 \\ \ddot{x}_1 \\ \dddot{x}_1 \end{bmatrix} \tag{7.7}$$

Using the "numpy.linalg" module, the left matrix can be inverted and multiplied with the most right matrix. The resulting vector is equal to the coefficients vector. Now that all coefficients are known, for each spline, four polynomials can be collected to get a full positional description of the desired drone trajectory at any point in time. The result is shown in Figure 7.6. It is noteworthy that the trajectory with the 90-degree angle sways into the corner before actually taking it. This is because the acceleration is already specified to be pointed into the corner at the red markers, and the most efficient way to attain this is by swaying into the corner first.

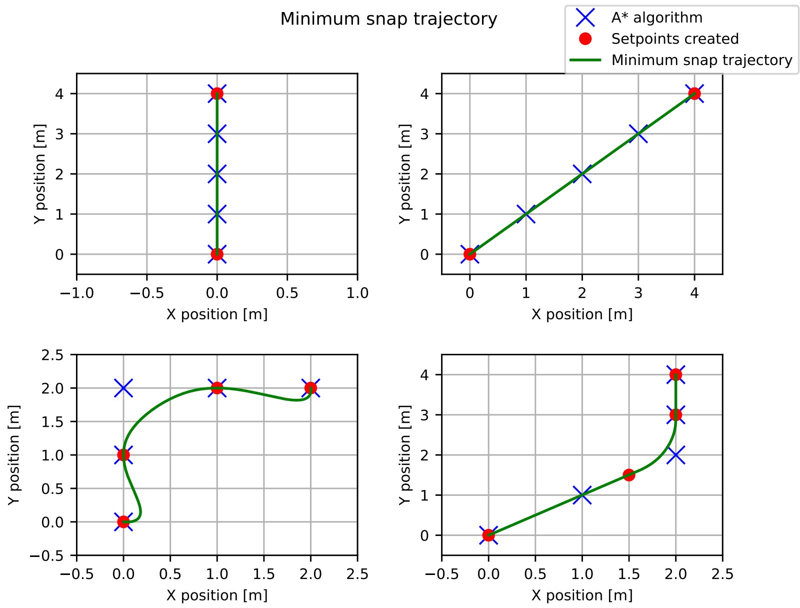


Figure 7.6: Minimum snap trajectory demonstration

7.4. Simulation Assumptions, Inputs and Evaluation

In this section the assumptions made for the simulations are given. Furthermore, the inputs parameters inside the simulation are given and explained. Finally the evulation of the developed model is performed.

7.4.1. Assumptions

Different assumptions have been made during the development of the simulation. The most important assumptions with their expected effects are:

1. The litter distribution is known before the operation starts. During real operations, the litter locations have to be discovered by reconnaissance drones. This will increase the total operating time.
2. The obstacles are known before the operation starts. During real operations, the main obstacles are inputted into the pathplanning system beforehand. However, there also will be obstacles which are discovered during operations, which makes the flightpath a little longer for the drone that discovers the obstacle. Therefore, real operations would take a little time longer.
3. The pathplanning is performed in 2D. In a later stage of the project, it would be desirable to plan to fly over obstacles. When a 3D pathplanner is implemented, the operation would take less time.
4. A standard travel height of 5 meters is assumed. All drones that fly, first go to this height to avoid obstacles and keep a safe distance from humans. This does not have much influence on the operation time.
5. All power values, other than the flying power are assumed constant. Therefore, it does not take a difference in power into account between driving on stone or grass, or whether the computer is performing a lot or a little number of calculations.
6. The drones have to land 3 meters from the litter
7. The drive velocity of the drones is 1 m/s.

8. The time to pick litter is two seconds.
9. The time to drop off litter is 20 seconds for the brushes and 2 seconds for the grabber.
10. The total amount of power required by the drone is 1.5-2 times the amount necessary to hover. The effect of this assumption is dependent on the characteristics of the drone and needs experiments to achieve a better model. However, the simulation does include that the propellers generate more thrust to accelerate. Therefore, it is expected that this assumption is overestimating the power usage and a value of 1.5 is chosen in the simulation.
11. When the operation is done, the operator does not switch the drone's grabbing mechanism. During the real operation, this will be possible and it would decrease the total operation time.

7.4.2. Standard Input Parameters

For all the simulations that are run, a standard set of input parameters are used which are most of the time varied one at the time to gather information on the effect of this parameter. Most of the parameters are based on the real design performed in chapter 5. The other values were assumed in section 7.4. In Table 7.1 and Table 7.2, these values are presented

Table 7.1: Overview of simulation inputs regarding the different drone and litter types

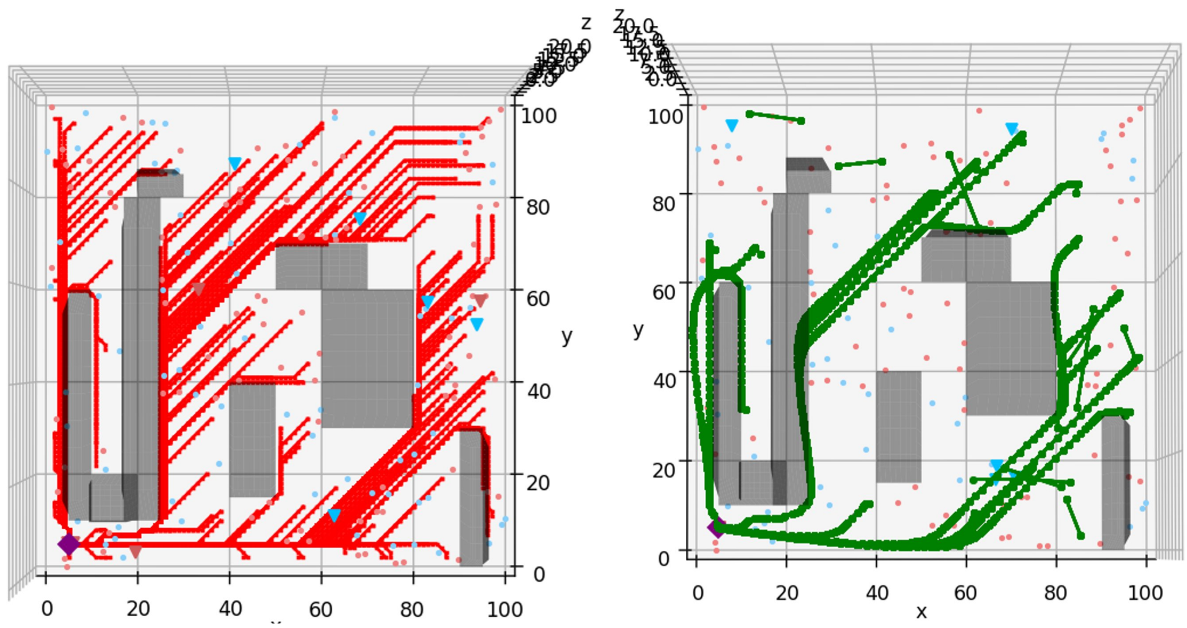
Variable [unit]	Small drone/litter value	Large drone/litter value
Drone properties		
Amount [-]	2	4
Drive velocity [m/s]	1.0	
Landing distance from litter [m]	3.0	
Maximum litter storage [ml]	500	0
Inertial properties		
Mass [kg]	4.0	
Moment of inertia around x [kgm^2]	0.05193	
Moment of inertia around y [kgm^2]	0.05885	
Moment of inertia around z [kgm^2]	0.10289	
Power values		
Power flight computer [W]	10.0	
Power object detection [W]	20.0	
Power grabbing system [W]	20.0	5.0
Power during driving [W]	30.0	
Energy in battery [J]	1.278.720	
Minimum battery level [%]	10.0	
Maximum battery level [%]	90.0	
Factor for wind/disturbances [-]	1.5	
Waiting times		
Time to pick litter [s]	2.0	
Time to drop litter [s]	20.0	2.0
Time to replace battery [s]	60.0	
Propulsion/control system properties		
b [Ns^2]	$6 \cdot 10^-6$	
k [Nms^2]	$3 \cdot 10^-8$	
Length from center to propeller [m]	0.32	
Area of propeller radius [m^2]	0.05067	

Table 7.2: Overview of simulation inputs regarding area and simulation properties

Variable [unit]	Value
Area properties	
x length $[m]$	100
y length $[m]$	100
Ground station location	
x position $[m]$	5.0
y position $[m]$	5.0
Pathplanning parameters	
Grid resolution $[m]$	1.0
Obstacle locations [array]	Not included
Simulation parameters	
Time step $[s]$	0.01
Obstacle locations [array]	Not included

7.4.3. Evaluation of the Developed Model

Now that the model has been developed, it can be checked how well the model functions. Most processes are included and work well. The first process that could be improved is the power consumption of the drone. There is a large uncertainty on the factor to incorporate wind and disturbance effects and the other powers are estimated by a constant. Secondly, the results of the A* algorithm are showing the shortest route from the ground station to the litter, as shown in Figure 7.7a. However, the routes often are positioned next to obstructions. When a route is generated with the minimum snap function, routes are generated that pass through buildings, as shown in Figure 7.7b. During real operations, such a path is not acceptable. However, because these paths can be taken when shifted slightly, it is assumed that these simulations will produce results that are representative of the final operation. In the next iteration of the simulation, an alternative for the A* algorithms shall be implemented that generates routes in the middle between obstacles. These paths do not take much distance but are a lot safer. Moreover, safety bounds should be implemented where the minimum snap function can not generate waypoints but should decrease the speed to be able to make the turn. There also are some extra lines shown in Figure 7.7b. These are the routes of the drones with brushes to go from one piece of litter to the next. It can be seen that these routes do not cross obstructions.



(a) Output of the A* algorithm

(b) Output of the minimum snap function

Figure 7.7: Paths generated by the pathplanning algorithms

7.5. Simulation Results and Sensitivity

At this point, the entire model has been described and is built. Now, experiments can be performed to size the system. The fleet size is the main important number to determine. This is done by positioning obstructions in a way that represents a typical urban area. In the simulation, the area size and ground station position can also be changed. During real operations, it is possible that there is no suited place for the ground station in the middle of the area. It is still needed for the ADIOS system to comply with the requirements. Therefore, in the simulations to determine the fleet size, the ground station is positioned in a corner of the area, at position 1 of Figure 7.3. Moreover, the cleaning area does not have to be square.

7.5.1. Number of Drones

To choose the number of drones necessary in the ADIOS system, a range of simulations have been performed with different numbers of drones. The results of these simulations are shown in Figure 7.8

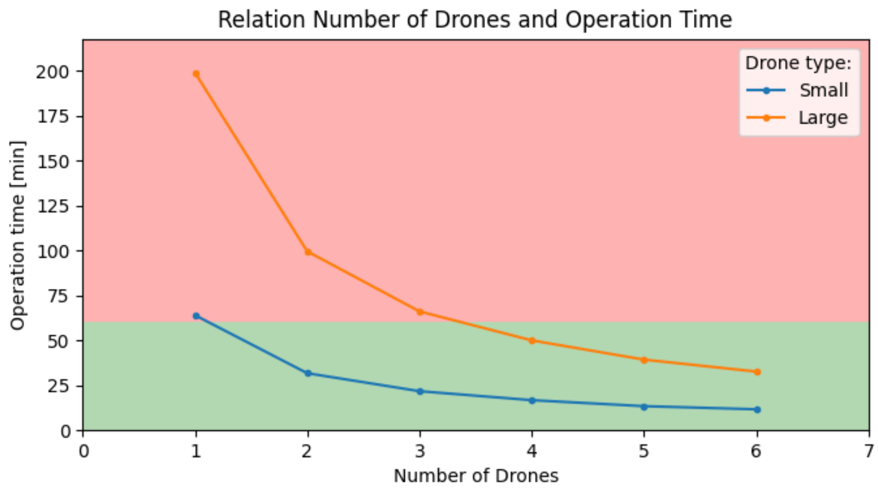


Figure 7.8: Simulation results when the drone number is varied. The shaded area indicates compliance with the requirement that the area should be cleaned within an hour.

It can be seen that the drones collecting small litter only need two drones to be finished within one hour. Then, it is finished in forty minutes. Therefore, the brush drones can initially be used for the reconnaissance of the area. The grabber drones finish within an hour when there are a minimum of four. Then, it takes the total system 50 minutes to perform the operation. Since the first litter pieces will be discovered almost instantly when the reconnaissance starts, the reconnaissance will not have much effect on this total cleaning time. Therefore, these results are sufficient for the final design. There also is a possibility to include a reserve drone in the ground station. However, there are also maintenance capabilities included in the ground station, and when the drones are very reliable, it might not be worth it to always carry a reserve drone. Therefore, this decision can be made based on the reliability of the drone. Moreover, there are multiple reserve pickup systems available which improve the reliability and generate the possibility to change the litter type collected by a drone, which reduces the impact if one drone becomes inoperative.

7.5.2. Battery sizing

Another application for the simulation is to check whether the batteries perform according to expectations. Requirement SYS-TE-QN-3-1 states that each drone has to be able to fly for at least 20 minutes. Figure 7.9 shows the battery level throughout the operation. During the flying phase of each drone, a factor to account for the wind was introduced. In subsection 7.3.2 a value of 1.5-2.0 was found. During the other simulations, a value of 1.5 was used. However, the value of 2.0 is also included in the graph.

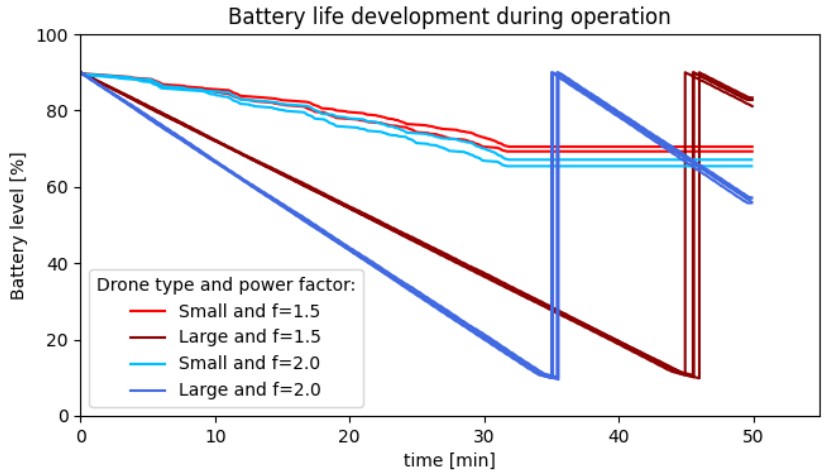


Figure 7.9: Battery life of all drones during simulation for different factors to account for wind effects

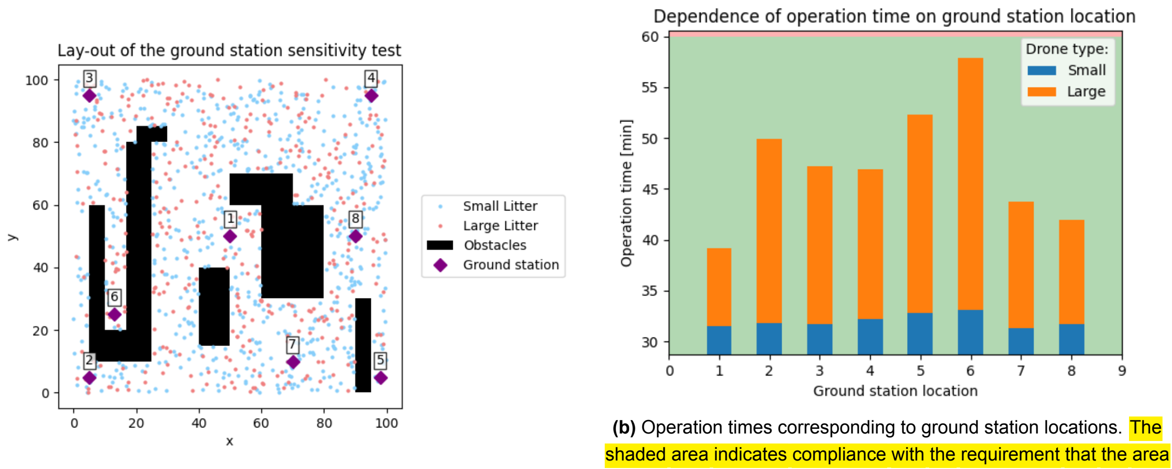
In Figure 7.9, it can be seen that the slope of the battery life of the small drones is much shallower than the lines of the large drones. This is caused by the possibility to store litter in the small drones. Because of this, they do not have to return to the ground station after every collected litter piece and can grab the next piece close by. Often, this means that the drone can drive to the new destination without flying, which requires much less energy. This can be seen in Figure 7.9 by the irregular slope of the small drones. Sometimes the same slope is reached as the large drones have, but on average it consumes less power, and thus a less steep slope. This effect is also the main reason for the system to be able to fulfil the requirements with almost half as many drones compared to the initial estimation performed in the midterm analysis and that the drones can operate for much longer than estimated in section 5.5 [19]. Secondly, it can be concluded from Figure 7.9, is that the total operation time is not sensitive to the factor with which the flying power is multiplied to compensate for wind effects. Even if the wind effects cause the drone to consume double the power compared to hover, it still only has to charge once.

7.5.3. Simulation Sensitivity

Because the simulation results are found, the last necessary thing is to check how much these results depend on the inputs of the simulation. This will be checked by multiple sensitivity tests. First, the sensitivity of the ground station position will be evaluated. Then, the dependence on the fraction of small litter in relation to the large litter, the dependence on the battery size and the variation from different pseudorandom seeds will be researched. Lastly, the dependence on the assumed power values is discussed.

Ground station position

The results from the simulation were obtained by positioning the ground station in the corner of the area. This was chosen to incorporate a non-square area or a non-optimal position of the ground station. In this part, it will be tested what effect it has when the ground station is repositioned to other locations. The ground station is repositioned to the locations shown in Figure 7.10a. These locations yield the results shown in Figure 7.10b.



(a) Different ground station positions considered

(b) Operation times corresponding to ground station locations. The shaded area indicates compliance with the requirement that the area should be cleaned within an hour.

Figure 7.10: Sensitivity to Ground Station Position

The other simulations performed in this section were done from position 2. It can be seen from Figure 7.10 that this is not the most limiting position for the operation time. However, the two most limiting cases are inside a small passage, where the drones can only exit on one side. During real operations, it is not realistic to position the ground station in such a position. However, the results show that these positions are still sufficient to finish the operation within one hour. Additionally, the expected outcome that the middle position (position 1) results in the smallest operation time, is confirmed by this analysis. Therefore, ideally, a place is found as close to the middle of the area as possible.

Moreover, it can be seen that the location of the ground station has a large influence on the total operation times. When the ground station is positioned at location 1 in Figure 7.10a, the operation time is 15 minutes shorter than at location six. Since the sizing is performed such that the system is able to fulfil the requirements when the conditions are not ideal, this often means that the requirements will be met with a margin. This margin is checked by positioning the ground station at position 1 and increasing the amount of litter until the operation takes longer than an hour. The result of this experiment is shown in Figure 7.11. It can be concluded that for the chosen obstruction layout, and an optimal ground station location, there can be 1500 pieces of litter while still fulfilling the requirements.

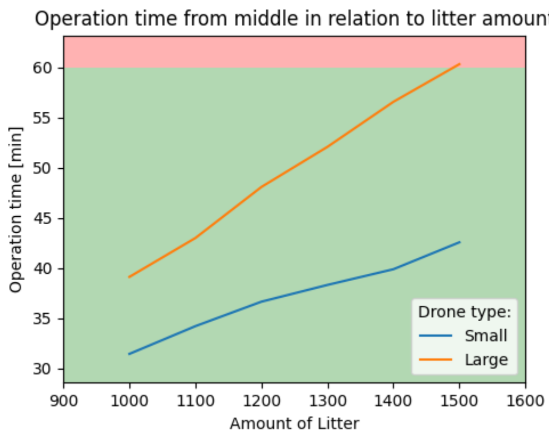
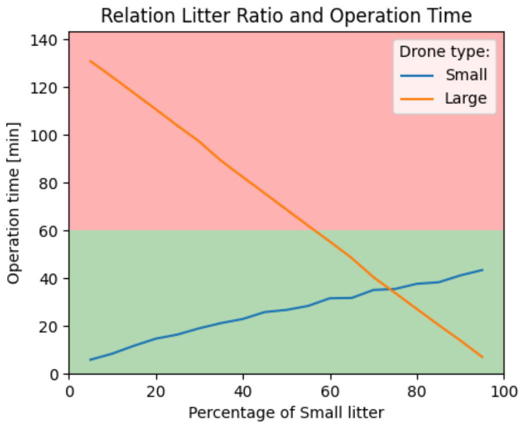


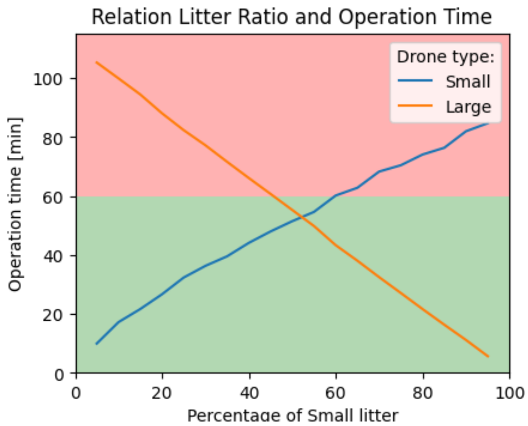
Figure 7.11: The operation time with a varying amount of litter and a ground station at position 1 of Figure 7.10a. The shaded area indicates compliance with the requirement that the area should be cleaned within an hour.

Litter Fraction

The next sensitivity of the fraction of small litter could be the most important one during real operations. This is because the litter distribution can vary a lot between different places. During this analysis, the total amount of litter is fixed to a thousand pieces. However, the percentage of litter type that can be cleaned by each drone is changed. Figure 7.12a shows the results. It is clear that the large drone is much more sensitive than the small drone to the amount of litter it must clean. This is logical since the large drone must fly back to the ground station for every litter piece. In subsection 5.1.1, it was found that 64 % of litter in the urban area can be cleaned by the small drone. When an area must be cleaned which contains much more small litter, this is no problem. When the small litter amount is decreased below 58 %, there is too much large litter for the large drones to clean, since the orange line in Figure 7.12a enters the red area. However, because of the modular design, this is no problem because the small litter drones have dropped below 30 minutes. This means one drone of the small type can be equipped with a grabber instead of a brush. When this is done from the start, this will result in Figure 7.12b. It is then possible to complete the operation within an hour if the small litter is at least 45 %. This increased margin from 6 % to 19 % creates a good buffer which is not expected to be exceeded. On this new margin, the small drone is done in approximately 50 minutes. This single drone also must be able to perform reconnaissance, so this value of 45 % could be increased by a few percent to increase the reconnaissance time.



(a) Litter ratio dependence for 2 small, and 4 large drones



(b) Litter ratio dependence for 1 small, and 5 large drones

Figure 7.12: Operation time dependency on the fraction of small litter. The shaded area indicates compliance with the requirement that the area should be cleaned within an hour.

A second conclusion that can be drawn from Figure 7.12 is related to the slope of the two figures. In Figure 7.12b, the slope of the small drone is approximately equal to the slope of the large drone, while the quantity of the large drone is five times the quantity of the small drone. Therefore, it can be concluded that the small drone is five times as effective due to its capability of storing litter.

Battery Size

The performance of the battery is an additional important parameter in the simulation. Especially because there are still a few assumptions related to the power calculations in the simulation. To test how sensitive the simulation is to the battery size, the energy that the battery stores is reduced in combination with the mass that this reduced energy would consist of. The amount of battery replacements that the drones in the simulation must have, in combination with the total operation time is plotted in Figure 7.13. There are two sets of lines included which correspond to the wind and disturbance compensation factor in the simulation. It can be concluded that the battery size can be reduced to at least 70 % to still only have to recharge once. It can be reduced to at least 35 % to be recharged twice. Therefore, these changing values are very far away from the current situation and the simulation is not very sensitive to changes in the battery storage. However, these results do pose a new possibility for a redesign of the drones, such that they can become lighter. Since the drone controller is tuned for a 4 kg drone, the system can deviate from real values when getting far away from a 100 %. However, this is a promising result for a future version of the ADIOS system.

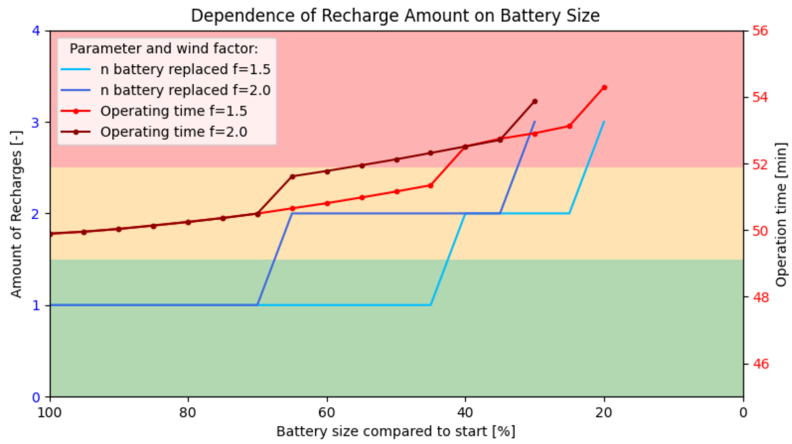


Figure 7.13: Amount of battery replacements necessary if the battery size is reduced. The background colours indicate the number of battery replacements that have to be taken in relation to the requirements. The shaded area indicates compliance with the requirement that each drone must be able to operate for 20 minutes before recharging and corresponds to the blue lines.

Pseudorandom Seed

In the simulation, the litter locations have been determined randomly by using the random module in Python. A seed was used to obtain the same results when the experiment was repeated. However, this could generate a system that is overfitted to the litter distribution generated by a specific seed. To test whether this is the case, 25 simulations have been performed with different seeds. The result of this experiment is shown in Figure 7.14. The results show that the litter distribution does have some influence on the total operation time of the simulation. However, the maximum deviation from the mean value is 3.26 % for the small drone and 2.25 % for the large drone and all the operation times are still shorter than an hour. Therefore, it can be concluded that the system is not overfitted to the specific seed used.

