

Spin It Up!

AE3200 Design Synthesis Final Report
Group 18

Delft University of Technology



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Executive Overview

Mission Definition

The last-mile delivery market accounts for the majority of a shipment's total cost¹. This market segment was valued at USD 167.36 billion in 2025, and is expected to reach USD 348.85 billion in 2033², while the disaster-relief market is valued at USD 14.18 billion and is expected to grow at a compound annual growth rate above 7.48% between 2025 and 2035³. Drones are considered increasingly often for cargo transport as an alternative to conventional helicopter-based logistics, due to lower operational costs, reduced emissions, and improved safety. Because of this, the autonomous drone delivery market size is expected to increase sevenfold over the next ten years⁴. However, current hybrid drone systems remain limited in payload capacity, while conventional multi-rotor configurations are inefficient for long-range transport. Recent developments [1] show that multiple drones could cooperatively transport heavy payloads suspended with cables. Additionally, the capacity could be easily increased by adding more units. Most modern systems rely on multi-rotor drones, which allow for vertical take-off and landing but are inefficient over long distances. Hybrid drones address this by combining hover capability with efficient forward flight using wings.

Spin it Up! Project Objective Statement

Design a sustainable, efficient, and cost-effective cooperative multi-hybrid-drone system to transport cargo over long distances, by a team of 11 students in 10 weeks.

The Spin it Up! project focuses on developing the Dronado system, which targets deliveries from distribution hubs to rural areas and emergency disaster-relief logistics markets as an alternative transport solution. As detailed below, the system is substantially more cost-efficient and sustainable than existing helicopter and drone delivery solutions.

Why Dronado?

- **vs. Robinson R44 (helicopter):** Five times more cost-efficient (0.0014 vs. 0.007 EUR/km/kg) and zero in-flight CO₂ emissions, compared to 0.00077 kg CO₂/kg/km for the R44^a.
- **vs. DJI FlyCart100 (multi-rotor drone):** Approximately 33% faster delivery (72 vs. 54 km/h) at roughly half the cost per kilometre per kilogram (0.0014 vs. 0.0027 EUR/km/kg).
- **vs. Trucks/Vans:** Independent of road infrastructure; critical for disaster-relief zones where roads are damaged or impassable, and for rural areas with poor connectivity.

^aURL https://robinsonstrapistorprod.blob.core.windows.net/uploads/assets/r44_2_eoc_1_july_2024_95eda9a3ae.pdf [accessed 11.06.2026]

Hardware Design

To design the hardware of the drones, an iterative approach is adopted. The diagram outlining this sizing procedure is presented in Figure 1.

¹URL: <https://www.ascm.org/topics/last-mile-delivery> accessed 17.06.2026

²URL <https://www.grandviewresearch.com/industry-analysis/last-mile-delivery-market-report> accessed 14.06.2026

³URL <https://www.marketresearchfuture.com/reports/disaster-relief-logistic-market-28824> accessed 14.06.2026

⁴URL <https://www.gminsights.com/industry-analysis/autonomous-last-mile-delivery-market> [accessed 14.06.2026]

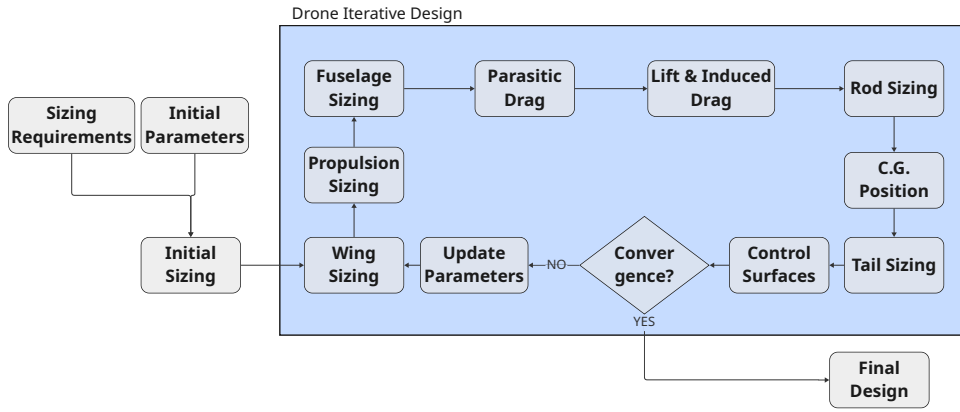


Figure 1: Flow diagram of drone design process.

The drone design is driven primarily by the need to minimise the total number of drones in the system, while ensuring sufficient load-carrying capability per drone, a challenge compounded by the 10 kg system weight limit. Because the take-off manoeuvre of other payload-carrying drone systems is more driving in their design than the cruise phase, they cannot achieve a highly efficient cruise phase. This means that a significantly higher number of drones would have to be used in the system for the same single drone mass, increasing the total system cost. A better adapted design is achieved by offloading payload lifting to the fixed wing during take-off and landing, allowing the propellers to be optimised exclusively for forward flight efficiency. This leads to a design highly optimised for the cruise phase, which could outperform existing drones in range due to high aerodynamic efficiency, while providing substantial payload carrying functionality.

Unlike conventional multi-rotor systems, no dedicated vertical take-off and landing (VTOL) rotors are required: rotatable propellers handle thrust for both cruise and take-off, eliminating the drag penalty fixed VTOL rotors would otherwise impose in forward flight. The E423 airfoil is selected for its high lift at low Reynolds numbers, while the fuselage and layout are shaped to minimise parasitic drag. The mass budget drives structural choices toward Expanded Polypropylene (EPP) foam, Glass Fibre Reinforced Polymer (GFRP) laminated wings, and a commercial off-the-shelf (COTS) Carbon Fibre Reinforced Polymer (CFRP) supporting structure, limiting weight and manufacturing complexity, while detachable wings ensure compliance with the van transport constraints. The resulting design in Figure 2 reflects integrated optimisation across propulsion, aerodynamics, and structures. Considering the electrical subsystem, a leader-follower architecture is implemented in which all three drones carry identical electronics. With this, any drone can assume the leader role upon failure. Navigation uses moving-baseline real-time kinematic (RTK) global navigation satellite system (GNSS) combined with ultra wideband (UWB) ranging to achieve centimetre-level relative positioning, alongside dedicated sensors for cable tension, angle of attack, and airspeed. All five system nodes — three drones, the payload connection, and the ground station — communicate over a unified mesh network.

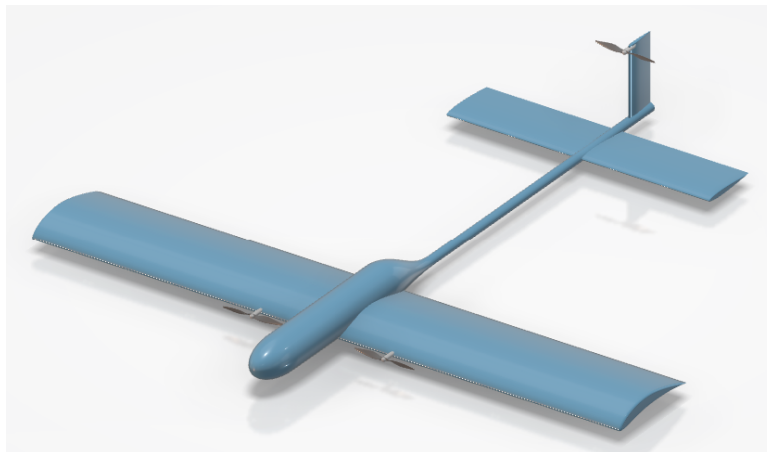


Figure 2: Final drone design.

Design Summary

Configuration

- 3 Drones
- 3 Propellers
- Span: 3.0 m
- Length: 3.0 m
- Modular wing design

Mass

- Drone Mass ($\times 3$): 7.8 kg

- Payload and Carriage Mass: 57.5 kg
- System Mass: 80.9 kg

Cost

- Total Cost Per Drone ($\times 3$): 4600 EUR
- Payload Carriage Cost: 2100 EUR
- Total Estimated System Cost: 15900 EUR

Energy

- Total Mission Energy: 1800 W h

The payload is carried in a polyester webbing net with a payload carrying capacity of 2.5 tons. This enables scalability of the system without requiring a new net in case the payload mass, size or shape is altered. Due to the novel spinning manoeuvre necessary to lift the payload vertically, the payload connector features a swivel in order to let the drones spin independently and a brake to stop the payload from spinning at cruise.

Guidance and Control

The proposed mission profile is an ambitious task for the guidance and control of the system. It involves, among other things, managing hybrid take-off and landing with propeller tilt, collaboratively lifting a heavy payload of 50 kg which induces high loads into the system, and transitioning from a spinning motion into straight cruise and vice versa. All of this while the unmanned aerial vehicles' (UAVs') motion is coupled through the cable dynamics.

While there exists research on cable-suspended payload manipulation with spinning fixed-wing UAVs [2], it has been done for small UAVs and a light payload. Additionally, the transition manoeuvre to cruise has only been theorised and for full-scale aircraft, where the payload represents less than a third of the take-off weight [3]. Furthermore, there exist no studies on the transition from cruise to spinning. This showcases the novelty of this system, because it performs this complex mission profile, while the UAVs deal with cable loads that are more than double their weight.

In order to tackle this non-trivial problem, a divide-and-conquer design philosophy is adopted. The software architecture is thus split into two modules: the trajectory planner and the flight controller. The former generates optimal full mission trajectories for the UAVs from the operators' input such that the payload follows a standard target trajectory, dictated by the mission profile. Once this trajectory has been fully defined, it is fed into the flight controller: a cascaded proportional-integral-derivative (PID) controller selected for its simplicity and wide use in fixed-wing UAVs [4]. It ensures the drones follow the trajectory using roll, pitch, yaw, and thrust commands.

UAV Controller

A cascaded PID controller is selected for its simplicity and wide use in fixed-wing UAVs [4].

Trajectory Planner

An Optimal Control Problem (OCP) is formulated to find the optimal UAV trajectories with a non-linear three degrees of freedom model of the UAV dynamics, including simplified cable and payload dynamics. In order to ensure that the resulting trajectories comply with physical limits of the UAVs, a series of constraints were applied. First, the states and control variables of this model (e.g. airspeed, thrust, etc) were bounded using the operational limits obtained from the hardware design. The rates of rotation were also restricted following the sizing of the control surfaces. Cable entanglement was especially important given the complexity of the transition from spinning to forward cruise and vice versa, so a constraint to avoid this was also implemented. The equations of motion were also discretised and enforced as equality constraints, ensuring dynamical consistency.

The objectives of this OCP should reflect the real goals of the system, the main ones being to transport the payload from the base to the delivery site and reducing energy consumption in doing so. Therefore, one term of

the multi-objective cost function ensures that the payload follows the defined reference trajectory by penalising deviations from it. Another term penalises power usage, ensuring energy-efficient transport of the payload. Additional terms were included to smoothen the state and control variables, minimise energy consumption or encourage collaborative payload carriage.

Trajectory Planner Functionality

The planner computes dynamically feasible UAV states and control histories while satisfying the vehicle, cable, and mission constraints. The solution is optimised with respect to the selected multi-objective cost function.

With the OCP being formulated, it would be unrealistic to optimise the full trajectory in a single run. That is why it is chosen to split the problem into small parts and solve it in a receding horizon fashion. This also brings the system closer to the end goal of online computing trajectory planning, as it allows for real-time updates and reduces computational time. Given the non-linearity of the OCP, the Internal Point Optimiser (IPOPT) solver is selected as it allows for simple constraint implementation and is proven to be efficient for other Non-linear Model Predictive Control implementations [5].

Weights for the multi-objective cost function are tuned using Pareto filtering, which vastly improves the initial results obtained by tuning manually across all mission phases. The robustness of the solution is tested via a sensitivity analysis, which reveals the solution of the transition from cruise to spinning descent is especially sensitive. Effort should be dedicated in the future to find a more robust tuned solution.

Final Mission Profile

The full optimised trajectories of the UAVs and the payload are shown in Figure 3.

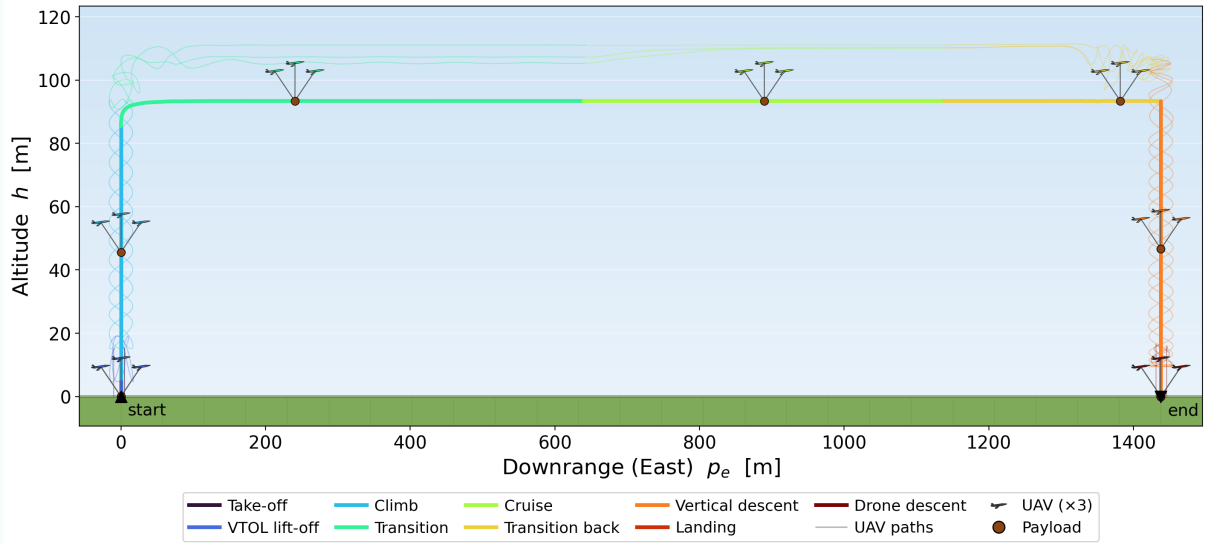


Figure 3: Overview of the trajectory for all mission phases generated by the trajectory planner with the tuned weights. The cruise phase was set to 500 m for computational efficiency and figure clarity, although it can be easily adjusted to the full 20 km mission range.