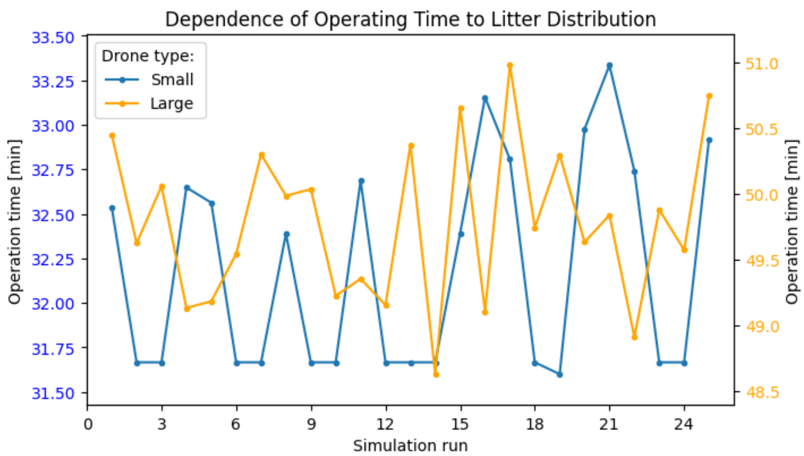


Figure 7.14: Operation times when the seed for the random module is changed

Assumed Power Values

During the development of the program, the power values other than the power required for flying have been estimated. These are the power needed for the flight computer, object detection, driving and grabbing. In total, these powers add up to 80 W. The power needed to fly the drone has an average of 465 W, and the batteries do not have to be replaced when the power factor is increased from 1.5 to 2.0 (465 W to 620 W on average), as shown in subsection 7.5.2. From the combination of these two facts, it can be concluded that the system is not sensitive to small changes in the power values assumed.

8 Performance Analysis

8.1. Structural Analysis

Before performing the structural analysis, it is essential that the different materials used in the drone are defined. The arms of the drone are made of carbon fibre, the suspension parts are made out of TPU and the rest of the structure is PLA. To determine whether the drone structure is able to withstand the operational loads sufficiently, a structural analysis is performed. One can determine an object's structural performance with a wide range of methods. For complex shapes, techniques like the finite elements method can be used to find the most critical points when under a specific load. However, the drone design of ADIOS is a relatively easy assembly for which the critical situations can be determined quite straightforwardly. The most severe loads occur during lift and landing, so after analysing the structural response of these, the final dimensions of the drone structures can be established. The first and second cases will be analysed in subsection 8.1.1 and subsection 8.1.2, respectively.

8.1.1. Case 1: Lift

During lift, loads are exerted on the arms of the drone (Figure 8.1). While the six propellers generate force upwards, the drone's weight acts toward the ground, causing bending in the arms. To analyse this situation in a practical manner, some assumptions should be made:

- The torque created during turning is caused by an offset angle of 5° at a small distance and can therefore be neglected.
- The lift of the propeller acts as a point load.

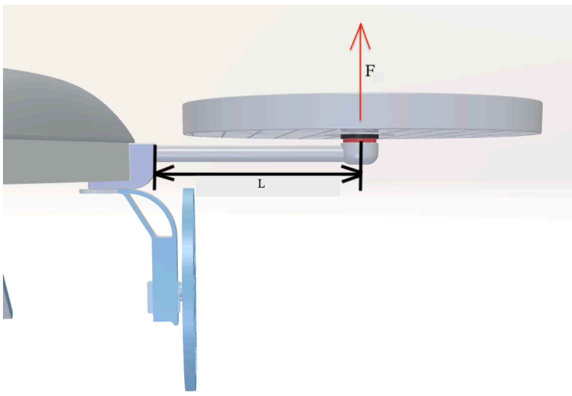


Figure 8.1: The load case during lift

The maximum moment M is caused at the furthest distance from the lift force, at a distance L = 150 mm, and can simply be calculated through $M = F \cdot L$. Furthermore, the thrust-to-weight ratio is equal to 2, thus the maximum force F exerted by one propeller is equal to $(2g \cdot m)/6$. Here, m is the mass of the drone, equal to 4.5 kg. The stress caused by the bending moment can then be calculated with Equation 8.1[89]:

$$\sigma = \frac{My}{I} = \frac{2g \cdot m \cdot Ly}{6I} \tag{8.1}$$

Here, y and I represent the distance from the neutral axis and the moment of inertia, respectively. The arm has a circular hollow section with an inner and outer diameter of 9 and 12 mm, respectively.

The moment of inertia I is thus equal to $(d_{outer}^4 - d_{inner}^4)\pi/64$, so 20413.94 mm^4, and for y the maximum distance of 6 mm is used. Therefore, the maximum bending stress that occurs during lift is 108.124 kPa.

Most commercial carbon fibre materials possess a flexural strength of approximately 300 MPa [122]. The lift stress is about 0.036% of this, and shall therefore not lead to failure of the arms.

8.1.2. Case 2: Landing

The second case which could lead to structural failure of the drone is during landing. As explained in section 5.6, the wheels are made of PLA, which has a high Elastic Modulus (3.5 Gpa) and high Shear Modulus (1.3 GPa) [51]. Therefore, the part to be analysed by this impact is the suspension. As can be seen in Figure 8.2, the suspension is the attachment of the wheel with the rest of the drone, and it consists of a diagonal part and an arc-shaped part. Its material is TPU, providing flexibility and elasticity, to be able to absorb and distribute the loads, while having high flexural stress. To analyse a landing impact, one must make a couple of simplifications:

- The wheel and servo pass the load of the impact to the attachment while preserving its initial integrity. While this is in reality never the case, assuming this leads to some redundancy as the PLA wheels can absorb some of the impact as well.
- The diagonal part of the suspension should be sufficient to carry all loads. This way, the arc-shaped part acts as redundancy, while simplifying the analysis.
- For the drop, air resistance is neglected. This results in a larger impact and is therefore a safe assumption.
- The impact load acts as a point load.

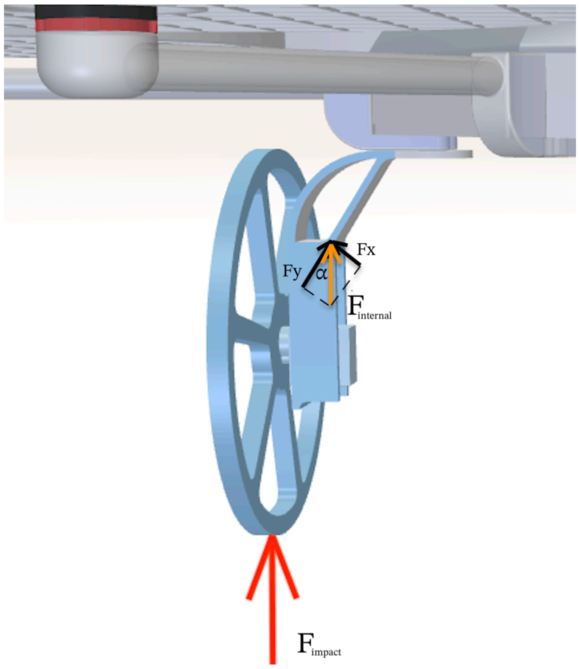


Figure 8.2: The load case during landing

In Figure 8.2, it is shown that the impact load causes the internal load F in the suspension. Its axial component F_Y will cause compression, whereas the transverse component F_X causes bending stresses.

To determine what impact load to design for, an uncontrolled drop of 0.5 meter is considered as a maximal acceleration. While disregarding the air resistance, the time t before hitting the ground can be calculated through $height = 0.5 \cdot g \cdot t^2$ and is equal to 0.319 seconds. Then, the velocity with which the drone hits the ground is $g \cdot t$, namely 3.132 m/s. To determine the force of the impact, one must consider the displacement when absorbing the impact. This value is, however, still unknown, as the load determines this. Therefore, an extreme case is used, where the impact is absorbed in only 1 cm. This then leads to an impact time of 0.006385 seconds, causing a deceleration of 490 m/s^2. In an ideal case, this deceleration should be multiplied with half of the weight as the impact is divided over two wheels. However, in this analysis, an asymmetrical drop is considered as well, leading to a maximum impact force of 2207.25 N.

The angle α (as shown in Figure 8.2) of the diagonal suspension part with respect to the wheel is equal to 32°. This means that the axial and transverse component of the load are equal to $F \cdot cos(32°)$ and $F \cdot sin(32°)$, so 1871.85 N and 1169.66 N, respectively.

The compression stress due to the axial component can be calculated through Equation 8.2:

$$\sigma = \frac{F_Y}{A} \tag{8.2}$$

[80] Where A is the area of the cross section, which is equal to 4.58 $\cdot 10^{-5}$ m^2. This leads to a compression stress of 40.8 MPa.

Furthermore, the bending stress due to the transverse component can be calculated with Equation 8.1. As the length L is equal to 0.0377 m, the moment M is equal to 44 Nm. The moment of inertia I of the cross section is equal to 1.536 $\cdot$ 10^{-12}, so the stress that occurs during bending is 36.517 GPa.

The flexural strength of TPU is 60–97 MPa [80]. This means that the bending stress exceeds the allowable stress. Therefore some design iterations are needed. When reconsidering Equation 8.1, one can calculate a moment of inertia that is sufficient to withstand 60 MPa. This new moment inertia is equal to 1.87 $\cdot$ 10^{-9}. To reach this value, the height of the cross section should be equal to 10.76 mm. Hence, there is opted for this design change, as is does not result in noticeable changes in the weight or sizing. Ultimately, the design change is easily implementable in the production plan, as the suspension parts are 3D printed. Note that the arc-sized part of the suspension and the absorption of the wheels still serve as redundancy and that extreme values for the drop height, displacement and flexural strength are taken.

The compression stress can now be recalculated. For this, the ultimate case of an asymmetrical drop will be used, where α is zero (if it would be smaller than zero, the drone would tip over). Then, the force would simply be equal to 2207.25 N, and the new area A is equal to 1.937 $\cdot$ 10^{-4}. This leads to a compression stress of 11.4 MPa.

The maximum compressive strength for the TPU lattice structure is 5.34 MPa for 0.1 mm layer thickness [43]. This concludes that the suspension structure is sufficiently strong to withstand a 0.5 meter drop, along with redundancy.

8.2. Power Budget

The section serves to give the power usage of the system. It provides a sizing of the drone battery as well as a sizing of the ground station battery.

8.2.1. Drone Battery

The drone battery has been sized by calculating the minimum amount of battery capacity to fly for at least 20 minutes with one battery.

First, the average amp draw (AAD) needs to be calculated using Equation 8.3 [96].

$$AAD = AUW \cdot \frac{P}{V} \tag{8.3}$$

In Equation 8.3, the all-up weight (AUW) is the total weight of the drone including electronics and the battery. Assuming the Tattu 16000mAh battery which is 1.905 kg and an operational empty mass (OEM) equal to 2.5 kg, the AUW is approximately 4.4 kg [121]. P is the power required for the drone to lift 1 kg. A conservative universal estimate for drones is 170 W [96]. Finally, V is the voltage of the battery, which is 22.2 V for the Tattu 16000mAh battery since it has 6 cells in series. These values result in an AAD equal to 33.73 A.

Now, the flight time can be calculated using Equation 8.4 [96].

$$t = capacity \cdot \frac{discharge}{AAD} \tag{8.4}$$

In Equation 8.4, the capacity of the Tattu battery is $16\,000$ mAh, the discharge of the battery is usually from 90% to 10%, hence 80%, and the AAD is equal to 33.73 A. This results in a total flight time equal to roughly 23 minutes. Hence, the Tattu 16000mAh battery provides sufficient flight time for the ADIOS drones.

Note that the Tattu 16000mAh has a length of 190 mm, a height of 76 mm, and a width of 65 mm. The battery integrated into the drone can be seen in Figure 5.30.

It is important to note that the drone sizing was done using this drone battery sizing. However, during a later stage of the design process, a more accurate drone battery sizing was done using the simulation, as described in subsection 7.5.2. When the drone is driving on the ground to pick up litter, it requires less power than when it is flying. Therefore, energy is saved and the drones can operate for a longer period with one battery. In fact, this extends the battery life to roughly 45 minutes. This is quite a large difference compared to the initial 23 minutes. Although a high flight time is desired, it is also desirable to have a smaller drone, which can be achieved with a smaller battery. Hence, for future design iterations, it is recommended to investigate the effects on the size and weight of the drone when decreasing the battery size.

8.2.2. Ground Station Battery

This subjection serves to give a sizing of the ground station battery. The purpose of the ground station battery is to provide power to the components inside the ground station and to serve as a point from which the batteries of the drones can be charged. The total power draw for charging the batteries and powering the ground station is illustrated in Equation 8.5. In this equation P_{tot} is the total power draw needed for the system, P_{GS} is the power the ground station needs to function, n_{bats} are the number of batteries charging at any time and P_charge is the power draw per battery to charge it in an hour.

$$P_{tot} = P_{GS} + n_{bats} P_{charge} \tag{8.5}$$

The system uses 6 drones and each drone has 2 batteries continually charging. Assuming a computer with TT&C power of 500W, four monitors of 100W each result in a total ground station power usage PGS of 900W. The batteries of the drones selected in section 5.5 are recommended to be charged in one hour[9]. This results in a power draw of $P_{Charge} = 355W$. The total power draw for the system from the ground station battery is then $P_{tot} = 5.2kW$ Assuming that the system operates for six hours in a day and adding half an hour of contingency the total size of the ground station battery must be $33.8kWh$. If the ground station is an electric van the battery of the van can be utilised to power the system when it is sufficiently large. If this is not the case then a separate battery of this size must be added to the station. Battery packs can be created from small lithium-ion batteries to the desired size. Such a battery would cost approximately €$370, -perkWh$[10].

8.3. Aerodynamic Characteristics

The aerodynamic characteristics are important parameters that must be considered and designed for any aerial vehicle. This section gives an overview of all relevant aerodynamic characteristics of the drone.

- **Propeller Configuration, Type & Size:** In section 5.3, it was decided that drone would be a hexacopter, consisting of 6 rotors equally spaced from its neighbour to include redundancies in case of motor failure. It was further discussed that the toroidal propellers would be utilised due their superior performance in terms of thrust efficiency and noise in the propeller testing. It was further calculated that the propellers would be 10 inches in diameter to provide sufficient thrust and compromise between the lower power usage of smaller propellers and added weight gain of larger propellers
- **Thrust**: The maximum thrust can be calculated using Equation 5.3 mentioned in section 5.3. It was stated that the toroidal propellers have a diameter 10 inches and are 29% more efficient in comparison to conventional blade propellers. Given that the battery operates at 22.2V and taking the maximum current of 17.3A from the motor specifications, the maximum electrical power totals 384W. Using Equation 5.3 and incorporating the toroidal efficiency boost, the maximum thrust is calculated to be 3.5 kgf thrust per rotor, or 20kgf for the drone as a whole, which exceeds the 2.5/1 thrust-to-weight ratio. To produce an average of 6kgf of thrust, which is expected during operational flight, the system requires 87.2W per rotor
- **Endurance**: The total flight time for a drone without landing is calculated using the simulation to be 35 minutes. The operational time is calculated to be 45 minutes when the landing is taken into consideration as driving requires much less power
- **Wake Effects**: In the initial design phase. the wake effects were a huge concern as they were detrimental to the success of the operation as preliminary testing proved the wake powerful enough to scatter grounded litter even when the drone was hovering at a height of 2 m. The team considered many different design options to either reduce the wake effect or work around it. The team ultimately decided to for a versatile drone that can both fly and drive on the ground. This would allow for the drone to land a sufficient distance away from the target litter and drive up to it in order to pick it up. This ensures the wake effect does not interfere with the mission's success. Consequently, the wake effect of the drone can be disregarded as it will no longer affect

the success of the mission. Nevertheless, investigating the wake effect with different propellers or design options in order to remain fully aerial is recommended to mitigate the design complexity and weight increase surrounding the wheels and its respective structure

8.4. Summary table of performance characteristics

This section serves as an overview of all performance-related values of the drone.

Table 8.1: Overview of all performance parameters of the drones

Variable	Symbol [unit]	Value
Inertial properties		
Moment of inertia around x	I_{xx} $[kgm^2]$	0.0506
Moment of inertia around y	I_{yy} $[kgm^2]$	0.0577
Moment of inertia around z	I_{zz} $[kgm^2]$	0.1058
Mass	m $[kg]$	4.4
Operational Empty Mass	$OEM hspace5pt [kg]$	2.5
Endurance		
Battery capacity	Q $[mAh]$	16000
Battery energy	E $[kJ]$	1278.72
Single battery operation time	t_op $[min]$	45
Single battery flight time	t_{fl} $[min]$	35
Propulsion		
Thrust-to-weight ratio	T/W $[-]$	5:1
Maximum thrust	T $[kgf]$	20
Nominal propulsive power	P_{prop} $[W]$	523
Maximum flight speed in operation	V_op $[m/s]$	10
Noise		
Noise @ 5m distance	$-$ $[dBA]$	50
Ground station		
Total computer & monitor power	P_{GS} $[W]$	900
Total drone charging power	$P_{charging}$ $[W]$	4,300
Total battery energy	E $[kWh]$	33.8
Mass	m $[kg]$	405.2
AI Computer vision		
Model	[-]	YOLOv8n
Model resolution	$-$ $[pixels]$	960px960p

9 Risk Analysis

In order to successfully deliver a project, it is crucial to first identify risks and later manage potential threats that could impact the project's outcome. Risk analysis involves identifying potential hazards, analysing their likelihood and impact, and implementing strategies to monitor, mitigate or eliminate them. In the design of complex systems, risk analysis is especially important, as not all risks can be easily spotted and might have very severe consequences in the future. Therefore, a SWOT analysis is performed in section 9.1, after which the risks are analysed and mitigated in section 9.2.

9.1. SWOT Analysis

First, to better understand potential events influencing the technical aspects of the project, a SWOT analysis of risks was performed. It serves to clearly classify different helpful and harmful events and their potential impact on the project. The results can be seen in Figure 9.1

Helpful | Harmful

Internal Origin

Strengths:
- **STR-01**: Cheaper garbage collection than with manual labour
- **STR-02**: Faster garbage collection than with manual labour
- **STR-03**: Unmanned vehicles
- **STR-04**: Autonomous vehicles
- **STR-05**: Coverage area of 10000 m^2
- **STR-06**: Picking up at least 1000 pieces of garbage within an hour
- **STR-07**: Capability of accessing garbage in water and rough terrain
- **STR-08**: Less manpower needed
- **STR-09**: Sorting garbage after collection
- **STR-10**: Providing operator with information about area
- **STR-11**: The mobile van is electric
- **STR-12**: The system can be easily scaled
- **STR-13**: Reduced human risk as litter picking can be a dangerous job for humans

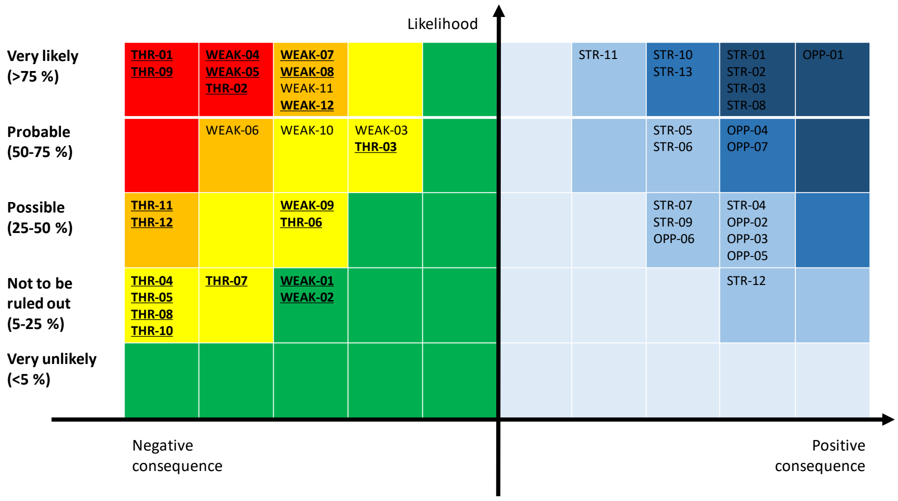
Weaknesses:
- **WEAK-01:** Battery size for coverage area of 10000 m^2
- **WEAK-02:** Number of drones for coverage area of 10000 m^2
- **WEAK-03:** Litter shall be sorted for recycling
- **WEAK-04:** Maintaining design within €100k budget
- **WEAK-05**: Completely autonomous and dependent on AI
- **WEAK-06**: More dependent on weather conditions than current cleaning systems
- **WEAK-07**: Team lacks experience of working with drones
- **WEAK-08**: Drones shall identify and not be harmful to wildlife, the environment and people
- **WEAK-09**: Product shall be developable within 3 years
- **WEAK-10**: Multiple drone types for various litter types are designed
- **WEAK-11**: Drones can only carry a limited payload
- **WEAK-12:** Wake of drone interferes with litter

External Origin

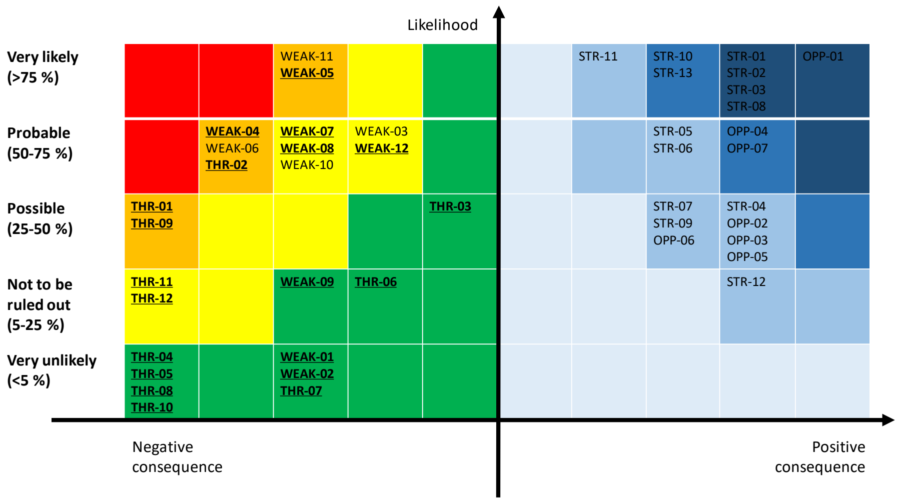
Opportunities:
- **OPP-01**: Useful for cleaning public areas
- **OPP-02**: A better allocation of public resources is possible
- **OPP-03**: Can be sold to other countries
- **OPP-04**: Technologies developed by other companies can be used
- **OPP-05**: System can be implemented by the government
- **OPP-06**: Collected data can be used to analyse litter patterns and use them for litter reduction strategies
- **OPP-07**: Drones are versatile and can be used in various environments

Threats:
- **THR-01**: New certification regulations for drones and/or airspace are introduced
- **THR-02**: Development of a new technology and systems leads to unforeseen costs
- **THR-03**: New competitors enter the market
- **THR-04**: Environment or people are harmed due to drone failure
- **THR-05**: Drone communication systems are hacked by a malicious entity
- **THR-06**: Cost of drone and payload parts for the proof of concept exceed the budget
- **THR-07**: Extreme weather conditions
- **THR-08**: Drones are vandalised by general public
- **THR-09**: Government imposes new regulations of drone-human proximity
- **THR-10**: Privacy of pedestrians is violated due to system failure
- **THR-11**: External technology used in the system is discontinued
- **THR-12**: People attempt to steal/destroy the drones

Figure 9.1: SWOT analysis of technical risks



(a) Risk-opportunity map before risk mitigation



(b) Risk-opportunity map after risk mitigation

Figure 9.2: Risk-opportunity map for organizational risks. X-axis represents the consequences, all events left of the y-axis have negative consequences and vice-versa. The y-axis represents the likelihood of the event. All mitigatable risks are in bold and are consequently moved from the upper figure to the lower figure by mitigating the risk. The graph layout is based on [27].

9.2. Risk Analysis and Mitigation

After the risks have been identified, their severity and likelihood were assessed. The results can be seen in Figure 9.2a. Some of the risks were identified as mitigatable, as the team has a certain level of control over them. They are shown in bold underlined text in Figure 9.2. Other risks were classified as non-mitigatable, since the team does not possess any control over them and their origin is fully out of reach.

9.2.1. Risk Consequences

After risks have been identified, their consequences can be evaluated. This evaluation can be subsequently used to choose appropriate mitigation and monitoring strategy. The results are presented below:

- **WEAK-01**: Limited battery life may result in incomplete coverage of the targeted area, leaving litter uncollected.
- **WEAK-02**: Insufficient number of drones may result in incomplete coverage of the targeted area, leaving litter uncollected.
- **WEAK-03**: If the sorting mechanism is not efficient or accurate, the recycling process may be

compromised, leading to improper disposal or contamination of recyclable materials.

- **WEAK-04**: Design limitations due to budget constraints may compromise the overall effectiveness, quality, or capabilities of the system.
- **WEAK-05**: Reliance on AI for autonomous operation introduces the risk of errors or malfunctions, which could lead to drones malfunctioning, getting lost, or causing accidents.
- **WEAK-06**: Adverse weather conditions, such as strong winds or heavy rain, may significantly impact the drones' performance and hinder their ability to effectively pick up litter.
- **WEAK-07**: Inexperience with drones may result in design flaws, operational inefficiencies, or safety risks, potentially leading to accidents, poor performance, or increased maintenance needs.
- **WEAK-08**: If the drones fail to identify wildlife or if they inadvertently cause harm to the environment or people, it could lead to negative ecological impacts, injury, or legal issues.
- **WEAK-09**: Strict development timeline may lead to rushed decisions, compromising the system's functionality, reliability, or safety.
- **WEAK-10**: Designing and maintaining multiple drone types may increase complexity, cost, and maintenance requirements, potentially impacting the overall effectiveness of the system.
- **WEAK-11**: Limited payload capacity may result in frequent trips to empty the drones or leave certain types of litter uncollected, reducing the system's overall efficiency.
- **WEAK-12**: The wake or air disturbance created by drones may scatter or displace litter, making it more challenging for the drones to effectively pick it up.
- **THR-01**: New regulations could dramatically change the requirements imposed on the system and the operator, thus rendering the system non-functional.
- **THR-02**: Unexpected technological advancements may render the system outdated or less competitive, requiring costly upgrades or redesign to remain relevant.
- **THR-03**: Increased competition may impact market share and profitability, necessitating improvements or adjustments to maintain a competitive edge.
- **THR-04**: If the system malfunctions or drones fail, it could result in accidents, property damage, or harm to the environment or people, leading to potential legal liabilities and reputation damage.
- **THR-05**: If the communication systems are compromised, the drones' control may be hijacked, potentially leading to unauthorised use, accidents, or misuse of the system for malicious purposes.
- **THR-06**: If the cost of drone and payload parts exceeds the allocated budget, it may lead to financial constraints, delays in development, or compromises in the quality and performance of the system.
- **THR-07**: Severe weather conditions, such as storms, heavy rain, or extreme temperatures, may render the drones inoperable or significantly reduce their efficiency, leading to delays in litter collection or potential damage to the drones.
- **THR-08**: Acts of vandalism on the drones can result in damage or destruction of the equipment, rendering the system temporarily or permanently non-functional, and causing financial losses and disruptions to the litter collection process.
- **THR-09**: If the government imposes regulations restricting the proximity of drones to humans, it may limit the operational capabilities or require costly modifications to ensure compliance, potentially reducing the system's effectiveness or increasing development costs.
- **THR-10**: If the system fails to maintain privacy standards, it may result in the unintentional capture or sharing of personal data or images of pedestrians, leading to privacy violations, legal issues, or reputation damage.
- **THR-11**: If the external technology, such as sensors or communication systems, used in the system is discontinued, it may lead to compatibility issues, increased maintenance costs, or the need for system redesign to accommodate alternative technologies. This can cause delays and additional expenses.
- **THR-12**: If the general public attempts to destroy and steal the drones it could impair the capabilities of the system in terms of coverage area and efficiency. Moreover, it could potentially bring additional costs for the clients using the system.