Integrated Final Design

Dronado operates as an integrated cyber-physical system composed of three system segments: the airborne swarm, the payload carriage, and the ground station. Together, these elements allow for the cooperative transportation of a 50 kg payload over 20 km. The airborne segment consists of the structures and propulsion of the UAVs, their onboard sensors, communication hardware, drone controllers, and the trajectory planner. The payload segment consists of the net, cables, and connector, containing the payload sensors. The ground segment consists of an operator interface through which the operator can determine the mission range, cruise altitude, number of drones, and perform an emergency landing, while also receiving mission information and monitoring

it.

Prior to departure, the operator needs to specify the mission parameters through the user interface. With this, the trajectory planner can compute optimal trajectories for the swarm. These trajectories will be loaded in all drones' central computers, and the leader drone will command the trajectories to each one of the UAVs during flight. The path of each one of the drones is tracked using an individual controller in each one of the UAVs. Telemetry from all UAVs and payload sensors is continuously transmitted to the ground station, allowing the operators to monitor the status of the system through the user interface, visualised in Figure 4.

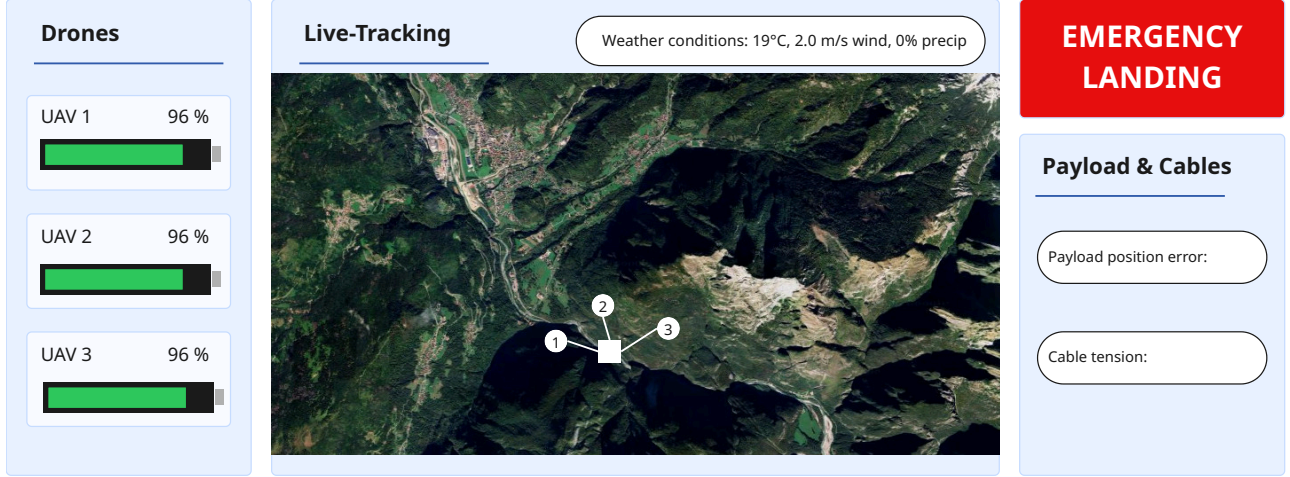


Figure 4: Example of the ground station interface used for mission supervision. The interface displays vehicle battery levels, cable tensions, payload tracking error, weather conditions, mission progress, and emergency landing button. The map background was obtained from Google Maps and shows the area over the Italian alps.

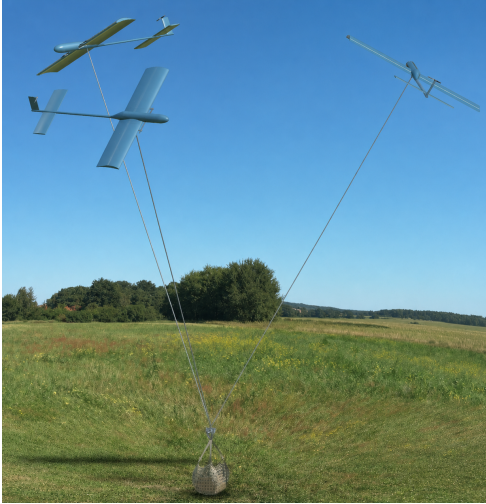


Figure 5: Physical overview of the Dronado system, showing the three-UAV swarm connected to the payload.

The integration between all the physical components described in the previous hardware design section can be visualised in Figure 5. All hardware components can be easily connected using carabiner clips, which allows for easy replacement of the drones and the payload.

The Dronado system has a very strong coupling between its subsystems. Vehicle sizing directly defines the operational limits used by the trajectory planner, while the generated trajectories drive the design of the payload connection to allow for the spinning manoeuvre for landing and take-off. Similarly, the generated trajectories determine the sensors required for the airborne and payload segments.

Table 1 summarises the key parameters that define the integrated system.

Table 1: System-level parameters of Dronado.

Category	Parameter	Symbol / Unit	Value
Mission	Nominal mission range	R [km]	20
	Nominal cruise speed	V_{cruise} [m s ⁻¹]	20
Operation	Number of operators	[-]	2
	Maximum set-up time	t_{setup} [min]	40

Continued on next page

Category	Parameter	Symbol / Unit	Value
	Total mission time	t_{mission} [s]	19.4 min
Operational Area	Required take-off area	A_{TO} [m ²]	855.3
	Storage volume	V_{storage} [m ³]	1.47
Cost	System parts cost	C_{sys} [EUR]	15 900
Material Footprint	Recyclable mass fraction	[%]	60.2
	Material-production emissions	[kg CO ₂ e]	182.4
Safety	One-drone-failure cruise range	R_{fail} [km]	1.35–6.38

Feasibility

The main challenges in realising Dronado are onboard trajectory computing and certification. Using the *acadoss* optimiser and smaller receding horizons with non-equidistant segments will allow the trajectory planner to operate sufficiently quickly within the limited resources of the onboard flight computer. Certification of Dronado is out of the scope of the DSE, but will involve consulting with European Union Aviation Safety Agency (EASA) to ensure the system operates safely within society. Certification outside of Europe will involve similar consultations with relevant regulatory authorities.

The drone's final mass (7.8 kg) and the system's cost (15,900 EUR) fall within the client's budget. A mass contingency of 2.2 kg and cost contingency of 4,100 EUR are available for future development stages. Thorough verification and validation efforts, performed throughout the entire project timeline, ensure a high level of confidence in the design fulfilling all the user requirements. In addition, further steps that need to be performed to fully validate the system are identified.

The two major system failures are also addressed: one-drone failure and one-engine-inoperative. The system can still operate safely in each case. If one drone fails, the remaining two drones can carry the payload and inactive drone to a safe location. If one of the wing engines fail, the rudder can counteract the resulting yaw moment. If the tail engine fails, the wing and tail of the drone can ensure longitudinal stability.

By the end of the DSE, Dronado has reached Technology Readiness Level 3, with the post-DSE roadmap targeting to begin operations by 2029. The system is designed for university scale manufacturing and is estimated to be manufacturable within a month, supporting a realistic and credible path to the market.

Sustainability Approach

Sustainability is taken into consideration in all phases of the Dronado system, from its design phase to its end-of-life, following a Life Cycle Analysis timeline.

In the design phase, recyclable off-the-shelf components are selected where possible to maximise the recyclable mass fraction of the system, which is a conservative estimate since the composition of the selected motors and electronic systems are not given and their recyclable mass fraction is thus set to 0. Improvements in recycling techniques in the years before Dronado enters the market are expected to increase this figure further. The total carbon dioxide equivalent of material procurement for the system is estimated at 182.4 kg.

In the manufacturing phase, simple, low-energy production methods are used wherever possible, such as hot-wire cutting for the EPP foam wing and tail and hand lay-up for composite parts. Standard, commercially available components such as CFRP rods, carabiner clips and polyester net and ropes can also be sourced second-hand, contributing to a circular economy.

During operations, system lifetime is maximised through proper battery storage, careful mission planning and regular component inspection and maintenance. The Dronado system is fully electric, meaning that its batteries can be charged using renewable energy sources which are widely accessible in the Netherlands.

At end-of-life, the system will be disassembled and recycled. Working components that cannot be recycled, such as functional sensors, can be sold second-hand or donated to TU Delft student teams. Non-recyclable parts will be disposed of safely at the appropriate facilities.

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List of Symbols

A	Cross-sectional area	$C_{m,\text{payload}}$	Payload-induced pitching moment	e_x, e_y, e_z	Position tracking errors in global axes
A_1	First Fourier coefficient (LLT)	$C_{m,\text{min}}, C_{m,\text{max}}$	Pitching moment coefficient limits	f	Signal frequency
AR	Aspect ratio of the wing	C_{m_α}	Pitching moment derivative w.r.t. AoA	F	External force
b	Wingspan	C_{m_q}	Pitch damping derivative	FF	Form factor
b_E	Elevator span	C_{m_u}	Pitching moment derivative w.r.t. speed	$\mathbf{F}_{\text{pay}}$	Resultant force on payload
b_h	Horizontal tail span	C_n	Yaw moment coefficient	F_n	Natural frequency
b_R	Rudder span	C_{n_β}	Yaw stability derivative w.r.t. sideslip angle	g	Gravitational acceleration
b_v	Vertical tail span	C_{n_p}	Yaw moment derivative w.r.t. roll rate	g_0	Gravitational acceleration
c	Wing chord length / Speed of sound (acoustic)	$C_{n_{\delta_r}}$	Yaw control derivative	G_r	Receiver antenna gain
$\bar{c}$	Mean aerodynamic chord	C_P	Power coefficient	G_t	Transmission antenna gain
c_a	Aileron chord	C_T	Thrust coefficient	h	Altitude
c_E	Elevator chord	C_{X_α}	Longitudinal force derivative w.r.t. AoA	$\dot{h}$	Rate of climb
c_h	Horizontal tail chord	C_{X_q}	Longitudinal force derivative w.r.t. pitch rate	$\mathbf{h}$	Inequality path constraint vector (OCP)
c_R	Rudder chord	C_{X_u}	Longitudinal force derivative w.r.t. speed	I	Motor current
c_v	Vertical tail chord	C_{Y_β}	Side force derivative w.r.t. sideslip angle	I_0	No-load motor current
c_w	Wing chord	C_{Y_p}	Side force derivative w.r.t. roll rate	I_{xx}	Moment of inertia about roll axis
C_{bat}	Battery capacity	$C_{y_{\delta_r}}$	Side force control derivative	I_{yy}	Moment of inertia about pitch axis
C_D	Drag coefficient	C_{Z_α}	Normal force derivative w.r.t. AoA	J	Advance ratio (propeller) / OCP cost function
C_{D_0}	Zero-lift drag coefficient	C_{Z_q}	Normal force derivative w.r.t. pitch rate	J_{qn}	Bessel function of the first kind
C_f	Skin friction coefficient	C_{Z_u}	Normal force derivative w.r.t. speed	k	Axial stiffness / Cable stiffness
C_ℓ	2D airfoil lift coefficient	d	Transmitter–receiver distance (link budget)	K_{aw}	Anti-windup gain
$C_{\ell_{\text{max}}}$	Maximum 2D airfoil lift coefficient	d_{min}	Minimum UAV separation distance	K_d	Derivative gain
C_L	Lift coefficient	D	Drag force	K_I	Integral gain
$C_{L_{\text{cr}}}$	Cruise lift coefficient	e	Oswald efficiency factor	K_i	Integral gain
$C_{L_{\text{max}}}$	Maximum lift coefficient (stall)	E	Young's modulus / Specific energy of battery	K_p	Proportional gain
$C_{L_{\text{opt}}}$	Optimum lift coefficient (max L/D)	$\mathbf{E}$	Power sharing weighting matrix	K_t	Motor torque constant
C_{L_α}	Lift curve slope			K_V	Motor velocity constant
$C_{L_{\alpha h}}$	Horizontal tail lift curve slope			L	Lift force / Distance to observer (acoustic)
$C_{L_{\alpha v}}$	Vertical tail lift curve slope			L_{AE}	A-weighted sound exposure level
C_l	Roll moment coefficient			L_{Aeq}	A-weighted equivalent continuous SPL
$C_{l_{\text{max}}}$	Maximum roll moment coefficient			L_c	Nominal cable length
C_{l_β}	Roll moment derivative w.r.t. sideslip angle			L_{cable}	Cable length
C_{l_p}	Roll damping derivative			L_0	Cable unstretched length
C_m	Pitch moment coefficient			L_m	Miscellaneous link losses
$C_{m_{ac}}$	Pitching moment coefficient (aerodynamic centre)				