9.2.2. Risk Mitigation

After the mitigatable risks have been identified, a plan of resolution and monitoring could have been developed. The results are presented in the following list:

- **WEAK-01**: The drones shall communicate with each other (using the ground station as a relay) to limit the area covered by a single drone. Moreover, safety factors should be applied to the capacity of the battery. This will be monitored and kept in consideration throughout the design phase of the drone and the system as a whole.
- **WEAK-02**: The drones shall communicate with each other to limit the area covered by a single drone. Moreover, safety factors should be applied to the capacity of the battery. This will be monitored and kept in consideration throughout the design phase of the drone and the system as a whole.
- **WEAK-04**: Thorough planning and continuous cost analyses can be utilised to keep track of costs and provide a financial breakdown of the design and project. When an item is highlighted as too high in cost, alternative solutions/products must be considered and used.
- **WEAK-05**: Human interaction with the system shall be ensured such that the design is not fully dependent on AI and not fully autonomous. For example, the operator shall be able to manually override the autonomous steering and take control of the drone. This risk will then also be monitored by the operator who could have an overview of the drones through telemetry and camera view.
- **WEAK-07**: The coaches and internal and external experts shall be contacted regularly for tips and expertise when the team is unsure of a certain aspect to aid our design and project. This will be monitored by the team.
- **WEAK-08**: It shall be ensured that the drones are able to identify all kinds of items and animals and that each drone maintains a safe distance from them. Furthermore, a large error margin shall be implemented in terms of the detection of animals. Again, the drones could have an override system where the operator can intervene in case the drone is unable to identify something or it is approaching too close to something. The risk will be monitored by the team by including protocols within the software and the operator will also have a role in monitoring this risk.
- **WEAK-09**: A plan for the next 3 years to identify a timeline for the project and the duration required for all tasks shall be created. This will be monitored by the team to ensure the project remains on schedule.
- **WEAK-12**: Wake effects shall be considered in the aerodynamic design of the drones. For example, a sufficient margin between the rotors and the ground could be considered to ensure the wake has minimal effects on grounded litter. This will be monitored by the drone hardware team who design for the aerodynamic characteristics of the drone. Moreover, tests with a prototype shall be conducted to experimentally assess the impact of the wake.
- **THR-01**: Regular monitoring of legal proceedings of the government in that area shall be conducted. Furthermore, local aviation experts can be consulted in order to assess possible future legal trends. Nevertheless, aviation is a heavily regulated area and can be impacted very rapidly by unpredictable accidents. Therefore, it is still possible that an unforeseen regulation will be introduced, thus heavily impacting the system.
- **THR-02**: Developing new technologies requires an investment of substantial resources, which poses a risk of not getting a sufficient return from the investment if the technology eventually underperforms. This can be mitigated by using existing technologies that are proven to perform as expected at a given cost.
- **THR-03**: The market shall be monitored constantly in order to keep track of potential competition and maintain an advantage within the market. Additionally, new technologies that have been developed can be patented in order to ensure that competition will not make use of them.
- **THR-04**: Fail safes shall be introduced in order to ensure that the drone is safely grounded upon failure. Furthermore, extensive telemetry should be implemented in order to constantly monitor the parameters of the drone to make sure it behaves as expected. A geofence system can also be implemented in order to ensure that the drones stay within the area defined by the operator.
- **THR-05**: The risk of being hacked can be minimised by performing extensive safety checks. Cryptographic techniques can be implemented to ensure that communication cannot be intercepted

by a third-party entity. Preferably, communication protocol should be made open source in order to enable independent open-source communities to verify the software and find potential vulnerabilities. The disadvantage of this approach is that it poses a risk of the software being used by the competition, which could have a negative financial impact.

- **THR-06**: A clear plan for developing the demo shall be established in advance. Furthermore, there is a possibility of borrowing the drone and necessary hardware from the faculty.
- **THR-07**: Weather forecasts should be monitored regularly in order to predict rough conditions and operate the system only if there is no risk of interference with the weather.
- **THR-08**: Educational campaigns should be introduced in order to ensure that the public is aware of the purpose of the system. Furthermore, fines should be imposed on everyone that interferes with the operation of the drones. Finally, the operator should maintain visual contact with the drones whenever possible in order to prevent potential vandalism.
- **THR-09**: Similarly to new airspace regulations, monitoring of legal proceedings of the government in that area should be performed. Furthermore, local aviation experts can be consulted in order to assess possible future legal trends. Nevertheless, aviation is a heavily regulated area and can be impacted very rapidly by unpredictable accidents. Therefore, it is still possible that an unforeseen regulation will be introduced, thus heavily impacting the system.
- **THR-10**: There is a large risk related to the malfunction of drones violating the privacy of pedestrians which could be mitigated by including ensuring in the software that the drone should immediately safely land away from pedestrians if it experiences a malfunction and include an override system where the operator can intervene to avoid pedestrians.
- **THR-11**: The risk associated with external companies whose products are used in the design becoming discontinued can be mitigated by keeping in close contact with the company so that the team can be notified well in advance if this is to happen. This will allow for another product/-company to be found before the previous one is discontinued. This will be monitored by the team, notably the person responsible for the product in relation to the design (e.g. chief drone hardware responsible for knowing about the continuation of outsourced drones).
- **THR-12**: The drones should be able to detect an attempt of adversarial behaviour and react accordingly. Computer vision algorithms shall be incorporated to ensure that a minimum distance from humans is kept at all times, which will also ensure that people are not able to engage in physical contact with drones.

After developing a mitigation strategy, each risk is reevaluated. The results are presented in Figure 9.2b.

10

Return on Investment and Operational Profit

The expenses of the ADIOS company must be determined. The costs and the revenues the ADIOS company can realistically obtain are illustrated in this chapter. In section 10.1 the cost breakdown structure of the company is illustrated. In section 10.3 the operational costs are estimated for the system. In section 10.4 the return on investment for the system is estimated.

10.1. Cost Breakdown Structure

In this section, the costs for all subsystems are estimated. The costs are estimated for all components and processes necessary for the production and development of the system. In Figure 10.1 the cost breakdown structure of the company can be seen.

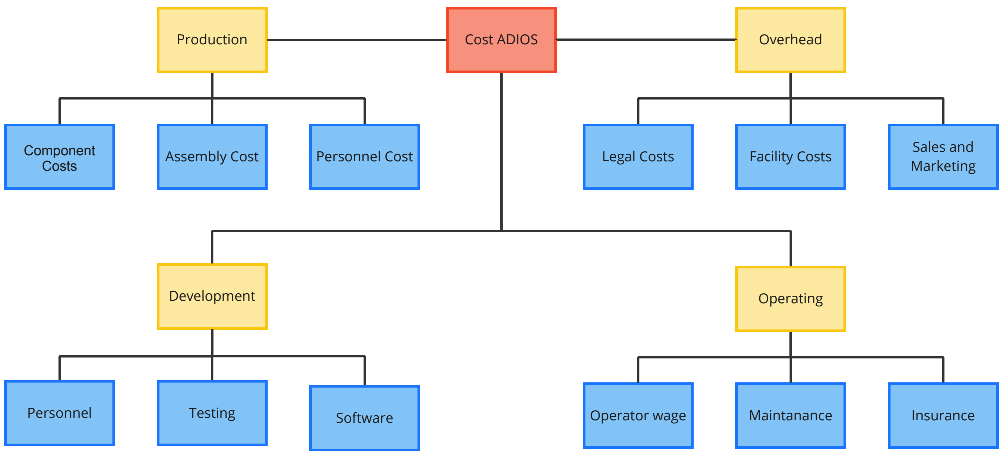


Figure 10.1: Cost Breakdown Structure of ADIOS

10.2. Development and Manufacturing Costs

This section serves to give an estimate of the development and manufacturing cost of the complete system. The development cost is estimated by comparing the system with other drone system companies and their expenses. Moreover, detailed costs for individual parts of the systems are presented to calculate the total cost of the entire system.

10.2.1. Development Costs

The system as presented in this report requires further development in order to be a valid commercial product. The cost of development will be a combination of building a working prototype, bringing the product to mass production, designing the onboard software solutions, testing the product, and certification. Throughout the development personnel must be paid, prototypes must be paid and several facilities should be leased or bought. These costs are estimated from different autonomous drone system companies and the funding they received. In Table 10.1 a list of selected reference companies can be obtained.

Table 10.1: List of autonomous drone system companies

Company	Funding in Million €	Number of employees
Flyability [11]	38.7	51-100
Exyn Technologies [12]	50.7	51-100
Near Earth Autonomy [13]	16.8	51-100

The scope of ADIOS is similar to the companies listed in Table 10.1. The funding required for ADIOS in order to develop its systems is deemed similar to these companies. The development cost for ADIOS is assumed to be the average of this list, resulting in an estimated development cost of €35.4 Million. The number of employees needed to develop the system is deemed to be of similar size to these companies. The deemed number of necessary employees to develop the system is approximately 75. Assuming a 3.5% interest rate and a payback of 30 years results in monthly payments of €158,962.

10.2.2. Manufacturing Costs

For the design, the components have been selected. The list of components can be seen in Table 10.2 and Table 6.1. In future iterations of the system, this component selection is subject to change and increase. Integration of the components requires further development. The cost of manufacturing is building the individual components when needed and incorporating them together. Below a list of subsystems can be seen and their respective costs.

Payload

The payload for the drones consists of two custom pick-up mechanisms. These pick-up mechanisms consist of a claw and a brush system. The claw pick-up mechanism is made from biodegradable PLA plastic. All pick-up mechanisms will be 3D-printed, which can be outsourced. In order to estimate the price of the 3D printing, the parts are uploaded to [6], on which the price is estimated by means of a quotation. The resulting cost estimates can be seen in Table 10.2.

Electric Systems and Battery

The batteries on board the drone are LIPO batteries which will be bought off the shelf. The ground station will utilise the battery present in the leased electric van.

Propulsion

The motors of the propulsion system are chosen off the shelf. The rotors must be produced. The rotors are outsourced to a third-party company, for which an estimate of the cost is presented in Table 10.2 [6].

Frame

The frame of the drones is produced from a biodegradable PLA. The frame production will be outsourced to an external company and will be 3D printed [6]. The cost of the frame is determined similarly to the pick-up mechanism by means of a quotation on [6]. The estimated cost is presented in [6].

Drone Arms

The arms weigh 693 grams in total. The arms shall be produced by an outside company as the total amount needed is not deemed large enough. The cost is approximately €130,- per kilo[1]. Per drone, the cost of making the arms is then approximately €91,-.

Assembly and indirect cost

The cost of assembly of the drones is estimated to take approximately 130 work hours to assemble the whole system. This is done by a team of 10 people. The testing cost of a drone is assumed to cost €50,- per drone. The cost of assembling the complete system and testing the six drones is estimated to be €2900.

Total cost per system

Table 10.2: Cost of components of the Drone

Components	**Subsystem**	**Estimate Price in €**	**Amount needed**	**Total Cost in €**
Frame	Structure	80	1	80
Arms	Structure	15.17	6	91
Wheels	Structure	5	2	10
suspension	Structure	20	2	40
Motors	Propulsion	90	6	540
Servos	Electronics	14	2	28
Propellers	Propulsion	20	6	60
Flight Controller	Electronics	130	1	130
Electronic Speed Controllers	Electronics	40	6	240
Battery	EPS	320	3	960
Radio Transceiver	Electronics	20	1	20
Radar	Electronics	335	1	335
Sonar animal Repeling	Electronics	25	1	24
GPS Module	Electronics	25	1	25
Cameras (binocular vision)	Electronics	150	1	150
Onboard Computer (Jetson Orin NX 8GB)	Electronics	450	1	450
4G LTE/5G modem	TT&C	93	1	93
LED lights	Electronics	2	1	2
Propeller Guards	Propulsion	30	6	180
Payload(claw pick-up mechanism)	Pick-up	40	ł 4 for every 6 drones	26.8
Payload(Brushes pick-up mechanism)	Pick-up	40	2 for every 6 drones	13.2
Miscellaneous (cables, connectors, etc.)		20	1	20
Total per drone				**3518**

Finally, from Table 10.2 and Table 6.1 it can be obtained that the cost of all parts of the entire system with six drones and the ground station is €24000,-. Including replacement parts as 20% of the value of the entire system brings the cost to €26400,-. Together with the assembly, this brings the total estimated cost to €29300,-. Assuming a 3.5% interest rate and a payback of 10 years results in monthly payments of €290,- per system.

10.3. Operational Costs

The operational costs are essential to know for the system. The system is built and then used for the services of municipalities. The cost of running a system includes the cost of the operator, the cost of leasing a van, the cost of electricity the system uses, and the cost of maintenance.

10.3.1. Operator Cost

The operator is the person responsible for running the system. The operator of the system requires special drone training to take over the drones if the need arises. The operator is present at all times when the system is in operation and drives the system to the desired location for cleanup. The system is driven from the company location to the operating location. Driving to and from the location takes time. It is taken that a working day is 8 hours. Assuming the operator drives a maximum of two hours per day and operates the system for 6 hours with a salary of €25,- this results in a cost for the operator of €200,- per day.

Van Choice

The ADIOS will lease vans for its system. The installable system can be installed in any electric van of sufficient size and with sufficient battery capacity. In the renders shown in Figure 6.4 the 2020 model of the Mercedes-Benz Sprinter is shown. These can be leased from €571,- per month[14]. Leased vehicles can typically be modified as long as the modification are removable [99]. This is what the installable system is designed for. An insurance policy must be taken out in addition to the lease of €60,- per month [56]. Assuming that the system operates for 6 hours per day and 250 days per year results in a cost per operating hour of €5.08,-.

10.3.2. Maintenance Cost

The maintenance costs of the system are the costs of the components when they break or get worn down and must be replaced. The cost then is the sum of the costs of parts that must be replaced and the cost of performing the inspection. The main components that must be regularly replaced on the drones are the batteries and the motors. These have a low mean time between failures and have typical know values. With the known costs of these systems, the costs of replacing the parts can be estimated. The other parts have a much higher mean time between failure(MBTF) and are considered negligible in cost compared to the motors and batteries.

Motors

The MBTF of motors is around 750 hours[73]. There are a total of 6 motors on each drone. The cost of a single motor as can be seen in Table 10.2 is approximately €90,-. The total system has 36 motors. This leads to a cost per hour of €$4.32/h$.

Battery

There are 2 types of batteries in the system. The batteries on the ground station and the batteries on the drones. Batteries are a sturdy component and can break. Batteries degrade over time each time they are discharged. During operation, the batteries are drained and charged.

The drones have a maximum flight time of 25 minutes on a full charge. During an hour of operating time a total of 2 batteries. After the batteries have degraded with more than 20% the batteries can no longer fulfil the 20 minutes requirement and must be replaced. The degradation of batteries depends on a variety of factors, including temperature, the number of discharge cycles, and the depth of discharge. Degrading to 80% of its original capacity takes approximately 300 to 500 charge cycles [7]. 400 Cycles are assumed for the battery on a drone. When this number of cycles is exceeded the battery must be replaced. Each battery cycles once per hour of operation per drone. There are a total of 3 batteries per drone. For a total of six drones this results in a cost of €14.40 per hour of flying operation. Assuming 6 hours of operation per day the batteries last approximately 70 operating days.

The battery on board the ground station cycles each day of operation. The ground station battery is a lithium-ion battery that can sustain many more charge cycles than the drone system. After approximately 3000 cycles the ground station battery is at 80 % of its maximum capacity[81]. This is after 12 years of operation. After this time it must be replaced. This results in a cost per operating hour of €0.10.

Miscellaneous Cost

The miscellaneous cost of the rest of the system is assumed to be 10% of the costs of the main maintenance cost. This results in a cost per operating hour of € 2.34.

Inspection Cost

In subsection 14.1.3 the inspection is explained. This inspection takes approximately one hour and is part of the operator's salary. The system check that is performed every three months costs a day of work and therefore costs' the company that day's income. It is therefore assumed to cost €330,- per month. This results in a cost per operating hour of €2.64.

Total Maintenance Cost

The total cost of maintenance of the system is €28.37 per operating hour.

10.3.3. Electricity cost

The system is fully electric. The costs of electricity must be taken into account by the customer. Power is drawn from the grid. During the charging of the batteries, there is a loss of efficiency. The primary drawing of power from the system is the drones. Assuming a computer with TT&C power of 500W, four monitors of 100W each result in a total ground station power usage P_{GS} of 900W. Batteries are continuously charging at the ground station each hour. Taking the efficiency loss of charging the ground station battery from the grid $\mu_{grid} = 0.95$ and the efficiency loss from charging a drone battery as $\mu_{bat} = 0.99$. The power the system takes at any time can be seen in Equation 10.1. In this equation, n_{bats} are the number of drone batteries that are charging at any time, P_{charge} is the power draw of the drone batteries during charging, and P_{GS} is the power that the ground station uses.

$$P = n_{bats} P_{charge} \mu_{grid}^{-1} \mu_{bat}^{-1} + P_{GS} \mu_{grid}^{-} 1 \tag{10.1}$$

During operation, two batteries are charged per drone. This results in 12 batteries charging. P_{charge} is equal to $355W$ when the battery is charged in an hour. The power draw of the system for an hour of operation is then 5.5 kWh. With an electricity price in the Netherlands per kWh of € 0.62[15] this results in approximately €3.4 per operating hour.

10.4. Return on Investment and Operational Profit

In this section, the revenue and operating income of the company are estimated. Furthermore, the return on investment time is estimated.

10.4.1. Company Expenses

Establishing the company expenses is difficult. The company expenses must be subtracted from the gross income to calculate the operating income. The main expenses are "Marketing and Sales" and "Research and Development". The money allocated to these departments is assumed to be a fraction of the revenue. In the 2015 corporate report[16] of "Parrot" a large company in the drone industry. The company spent 18% on research and development and 18% on sales and marketing costs and 6% on administration costs. This report was chosen because the company made money this year. Company expenses will be assumed to be 42% of revenue.

10.4.2. Monthly expenses

Throughout the operation, several expenses are made. They consist of the operational costs, the down payment per system to buy and assemble each drone system, and the down payment for the funding. A summary of the expenses per drone system can be found in Table 10.3

Table 10.3: Operating expenses per drone system, including six drones and a ground station

Group	**Subgroup (if applicable)**	**€/h**	**€/day**	**€/month**
Maintenance	Engines	-4.3	-34.4	-688
	Batteries	-14.4	-115.2	-2304
	Gs battery	-0.14	-1.12	-22.4
	Misc	-1.884	-15.072	-301.44
	Inspection			-333
Operator			-200	-4000
Electricity			-40	-800
Lease van				-631
Total expenses per system				**-9080**
Down payment system acquirement				-266
Total expenses including down payment per system				**-9350**

10.4.3. Pricing

The ADIOS pricing should be above the costs. A company like ADIOS provides services for a daily fee, rather than selling actual systems. The purpose of the ADIOS is to replace human labour in cleaning. This labour in the Netherlands is typically performed through community service or volunteers. For a price comparison, the ADIOS is compared against minimum wage workers.

Field Work

From fieldwork by the team, it was found that a person can pick up approximately 2 pieces of litter every minute. The result of this is that a team of approximately 9 people pick up 1000 pieces of litter within an hour. It may be assumed that a municipality can hire people to pick up litter at minimum wage of €12.79,- per hour [25] for 8 hours of work a day. This results in a cost for the municipality of €920,- per day with 8000 pieces of litter being picked up. The ADIOS must be priced below this cost for it to be chosen by any municipality instead of minimum wage workers. The price is set to be 10% more economical to use than minimum wage workers. This results in a price of €828,-. The ADIOS can clean for 6 hours. This results in a minimum of 6000 pieces picked-up. The cost of the system for identical work must therefore be €630,- per day.

Figure 10.2: Monthly profit vs number of working systems for several prices.

10.4.4. Return on investment

From the comparison with other similar companies, the development cost of the system is estimated at €35.4 Million. In Figure 10.2 the monthly profit ADIOS makes can be seen. The graph illustrates the monthly profit the company makes assuming a certain price per day asked for operating the system. The graph includes tax in the Netherlands of 19% when the profit is bellow €200000,- per year and 25.8% above that. The graph assumes that the systems are built and function to make a profit. This is included in the initial investment of €35 Million for the development mentioned in subsection 10.2.1.

With the competitive price per day of €630,- to function better than minimum wage workers ADIOS can not make a profit. Pricing must be around €1000,- per day for cleaning to break even with 75 working systems. The ADIOS system can be made attractive for companies or municipalities when they are unable to find human labourers.

With the competitive price of €630,- per day the company cannot break even. However, when a price per day of €1000,- is assumed with 200 functioning systems return on investment is approximately 91 months. After this time the profit the company makes exceeds the invested amount and the accumulated costs up to that point. The company then makes a profit of €224K per month. The company could choose to start operating more systems. This would increase the profit of the company.

11

Sustainable Development Strategy

Project ADIOS is an attempt to greatly increase the sustainability of the environment and its resources, which are currently under threat. In 2015, the 2030 Agenda for Sustainable Development was deliberated at United Nations Sustainable Development Summit, with 17 Sustainable Development Goals at its core. The ADIOS is an attempt to act on 7 of those Goals, namely 3: Good Health & Wellbeing, 6: Clean Water & Sanitation, 11: Sustainable Cities & Communities, 12: Responsible Consumption & Production, 13: Climate Action, 14: Life Below Water and 15: Life on Land. This is a commendable attempt with huge benefits and the measures taken to implement this are discussed in this chapter[17].

Waste and litter have been shown to have great effects on the planet and it could compromise the resources of future generations. Their effects on the environment, wildlife and even human health indicates that collecting and disposing of litter responsibly contributes to the sustainability of the environment. Furthermore, once the litter has been collected, it shall be brought to the correct waste facilities to be recycled where possible, which enhances a circular economy, also contributing to sustainability. The recycling of materials reduces the production of new materials, which reduces energy use and the quantity of the materials being newly produced.

Although this project aims to reduce human environmental impact by removing human trash, it should be ensured that the system will not generate unnecessary harm to nature during its operation. The list below highlights different stages of the project life and its development with the incorporated logic. Several system design choices were made intentionally with sustainability in mind and are presented in the following list, among other general protocols. Some include human and economic sustainability aspects as well, such as item 3g, item 2c and item 1d.

1. Design of the system
    (a) Incorporation of sustainable materials such as PLA and Bamboo Fibres to ensure that the design is durable and long-lasting to minimise the production of new materials or systems and to ensure circular material economy
    (b) Use of an electric van powered by green energy to mitigate greenhouse gas emissions from fossil fuels
    (c) Modular design of drone ensures high versatility and allows for easier repair of broken parts or upgrade to newer parts without designing and producing a whole new system, lowering costs and waste
    (d) Human-friendly appearance to positively reinforce the public which can help tackle the source of the problem
    (e) In the future, create variants of the product for different environments to optimise energy use for different altitudes and conditions
    (f) Use of Li-ion batteries in the ground station as these can withstand thousands of recharge cycles without large efficiency losses
    (g) Efficient design of brush pick-up mechanism to only require a servo to spin the brush and not the bucket

(h) Hexacopter design to ensure there is motor redundancy in case of motor failure to ensure drone is still functional and does not immediately crash

2. Production of the system

   (a) Use of commercial and off-the-shelf product as these already have systems in place for production saving time and money
   (b) Minimal use of high-energy and expensive materials like carbon fibre to reduce emissions and cost, although it is very durable and strong so it does not need to often be replaced
   (c) Implement local production and use local goods to reduce unnecessary transport costs and emissions, such as the materials being sourced from EU countries
   (d) Use renewable energy in production to mitigate greenhouse emissions produced in fossil fuel combustion
   (e) Minimal use of materials that are produced from oil such as TPU to minimise greenhouse emissions
   (f) Use of Bamboo Fibres in the brush as these are renewable and organic
   (g) Use of PLA plastic as it is made of organic materials so it is renewable
   (h) Precision 3D printing of components to reduce waste

3. Operation of the system

   (a) Distribute collected trash to recycling/waste facilities to avoid extra post-processing and to reuse materials
   (b) Concept is prototype tested to ensure functionality of system and to not generate more litter during operation as this will compromise the mission goal
   (c) Durable drone structure to ensure parts do not easily break-off during operation
   (d) Ultrasonic speakers to deter animals avoiding any harm to fauna
   (e) Wide-view camera and radar to detect objects and people to avoid collisions
   (f) No picking-up of litter stuck in bushes/trees to avoid damage to flora
   (g) Toroidal Propellers rotors to reduce the noise of the drones to minimise the impact on people and the surrounding environment
   (h) Toroidal Propellers as the testing has proven them to be more efficient therefore using less power
   (i) Flashing LED lights to alert nearby people of its presence to avoid collisions/interference
   (j) Propeller guards to protect any flora, fauna and people from being damaged in any potential collisions with the drone
   (k) Spare batteries which can be quickly and easily be swapped in the drone to reduce down-time of operation
   (l) Manual override system to ensure the human operator can intervene at any point to avoid any potential damage or mishaps
   (m) Power the system using electricity generated from renewable sources such as solar or wind to mitigate greenhouse emissions

4. End-of-life of the system

   (a) Recycling the batteries to minimise waste
   (b) Put broken parts into specialised repair/recycle facilities to reduce the production of parts
   (c) Reusable ground station (parts) so that it can be used for other purposes involving communications or litter storage after use
   (d) Use of biodegradable and compostable materials such as PLA and Bamboo Fibres
   (e) Recycling of materials such as Carbon Fibre and TPU to reduce landfill and production of new materials

5. Non-environmental sustainability

   (a) The team shall respect each other's input and contribution of the project, to ensure social sustainability.
   (b) The team minimised costs throughout the entire process of the building of the prototype by purchasing components which are only strictly required and using spare parts available at MAVLab, to ensure economical sustainability

By following this strategy throughout the project duration, the environmental impact as well as other sustainability aspects are minimised.