L_p	Free space propagation loss	Re	Reynolds number	β	Sideslip angle / Observer angle
L_{tail}	Tail aerodynamic load	$\bar{r}_k$	Mean UAV offset from payload at node k	γ	Flight-path angle
m	Mass of the system / Mass	R_w	Motor winding resistance	γ_{max}	Maximum flight-path angle
m_{ac}	Airfoil moment about aerodynamic centre	S	Reference wing area	δ_a	Aileron deflection
$m_{battery}$	Battery mass	S_E	Elevator area	$\delta_{a,max}$	Maximum aileron deflection
m_{pay}	Payload mass	S_h	Horizontal tail area	δ_e	Elevator deflection
n	Number of propeller blades	S_{pay}	Payload reference area	$\delta_{e,max}$	Maximum elevator deflection
n_0	Initial propeller speed (sizing)	S_R	Rudder area	δ_r	Rudder deflection
N	Ground reaction force on payload	S_v	Vertical tail area	δ_t	Rotor tilt angle
N_h	Receding horizon length (nodes)	S_w	Wing planform area	$\tan \delta$	Material loss factor
N_{apply}	Number of nodes applied per solve	SPL	Sound pressure level	ε_L	Cable length tolerance
$\hat{n}_{ref}$	Desired lean direction unit vector	T	Thrust force	ε_T	Thrust convergence tolerance (sizing)
N_t	Number of discretisation nodes	$\mathbf{T}$	Cable tension matrix	ϵ_{ent}	Cable entanglement margin
N_{UAV}	Number of UAVs	$\bar{T}_{C_k}$	Mean cable tension across swarm at node k	ζ	Damping ratio
p	Roll rate	T_c	Cable tension	η_h	Horizontal tail dynamic pressure ratio
p_e	Eastward position component	$\mathbf{T}_C$	Cable tension vector	η_v	Vertical tail dynamic pressure ratio
p_n	Northward position component	T_g	Glass transition temperature	η_{total}	Total propulsive efficiency
p_q	RMS acoustic pressure (harmonic q)	$\hat{\mathbf{u}}_i$	Unit vector from payload to i th UAV	$\boldsymbol{\eta}_k$	Zero-mean unit-variance random vector at step k
p_{ref}	Reference acoustic pressure	$\mathbf{U}$	Stacked system input vector (OCP)	θ	Pitch attitude angle
$\mathbf{p}_{pay}$	Payload position vector	V	Flight speed	λ	Eigenvalue / Wavelength
P	Power	V_{bat}	Battery voltage	μ	Dynamic viscosity / Bank angle
$\mathbf{P}$	Payload tracking cost weighting matrix	V_{cr}	Cruise speed	μ_{max}	Maximum bank angle
P_r	Received signal power	V_{emf}	Back-EMF voltage	ξ	Damping ratio
P_t	Transmitted signal power	V_h	Horizontal tail volume coefficient	π	Mathematical constant π
q	Pitch rate / Harmonic number	V_i	Airspeed of i th UAV	ρ_i	Position offset of i th UAV from payload
q_{min}	Minimum dynamic pressure	V_{min}, V_{max}	Minimum and maximum airspeed limits	ρ	Air density
$\mathbf{Q}$	State rate cost weighting matrix	V_v	Vertical tail volume coefficient	σ	Wind speed std. dev. / Cable chirality sign (± 1)
r	Yaw rate	$\mathbf{v}$	Velocity vector	σ_b	Bending stress
$\mathbf{r}$	Relative position between connected elements	$\mathbf{v}_{pay}$	Payload velocity vector	σ_k	Smoothstep gate function at node k
R	Propeller radius / Mission range	$\mathbf{v}_{rel}$	Relative velocity between connected elements	σ_{allow}	Allowable stress
$\mathbf{R}$	Control rate cost weighting matrix	$W(\cdot)$	Scalar cost function weight (subscript denotes term)	τ	Turbulence correlation time / Shear stress
R_{BE}	Inertial-to-body rotation matrix	$\mathbf{w}_k$	Wind velocity vector at time step k	τ_a, τ_e, τ_r	Control surface effectiveness factors
		$\mathbf{x}$	State vector	ϕ	Roll attitude angle
		$\mathbf{X}$	Stacked system state vector (OCP)	χ	Heading angle
		x_{cg}	Centre of gravity position	ω	Angular velocity
		α	Angle of attack	ω_n	Natural frequency of the cable
		$\alpha_{min}, \alpha_{max}$	Angle of attack limits		

1. Introduction

The increasing demand for sustainable and efficient cargo transportation is driving the search for alternatives to conventional logistics systems [6]. Existing transport methods, such as trucks and helicopters, are associated with high operating costs, significant environmental impact [7, 8], and infrastructure constraints. While unmanned aerial vehicles (UAVs) offer a promising alternative [9], current drone-based transport solutions are each sized around a single design payload: multi-rotor drones provide excellent vertical take-off and landing capabilities but are inefficient over long distances, whereas fixed-wing aircraft offer higher efficiency at the cost of operational flexibility [10, 11]. In both cases, capacity is fixed at design time, and accommodating heavier or lighter loads requires re-engineering the product rather than reconfiguring the system, so conventional solutions scale poorly with mission demand. This leaves a gap for a cargo transport system that pairs long-range efficiency and VTOL capability with payload scalability to meet varying mission requirements [12, 13].

Mission Need Statement

Provide a scalable and energy-efficient aerial cargo transport system capable of delivering payloads over long distances without reliance on ground infrastructure.

While the mission need statement defines the broader transportation challenge, it remains too general to directly guide the design process. Therefore, the mission need was translated into a more specific project objective that reflects the scope, resources, and time frame of this Design Synthesis Exercise.

Project Objective Statement

Design a sustainable, efficient, and cost-effective cooperative multi-hybrid-drone system capable of transporting cargo over long distances, developed by a team of 11 students within a period of 10 weeks.

With the objective of the Spin it Up! project defined, the Dronado system is proposed to fulfil it. Throughout the report, the name Dronado will be used to refer to the system. Dronado presents a novel alternative to conventional transportation methods, in which multiple UAVs cooperatively carry a single suspended payload. Each UAV connects to the payload through a dedicated carriage mechanism that distributes the load, allowing the system to scale to heavier payloads by adding UAVs rather than enlarging any single vehicle. A trajectory planner then computes an optimal, coordinated trajectory for each UAV, and a controller drives the drones to follow it. This report documents the process from concept selection through to the final detailed design of the complete system.

Chapter 2 analyses the market environment, identifies relevant stakeholders, and evaluates the competitive position of the concept. Chapter 3 presents the design concepts considered and the trade-off analyses performed to select the preferred solution. The selected concept is then further defined through a functional analysis in Chapter 4. Chapter 5 to 6 establish the overarching design framework by addressing technical risks, sustainability considerations, and the design methodology adopted throughout the project.

The detailed subsystem design is presented in Chapter 7 to 15. These chapters cover the aerodynamic, structural, propulsion, electrical, communication, guidance and control, trajectory optimisation, flight control, and simulation aspects of the system. Verification and validation activities are included where applicable to assess compliance with the established requirements.

The integrated system is subsequently evaluated from a system-level perspective. Chapter 16 describes the overall verification and validation approach, while Chapter 17 to 19 assess critical design considerations, budget allocation, and system performance. Chapter 20 presents the final system description, integrating the results of the individual subsystem designs.

Chapter 21 to 25 address implementation, including production, operations, reliability, sustainability, and future development. Finally, Chapter 26 and Chapter 27 present recommendations for future work and conclusions.

2. Market Analysis

In this chapter, the market areas for Dronado will be defined and analysed. First, the market is defined in Section 2.2, then stakeholders are identified in Section 2.3. The system is directly compared to its market alternatives in Section 2.4, and a SWOT analysis for Dronado is provided in Section 2.5.

2.1. Dronado System Overview

The Dronado system consists of three fixed-wing drones, each equipped with three movable propellers. The drones are connected through ropes to a central payload connector, which carries the payload underneath the formation. This configuration enables coordinated payload transport and offers scalability, as additional drones could increase the system's lifting and transport capability.

The swarm is operated through a user-friendly interface, where the operator defines the mission parameters and the system automatically generates feasible trajectories for each drone. These trajectories are then tracked using a cascaded PID control architecture.

This overview provides the technical context needed to assess the system's market potential in terms of cost, performance and operational carbon emissions.



Figure 2.1: Physical overview of the Dronado system during cruise.

2.2. Market Definition

The recent growth of e-commerce requires new, more efficient and sustainable alternatives for transportation of goods [6]. Dronado is a novel, sustainable drone-swarm transportation system that enables operators to define missions through a user-friendly interface, which automatically generates the coordinated trajectories for the UAVs. The versatility of the Dronado system allows it to enter two logistic market segments: rural and hard-to-access last-mile delivery and emergency logistics. These areas require a delivery system capable of operating with limited infrastructure, meeting urgent delivery times, and reaching inaccessible destinations, capabilities that Dronado is designed to provide. These market segments are described in detail in the following sections.

Rural and hard-to-access last-mile delivery

The last-mile delivery market can account for 53% of shipment's total cost¹, which makes it usually the most expensive part of the transport chain. It is the final transport step between a distribution point and the final user. This market segment was estimated at USD 167.36 billion in 2025, and is projected to reach USD 348.85 billion in 2033². More in detail, the autonomous last-mile delivery market size is USD 1.6 billion in 2026 and is expected to grow to USD 11.5 billion in 2035³. Although these numbers concern the whole market, the smaller rural last-mile delivery is following the same trend⁴. For deliveries to remote rural areas, vans are often too slow, expensive or unreliable due to low delivery density or poor infrastructure [14]. These remote locations include farms, islands, mountain communities and small towns far from distribution centres. In these cases, the

¹URL <https://www.ascm.org/topics/last-mile-delivery/> [accessed 17.06.2026.]

²URL <https://www.grandviewresearch.com/industry-analysis/last-mile-delivery-market-report> [accessed 14.06.2026.]

³URL <https://www.gminsights.com/industry-analysis/autonomous-last-mile-delivery-market> [accessed 14.06.2026.]

⁴https://english.www.gov.cn/archive/statistics/202308/15/content_WS64db757fc6d0868f4e8de941.html [accessed on 18/06/2026]

Dronado system can provide a more direct transport option, especially when the road distance is much longer than the straight-line distance, or the payload is too heavy for small delivery drones. Furthermore, these remote areas usually have large available fields, where the system could effectively land.

Emergency, medical, and disaster-relief logistics

This market area targets transportation of goods such as medical supplies, emergency tools, food, water, batteries, and other essential cargo to locations affected by floods, landslides, earthquakes, storms, or infrastructure failure. An example of this is Hurricane Maria in September 2017, where researchers estimate most deaths were caused by loss of access to medicines, which demonstrated that helicopter emergency logistics are limited during large-scale disasters, especially when many disperse communities require simultaneous support. The current approach being developed and tested in Puerto Rico to solve these problems is autonomous drone delivery⁵.

The current disaster relief logistics market is valued in USD 14.18 billion and is expected to grow at a compound annual growth rate above 7.48% between 2025 and 2035⁶. The target area for Dronado in this market is the delivery of medium-weight emergency cargo over distances of around 20 km.

2.3. Stakeholder Analysis

All these market segments are growing rapidly. To succeed in them, collaboration between the various stakeholders is important for its success. Table 2.1 summarises the main stakeholders for the Dronado system.

Table 2.1: Main stakeholders for the Dronado system. Stakeholders are divided into key and others.

Key Stakeholders		
ID	Stakeholder	Description
OPR	Operators and maintenance personnel	People responsible for operating the system. The system should therefore be user-friendly, require limited training, and allow safe operation.
CUS	Customers	Customers depend on the specific market segment. They may include logistics companies, industrial site operators, hospitals, clinics, rural communities, or people requiring emergency supplies.
CIV	Civil aviation authorities (EASA)	Regulatory bodies responsible for certification and safety requirements for UAV operations.
POP	Local populations	People living near or below the operating area, who want low disturbance to their community, safety, and privacy.
FAU	Fauna	Wildlife that may be affected by noise, flight paths, or landing areas.
Other Stakeholders		
ID	Stakeholder	Description
INS	Insurance providers	Organisations that provide liability and operational risk coverage, influencing the feasibility and cost of commercial operation.
ENG	Engineering and internal manufacturing team	The in-house team responsible for designing, producing, testing, and maintaining Dronado. They need feasible technical requirements, manufacturable components and clear subsystem interfaces.
GIN	Ground infrastructure providers	Organisations or site owners providing landing areas, storage locations, maintenance space, and other supporting infrastructure.
COM	External component providers	External suppliers of off-the-shelf parts (motors, batteries, electronics). They determine part cost, lead time, and availability, which constrain the design space available to the engineering team.

These stakeholders were classified according to their relative interest and influence to define the appropriate

⁵URL <https://www.directrelief.org/2018/08/direct-relief-merck-and-partners-test-temperature-controlled-autonomous-drone-delivery-system-for-medicines-in-puerto-rico/> [accessed 14.06.2026.]

⁶URL <https://www.marketresearchfuture.com/reports/disaster-relief-logistic-market-28824> [accessed 14.06.2026.]

engagement strategy for each group. Figure 2.2 shows the position of each stakeholder group within the matrix. The labels shown in the figure correspond to the stakeholder IDs defined in Table 2.1.

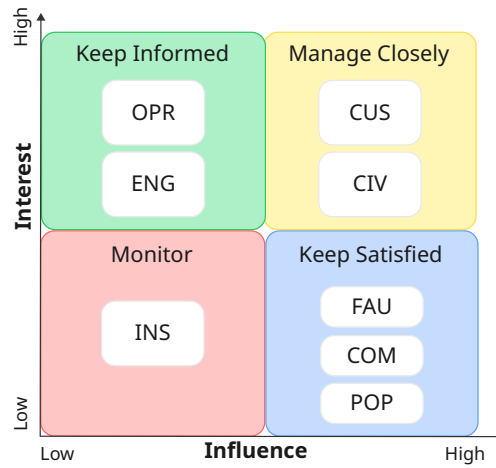


Figure 2.2: Stakeholder interest–influence matrix.

2.4. Competitive Positioning

The development of Dronado is motivated by the need for a more efficient, flexible, and sustainable alternative to existing transport solutions. This section quantifies the system’s market competitiveness by analysing the key factors affecting its commercial potential. Comparison will be made to the Robinson R44, a widely used lightweight helicopter, also used to carry suspended loads, and the DJI FlyCart100, a partially autonomous delivery drone with similar payload carrying, velocity and range characteristics as Dronado. The following section addresses the four main factors influencing the system’s competitiveness.