12 Prototype

A significant element of this project was the prototyping of proposed solutions. After consultation with the project tutor, it was decided to prepare a proof-of-concept device as a part of the project. The main reasoning behind this decision was the unique scope of the mission that cannot be compared with already existing solutions. Manufacturing a physical system that we could test and see during operations could have significant consequences on the whole design loop. The plan and allocation of resources are discussed in section 12.1, and the drone and computer vision in section 5.2. Finally, the section ends with the pick-up mechanism in section 12.3.

12.1. Plan & Resources Allocation

After getting approval for the prototype development from the project tutor a detailed plan had to be developed. This, however, was a task beyond the intellectual horizons of the group and would require much more time than available to learn required topics at a sufficient level. Thus several appointments were made with faculty members, from which the most important ones were with:

- Dr Salua Hamaza, Assistant Professor in Aerial Robotics & Director of the BioMorphic Intelligence Lab at TU Delft
- Dr ir Christophe de Wagter, Researcher in MAVLab
- Erik van der Horst, Technical staff - RPAS Manager in MAVLab
- Dr Guido de Croon, Full Professor in MAVLab
- Dr Ewoud Smeur, Assistant Profesor in MAVLab
- Dr Daniele Ragni, Associate Professor in FPT (Flow Physics and Technology) Department
- Johan Boender, General Technical Support in Aircraft Hall

Their invaluable help was crucial for our understanding and gathering the required resources. After initial meetings, the prototype was divided into 3 branches:

1. Computer vision & AI
2. Hardware
3. Pick-up mechanism

which were developed thanks to the continued support of the aforementioned people.

12.2. Computer vision & AI

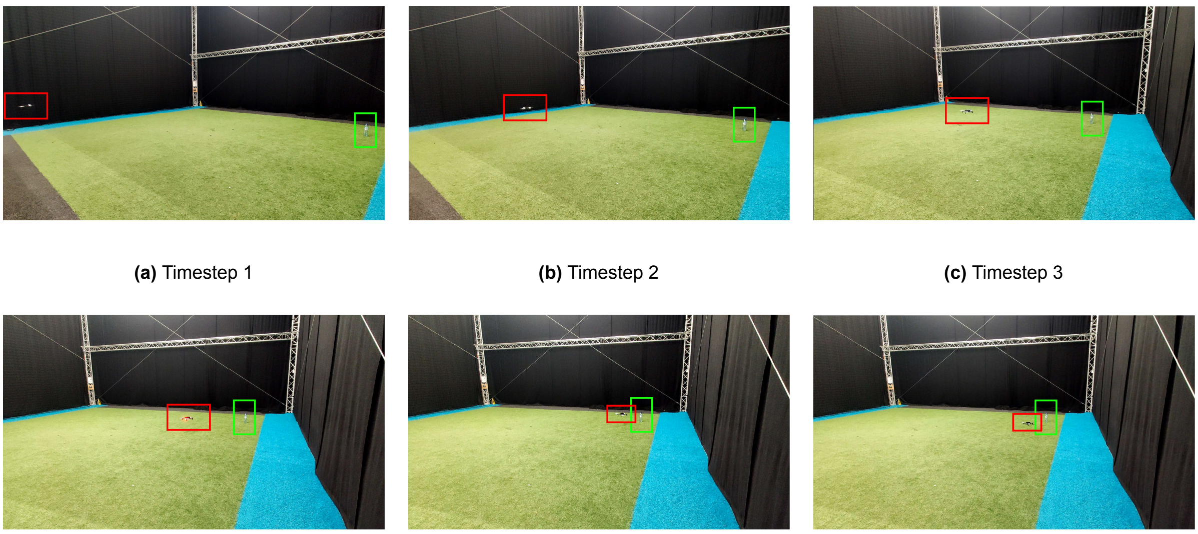
Since the start of the project, autonomy has been a crucial requirement for the system, since failing to achieve autonomy would render human labour more appealing than a drone system. As a first step in achieving autonomy, YOLOv8n is selected as the model for litter detection, as outlined in section 5.2. However, this is only a component of the overall solution. The system must also effectively utilise the AI outputs to approach the litter with accuracy. To evaluate the feasibility of an autonomous drone approach to litter retrieval, where AI provides the sole guidance as to where the litter is located, we aim to implement autonomous litter retrieval on the Parrot Bebop 2 drone, which is selected due to the availability of several libraries that provided a solid foundation for a more time-efficient integration. Moreover, its certification as a toy ensures inherent safety, eliminating any safety concerns throughout the testing.

During preliminary research, we initially implemented the AI integration on the drone camera using the Pyparrot library in Python. However, this approach presented several challenges, since despite Python's inherent comprehensibility and minimal coding requirements, its execution speed was slow. The cycle of capturing an image, processing it off-board, and sending it back to the drone introduced a significant latency of $1000\ ms$ - $1500\ ms$, rendering it impractical for use in a control loop.

To improve the latency, we utilised an open-source C++ library called ViSP (Visual Servoing Platform) as the foundation for integrating AI into the control loop, which reduces the latency to about $200\ ms$ - $400\ ms$. The ViSP team describes it as a modular cross-platform library that enables prototyping and development of applications utilizing visual tracking and visual servoing techniques at the heart of the research done by IRISA [18]. Within this library, two key integrations of the ViSP library are the foundation of our autonomous litter approach system: Servo Bebop 2 and OpenCV Detector.

The Servo Bebop 2 integration offered a solution for autonomously tracking a predefined QR code using classical computer vision techniques, without involving machine learning. Initially, attempts were made to integrate TensorRT with this code, but due to the steep learning curve, the limited available time and the lack of default YOLOv8 integration, it was deemed infeasible to continue developing our system based on TensorRT. Consequently, we opted for the OpenCV Detector as it has default integration with YOLOv8, despite its slower inference time. However, it is worth noting that future recommendations suggest using TensorRT over OpenCV, as TensorRT provides significantly faster inference times, approximately 10 times faster, which is particularly crucial for later integration on devices such as the NVIDIA Jetson (see subsection 5.2.3).

After successfully integrating Servo Bebop 2 and OpenCV Detector in C++, which required a substantial amount of custom coding, iterative testing was conducted in the CyberZoo. The outcomes of these tests were highly encouraging: once the operator initiated takeoff, the drone exhibited the capability to autonomously detect litter, approach it, and land autonomously at a predefined distance. An illustration demonstrating this process from a third-person view is provided in Figure 12.1. Moreover, the same illustration from a first-person view is shown in Figure 12.2.

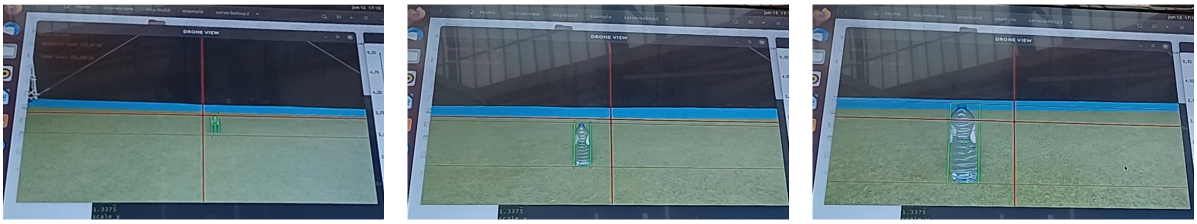


(a) Timestep 1 **(b)** Timestep 2 **(c)** Timestep 3

(d) Timestep 4 **(e)** Timestep 5 **(f)** Timestep 6

Figure 12.1: Stop motion movie of the autonomous approach of litter using the Parrot Bebop 2 drone from a third-person view. The red square indicates the drone and the green square indicates the detected litter, in this case, a bottle.

Based on the previous illustrations, it can be concluded that the implementation of the AI model to achieve an autonomous litter approach has been successful. Building upon this achievement, future



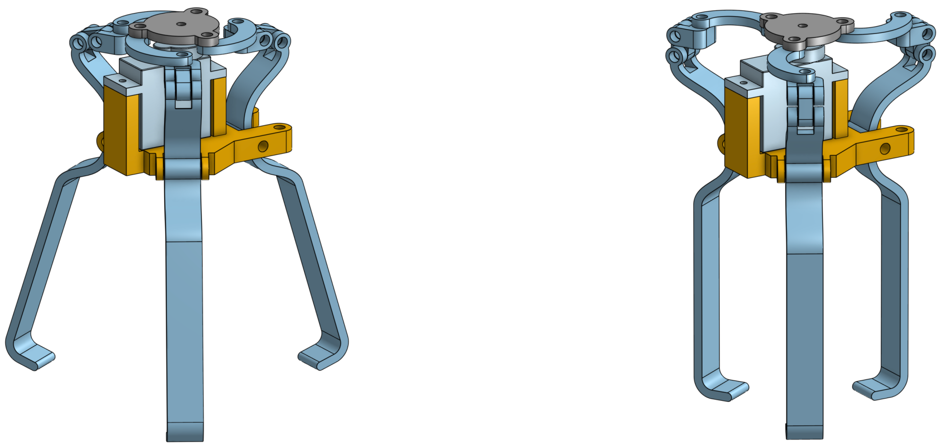
(a) Timestep 1 (b) Timestep 2 (c) Timestep 3

Figure 12.2: Stop motion movie of the autonomous approach of litter using the Parrot Bebop 2 drone from a first-person view. The green square indicates the litter, in this case a bottle, detected by the AI model, and the red cross indicates the centre of the image.

work on the Bebop 2 drone includes scanning an area for litter and converting the detected litter into actual coordinates, which can consequently be used in path planning to allow for efficient deployment of drones. Moreover, having achieved successful autonomous detection, approach, and mapping of litter, we recommend the following two steps for future development. Firstly, the previous code should be implemented in TensorRT on an NVIDIA Jetson, enabling onboard AI image processing. Additionally, the same system should be applied to drones of similar size as the final design, which can be tested at outdoor locations such as Valkenburg near Leiden.

12.3. Pick-up mechanism

Special consideration was given to the pick-up mechanism, as it is a crucial part of the whole operation. Several iterations of the pick-up mechanism were tested, in order to come up with one that would be able to pick up litter efficiently with a minimal number of failures. The final design can be seen in Figure 12.3.



(a) Extended pick-up mechanism (b) Retracted pick-up mechanism

Figure 12.3: Pick-up system render

12.4. Hardware

A crucial part of the prototype was validating and testing hardware that could be used for the final design. The components used in the prototype include the following:

- **Omnibus F4 flight controller**: used to run open-source Betaflight flight control software. It runs an algorithm that is equivalent to the control software that will be used in the final design's controller. Therefore, it validates that the control algorithm is capable of keeping the drone stable in flight after the pick-up sequence has been performed and the drone's centre of gravity and moments of inertia have changed.

- **Racestar BR2205 motors**: used to validate that the selected motors are capable of providing enough thrust.
- **T-MOTOR ESC F30A**: used to validate that the selected ESCs are capable of handling enough current flow.
- **Tattu 3S 100C 1300 mAh battery**: used to validate that the selected battery is capable of ensuring sufficient flight time.
- **EMAX ES08MD 13g servo**: used to validate that the pick-up mechanism can be successfully activated using a servo and has sufficient grip strength.
- **SG90 mini servo 360 degrees**: used to validate that the wheels can be propelled using servos and has sufficient torque.
- **Lumenier SM-600 FPV camera**: used to capture video from the drone's perspective to enable the operator to control it remotely in case of failure.
- **Tramp HV 5.8 GHz video transmitter**: used to cast analogue 5.8 GHz transmission to the ground station. It diverges from the final design since there a digital transmission over the 4G network will be used, thus making its characteristics significantly different. However, it is still used to validate the possibility of the operator controlling the drones using FPV transmission.
- **FrSky R-XSR Ultra receiver**: used to receive manual input from the operator sent by the remote controller. It diverges from the final design since there a digital transmission over the 4G network will be used, thus making its characteristics significantly different. However, it is still used to validate the possibility of the operator controlling the drones remotely.

Furthermore, the operator of the prototype is equipped with additional peripheral hardware, which enables them to control the drone remotely. This hardware includes the following:

- **Radiomaster TX12 MKII**: radio transmitter used to manually control the drone. It is the same model that is used in the final design to manually overtake a drone in case of failure and thus it is validated that it possesses all the necessary functionalities and fulfils the range requirements.
- **Eachine ROTG01 5.8 GHz video receiver**: used to receive analogue 5.8 GHz transmission from the drone's camera. It diverges from the final design since there a digital transmission over the 4G network will be used, thus making its characteristics significantly different. However, it is still used to validate the possibility of the operator controlling the drones using FPV transmission.

The render of the prototype is shown in Figure 12.4. The frame is 3D printed using PLA, the suspension mechanism is 3D printed using TPU and the wheels are laser cut from a sheet of plywood.

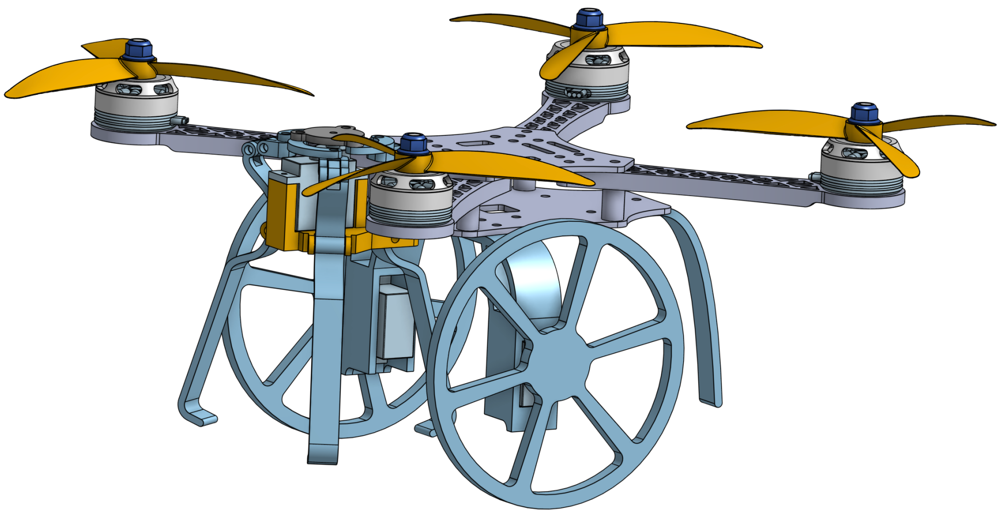
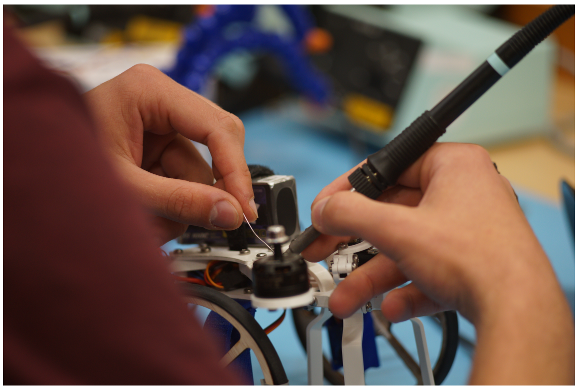


Figure 12.4: Prototype render

The prototype was assembled in Mavlab at the Aerospace Engineering faculty. Some parts of the work process are depicted in Figure 12.5.

(a) Assembling the drone in the Mavlab



(b) Soldering in the Mavlab

Figure 12.5: Work in the Mavlab

One of the biggest challenges in developing the prototype was implementing the electrical block diagram architecture, which is depicted in Figure 12.6. The most prominent issue was controlling the three servos directly from the flight controller since servos require special GPIO pins with pulse width modulation functionality. The controller has a limited number of such pins and therefore had to be reprogrammed using Betaflight's command-line interface. This involved remapping some of the UART pins such that they can be used to output servo signals. Furthermore, channel forwarding had to be implemented such that outputs from the receiver's channels are directly translated to the servo pins. Once this was successfully implemented, it was possible to control three servos directly from the remote controller.

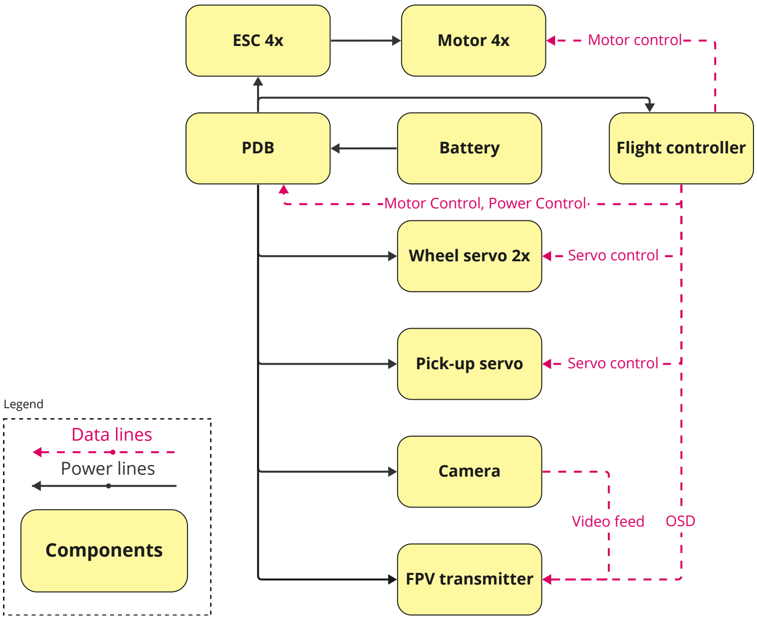


Figure 12.6: Prototype electrical block diagram

The flight mode that was chosen for testing was the Angle mode, which stabilises the drone and ensures that a certain threshold of pitch and roll angles is never exceeded. Several test flights were performed with the prototype, which confirmed that it is indeed capable of achieving a stable flight, driving on the ground and picking up trash.

The final assembled design is shown in Figure 12.7. Furthermore, Figure 12.8 shows the complete pick-up operation. First, the drone approaches the trash, picks it up and flies away. It was confirmed that the drone is still capable of flying stably with the trash being held in the mechanism.

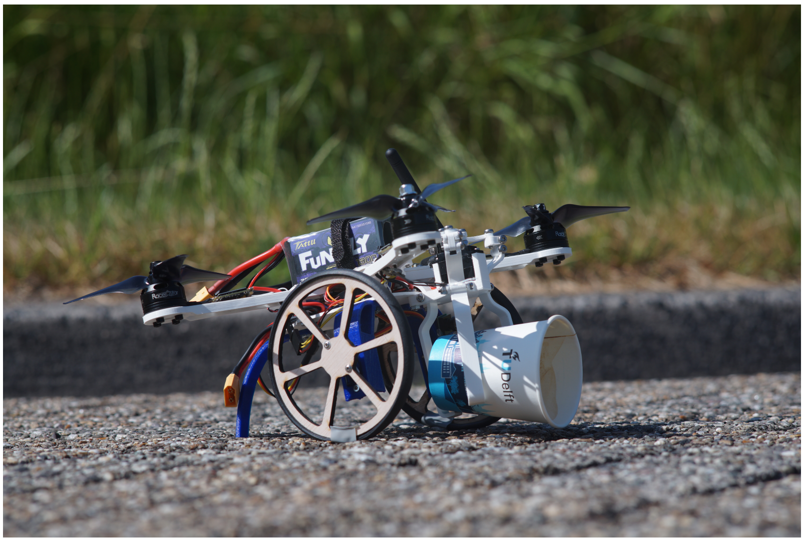


Figure 12.7: Final version of the prototype

(a) The trash is approached

(b) The trash is picked-up

(c) The trash is lifted

Figure 12.8: Trash pick-up operation

12.5. Interviews

Throughout the DSE, the team arranged interviews and consultations with members of the TU Delft faculty in order to receive expert advice and feedback.

Dr Salua Hamaza

To get more ideas for the prototype pick-up mechanism, the team consulted Dr Salua Hamaza. After an insightful meeting, two additional ideas were generated. The first idea was the use of a passive suction mechanism. Using suction cups, the drone can stick to litter and pick it up. With some creative engineering, a simple mechanism can be designed to then break the vacuum, causing the litter to drop down. The second idea was to not use the drones for pickup, but simply use their wake gusts to move litter to a central location, where either a human or a ground drone can actually pick the litter up.

Erik van der Horst

Without any doubt, Erik was the most relevant person for the prototype, without which most of our ideas would not be possible.

Dr Guido de Croon

At the beginning of the project, the whole idea of making a prototype was consulted with Dr Guido de Croon. He gave us his point of view on the prototype and its development as well as facilitated getting us access to required facilities like CyberZoo for safe drone testing and MAVLab for working on electronics tasks.

Dr Daniele Ragni

In order to discuss tips and feedback for reducing noise, a consultation with Dr Daniele Ragni, a member of the Aeroacoustic team of TU Delft, was arranged. Advice was given with respect to the propeller types and a paper discussing the methods for reducing propeller noise was shared.

13 Verification and Validation

During the development of the ADIOS system, a lot of calculations have been performed and assumptions have been made. During each calculation, errors can be made, which is the reason that verification methods have to be performed. Especially for software programs, it is easy to leave mistakes in the code. Therefore, for every software written, the verification strategy will be discussed in section 13.1. Additionally, the assumptions taken during the calculation must also be tested whether they comply with the real application. Since the final design is not built yet, for most subsystems it is not yet possible to check whether they comply with the real world. However, a prototype already has been made which can provide validation for certain subsystems. An overview of this will be discussed in section 13.2

13.1. Code verification

13.1.1. Unit tests

The first step to code verification is unit tests, to make sure that every function works properly. In Table 13.2, an overview of all unit tests performed on the operations simulation is shown. Similarly, in Table 13.1, an overview of all unit tests performed on the drone state space and control system is shown. Note that two unit tests only partially passed. Both functions belong to the minimum_snap_path_planner. The parts of these functions that do not properly work yet, are the acceleration and jerk that are set at all setpoints. The reason for this is that implementing it takes a lot of time. So for time constraints, the acceleration is only set for 90-degree corners, and the jerk is always set to 0 at all setpoints.

Test ID	Function name	Function description	Testing method	Result
SS-1	quadcopter_full_state_space .get_A()	Returns the drone state matrix	Hand calculations	Passed
SS-2	quadcopter_full_state_space .get_B()	Returns the drone input matrix	Hand calculations	Passed
SS-3	quadcopter_full_state_space .get_C()	Returns the drone output matrix	Hand calculations	Passed
SS-4	quadcopter_full_state_space .get_D()	Returns the drone feed-forward matrix	Hand calculations	Passed
SS-5	quadcopter_full_state_space .get_U_hexa_config()	Calculates the state space input vector from motor rotation speeds	Hand calculations	Passed
LQR-1	LQR_controller_hexa .saturate_w2()	Saturates the rotor speeds, with physical bounds	Automated output verification	Passed
LQR-2	LQR_controller_hexa .get_motor_rotation_speeds()	Calculates and returns all motor rotation speeds based on the drone current state and desired state	Hand calculations	Passed

Table 13.1: Control system unit tests

Test ID	Function name	Function description	Testing method	Result
MS-1	minimum_snap_path_planner .get_vandermonde()	Returns the Vandermonde matrix for polynomial interpolation, based on a t0 and t1	Hand calculations	Passed
MS-2	minimum_snap_path_planner .get_polynomial_from_coeffs()	Assembles and returns a time polynomial, from a coefficient vector	Automated output verification	Passed
MS-3	minimum_snap_path_planner .create_setpoints_from_Astar()	Calculates the setpoints between which splines should be created	Automated output verification	Partially passed
MS-4	minimum_snap_path_planner .get_wind_direction()	Returns the wind direction (45 degree increments), based on 2 points in space	Automated output verification	Passed
MS-5	minimum_snap_path_planner .get_velocity_and_accel_ from_dir()	Determines the correct velocity and acceleration for a given setpoint	Automated output verification	Partially passed
MS-6	minimum_snap_path_planner .create_spline()	Constructs a minimum snap time polynomial between 2 setpoints	Hand calculations	Passed
MS-7	minimum_snap_path_planner .create_trajectory()	Creates a series of time polynomial splines from an array of A star setpoints	Automated output verification	Passed
L-1	litter.__init__()	Instantiates a litter object	Automated output verification	Passed
GF-1	generalFunc.dist2d()	Returns the absolute distance between two Cartesian points in 2D space	Automated output verification	Passed
GF-2	generalFunc.dist3d()	Returns the absolute distance between two Cartesian points in 3D space	Automated output verification	Passed
I-1	inputs.py	Dictionary that takes all user defined inputs	Automated verification of dictionary structure	Passed

Table 13.2: Operations simulation unit tests

13.1.2. Subsystem tests

In this section, various larger components will be tested to make sure that functions interface with each other correctly. These tests were previously proposed in [19]. However, due to time constraints, some of the less vital tests have been left out, such as the system linearity test.

Control system - equilibrium test

In Figure 13.1, the results of the equilibrium test are shown. It shows that when the drone is given non-zero initial conditions, it still returns to its equilibrium position, which is set to be x, y, z, yaw = 0.

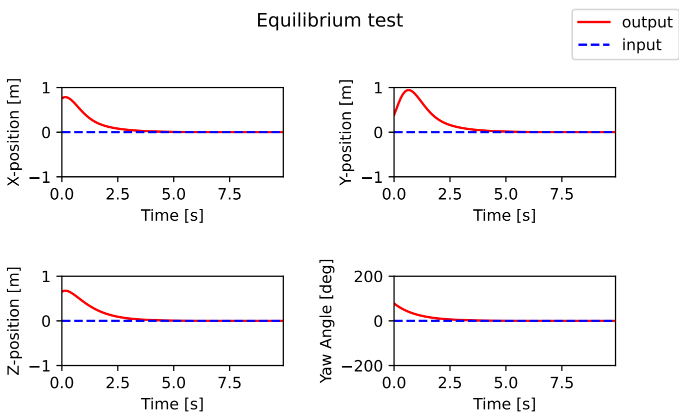


Figure 13.1: x, y, z, and yaw plots of the equilibrium test

Result: Passed
Conclusion: Equilibrium exists as desired.

Control system - System decoupling test
In Figure 13.2, the results of the decoupling test are shown. The plots make clear that an input in a specific degree of freedom does not have any effect on the output in other degrees of freedom.