2.4.1. Comparison Criteria

To assess the competitiveness of the system it is necessary first to define which criteria will determine it. Three main factors have been considered: cost, performance, and sustainability. The following sections describe in detail how each one of these factors is quantified for the current system. For each one of the metrics the estimated values will be calculated for the two main competitors: the Robinson R44 and the DJI FlyCart100.

Cost

In this section, the total cost each market competitor will be analysed. This will be done by quantifying cost with the metric of cost per distance per kilogram transported, EUR/km/kg, at maximum payload capacity, which allows for measuring the amount of money it takes to transfer some payload. This metric allows a fair comparison with other competitors, such as drones, trucks, and helicopters.

The plain hardware cost of Dronado is given by STK14, stating the system should cost not more than 20,000 EUR. Its manufacturing costs, and the following market price are not yet clear. The product is still in its design phase, after which large prototyping, testing, and development phases follow, as will be specified in Chapter 25. To estimate the final market cost of the system, we take a realistic but rough approximation of 40,000 EUR, based on readily available drones of around the same weight, like the DJI Matrice 350 RTK ⁷. Assuming a life cycle time of around 10 years, including maintenance and replacement where needed, like a yearly overhaul with battery replacement, costs would be around 60,000 EUR for ten years. Assuming 500 operating hours per year, this would amount to around 3.60 EUR per mission. Operating costs consist only of energy costs and potential piloting costs, which will not be taken into account for this baseline calculation since the system can operate autonomously. Energy costs are calculated through the electrical energy used per mission. Adding up purchase, maintenance, and operating costs, the total price per kilogram per kilometre is 0.0014 EUR/km/kg

Helicopter expenses are quantified in an operating costs estimation by the manufacturer Robinson ⁸. This

⁷<https://www.dji.com/nl> [accessed on 16/06/2026]

⁸https://robinsonstrapistorprod.blob.core.windows.net/uploads/assets/r44_2_eoc_1_july_202

document indicates a total operating cost of 270 EUR per operating hour. While this calculation already includes fuel, manufacturing, and maintenance costs, this calculation assumes no ground handling, pilot and hangar costs. Also, this document assumes normal operation conditions, whilst when moving a suspended payload, the lift required and the extra drag cause a higher fuel usage.

500 flight hours per year are assumed, just as in the operating costs estimation. Together with a hangar rent of around 1200 EUR per month⁹, this leads to an increase of 28.8 EUR per flight hour. Adding a pilot's wages, this increases again by around 25 EUR per hour¹⁰. Ground handling costs are around 75 EUR per mission¹¹, and by conservatively estimating a mission time of around 2.5 hours, this would add 25 EUR per flight hour. Adding this up, the R44 costs approximately 350 EUR to operate per hour. To convert this number, to the global metric defined previously, the helicopter cruise speed is assumed at $V_{cr} = 75$ KIAS [8], which results in cost per payload weight per meter of 0.007 EUR/km/kg. This number should be treated with caution however, as many of these helicopter specific costs selected vary largely.

The FlyCart100's yearly expenses are analysed the same as the R44's and Dronado's. Yearly operating hours are 500, the system lasts 10 years, and yearly 5% of the total system price is reserved for maintenance. This leads to around 1.05 EUR per mission, resulting in a contribution 0.001 363 EUR/km/kg. Its operational costs are low: Set-up is not necessary, and operation does not need a middleman: It can be done autonomously¹², or controlled by the receiver or sender, where, in the latter case, expenses have to be incurred for this certified operator. In its maximal range configuration the FlyCart100 uses two 42 A h 52 V batteries, and cruises at a cruise speed of 15 m s^{-1} whilst carrying a payload of 65.3 kg. Using current electricity prices, and assuming all energy is consumed during flight, the drone operational cost added is 0.001 347 EUR/km/kg, which results in a total cost per kilometre per kilogram of 0.0027 EUR/km/kg.

Delivery Speed

The second competitive comparison made between market competitors looks at delivery speed, measured in the delivery velocity for a reference mission. Aerial systems do not have to wait for traffic, and can mostly take the most direct route through the air. By using nominal regulatory maximum speeds and adding the penalty, the Robinson R44 achieves a delivery speed of 136 km h^{-1} , the FlyCart100 54 km h^{-1} , and Dronado 72 km h^{-1} . This places Dronado between conventional helicopters and multirotor cargo drones, offering significantly faster deliveries than existing drone solutions while maintaining lower operating costs and emissions than helicopters.

Range

Range is another key criterion which can not be left out when analysing aerial delivery solutions, is its range. Where the range of the FlyCart is 12 km, the ranges of the Dronado system and the R44 require some analysis. A key feature of the Dronado system is its scalability, meaning more drones can be added to the swarm when more range is demanded for the mission, although adding drones to the swarm would also increase cost. This scalability is illustrated in Figure 19.2. The range of the R44 depends heavily on how much payload it carries. Since a helicopter can not exceed its maximum gross weight, every kilogram saved on the payload is a kilogram of fuel added. Subtracting an 800-pound maximum external load and a 170-pound pilot from the Robinson R44's roughly 1,000-pound useful load leaves only 35 pounds of available weight for fuel. Because the helicopter consumes approximately 15 gallons of fuel per hour, this restrictive 5.8-gallon allowance equates to a theoretical flight time of just 23 minutes before engine starvation. Multiplying this with a cruise velocity of 136 km h^{-1} , an approximate range of 52 km is obtained.

Operation Carbon Emissions

The last criterion that will be examined are the greenhouse emissions emitted during operation. Although there are a lot of aspects to sustainability, as explained in Chapter 24, sustainability in this market analysis will

4_95eda9a3ae.pdf [accessed on 11/06/2026]

⁹(Vliegvelde Teuge, private communication, 15 June, 2026)

¹⁰<https://helijobs.net/2022/02/aw139-ec135-police-pilot-the-netherlands/> [accessed on 15/06/2026]

¹¹<https://denhelderairport.nl/wp-content/uploads/2025/01/Basic-Handling-rates-DHA-2025.pdf> accessed on [15/06/2026]

¹²<https://www.dji.com/nl/media-center/announcements/dji-release-dji-flycart-100> [accessed on 15/06/2026]

be quantified through the metric CO₂ emissions per kilogram of payload transported per kilometre travelled. For helicopters, this is 0.000 77 kgCO₂/kg/km^{13 14}, where both the multirotor solution and Dronado will be assumed charged with sustainably harvested electricity, and as such their emissions are assumed zero.

2.4.2. Competitiveness Analysis

Now that all the criteria for assessing competitiveness have been defined, the main competitors and Dronado are quantitatively compared in Table 2.2. From this comparison it can be concluded that Dronado has the specifications and the profitability to make a direct impact with its efficient and sustainable aerial delivery capabilities. It is seen that for long range and heavy payloads the fossil-fueled helicopter is still superior in performance, and for small payloads and shorter ranges the multirotor, but for moderate ranges and payload weights Dronado is the most effective solution.