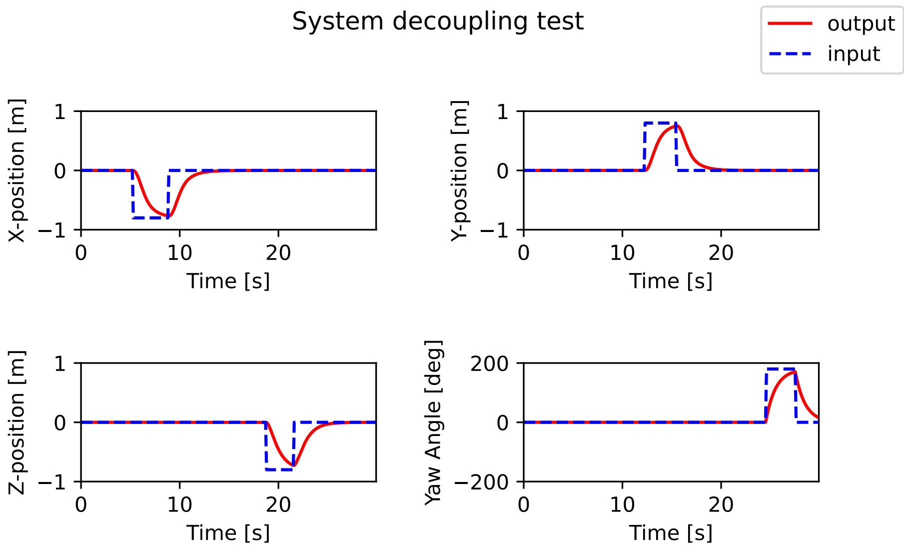


Figure 13.2: x, y, z, and yaw plots of the system decoupling test

Result: Passed
Conclusion: All degrees of freedom are properly decoupled.

Control system - Step disturbance test
In Figure 13.3, the results of the step disturbance test are shown. Along the x, y and z axes of the drone, forces of 0.3N are applied. Although the system does remain stable, it keeps a steady state error. This implies that any constant force will permanently offset the drone from its desired location. This constant force could be for example a constant wind force, or a c.g. offset.

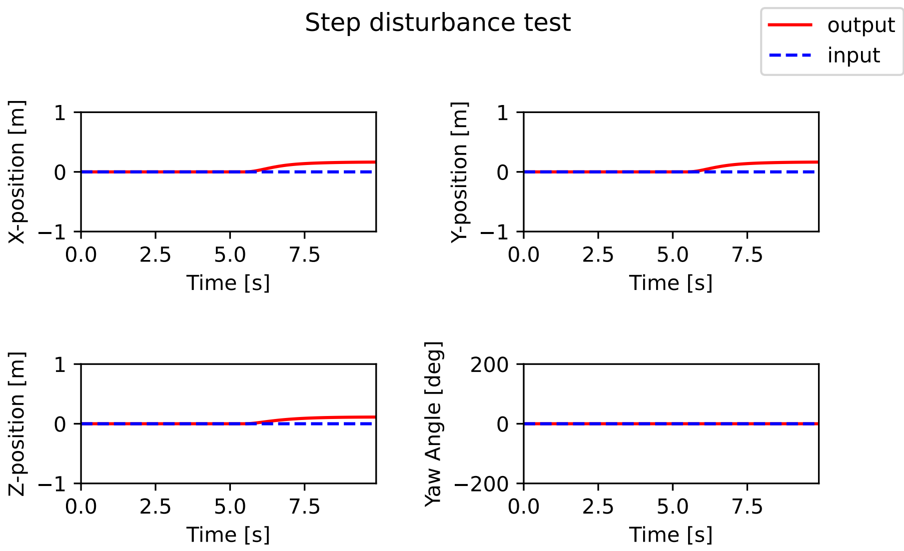


Figure 13.3: x, y, z, and yaw plots of the system step disturbance test

Result: Failed

Conclusion: An extra correction is needed. The easiest way to do this is by adding an integrating component, making the controller a LQI controller (Linear Quadratic-Integral). Such a component will increase the correction over time, which leads to a steady state error of 0.

Control system - Impulse response test

The final test of the control system consists of a verification of an impulse response. In this case, the system will be excited by applying an impulse moment on the y-axis. The response measured is the drone displacement in the x-direction. The hand calculations were performed by extracting all relevant equations from the state matrix, input matrix and gain matrix shown in Equation 5.12 and Equation 5.14 respectively. For an LQR controller, the state matrix is equal to (A - BK) [91]. The full state equation is shown in Equation 13.1. Here, X and U are the state vector and input vector respectively, as shown in Equation 5.13.

$$\dot{X} = (A - BK) \cdot X + B \cdot U \tag{13.1}$$

Now the transfer function from the y-moment to x-displacement $\frac{X(s)}{M_y(s)}$ can be obtained. From Equation 13.1, all relevant equations were obtained and are shown in Equation 13.2.

$$\ddot{x} = -g\theta, \quad \ddot{\theta} = -\frac{K_1}{I_{yy}} \cdot x - \frac{K_4}{I_{yy}} \cdot \dot{x} - \frac{K_8}{I_{yy}} \cdot \theta - \frac{K_{11}}{I_{yy}} \cdot \dot{\theta} + \frac{1}{I_{yy}} \cdot M_y \tag{13.2}$$

These equations can now be converted to the Laplace domain ($x(t)$ becomes $X(s)$, $\dot{x}$ becomes sx, etc.). Then, θ can be eliminated by combining both equations. Finally, the equation can be written in the final form $\frac{X(s)}{M_y(s)}$, as shown in Equation 13.3. The actual values for the variables are shown in Table 5.4.

$$\frac{X(s)}{M_y(s)} = \frac{g}{-I_{yy}s^4 - K_{11}s^3 - K_8 s^2 + K_4 g s + K_1 g} \tag{13.3}$$

Using the control.matlab module, an impulse response can easily be generated for this transfer function. In Figure 13.4, the impulse response of the simulation for various values of dt is compared to these hand-calculated values. For time steps of 0.01 and smaller, the simulation models the amplitude with an error within 2% of the hand-calculated value.

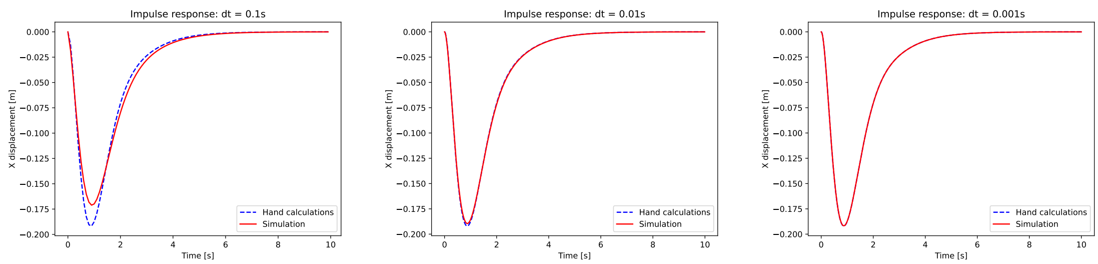


Figure 13.4: Impulse response test of the simulation, compared to a hand calculated response

Table 13.3: Amplitudes of impulse responses

dt [s]	Hand calculations amplitude	Simulation amplitude	Relative error
0.1	0.1920	0.1711	10.8%
0.01	0.1920	0.1894	1.35%
0.001	0.1920	0.1917	0.16%

Result: Passed

Conclusion: With a time step of 0.1s, the system is accurate enough to give rough estimates of behaviour. However, to properly model drone dynamics for e.g. performance, a time step of no larger than 0.01s should be used.

13.1.3. Verification of Simulation Model

Unit tests

The verification of functions inside the simulation loop was performed during the development. Each time a function was added, the start and end times, and affected variables were printed and manually checked whether they correspond to the expected values. The values returned were also printed to see if they are in the right format. When an error was registered, the functions were rewritten. Moreover, there is a plotting function added to the simulation to make more verification techniques possible. The simulation can be run in real-time which can be used to verify the waiting times posed on the drones, for example when picking up litter.

System tests

When each function in a software program does the right thing, it does not always mean the entire program works. To test the integration of each function, systems tests are performed.

The first system test is performed by varying the timestep and plot the total operation time to check for convergence. When the total operation time is almost constant, the program has converged. The result of this test is shown in Figure 13.5. Initially, the backwards Euler scheme was implemented to be able to take a larger timestep since the program would diverge when the program would take a larger timestep than 0.001 seconds. However, from Figure 13.5 it can be concluded that from a dt of 0.02, the line starts to drift away from the converging value. Therefore, it is chosen to perform all simulations with a timestep of 0.01 seconds.

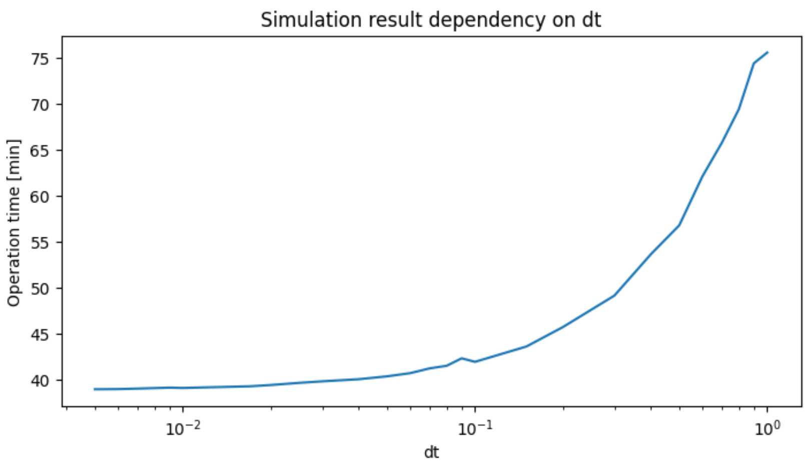


Figure 13.5: System test to check whether the right timestep was chosen

The rest of the system tests can be done by evaluating the graphs from section 7.5. From Figure 7.8, it can be seen that when the number of drones of one type doubles, the time it takes to clean the area is halved. Therefore, the simulation behaves as expected.

From Figure 7.9, four tests can be performed. The first test is to make sure the battery level in each drone does not go below and above the minimum and maximum battery levels. Visually, it can be seen that this does not happen in the entire operation and thus, this test has passed. The second test is regarding the factor with which the flying power is multiplied to account for wind and disturbance effects. From the graph, it can be seen that the drones with a higher factor also drain faster, which is expected. Therefore, this test has also passed. The third test is to connect the total operation time to the number of battery replacements. Although batteries of the blue lines in Figure 7.9 drain faster, they still only need to recharge once. Therefore, they should approximately have the same end time as the red lines. It can be seen that this is the case since both operations finish at 50 minutes. Lastly, the difference in the slopes between the large and small drones in Figure 7.9 can be compared. On average, the small drones have a shallower slope than the large drones. This is logical since these drones drive a much larger fraction of the total operation time, which used less power. Therefore, this test has also passed.

From Figure 7.10, a verification test can be performed by making sure the results are logical with the ground station location they correspond with. It is logical that the location from which it takes the longest time to clean the area, are locations five and six. Since they are located in a gap which can only be exited on one side, it is logical that they take the longest. The locations that take the smallest amount of time, are locations one, seven and eight. For location one, this is expected because it is in the centre of the area, which makes the average distance to each litter piece minimal. For locations seven and eight, this same reasoning can be applied since they are the only other ground station positions which are not in a corner or a gap. Therefore, these results are according to expectation and this system test is passed.

From Figure 7.13, two system tests can be performed. The first system test is whether the batteries need to recharge more when the battery size is reduced. As the blue lines are directed upwards, this is true and this test is passed. The second test that can be performed is whether the operation time is at least one minute longer when the drones have to be recharged once more. At all locations where the blue lines take a step, the red lines also take a step of at least one minute. Therefore, this test is passed.

From Figure 7.12, a system test can be deduced regarding the number of drones. When the number of small litter drones is reduced, the time ramps up more steeply when more small litter is added. Moreover, when this drone is changed from a small litter drone to a large litter drone, the position where the two types of drones are done at the same time moves to the left, which means that there is less litter for the small drone. This is according to expectations once more. Therefore, this system test is also passed.

13.2. Validation by the Prototype

As described in chapter 12, an extensive verification & validation was performed by the means of the prototype. It served the purpose of checking whether the design can be successfully implemented in reality. This approach proved to be very beneficial, as it allowed the team to discover the magnitude of the wake effect issue. Thanks to that, more effort was delegated to fixing this issue, which in the end proved to be one of the most significant challenges of this project. Furthermore, designing various pick-up mechanisms allowed for an iterative design process thus ensuring an efficient design that works in practice. Finally, actually building the drone ensured that it is feasible to implement the final design in reality.

14

RAMS Characteristics

RAMS stands for reliability, availability, maintainability and safety. To ensure that the system is sufficient all these criteria, they need to be considered during the development phase of the product. Thus, this chapter serves as an outline for defining all characteristics and philosophies regarding RAMS.

14.1. Reliability

The 'R' in RAMS stands for reliability. In this section, all aspects with respect to reliability will be considered. First, an outline is given for the reliability philosophy. Then, the general failure behaviour of the product is analysed. Finally, a set of measures is written down to cope with these failures to maximise reliability.

14.1.1. Six Sigma Philosophy

To ensure the reliability of the product, a philosophy called 'Six Sigma' [123] is applied. This implies that the odds of failure of a product or service are six standard deviations away from the mean. In other words, the failure rate shall be at most one in a million. However, in practice, the actual target depends on the type of product. In a later design stage, this target value shall also be specified for ADIOS.

14.1.2. Product Failure Behaviour

Although every product is unique in its own way, its failure rates seem to follow a general trend over time. In the early stages of a product, there are many failures due to either development mistakes or unforeseen circumstances and use cases. These failures are called 'Infant Mortality' failures, and will gradually decrease over time. Then, during the use of the product, the failure rate will remain constant for a while. At the end of a product's lifetime, the failure rate will increase again. These failure modes are caused by wear and tear of the product components themselves. This time-dependent behaviour of failure can be modelled using the bathtub curve [131], as shown in Figure 14.1.

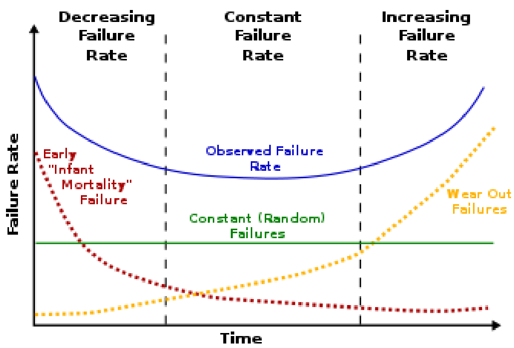


Figure 14.1: Bathtub curve, showing the time-dependent behaviour of failure rate

Since each region is characterised by different failure modes, each region needs its own set of failure reduction strategies.

14.1.3. Failure Rate Reduction Strategies

To strive for a failure rate that is lower than the maximum, as described by the Six Sigma philosophy, various measures are taken. For each region described in subsection 14.1.2, a set of measurements is taken.

Early product stage

The early product stage is characterised by development-related failures. the following measures have been taken to minimise these failures:

- **Proper development plan**: By defining a proper development plan, it is ensured that as many aspects of the design and as many use cases as possible are accounted for.
- **Extensive testing**: Testing is a good way of discovering system faults. It happens in a controlled environment. This means that system failure will not lead to dangerous situations and for this reason, the system can be pushed to its limits to safely discover system defects. It is also an excellent way to discover whether or not the existing functionality is sufficient.
- **Customer-in-the-loop development**: By keeping the customers involved in the development process, more information and customer feedback can be collected about the system's performance. This makes it easier to track down system defects and fix them. As a bonus, this will also increase customer satisfaction, which could lead to more customers and eventually profit.

Main product usage stage

The middle region of Figure 14.1 is mainly characterised by random failures. Such failures can be of any nature, so are hard to actually stop. Thus the goal of some of these measurements is not necessarily to stop failures but rather to prevent component failures causing system failures. So far, the following measures have been taken:

- **Redundancy**: Many subsystems contain more components or functionalities than are necessary for normal operating conditions. The reason for this is that if a certain component or function fails, this will not result in the failure of the system. For example, the hexacopter configuration used for the ADIOS drones allows for single, or sometimes even double rotor failure. In such cases, the drones are still able to fly back to the ground station.
- **Minimise downtime**: In case of a subsystem failure, the drones can still fly back to the ground station. It is made sure that there are plenty of spare parts at the ground station, such that the faulty parts can be replaced. As explained in section 14.3, the system features high modularity, such that these repairs can be done quickly. This minimises downtime. More details can be found in subsection 6.1.3.
- **Cybersecurity**: Since the system relies on wireless, digital communication, it is very susceptible to hackers. To prevent the system from being hacked, it is imperative that proper encryption and other security protocols are used.

Late product stage

The final region is characterised by failure rates due to wear and tear. To reduce failures of this nature, the following measures have been taken:

- **Part inspections**: To minimise mechanical failures, all mechanical parts are subjected to inspection. An extensive inspection is performed every 3 months, and a quick inspection is performed every day. This eliminates a few failure modes such as, but not limited to rotor failure and landing gear failure.
- **Simplicity over complexity**: Prone failure mechanical parts are designed to be simple and robust instead of complex. This does sacrifice some performance, but greatly reduces the failure rates of these parts. For example, the landing gears of the wheels do not contain a conventional spring suspension system but are instead made from a single piece of flexible material.

14.2. Availability

Availability is all about maximising the total up-time of the system. The main causes of downtime are travel time (the operator needs to drive to the location where litter must be collected), battery charge time and component failure.

14.2.1. Travel Time

Unfortunately, the travel time is something that cannot be worked around from a technical perspective. However, its effect can be reduced by for example operating in the same area for longer amounts of time. Though, this is highly dependent on the amount of litter in the area to be cleaned. Thus, solving this issue is more of a logistical challenge than a technical one.

14.2.2. Battery Charge Times

Charging batteries takes longer than using them. This means that in case each drone has one battery, a lot of time would be lost recharging batteries. This is not the case, however. Each drone will fly for 20 minutes on a single battery charge. Each battery takes an hour to recharge in the ground station. Thus at least 4 batteries are required per drone: 1 in the drone while 3 are charging. This ensures continuous operation of each drone.

14.2.3. Component Failure

To minimise the downtime due to component failure, there are spare parts and an operator present, as shown in subsection 6.1.3. Due to redundancy, drones can still make it back to the ground station in case of component failure. When the drone arrives, the operator can replace the faulty part(s). Due to the modularity of the system, this takes little time.

14.3. Maintainability

Maintainability refers to how easily the system can be maintained or repaired. However, this section also serves as an outline for the overall maintenance procedure of the drone.

14.3.1. Maintainability Enhancing Aspects

To ensure maintainability, the following aspects have been thoroughly kept in mind:

- **Modularity**: The system is designed to be as modular as possible. Replacing any part is just a matter of undoing a few screws and cable connections. This way, it is easy to replace any faulty part.
- **Off-the-shelve parts**: Many drone parts used are off-the-shelve. This includes all servos, sensors, antennae, computers, etc. When more parts are needed, they can simply be ordered from the supplier.
- **Documentation**: All aspects of maintaining the drone will be well documented. This makes replacing parts and maintaining the drones a lot easier and quicker.

14.4. Safety

ADIOS is an autonomous drone system. Because it is autonomous, it is hard to see what is going on inside these drones. This raises some serious safety concerns. In this context, safety refers to the risk of physical harm to humans or animals present in the operating environment.

In this section, these safety concerns are addressed by coming up with a set of measurements to ensure safety. Note that this section is closely related to section 14.1, as failures cause safety threats. So all measures to increase reliability will indirectly also enhance the system's safety. Additional safety measures are shown below.

- **Compliance with drone regulations**: By complying with all regulations, there is already some level of safety expected from the system. However, since this type of system is very new, there are not yet many rules in place for large-scale autonomous drone flight.
- **Drone altitude**: The drones will fly at an altitude of 5 meters. Only when a litter piece needs to be approached, will they come down. This minimises the risk of drones hitting humans or animals on the ground.

- **Collision avoidance**: The trajectory that each drone flies is provided by a central system. However, each drone locally runs a collision avoidance system that intervenes with the central path planning algorithm in case it sees unexpected objects, people or animals.
- **AI safety**: Systems that involve any level of safety do not use AI if possible, as AI is often unpredictable and unexplainable. However, AI is excellent for optimizing procedures and operations that do not involve safety, e.g. the detection and mapping of litter.
- **Safe fail**: By incorporating redundancy, as shown in section 14.1, component and subsystem failures can safely happen. For example, in case of a communication loss, the drone can autonomously fly back to the ground station, after which the power is automatically deactivated. If for any reason the drone cannot fly back to the ground station, it will land at a safe location and once again power is deactivated.
- **Constant monitoring**: Although the system is fully autonomous, a human operator is present at all times who monitors the drone camera feeds, locations, etc. This operator can manually take over the controls of a drone at any time. A more extensive description can be found in subsection 6.1.2.
- **Propeller guards**: In case all safety measures fail and a drone does make contact with a human being or animal, propeller guards ensure that the spinning propellers will not hit anyone.

15 Production Plan

15.1. The Product

The final product includes 6 drones, two of which pick up small pieces of litter and four of which pick up big pieces. It also includes an installable system as a ground station. The drone contains several off-the-shelf parts and some parts that need to be produced. The off-the-shelf parts per drone include:

- Battery
- 2 360-degree Servos for driving the wheels
- 1 360-degree servo for the brushes as pick-up system or 1 300-degree servo for the grabber
- 6 Motors for propulsion
- Mobile Network Modem for communications
- Jetson Nano as the onboard computer
- Flight Controller
- Electronic Speed Controller
- GPS for positioning
- Radar for object detection
- Ultrasonic Animal repeller
- Led Lights for visibility of the drone
- Cables for connections
- Stereo cameras for object detection, avoidance and other visuals

As for the parts that need to be produced:

- 6 toroidal propellers
- 6 propeller guards
- A frame for the components and structural integrity of the drone, including the structure for the wheels
- 2 wheels
- A pick-up system according to the use case of the drone

All these parts will be integrated into the drone, creating a complete assembly.

The installable system exists mainly only of ready-made components with the exception of the drone storage cabinets. All of these parts will be installed into a van from the customer, making the complete installation. These components include:

- 1 Drone storage cabinet with 6 drawers (bottom drawer has 2 wheels)
- 1 Large additional storage cabinet
- 1 Computer desk
- 1 Computer

- 4 Monitors including monitor stand
- Computer peripherals
- 2 Office chairs
- 1 Workbench with 1 cabinet and multiple storage bins (for small parts in case of repair)
- 2 Drone controllers
- 1 Charging station for the batteries
- 2 Garbage bins (1 on each back door)
- 6 landing pads

15.2. Inventory Management

In order to make sure that the system can be produced as soon as an order is made or to prevent the inventory gets too full, proper inventory management is required [72]. This means that at all times all materials should be available to produce a system. Additionally, it might be required that a complete system is ready and available for use if the demand for the product is sufficiently high.

Additionally, when maintenance or replacement is needed for a client, replacement parts should be available as quickly as possible. In order to achieve this the inventory of the company should be sufficiently extensive. Therefore the inventory should at all times, except for when new spare parts are being delivered or produced, include at least a whole system's worth of spare parts and material.

To make sure that this inventory is met, the ordering of parts and materials should be done efficiently. This means that as soon as a new system is sold and is being produced, or when spare parts are used, new parts will be bought so that new parts are available as quickly as possible.

In order to optimise the use of the materials, lean six sigma will be used. Lean six sigma combines the ideas of lean manufacturing and six sigma production [65]. Lean manufacturing is a philosophy that strives to minimise waste and increase effectiveness. Six sigma on the other hand is based on the statistical concept of standard deviation, where σ stands for the standard deviation. [33]. It strives towards optimisation of the production process in order to achieve a substantially low amount of defects and thus minimise waste. Within production, the mean and standard deviation of the production should be such that the limits for production are six standard deviations away from this mean, as such the term six sigma.

15.3. Resource Planning

Now that it has been defined how the inventory should be managed it needs to be defined what resources are used in the manufacturing. This includes not only materials but also equipment and human resources, such as workers or possible outsourcing.

15.3.1. Materials

As described earlier a significant proportion of the parts for the system will be bought ready-made. This means that only a few parts need to be actually produced. First, the prefabricated parts will be discussed and then the materials needed for the to-be-produced parts will be mentioned.

Prefabricated Parts

All the materials that need to be ordered are listed below, including the supplier:

- **For the Drone**
  - LiPo Tattu 16000mAh 22.2V Battery, from: Toemen Modelsport [121], amount: 1x
  - Either 2.3kg Serial Bus Servo for the grabbing pick-up system, from Waveshare [127], amount: 1x **or** a 360 degree MG996R Digital servo for the brushes, from: HobbyElectronica [62], amount: 1x
  - Waveshare 30KG Serial Bus Servo, from: Waveshare [128], amount: 2x
  - ECX 42 Flat UAV motor, from: Maxon Group [87], amount: 6x
  - NerdCam3D Mk.2 Stereoscopic FPV Flight Camera, from: getfpv [58], amount: 1x
  - 4G LTE Cellular BVLOS, from: Botlink [32], amount: 1x
  - NVIDIA Jetson Nano Module, from: Siliconhighway [109], amount: 1x
  - Pixhawk 2.4.8 PX4 Flight Controller, from: RCInnovations [104], amount: 1x

  - Flywoo GOKU HEX BS13A Electronic Speed Controller, from: getfpv [57], amount: 1x
  - Foxeer GPS M10Q-250, from; DroneShop [45], amount: 1x
  - Obstacle Avoidance Radar, from: FoxTechFPV [55], amount: 1x
  - M 161 Ultrasoon power kanon, from: Reichely [106], amount: 1x
  - TinysLEDs RGB RaceLiteWire Mini LED (4pcs), from Team BlackSheep [118], amount: 6x
  - OliYin 50 feet Cables, from: Amazon [22], amount: 1x

- **For the Ground system**
  - Mercedes eSprinter, from: Mercedez-Benz [48], amount: 1x
  - Philips 271V8LA/00, from: Cooolblue [39], amount: 4x
  - iiyama Monitorbeugel DS1002C-B1, from: Coolblue [37], amount: 1x
  - Keter Recyclingkast Split Basic, from: VidaXL [126], amount: 2x
  - TROTTEN IKEA desk, from: IKEA [69], amount: 1x
  - FLINTAN IKEA chair with castor lock, from: IKEA [68], amount: 2x
  - AMD Ryzen 4100 RGB Game Computer, from: bol.com [29], amount: 1x
  - Logitech MK120 Keyboard and Mouse QWERTY with mousepad, from: Coolblue [38], amount: 1x
  - RADIOMASTER TX12 MKII, from: Droneshop [46], amount: 2x
  - MMOBIEL Universele Drone Landing Pad Waterdichte Helipad 55 cm / 21.6 inch Oranje / Blauw, from: bol.com [30], amount: 6x
  - AVASCO Stellingkast Strong 176x90x45 cm, from: Hornbach [63], amount: 1x
  - HBM 115 Cm. Werkbank Met Houten Werkblad, from: HBM [61], amount: 1x

Material List for Fabricated Parts

The rest of the components of the drone need to be custom produced. For this various different materials are needed. To keep the costs at a minimum, it was chosen to outsource all production of these parts. It was chosen that the arms and propellers of the drone will be made of carbon fibre and the suspension of the wheels will be made of TPU. In subsection 5.1.3, it was discussed that the hairs of the brush are to be made of bamboo fibres. The rest of the drone is composed of biodegradable PLA plastic. An overview of the materials and their quantities and properties is given in Table 15.1. These materials were chosen with sustainability as a top consideration. The materials are sourced, where possible, from a local supplier to minimise carbon emissions from transportation. The materials are also chosen with a sustainable end-of-life process such as recycling or composting. Furthermore, it was also ensured that the cost of the materials was minimal, hence why carbon fibre is only used for the drone arms, as they require high strength and stiffness.

Material	Volume Required (m^3)	Density (kg/m^3)	Mass (kg)	Material Cost (€/kg)	Total Cost (€)	Tensile Strength (MPa)	Acquistion	End-of-Life	Miscellaneous
Carbon Fibre	2.38E-03	1750 [34]	4.16	130 [129]	541	3000 [34]	NL Supplier: Carbon-WebShop	Recycling	
TPU	1.77E-04 [103]	1200	0.213	36 [113]	7.66	29 [113]	DE Supplier: Snapmaker	Limited Recycling	For 3D printing
Bamboo Fibres	5.82E-05 [108]	500	0.0291	2 [21]	0.06	1500 [135]	NL Supplier: Bambooder	Biodegradable	Organic, Renewable
PLA	5.22E-03	1240 [112]	6.47	26 [112]	168	66 [112]	DE Supplier: Snapmaker	Compostable, Recyclable	Organic, Renewable, for 3D printing

Table 15.1: Table showing the materials used in the production of the design-specific components

15.3.2. Equipment and Machinery

As the production of the fabricated parts is outsourced, minimal equipment is required. All parts will be delivered ready for assembly, therefore only simple tools are required to assemble the system. These are as follows:

- Screwdrivers to fasten components together
- Soldering equipment to connect the electrical wiring
- Workshop tables
- Warehouse for the assembly of the system

15.3.3. Human Resources

A substantial amount of the drone will be made out of biodegradable PLA material. This will be done using injection moulding. Because the equipment is quite costly this process will be outsourced to an injection moulding company. This will be done in cooperation with Xometry Europe GmbH. Additionally, for the construction of the parts done within the company and for the assembly human forces are needed. For this, it is expected that around four people work on the production and assembly of the system, one for the production of parts, one for the assembly of the ground system and two for the assembly of the drones.

15.3.4. Assembly Process

As previously mentioned, the production of the fabricated design-specific parts will be outsourced, hence all parts and components will arrive ready for assembly. A warehouse is required to assemble the drone like an IKEA set in one location. Here the components are assembled together into sub-parts/subsystems (e.g. wheels, pick-up mechanisms, internal drone structure, ground station shelves etc) which are then assembled into the final drone and ground station systems. This is presented in more detail in Figure 15.1. The flow diagram shown gives a basic outline of the assembly steps. The steps themselves should be fairly simple as it is mainly screwing items together like an IKEA set. In the diagram, mounting refers to placing the item in the correct configuration and connecting it to electrical outlets for the monitors and computers in the ground station. Assembly steps stacked on top of each other refer to steps that can be done in parallel. Timestamps are placed above each step to give an insight into the duration of the assembly. The drone assembly takes approximately 130 work hours in total and the ground station requires roughly 20 hours. The assembly workforce will consist of 10 workers, 8 of which will mainly focus on the drone assembly and 2 on the ground station assembly. This is because the drone assembly requires more work hours. The workforce will be trained in both drone and ground station assembly to assist each other in case one is done early, as it is calculated the ground stations will be finished before the ground station. For 10 people, the total assembly time will take approximately 15 hours or 2 working days.

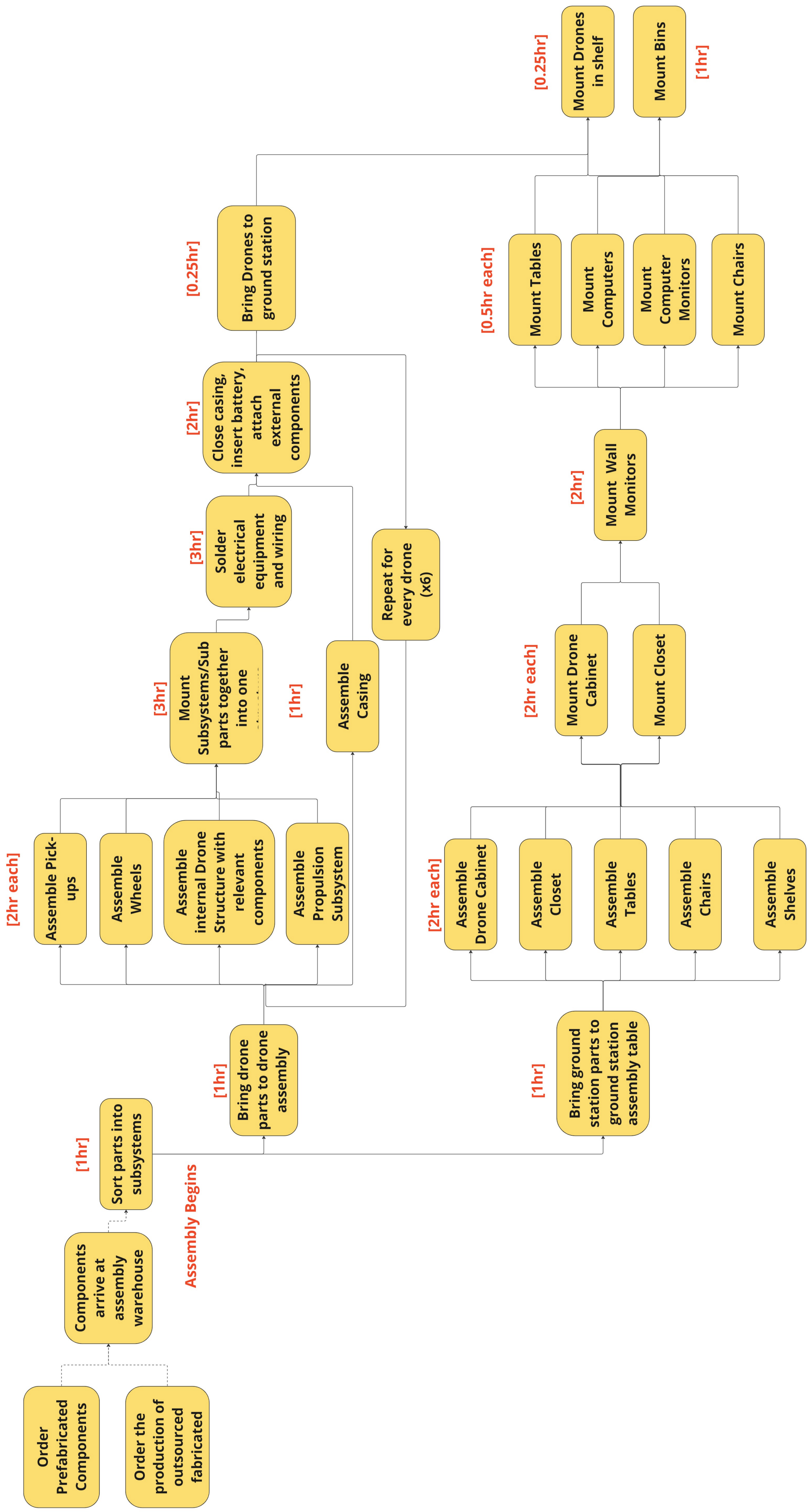


Figure 15.1: Time-ordered production plan for the ADIOS system

16 Future Recommendations and Development

In this chapter, the recommendations for the future of ADIOS are highlighted. During the project, some simplifications were made and a number of imperfections have been considered sufficient. In the upcoming sections, these will be addressed in a way that the system will be improved. Additionally, in section 16.5, a glance is cast at the steps that should be taken before ADIOS can be implemented globally.

16.1. Control System

As shown in Figure 13.1.2, the control system failed the step disturbance test. Applying a step disturbance leads to a steady state error in the position of the drone. In a real situation, many factors could cause such a steady-state error. Thus, this problem needs to be fixed. The best way to do this is to add an extra block to the system acting as an integral controller, making it an LQI controller (Linear-Quadratic-Integral controller). Such a controller will increase the force countering the disturbance over time, which completely eliminates the steady-state error. On top of this, all current gains are based on a preliminary mass of 4.0 kg, which is lower than the most recent estimate of 4.4 kg. Thus, the moment of inertia calculation should be redone.

16.2. Computer vision

To ensure optimal performance with minimal computational cost, it is advisable to stay updated on the latest advancements in deep learning techniques for object detection. Additionally, labelling the UAVVaste dataset with appropriate classes will allow for the optimal utilisation of different pick-up mechanisms. To achieve the highest performance, training the model on a customised dataset that matches the environment and the specific cameras employed by the drones is highly recommended. This tailored dataset will help maximise the model's effectiveness in real-world scenarios.

Furthermore, it is advisable to demonstrate the feasibility of mapping litter solely based on AI inputs and drone coordinates. This would enable the optimisation of drone allocation and utilisation based on the mapped litter locations. In addition, considering the successful implementation of autonomous detection, approach, and mapping of litter described in section 5.2, it is recommended to convert the previously mentioned code from section 12.2 to TensorRT on an NVIDIA Jetson. This implementation will facilitate onboard AI image processing. Furthermore, the same system should be deployed on drones of a similar size as the final design, allowing for testing at outdoor locations like Valkenburg near Leiden.

16.3. Operations

The simulation written for the operations did already consist of all major processes during normal operations of the ADIOS system. However, there are also some processes that were not included or were assumed by a parameter. The most important of these processes is the reconnaissance. The location of all litter pieces, and which drone type is able to collect them were assumed to be already known at the start of the operation. During real operations, the reconnaissance is performed at the start, and mistakes in the classification can be made. Another situation that can occur, is that drones in the beginning have to wait until more litter is discovered. Therefore, it would be valuable to include this process in the simulation. Moreover, path planning is currently performed in 2D on a fixed level of five meters. This does not optimally make use of the possibility for drones to fly over obstructions. Therefore, this should be added to the next version of the simulation. Some other new processes that should be included in a future version of the simulation are: to make a more accurate calculation for the power consumption of the components in the drone, to include the possibility to change the grabbing mechanism on the drone when it is finished, to include the possibility for obstructions to be added to the path planning while the drones are operating and to make sure the paths from the A* algorithm will not be drawn next to a building to avoid flying through the building.

In the analysis of the simulation, a range of tests have been performed to discover the robustness of the designed system. However, there also are some additional tests to be performed. Currently, the effect of different area sizes is taken into account by positioning the ground station in the corner of the area. In the future, also simulations would be necessary where the shape is changed. Furthermore, all tests have been performed with a layout that is chosen because it has some difficult-to-reach places, but is still to be expected during real operations. It would be necessary to perform tests on different obstacle layouts to check whether the system still functions to expectation. Lastly, it was found that the brush drones are five times as effective as the grabber drones because they can store litter. Therefore, it would be valuable to research whether a grabbing mechanism for large litter can be designed that also has a storage space.

As shown in section 13.1, the setpoint generation code for the minimum snap trajectory planner partially fails unit tests related to setting the acceleration and jerk at setpoints. This is not because the code is broken, but simply because it was not possible to implement these features within the time scope. Thus, it should be good to implement these features. Properly defining the acceleration and jerk at each point ensures proper paths for the drones to fly. This fixes the problem of drones occasionally flying through walls.

16.4. Propulsion

The use of toroidal propellers is an innovative step in reducing propeller noise and increasing efficiency. It is recommended to continue testing the toroidal propellers, both individually and in the hexacopter configuration, using the correct material and dimensions to obtain accurate reliable thrust and noise data for the system as a whole and to investigate the interference effects of having multiple rotors in close proximity.

Furthermore, the design could consider a quadrotor with counter-rotating propellers. Counter-rotating propellers have been shown to improve thrust efficiency up to 50% and reduce noise [41]. Having 2 motors on each arm also increases the safety of the system as there is a spare motor at each arm. There is, however, a considerable weight increase as each rotor requires double the motors and propellers, hence why it was not considered for the current hexacopter design, which is already heavy. In addition, counter-rotating propellers could utilise a phase-synchronised system where the phases of the counter-rotating propellers are coupled such that tip vortices destructively interfere, reducing noise [94].

16.5. ADIOS Project Design & Development

To visualise the steps that be taken towards the global implementation of ADIOS, a flow diagram is created. This diagram is shown in Figure 16.1. As stated before, after the day of the symposium, the team could start a business. This is what happens in the first phase after the DSE. Then, many activities can be performed parallel to each other. Firstly, the overall system should be further designed to increase its performance. Next to this, the ADIOS drones should be diversified so that they would be able to operate in a wide variety of areas, not only in non-crowded urban areas, while being able to pick up far more types of litter pieces. Ultimately, the system should be manufactured, after which it can be sold in the upcoming phase: the Selling Phase. Parallel to this phase, the ADIOS brand should get more recognition to increase sales, leaving more money for production as well as marketing. After

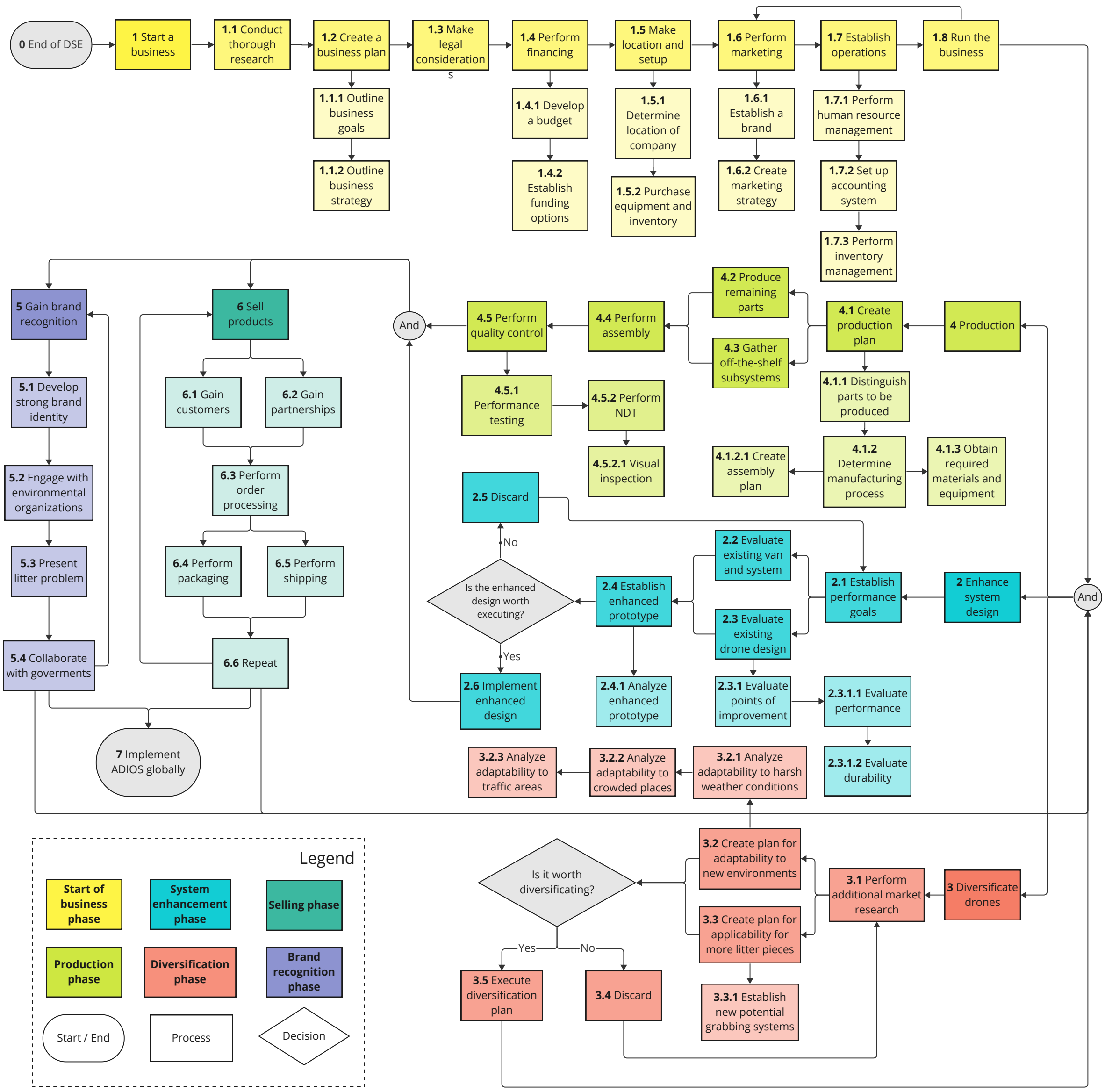


Figure 16.1: The Project Design & Development of ADIOS

all of this, the final step is the implementation of ADIOS on a global scale.

17 Conclusion

After conducting extensive testing, it was concluded that a fully flying drone solution was no longer feasible due to the significant wake effect observed. Consequently, an alternative solution was selected: a drone equipped with two wheels with an additional tail for stability. This modified drone utilises a landing approach near the litter and then drives a short distance to reach the precise location, instead of relying on flight and hovering over the trash for pick-up. By adopting this approach, both the wake effect and stability concerns associated with hovering over trash are effectively resolved.

The resulting system consists of drones with a hexacopter configuration utilising 10-inch toroidal propellers. In-house testing proved that toroidal propellers were 29% more efficient than conventional tri-blade propellers and 3.5dBA quieter, showcasing that the ADIOS drones are more efficient and quieter than traditional drones. Moreover, to address safety concerns that surround drones, the ADIOS drones employ propeller guards that cover the fast-spinning propellers.

A simulation of the operation was developed to size the number of drones. This simulation involved all major processes such as obstacle avoidance, a physical drone system and battery usage. From this analysis, it was concluded that the system will need to consist of six drones. For most use cases, two of these drones will be equipped with brushes and four will be equipped with a grabbing pick-up system. In the majority of use cases, the brush drones will be done substantially before the grabbing drones which makes them suitable to perform the reconnaissance of the litter. In total, this layout will be able to clean a wide range of areas within an hour. Since the ADIOS system is designed to be able to clean non-optimal areas within an hour, it often results that the area can be cleaned faster. In the obstacle layout used for the system sizing, up to 1500 pieces of litter can be cleaned by the system, while still leaving 20 minutes time for the drones with brushes to perform reconnaissance.

For autonomous trash detection, the YOLOv8n deep learning model was selected. It was trained on the UAVVaste dataset and demonstrated the ability to accurately detect trash. Furthermore, the system was tested on the Parrot Bebop 2 drone, which successfully exhibited the capability to autonomously approach trash based on the deep learning-detected trash.

Furthermore, a prototype was developed to validate the concept and showcase it in operation at the symposium. In order to achieve that, contact was established between certain members of the aerospace faculty to assist in the development as their expertise and experience greatly exceed the team's. After performing simple tests on litter subject to the wake of a small drone, it was noticed that this will be a major challenge for the team to overcome this as it severely hinders the success of a potential pick-up.

Based on the financial analysis, it can be concluded that the system has the potential to be profitable. With a net profit of €224,000 per month and a profit margin of 5.6%, assuming a price of €1000 per day per system and 200 daily operational systems, the financial outlook is favourable. Additionally, the break-even point for the initial investments is projected to be reached after 7.5 years, paving the way for a successful and prosperous company.

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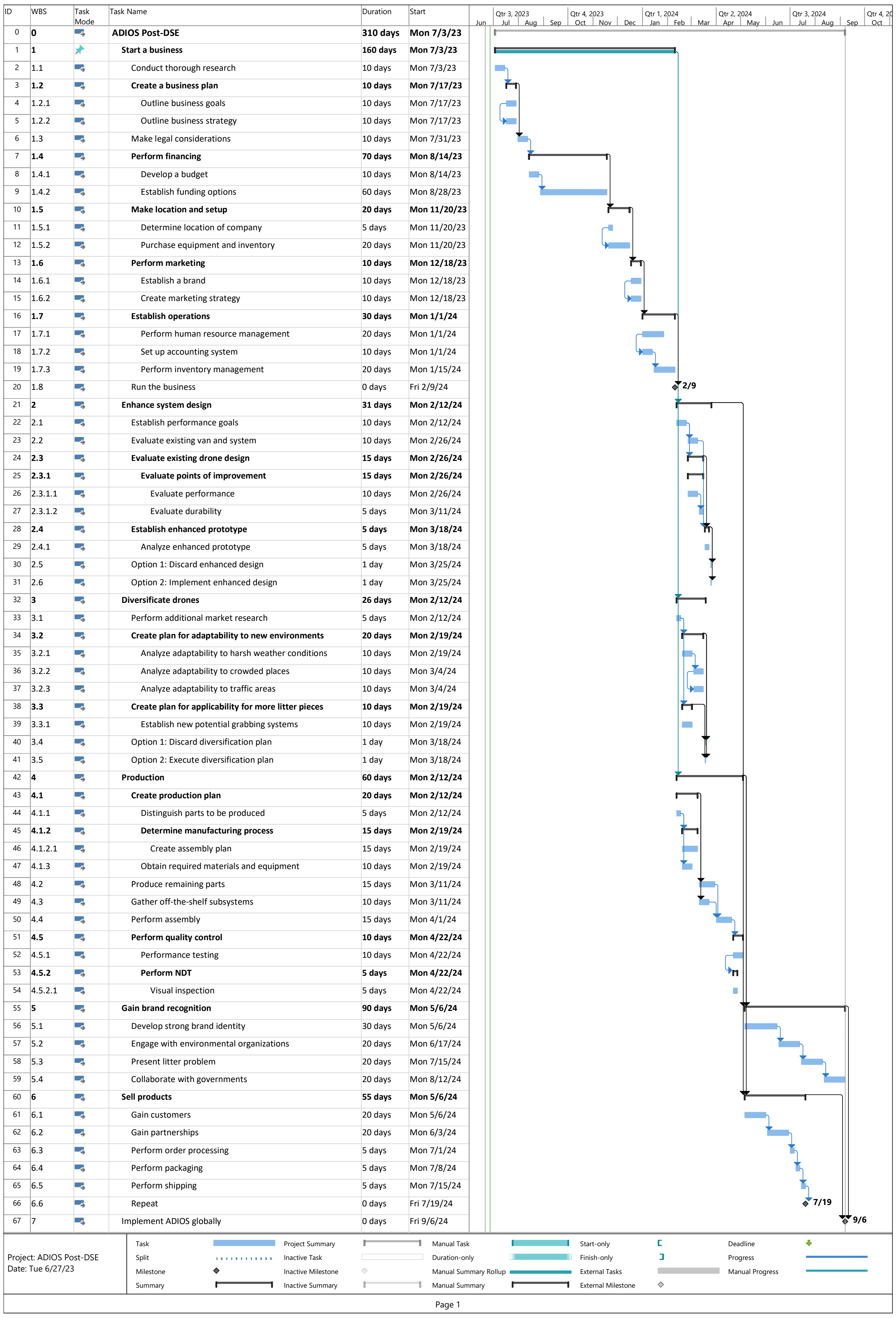
A

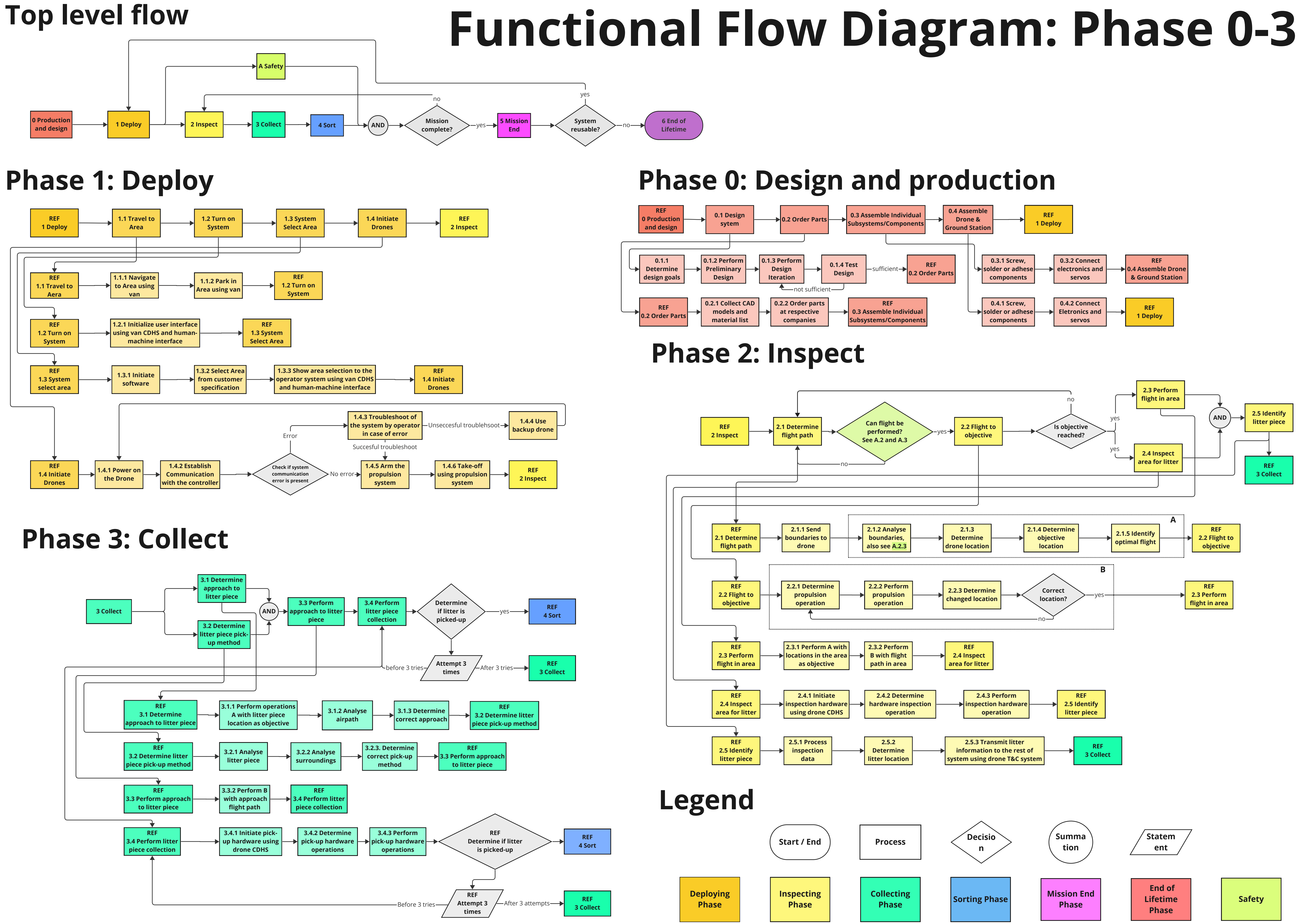
Gantt Chart, FBD and FBS

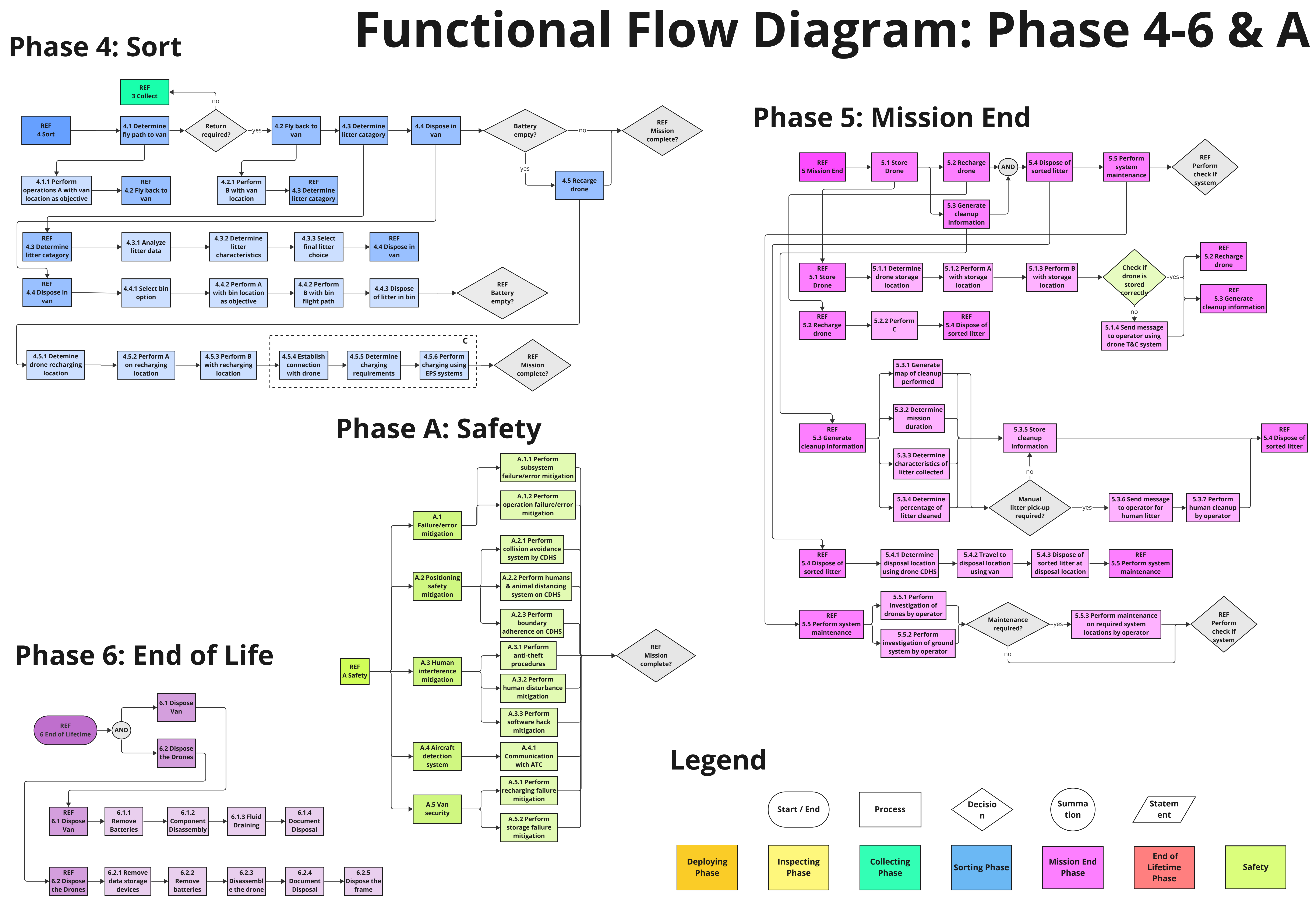


ID	WBS	Task Mode	Task Name	Duration	Start
0	**0**		**ADIOS Post-DSE**	**310 days**	**Mon 7/3/23**
1	**1**		**Start a business**	**160 days**	**Mon 7/3/23**
2	1.1		Conduct thorough research	10 days	Mon 7/3/23
3	**1.2**		**Create a business plan**	**10 days**	**Mon 7/17/23**
4	1.2.1		Outline business goals	10 days	Mon 7/17/23
5	1.2.2		Outline business strategy	10 days	Mon 7/17/23
6	1.3		Make legal considerations	10 days	Mon 7/31/23
7	**1.4**		**Perform financing**	**70 days**	**Mon 8/14/23**
8	1.4.1		Develop a budget	10 days	Mon 8/14/23
9	1.4.2		Establish funding options	60 days	Mon 8/28/23
10	**1.5**		**Make location and setup**	**20 days**	**Mon 11/20/23**
11	1.5.1		Determine location of company	5 days	Mon 11/20/23
12	1.5.2		Purchase equipment and inventory	20 days	Mon 11/20/23
13	**1.6**		**Perform marketing**	**10 days**	**Mon 12/18/23**
14	1.6.1		Establish a brand	10 days	Mon 12/18/23
15	1.6.2		Create marketing strategy	10 days	Mon 12/18/23
16	**1.7**		**Establish operations**	**30 days**	**Mon 1/1/24**
17	1.7.1		Perform human resource management	20 days	Mon 1/1/24
18	1.7.2		Set up accounting system	10 days	Mon 1/1/24
19	1.7.3		Perform inventory management	20 days	Mon 1/15/24
20	1.8		Run the business	0 days	Fri 2/9/24
21	**2**		**Enhance system design**	**31 days**	**Mon 2/12/24**
22	2.1		Establish performance goals	10 days	Mon 2/12/24
23	2.2		Evaluate existing van and system	10 days	Mon 2/26/24
24	**2.3**		**Evaluate existing drone design**	**15 days**	**Mon 2/26/24**
25	**2.3.1**		**Evaluate points of improvement**	**15 days**	**Mon 2/26/24**
26	2.3.1.1		Evaluate performance	10 days	Mon 2/26/24
27	2.3.1.2		Evaluate durability	5 days	Mon 3/11/24
28	**2.4**		**Establish enhanced prototype**	**5 days**	**Mon 3/18/24**
29	2.4.1		Analyze enhanced prototype	5 days	Mon 3/18/24
30	2.5		Option 1: Discard enhanced design	1 day	Mon 3/25/24
31	2.6		Option 2: Implement enhanced design	1 day	Mon 3/25/24
32	**3**		**Diversificate drones**	**26 days**	**Mon 2/12/24**
33	3.1		Perform additional market research	5 days	Mon 2/12/24
34	**3.2**		**Create plan for adaptability to new environments**	**20 days**	**Mon 2/19/24**
35	3.2.1		Analyze adaptability to harsh weather conditions	10 days	Mon 2/19/24
36	3.2.2		Analyze adaptability to crowded places	10 days	Mon 3/4/24
37	3.2.3		Analyze adaptability to traffic areas	10 days	Mon 3/4/24
38	**3.3**		**Create plan for applicability for more litter pieces**	**10 days**	**Mon 2/19/24**
39	3.3.1		Establish new potential grabbing systems	10 days	Mon 2/19/24
40	3.4		Option 1: Discard diversification plan	1 day	Mon 3/18/24
41	3.5		Option 2: Execute diversification plan	1 day	Mon 3/18/24
42	**4**		**Production**	**60 days**	**Mon 2/12/24**
43	**4.1**		**Create production plan**	**20 days**	**Mon 2/12/24**
44	4.1.1		Distinguish parts to be produced	5 days	Mon 2/12/24
45	**4.1.2**		**Determine manufacturing process**	**15 days**	**Mon 2/19/24**
46	4.1.2.1		Create assembly plan	15 days	Mon 2/19/24
47	4.1.3		Obtain required materials and equipment	10 days	Mon 2/19/24
48	4.2		Produce remaining parts	15 days	Mon 3/11/24
49	4.3		Gather off-the-shelf subsystems	10 days	Mon 3/11/24
50	4.4		Perform assembly	15 days	Mon 4/1/24
51	**4.5**		**Perform quality control**	**10 days**	**Mon 4/22/24**
52	4.5.1		Performance testing	10 days	Mon 4/22/24
53	**4.5.2**		**Perform NDT**	**5 days**	**Mon 4/22/24**
54	4.5.2.1		Visual inspection	5 days	Mon 4/22/24
55	**5**		**Gain brand recognition**	**90 days**	**Mon 5/6/24**
56	5.1		Develop strong brand identity	30 days	Mon 5/6/24
57	5.2		Engage with environmental organizations	20 days	Mon 6/17/24
58	5.3		Present litter problem	20 days	Mon 7/15/24
59	5.4		Collaborate with governments	20 days	Mon 8/12/24
60	**6**		**Sell products**	**55 days**	**Mon 5/6/24**
61	6.1		Gain customers	20 days	Mon 5/6/24
62	6.2		Gain partnerships	20 days	Mon 6/3/24
63	6.3		Perform order processing	5 days	Mon 7/1/24
64	6.4		Perform packaging	5 days	Mon 7/8/24
65	6.5		Perform shipping	5 days	Mon 7/15/24
66	6.6		Repeat	0 days	Fri 7/19/24
67	7		Implement ADIOS globally	0 days	Fri 9/6/24

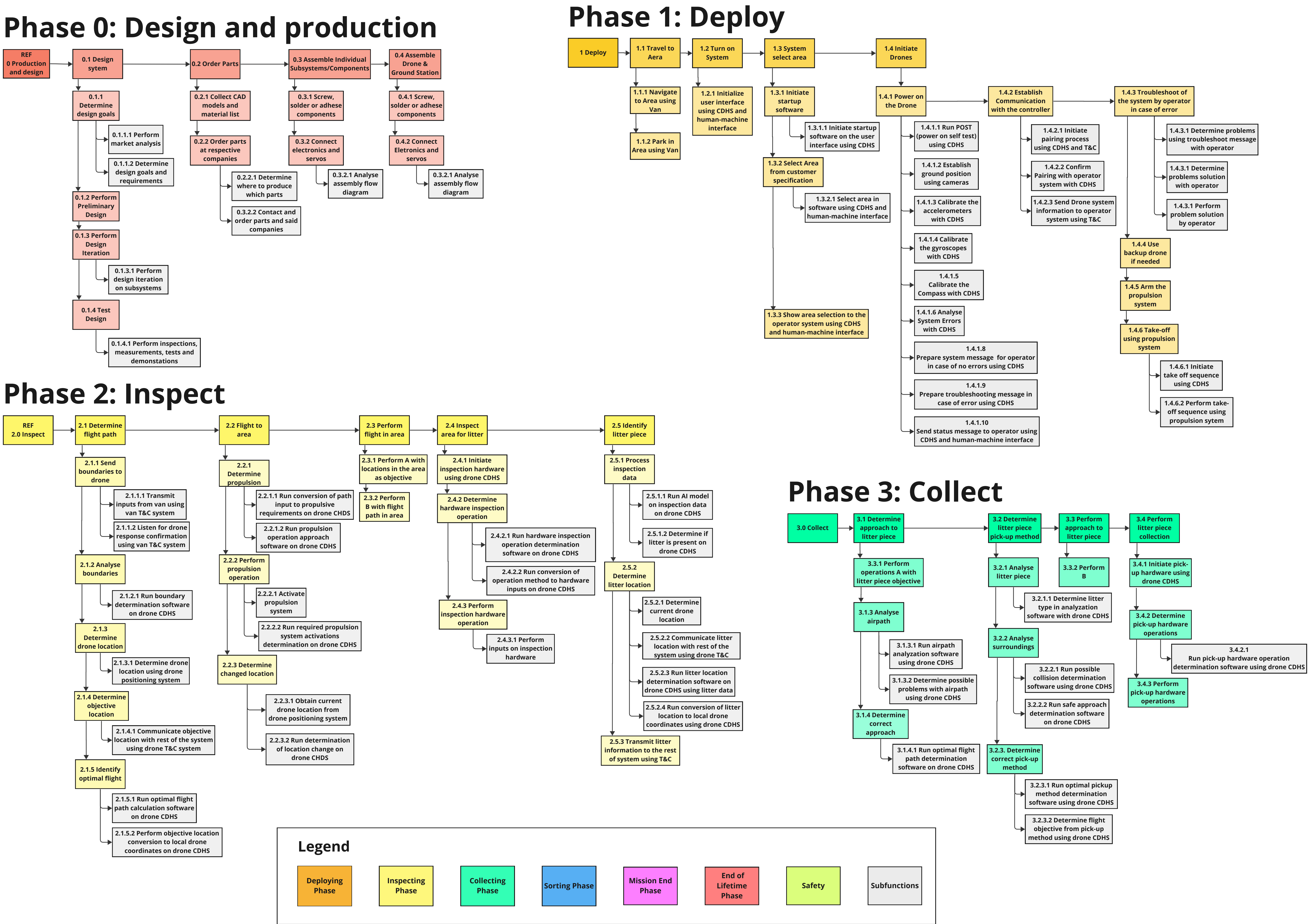
Figure A.1: Gantt chart

Functional Flow Diagram: Phase 0-3

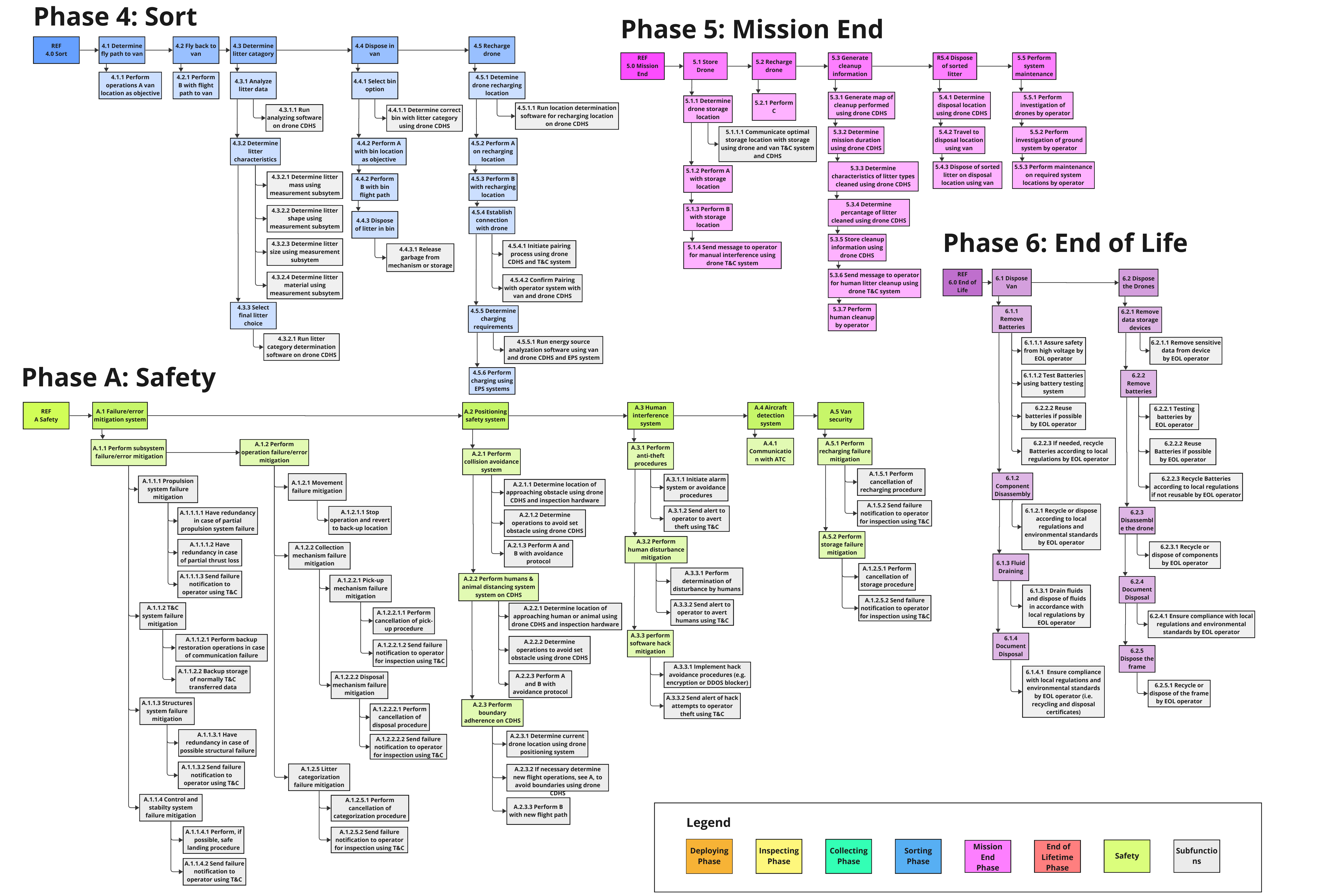



Functional Flow Diagram: Phase 4-6 & A
Phase 4: Sort
REF 3 Collect
REF 4 Sort
4.1 Determine fly path to van
Return required?
no
yes
4.2 Fly back to van
4.3 Determine litter catagory
4.4 Dispose in van
Battery empty?
REF Mission complete?
4.5 Recarge drone
4.1.1 Perform operations A with van location as objective
REF 4.2 Fly back to van
4.2.1 Perform B with van location
REF 4.3 Determine litter catagory
REF 4.3 Determine litter catagory
4.3.1 Analyze litter data
4.3.2 Determine litter characteristics
4.3.3 Select final litter choice
REF 4.4 Dispose in van
REF 4.4 Dispose in van
4.4.1 Select bin option
4.4.2 Perform A with bin location as objective
4.4.2 Perform B with bin flight path
4.4.3 Dispose of litter in bin
REF Battery empty?
4.5.1 Detemine drone recharging location
4.5.2 Perform A on recharging location
4.5.3 Perform B with recharging location
C
4.5.4 Establish connection with drone
4.5.5 Determine charging requirements
4.5.6 Perform charging using EPS systems
REF Mission complete?
Phase 5: Mission End
REF 5 Mission End
5.1 Store Drone
5.2 Recharge drone
AND
5.3 Generate cleanup information
5.4 Dispose of sorted litter
5.5 Perform system maintenance
REF Perform check if system
REF 5.1 Store Drone
5.1.1 Determine drone storage location
5.1.2 Perform A with storage location
5.1.3 Perform B with storage location
Check if drone is stored correctly
yes
no
REF 5.2 Recharge drone
REF 5.3 Generate cleanup information
5.1.4 Send message to operator using drone T&C system
REF 5.2 Recharge drone
5.2.2 Perform C
REF 5.4 Dispose of sorted litter
5.3.1 Generate map of cleanup performed
5.3.2 Determine mission duration
REF 5.3 Generate cleanup information
5.3.5 Store cleanup information
REF 5.4 Dispose of sorted litter
5.3.3 Determine characteristics of litter collected
no
5.3.4 Determine percentage of litter cleaned
Manual litter pick-up required?
yes
5.3.6 Send message to operator for human litter
5.3.7 Perform human cleanup by operator
REF 5.4 Dispose of sorted litter
5.4.1 Determine disposal location using drone CDHS
5.4.2 Travel to disposal location using van
5.4.3 Dispose of sorted litter at disposal location
REF 5.5 Perform system maintenance
REF 5.5 Perform system maintenance
5.5.1 Perform investigation of drones by operator
5.5.2 Perform investigation of ground system by operator
Maintenance required?
yes
no
5.5.3 Perform maintenance on required system locations by operator
REF Perform check if system
Phase A: Safety
A.1.1 Perform subsystem failure/error mitigation
A.1.2 Perform operation failure/error mitigation
A.1 Failure/error mitigation
A.2.1 Perform collision avoidance system by CDHS
A.2 Positioning safety mitigation
A.2.2 Perform humans & animal distancing system on CDHS
A.2.3 Perform boundary adherence on CDHS
REF Mission complete?
REF A Safety
A.3 Human interference mitigation
A.3.1 Perform anti-theft procedures
A.3.2 Perform human disturbance mitigation
A.3.3 Perform software hack mitigation
A.4 Aircraft detection system
A.4.1 Communication with ATC
A.5 Van security
A.5.1 Perform recharging failure mitigation
A.5.2 Perform storage failure mitigation
Phase 6: End of Life
REF 6 End of Lifetime
AND
6.1 Dispose Van
6.2 Dispose the Drones
REF 6.1 Dispose Van
6.1.1 Remove Batteries
6.1.2 Component Disassembly
6.1.3 Fluid Draining
6.1.4 Document Disposal
REF 6.2 Dispose the Drones
6.2.1 Remove data storage devices
6.2.2 Remove batteries
6.2.3 Disassemble the drone
6.2.4 Document Disposal
6.2.5 Dispose the frame
Legend
Start / End
Process
Decision
Summation
Statement
Deploying Phase
Inspecting Phase
Collecting Phase
Sorting Phase
Mission End Phase
End of Lifetime Phase
Safety

Functional Breakdown Structure: Phase 0-3



Functional Breakdown Structure: Phase 4-6 & A



B

Compliance Matrix

Table B.1: Requirements table

Identifier	Requirement	Met	Current performance	Rationale
UR-P-1	The system shall be able to survey the area and provide the operator with relevant information about the area.	✓		
UR-P-2	The system shall be able to take inputs from the operator about the spatial limits and constraints of the cleaning area.	✓		
UR-P-3	The drones shall be capable of identifying garbage and communicating that information to the operator and other drones.	✓		
UR-P-4	The system shall have several drones of various sizes and capabilities, the exact number and configuration have to be decided by the team after the initial research.	✓		
UR-P-5	The drones shall cover an area of around 10000 m^2 and pick up atleast 1000 pieces of garbage within an hour.	✓		
UR-P-6	The drones shall sort the garbage for easy recycling.	✗	The garbage is sorted into organic and non-organic.	Waste disposal sites are equipped with facilities for garbage sorting and therefore it doesn't have to be performed by the system. However, it is still beneficial to divide the garbage into organic and non-organic for easier and cleaner storage.
UR-P-7	The mobile van shall be electric.	✓		
UR-P-8	The system shall be easy to operate and shall not require a lot of attention from the operator.	✓		
UR-P-9	The operator required to operate the mobile van with the drones shall not be required to go through extensive training.	✓		
UR-SA-10	The drones shall not be harmful to birds, insects and other creatures.	✗	The drones are not capable of avoiding insects.	After consultations with the stakeholders it was determined that avoiding insects is not crucial in the context of this project. It was deemed that the current state-of-the-art obstacle avoidance technology does not allow for insect avoidance.

UR-SA-11	They shall be capable of identifying trees, plants, dogs, cats, frogs, birds, etc and stay away from harming any other creatures.	✓		
UR-SA-12	They shall be safe to operate within built environment.	✓		
UR-SA-13	They shall have GPS and /or other locating system to in order to optimize the cleaning.	✓		
UR-SA-14	They should comeback to the mobile van for docking and charging once their mission is over or if the drones are low on battery.	✓		
UR-SA-15	The drones should be capable of monitoring and reporting any malfunctions or dangerous situations.	✓		
UR-SA-16	The drones should be able to respect privacy of pedestrians/bystanders.	✓		
UR-SU-17	The drones and the mobile van shall be electric.	✓		
UR-EN-18	The design shall be such that a product can be developed based on this design within next 3 years.	✓		
UR-CO-19	The cost of such a mobile van and drones shall not exceed 100 kEuros	✓		
UR-OT-20	The DSE can start a company based on this project.	✓		

C

Requirements Table

Table C.1: Requirements table

Identifier	Type	Requirement
SYS-TE-QN		The mission shall be performed with sufficient output quantity
SYS-TE-QN-1	DRIVING	The number of drones shall be sufficient to perform the mission with sufficient output quantity
SYS-TE-QN-1-1		The drone system shall contain at least 10 drones.
SYS-TE-QN-1-2		There shall be at least 2 different drone types across the system for picking up different types of litter
SYS-TE-QN-2		The drone coverage area shall be sufficient to perform the mission with sufficient output quantity
SYS-TE-QN-2-1		The drone system shall cover an area of at least 10000 m^2 per hour per workforce
SYS-TE-QN-3		The drone endurance shall be sufficient to perform the mission with sufficient output quality
SYS-TE-QN-3-1	DRIVING	The drones shall be able to fly for at least 20 minutes before recharging with a maximum wind speed of 10 m/s
SYS-TE-QN-3-1-1		The drones shall have a battery with capacity of at least 300 Wh
SYS-TE-QN-3-1-2		The average power consumption of the propulsion system shall be less than 100 W
SYS-TE-QN-3-1-3		The average power consumption of the payload system shall be less than 25 W
SYS-TE-QN-3-1-4		The average power consumption of the CDHS system shall be less than 25 W
SYS-TE-QN-4		The drone range shall be sufficient to perform the mission with sufficient output quantity
SYS-TE-QN-4-1		The drones shall be controllable up to 500 m distance from the operator
SYS-TE-QN-4-2		The drones shall maintain full datalink connection with the ground station up to 200 m distance from the operator
SYS-TE-QN-4-3		The drones shall remain within a radius of 500 m from the operator
SYS-TE-QL		The mission shall be performed with sufficient output quality
SYS-TE-QL-1		The drones shall be stable during nominal operations
SYS-TE-QL-1-1		The drones shall be able to perform a stable landing within 5 seconds from a height of 2 m
SYS-TE-QL-1-2		The drones shall be stable in flight
SYS-TE-QL-1-2-1		The drones shall be able to hover stationary above a surface
SYS-TE-QL-1-2-2		The drones shall be able to restore to zero ground speed and zero vertical speed after a disturbance (wind, gust) within 1 second of the disturbance
SYS-TE-QL-1-2-3		The drones shall not bank more than 40 degrees during a disturbance (wind, gust)
SYS-TE-QL-1-3		The drones shall be stable during pick-up of litter
SYS-TE-QL-1-3-1		The drones shall be able to hover stationary above a surface during pick-up
SYS-TE-QL-1-3-2		The drones shall be able to restore to zero ground and zero vertical speed after a disturbance (wind, gust) within 1 second of the disturbance during pick-up
SYS-TE-QL-1-3-3		The drones shall not bank more than 20 degrees during a disturbance (wind, gust) while picking up litter
SYS-TE-QL-2		The system shall have a (remote) CDHS
SYS-TE-QL-2-1		The CDHS system shall have a failure rate of less than 0.0001 per hour
SYS-TE-QL-2-2		The CDHS system shall be able to handle path planning
SYS-TE-QL-2-3	DRIVING	The CDHS system shall be able to run a computer vision model

SYS-TE-QL-2-4		The CDHS system shall be able to perform flight control computations
SYS-TE-QL-2-4-1		The CDHS system shall be able to process sensor data from the drones
SYS-TE-QL-2-4-2		The CDHS system shall be able to make calculations for thrust vectoring
SYS-TE-QL-3		The aerodynamics of the drones shall not interfere with the mission of the drone system
SYS-TE-QL-3-1		The aerodynamic wake generated by the drone shall not compromise the picking ability of the drone
SYS-TE-QL-3-1-1		The aerodynamic wake effect shall not move the litter out of the camera view while approaching to pick up the litter
SYS-TE-QL-4		The drones in the system shall be able to determine their global position
SYS-TE-QL-4-1		The positioning system in the drones shall have failure rate of 0.005 per hour
SYS-TE-QL-4-2		The drones shall be able to determine their position with an accuracy of 3 meters
SYS-TE-QL-5		The system shall have a telecommunications system
SYS-TE-QL-5-1		Wireless communication between the drones and the van shall be possible
SYS-TE-QL-5-1-1		The minimum bandwith of the communication system between the drones and the van shall be 10 Hz
SYS-TE-QL-5-1-2		The minimum data rate of the communication system between the drones and the van shall be 150 bits per second
SYS-TE-QL-5-2		The telecommunication system shall have a reliability of 0.1 bit errors per second.
SYS-TE-QL-6	KEY	The drones shall have a litter pick-up system
SYS-TE-QL-6-1		The system shall be able to pick-up various types of litter
SYS-TE-QL-6-1-1		The drone system shall have 2 different litter-picking mechanisms
SYS-TE-QL-6-1-2	DRIVING	The drone system shall be capable of picking 15 different litter types
SYS-TE-QL-6-1-3		The drones shall have litter storage space of at least 500 cm^3
SYS-TE-QL-6-1-4		The system shall be able to continue normal operations when an operating drone has failed.
SYS-TE-QL-6-2		The pick-up system in the drones shall be able to pick litter in urban conditions
SYS-TE-QL-6-2-1		The pick-up system shall be able to pick-up litter from hard surfaces (eg. concrete, asphalt)
SYS-TE-QL-6-2-2		The pick-up system shall be able to pick-up litter from soft surfaces (eg. grass, earth)
SYS-TE-QL-6-2-3		The pick-up system shall be able to pick-up litter from moving surfaces (eg. water)
SYS-TE-QL-6-3		The pick-up duration shall be less than 5 s once it is in physical contact with the litter
SYS-TE-QL-6-4		The pick-up system shall have a failure rate of less than 10% of litter unsuccessfully grasped
SYS-TE-QL-6-5		The pick-up system shall not release the litter during flight
SYS-TE-QL-6-5-1		The pick-up system shall have a grasping force of at least 20 N
SYS-TE-QL-7	DRIVING	The system shall incorporate a litter sorting system
SYS-TE-QL-7-1		The system shall be able to recognize litter types of: metal, biodegradable, plastic, electronic, glass and residual waste
SYS-TE-QL-7-2		The litter shall be removable from the drone
SYS-TE-QL-8	KEY	The system shall operate autonomously
SYS-TE-QL-8-1		The drones shall fly autonomously
SYS-TE-QL-8-1-1		The drones shall fly Beyond Visual Line Of Sight (BVLOS)
SYS-TE-QL-8-1-2		The drones shall be able to perceive surroundings
SYS-TE-QL-8-1-2-1		The drones shall be able to detect litter during operation
SYS-TE-QL-8-1-2-2		The system shall be able to collect information regarding litter distribution and flight performance during operation
SYS-TE-QL-8-1-2-3		The system shall be able to analyze information during operation
SYS-TE-QL-8-1-2-4		The system shall be able to perform actions based on information autonomously during operation
SYS-TE-QL-8-2		The drones shall be able to collect litter autonomously
SYS-TE-QL-9		The drones shall be equipped with a propulsion system
SYS-TE-QL-9-1		The propulsion system shall have a failure rate of less than 0.16 per year
SYS-TE-QL-9-1-1		The propulsion device shall have a failure rate of less than 0.4 per year
SYS-TE-QL-9-1-2		The motors shall have a failure rate of less than 0.4 per year
SYS-TE-QL-9-2		The drones shall have a propulsive efficiency of at least 45 %
SYS-TE-QL-9-3	DRIVING	The drones shall be able to generate at least 480 N of thrust in nominal conditions
SYS-TE-QL-9-3-1		Each propulsion device in the drone shall be able to generate thrust of at least 80 N

SYS-TE-QL-9-4		The drones shall be able to keep flying with a one-engine failure.
SYS-TE-QL-9-4-1		The drones shall be able to generate at least 400 N of thrust without one engine
SYS-TE-QL-9-4-2		The drones shall be able to stay controllable without one engine
SYS-TE-QL-9-5		The motors shall have an efficiency of at least 90 %
SYS-TE-QL-10		The drones shall possess structural robustness
SYS-TE-QL-10-1		The structures shall be able to withstand the vibrations of the motors
SYS-TE-QL-10-1-1		The structures shall be able to withstand vibrations with the frequency of 12583 Hz
SYS-TE-QL-10-1-2		The structures shall be able to withstand vibrations with the amplitude of 0.05 m
SYS-TE-QL-10-2		The structures shall be able to withstand the total drone weight of 420 N
SYS-TE-QL-10-2-1		The structures shall be able to withstand the empty drone weight of 200 N
SYS-TE-QL-10-2-2		The structures shall be able to withstand payload weight of 220 N
SYS-TE-QL-10-4		The structures shall be able to withstand loads during manoeuvers
SYS-TE-QL-10-4-1		The structures shall be able to withstand loads during the maximum acceleration of 20 m/s^2
SYS-TE-QL-10-4-1-1		The structures shall be able to withstand a load factor of 2
SYS-TE-QL-10-5		The drones shall have a friendly appearance
SYS-TE-QL-10-5-1		The drones shall be deemed as friendly by 90% of people surveyed in a random representative sample
SYS-TE-QL-10-6		The structures shall withstand fatigue loads for 3 years
SYS-TE-QL-10-6-1		The structures shall withstand fatigue loads with ΔK of 1 MPa·√m
SYS-TE-QL-10-6-2		The structures shall withstand fatigue loads with K_max of 3 MPa·√m
SYS-TE-QL-10-7		The structures shall withstand impact with another object
SYS-TE-QL-10-7-1		The structures shall withstand impact with a solid concrete wall at a speed of 8 m/s
SYS-TE-QL-11	KEY	The system shall utilise a mobile van
SYS-TE-QL-11-1	DRIVING	The van shall allow for transportation of at least 10 drones
SYS-TE-QL-11-2		The van shall have secure mounting for at least 10 drones
SYS-TE-QL-11-2-1		The van shall have cargo space of at least <TBD>m^3
SYS-TE-QL-11-3		The van shall be capable of recharging the batteries
SYS-TE-QL-11-3-1		Battery recharging time to full must be less than 180 minutes
SYS-TE-QL-11-3-1-1		The van shall charge the battery with at least <TBD>W
SYS-TE-QL-11-3-2		The van shall have charging stations for at least 10 batteries
SYS-TE-QL-11-3-3		The van shall have a battery of at least <TBD>Wh
SYS-TE-QL-11-4		The van shall have a range of at least 100 km on a full battery
SYS-TE-QL-11-5		The van shall allow for transportation of at least 2 operators
SYS-TE-QL-11-6	DRIVING	The van shall be driveable with a Car Driving License B
SYS-TE-QL-12	DRIVING	The system shall have a human/machine interface
SYS-TE-QL-12-1		The human/machine interface shall not require more than 10 days of training for the operator
SYS-TE-QL-12-2		The human/machine interface shall enable the operator to specify the mission for the operating system
SYS-TE-QL-12-3		The human/machine interface shall provide the information necessary to determine whether a drone is in an emergency situation
SYS-TE-QL-12-3-1		The human/machine interface shall provide positional information of the drones
SYS-TE-QL-12-3-2		The human/machine interface shall provide telemetry data of the drones
SYS-TE-QL-12-3-3		The human/machine interface shall provide a camera feed of the drones
SYS-TE-QL-13	DRIVING	The system shall be able perform computer vision
SYS-TE-QL-13-1		The drones shall use cameras to perceive reality
SYS-TE-QL-13-1-1		The cameras of the drones shall have resolution of at least 480 p
SYS-TE-QL-13-1-2		The cameras of the drones shall capture video with at least 20 fps
SYS-TE-QL-13-1-3		The cameras of the drones shall have signal to noise ratio of at least 30 dB
SYS-TE-QL-13-1-4		The cameras that identify litter shall have a shutter speed between 1/8000 s and 8/8000 s in all operating conditions
SYS-TE-TI		The system shall perform the mission timely
SYS-TE-TI-1	KEY	The system shall collect at least 1000 pieces of litter per hour per workforce
SYS-TE-TI-1-1		The system shall recognize litter that can not be picked up
SYS-TE-TI-1-1-1	DRIVING	The maximum litter size that can be picked up shall be 20 x 8 x 8 cm
SYS-TE-TI-1-1-2		The system shall be able to estimate dimensions with accuracy of at least 80%
SYS-TE-TI-1-1-3		The maximum allowable force required to lift litter off the ground shall be 50 N
SYS-TE-TI-1-1-4		The maximum mass of the litter shall be 0.2 kg
SYS-TE-TI-1-1-5		The system shall be able to determine the thrust force during lift-off
SYS-TE-TI-1-2		The system shall not attempt to pick up a piece of litter more than 3 times
SYS-TE-TI-1-2-1		The system shall be able to count the number of attempts

SYS-TE-TI-1-2-2		The system shall be able to abort/move on while attempting litter pick-up
SYS-TE-TI-1-2-3		The system shall notify the operator upon unsuccessful pick-up procedure
SYS-TE-TI-1-2-3-1		The system shall provide the operator with a location of the unpicked litter
SYS-TE-TI-1-3		The drones shall be able to fly at a ground speed of at least 15 kts (7.72 m/s) for performance
SYS-TE-TI-1-3-1		The minimum achievable flight speed shall be 15 kts (7.72 m/s) when not carrying litter
SYS-TE-TI-1-3-2		The minimum achievable flight speed shall be 10 kts (5.14 m/s) when carrying litter
SYS-CON-PR	KEY	The system shall adhere to the privacy regulations
SYS-CON-PR-1		The system shall have secure camera footage
SYS-CON-PR-1-1		The telecommunication system shall be encrypted
SYS-CON-PR-1-2		The camera footage shall be stored in a local hard drive for at least a month
SYS-CON-PR-1-3		Faces in the camera footage shall be blurred on board the drones
SYS-CON-PR-1-3-1		The software on board the drones shall be able to detect faces in the footage
SYS-CON-PR-2		The drones shall not enter private property
SYS-CON-PR-2-1		The drones shall stay within the predefined public area
SYS-CON-PR-2-1-1		The drones shall use the positioning system to stay in the specified area
SYS-CON-PR-3		The drones shall not film people without permission in private areas
SYS-CON-PR-3-1		The drones shall inform the environment that camera footage will be taken
SYS-CON-PR-3-2		The system shall not use the camera footage for any other purposes than the mission
SYS-CON-RE		The project shall utilise the available resources
SYS-CON-RE-1		The system shall involve a human operator
SYS-CON-RE-1-1		The training period of the human operator shall be no longer than 4 weeks
SYS-CON-RE-1-2		The human operator shall have a Car Driving License B
SYS-CON-RE-1-3		The human operator shall be fit to drive for a maximum of 8 hours a day
SYS-CON-RE-1-4		The human operator shall be able plug in the drones for charging
SYS-CON-RE-1-4-1		The human operator shall be able to pick up the drones
SYS-CON-RE-1-4-1-1		Each drone shall weigh less than 15kg
SYS-CON-RE-1-4-2		The human operator shall be able to mount drones in the van
SYS-CON-RE-1-4-3		The human operator shall be able to intervene and fly the drones
SYS-CON-RE-1-4-3-1		The human operator shall have an overview of all drone activities
SYS-CON-RE-1-4-3-2		The human operator shall check drone activity for issues
SYS-CON-RE-1-4-3-3		The human operator shall be qualified to manually fly drone (see airspace regulations under legal)
SYS-CON-RE-2		The project shall involve transportation of items
SYS-CON-RE-2-1		The items ordered for the proof of concept shall be acquired locally where possible
SYS-CON-RE-2-2		The items ordered for the proof of concept shall be delivered by bike/electric vehicle where possible
SYS-CON-RE-3		The project shall involve the use of facilities
SYS-CON-RE-3-1		The proof of concept shall be developable within TU Delft facilities
SYS-CON-RE-3-2		The team shall work within TU Delft facilities
SYS-CON-RE-3-3	DRIVING	The proof of concept shall be performable within TU Delft facilities
SYS-CON-SU		The project shall incorporate sustainability
SYS-CON-SU-1		The emissions of the project shall be considered
SYS-CON-SU-1-1	KEY	The system shall not emit greenhouse gases during operation
SYS-CON-SU-1-1-1		The van shall be electric
SYS-CON-SU-1-1-2		The drones shall be electric
SYS-CON-SU-2	DRIVING	The environmental impact at the End of Life of the system shall be minimised
SYS-CON-SU-2-1		The hardware shall be at least 40% recyclable
SYS-CON-SU-2-2		The hardware shall be at least 80% reusable
SYS-CON-SU-2-3		Any batteries used in the system shall be recyclable or reusable
SYS-CON-SU-3		The project shall consider the material acquisition sustainability
SYS-CON-SU-3-1		Materials shall be acquired from recycled materials where possible
SYS-CON-COS		System costs shall stay within budget
SYS-CON-COS-1		The proof of concept hardware cost shall not exceed €500
SYS-CON-COS-2		Operational cost per piece of collected litter shall be less than when using manual labour
SYS-CON-COS-2-1		Operational cost should be cheaper than minimum wage worker
SYS-CON-COS-3	KEY	Development and production costs of the system shall not exceed €100k
SYS-CON-SCH		The project shall be finished on schedule
SYS-CON-SCH-1	KEY	The design shall be complete by 26.06.2023

SYS-CON-SCH-2		The proof of concept shall be complete by 26.06.2023
SYS-CON-SCH-3		The system shall be developable by April 2026
SYS-CON-LE		The system shall adhere to legal regulations
SYS-CON-LE-1		The system shall adhere to airspace regulations
SYS-CON-LE-1-1		The system shall be able to operate in a built-up environment
SYS-CON-LE-1-1-1		The system shall be compliant with the drone laws in the 'specific' category of EU Regulation 2019/947
SYS-CON-LE-1-1-1-1		The system shall be eligible for a LUC certificate in the European Union
SYS-CON-LE-1-1-1-1-1		Within the volume of air in which aircraft should be detected, at least 90% of aircraft shall be detected
SYS-CON-LE-1-1-1-1-2		The latency between a given command from the remote pilot and the response of the drone shall be less than 3 seconds
SYS-CON-LE-1-1-1-1-3	DRIVING	Every drone shall be able to fly faster than 50 knots (25.72 m/s) for regulation purpose
SYS-CON-LE-1-1-1-1-4		Every drone shall be able to climb faster than 500 ft/m (2.54 m/s)
SYS-CON-LE-1-1-1-1-5		Every drone shall be able to descend faster than 500 ft/m (2.54 m/s)
SYS-CON-LE-1-1-1-1-6		Every drone shall be able to rotate faster than 3°/s
SYS-CON-LE-1-1-1-1-7		The human/machine interface shall make it possible for the remote pilot to make a decision within 5 seconds when air traffic is detected
SYS-CON-LE-1-1-1-1-8		The tactical mitigation system shall have a failure rate of less than 1 per 1000 flight hours
SYS-CON-LE-1-1-1-2		The drones in the system shall operate at a maximum of 120 meters from the surface
SYS-CON-LE-1-1-1-3		The largest dimension between two propellers shall be less than 3 metres
SYS-CON-LE-1-1-1-4		The remote pilot shall have the competencies to be allowed to fly drones in the 'specific' category
SYS-CON-LE-1-1-1-4-1		The drone pilot shall have the ability to apply operational procedures (normal, contingency and emergency, flight planning, pre-flight and post-flight inspections)
SYS-CON-LE-1-1-1-4-2		The remote pilot shall have the ability to manage aeronautical communication
SYS-CON-LE-1-1-1-4-3		The remote pilot shall have the ability to manage the unmanned aircraft flight path and automation
SYS-CON-LE-1-1-1-4-4		The remote pilot shall have the skill of leadership, teamwork and self-management
SYS-CON-LE-1-1-1-4-5		The remote pilot shall have the skill of problem solving and decision-making
SYS-CON-LE-1-1-1-4-6		The remote pilot shall have situational awareness
SYS-CON-LE-1-1-1-4-7		The remote pilot shall be skilled in workload management
SYS-CON-LE-1-1-1-4-8		The remote pilot shall have the skill of coordination or handover, as applicable
SYS-CON-LE-2		The system shall adhere to noise regulations
SYS-CON-LE-2-1		The system shall remain within the noise limits specified by the Dutch government
SYS-CON-LE-2-1-1		The system shall produce less than 50 dB of long term average sound level on the facade of houses
SYS-CON-LE-2-1-2		The system shall produce less than 70 dB of maximum sound level on the facade of houses
SYS-CON-REL		The system shall be reliable
SYS-CON-REL-1		The drones shall have an unrecoverable failure rate of less than 0.1 failures per thousand flight hours
SYS-CON-REL-2		The drones shall not fail when exposed to outside conditions
SYS-CON-REL-2-1		The drones shall not fail when exposed to water in compliance with certification IP67
SYS-CON-REL-2-2		The drones shall not fail when exposed to dust in compliance with certification IP67
SYS-CON-REL-2-3		The drones shall be able to withstand temperatures with a minimum of -5 degrees C
SYS-CON-REL-2-4		The drone shall be able to withstand temperatures with a maximum of 35 degrees C
SYS-CON-REL-2-5		The drones shall at least be able to withstand winds with a maximum speed of 5 Bft (10.7 m/s)
SYS-CON-REL-2-6		The drones shall not exhibit corrosion during the life time of 3 years
SYS-CON-SA	KEY	The system shall be safe
SYS-CON-SA-1		The system shall be safe for fauna
SYS-CON-SA-1-1		The drones shall deal no physical damage to animals
SYS-CON-SA-1-1-1	KILLER	The drones shall maintain minimum distance of 1 meter from animals
SYS-CON-SA-1-1-1-1		The drones shall be able to fly out of the way of animals
SYS-CON-SA-1-1-1-2		The drones shall be able to detect animals
SYS-CON-SA-1-1-1-2-1		Computer vision shall detect animals with at least 98% accuracy
SYS-CON-SA-1-1-1-3		The drones shall be able to measure distance to objects with at least 0.2 m accuracy from within 5 m

SYS-CON-SA-1-1-2		The drones shall be able to abort mission when an animal gets within 1 meter of the drones
SYS-CON-SA-1-2		The system shall not disturb animals
SYS-CON-SA-1-2-1		The sound level of the system shall be less than 70 dB
SYS-CON-SA-2		The system shall be safe for flora
SYS-CON-SA-2-1		The drones shall do no harm to plants, trees and flowers
SYS-CON-SA-2-1-1		The drones shall be able to detect plants, trees and flowers
SYS-CON-SA-2-1-1-1		The drones shall be able to avoid plants, trees and flowers
SYS-CON-SA-2-1-1-2		The drones shall be able to incorporate plants, trees and flowers in flight path determinations
SYS-CON-SA-2-1-1-3		Computer vision shall detect plants, trees and flowers with at least 92% accuracy
SYS-CON-SA-2-1-2		The system shall not attempt litter pick-up when litter is entangled in plants, trees or flowers
SYS-CON-SA-2-1-3		The system shall inform the operator if litter is entangled in plants, trees or flowers
SYS-CON-SA-3		The system shall be safe for humans
SYS-CON-SA-3-1		The drones shall be kids-safe
SYS-CON-SA-3-1-1		The propulsion devices of the drones shall not be able to come into direct contact with human skin
SYS-CON-SA-3-1-2		The drones shall maintain a minimum distance of 5 meters from humans
SYS-CON-SA-3-1-2-1		The drones shall be able to detect humans
SYS-CON-SA-3-1-2-1-1		Computer vision shall detect humans with at least 99% accuracy
SYS-CON-SA-3-1-2-2		The drones shall be able to avoid humans
SYS-CON-SA-3-1-2-2-1		The drones shall have a minimal horizontal acceleration of 5 m/s^2
SYS-CON-SA-3-1-2-2-2		The drones shall be able to incorporate humans in real-time flight path determinations
SYS-CON-SA-3-2		The drones shall do no physical damage to humans during operation
SYS-CON-SA-3-3		The system shall not block, obstruct or interfere with humans
SYS-CON-SA-3-3-1		The system shall not pose danger to transportation devices
SYS-CON-SA-3-3-1-1		The drones shall maintain a minimum distance of 5 meters from transportation devices
SYS-CON-SA-3-3-1-1-1		The drones shall be able to detect transportation devices
SYS-CON-SA-3-3-1-1-1-1		Computer vision shall be able to differentiate between stationary and moving transportation devices
SYS-CON-SA-3-3-1-1-2		The drones shall be able to avoid collision with moving transportation devices
SYS-CON-SA-4		The system shall have emergency procedure
SYS-CON-SA-4-1		The drones shall not leave a predefined area
SYS-CON-SA-4-2		The drones shall be able to perform emergency procedure autonomously
SYS-CON-SA-4-2-1		The drones shall be equipped with standard emergency procedure
SYS-CON-SA-4-2-2		The drones shall be able to recognise emergency situation
SYS-CON-SA-4-2-3		The drones shall be able to initiate emergency procedure autonomously
SYS-CON-SA-4-3		Operator shall be able to perform emergency procedure
SYS-CON-SA-4-3-1		Operator shall be able to take full control of the drones
SYS-CON-SA-4-3-2		Operator shall have the information necessary to decide if there is an emergency situation
SYS-CON-SA-4-4		The drones shall be able to recognise theft attempt
SYS-CON-SA-4-4-1		The drones shall be able to recognise an attempt to move them out of a predefined area
SYS-CON-SA-4-4-1-1		The drones shall notify the operator upon theft attempt

D
Rotor Noise Harmonic Sound Levels

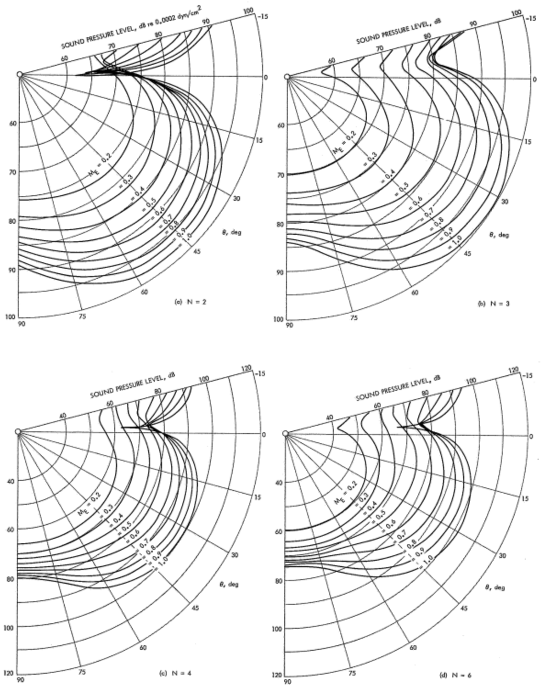


Figure D.1: Rotor noise harmonic sound pressure levels I, as functions of harmonic number, rotational Mach number, and angle from disc plane [85]

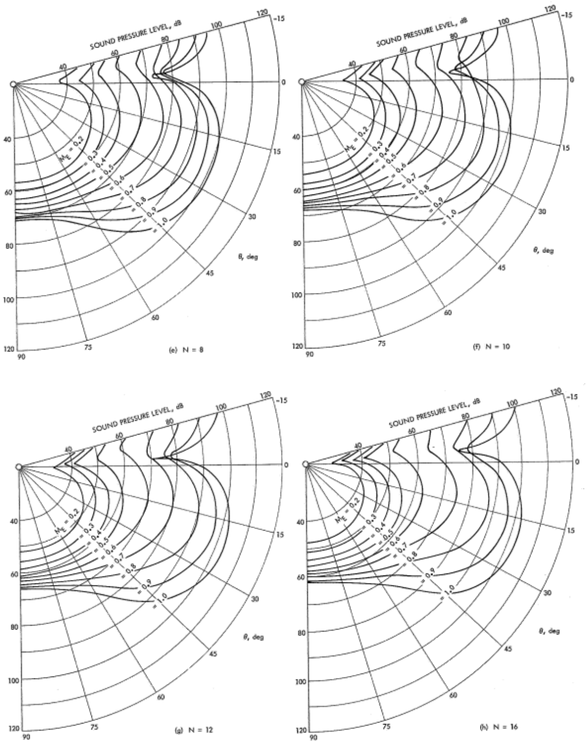


Figure D.2: Figure D.1 continued

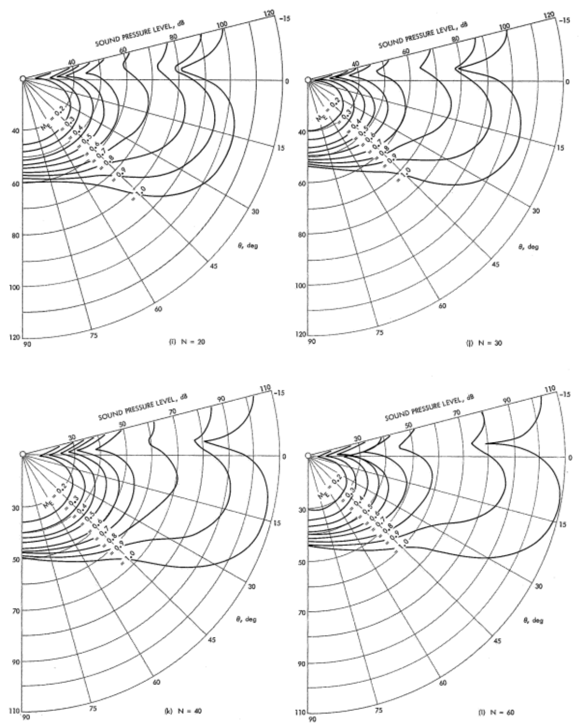


Figure D.3: Figure D.1 continued