Table 2.2: Quantitative comparison of the helicopter, multi-rotor and Dronado.

Criterion	Robinson R44	FlyCart 100	Dronado
Cost [EUR km ⁻¹ kg ⁻¹]	0.007	0.0027	0.0037
Delivery Speed [km h ⁻¹]	136	54	72
Range [km]	52	12	20 - 38
CO ₂ emissions [kgCO ₂ kg ⁻¹ km ⁻¹]	0.00077	0	0

2.5. SWOT Analysis

The main advantages and disadvantages of the Dronado system are summarised in a SWOT diagram in Figure 2.3. The Dronado system will have a smaller operational cost compared to competitors presented in Subsection 2.4.2. This is caused by the transition to efficient fixed-wing flight in cruise and the flexibility to adjust the amount of drones carrying the payload. Making the cruise phase more efficient is essential as the power of the system accounts for 40% of the life cycle cost of drone delivery systems according to Raghunatha et al. [15].

The flexibility to adjust the number of drones carrying the payload provides significant operational benefits. First, the system offers greater reliability than competing solutions, as the failure of a single drone does not result in failure of the entire system. Furthermore, the system is highly scalable: for heavier or lighter payloads, the number of drones can be adjusted accordingly, ensuring efficient utilisation of the fleet throughout its lifetime. The primary disadvantage of the Dronado system is the large take-off and landing area required for operation.



Figure 2.3: Dronado system SWOT analysis.

¹³https://robinsonstrapistorprod.blob.core.windows.net/uploads/assets/r44_2_eoc_1_july_2024_95eda9a3ae.pdf [accessed on 11/06/2026]

¹⁴<https://www.4air.aero/carbon-calculator> [accessed on 16/06/2026]

3. Design Concepts & Trade-Off

3.1. Design Concepts

This section summarises the design concepts considered for the development of the Dronado system, establishing the two trade-offs that drive final concept selection: drone configuration and payload carriage design. The Design Option Tree (DOT) methodology was used to explore each subsystem, eliminating infeasible options based on requirement violations, excessive complexity, or poor aerodynamic performance.

3.1.1. Drone Configurations

Four drone configurations are considered for the trade-off, illustrated in Figure 3.1: Figure 3.1a shows a **monoplane with three movable propellers**, two front and one rear, with a conventional tail. Figure 3.1b shows a **monoplane with two front movable propellers**, enabling VTOL without landing gear. Figure 3.1c shows a **flying wing tail-sitter** with two fixed wing-mounted propellers. Figure 3.1d shows a **monoplane with fixed propellers** in a lift-plus-cruise propeller arrangement.

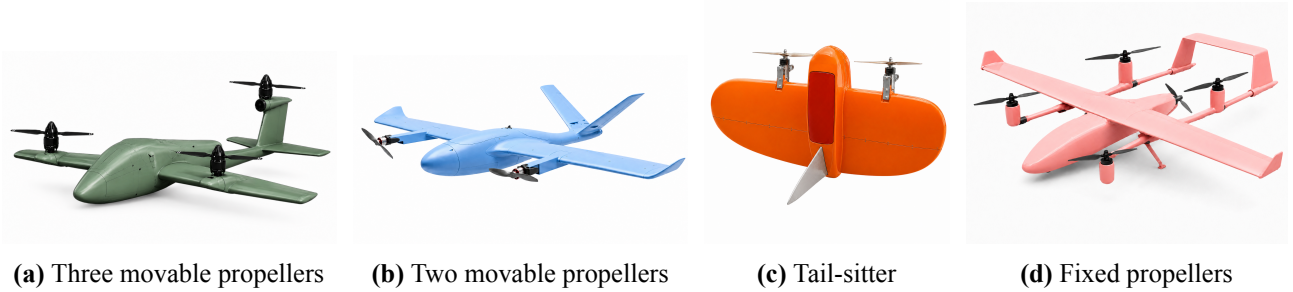


Figure 3.1: Overview of the four selected drone configurations considered for trade-off¹.

3.1.2. Payload Carriage Design

Two decisions were fixed across all payload concepts: a single-point carabiner clip connection, which decouples payload rotation from the drones and simplifies control, and a policy of leaving a failed drone hanging rather than releasing it, to avoid ground safety risks. Four holder geometries and stabilisation strategies were carried forward for the trade-off, shown in Figure 3.2: Figure 3.2a shows a **net**. Figure 3.2b shows an **airplane shape**. Figure 3.2c shows a **teardrop shape** relying on geometry alone. Figure 3.2d shows a **spheroid shape** for aerodynamic efficiency with a good internal payload volume.

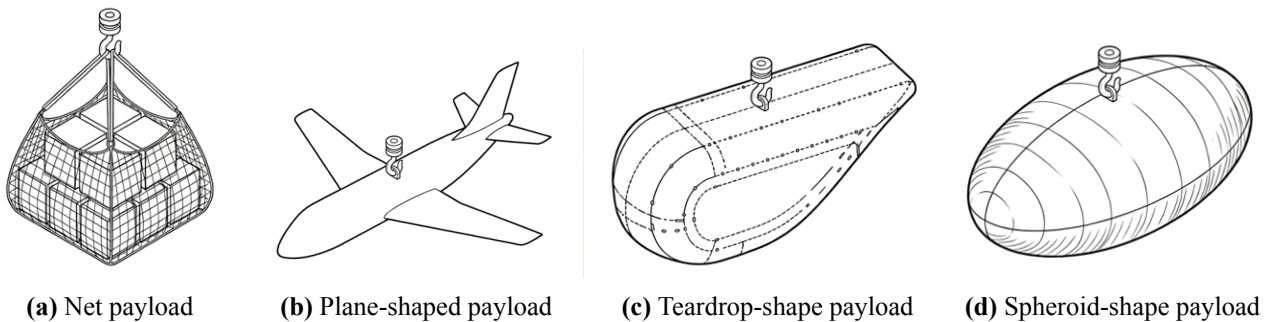


Figure 3.2: Four selected payload concepts considered for trade-off (author's sketches, refined using AI tools)²

¹Communication with ChatGPT, dd. 28/05/2026.

²Communication with ChatGPT, dd. 01/05/2026.

3.2. Trade-Off Analysis

This section presents the trade-off analyses used to support the selection of the final system configuration for both the drone platform and the payload carriage. Each concept is evaluated using a weighted set of design criteria to enable consistent comparison between alternatives. The weighting justification is omitted for conciseness. Instead, emphasis is placed on the justification of the assigned grades.

3.2.1. Drone Configuration

The trade-off for the drone configuration summarises the design deliberation of the team. The flying wing scores highest in aerodynamic performance and cost due to the absence of a tail, but receives the lowest control complexity score because of its coupled lateral-longitudinal dynamics. The monoplane with fixed propellers achieves the highest control complexity score, but the four unused VTOL propellers and their booms impose severe mass, drag, and cost penalties during cruise. The monoplane with two movable propellers scores well across most criteria but has a moderate control complexity during take-off. The monoplane with three movable propellers achieves the highest control complexity score among the monoplane concepts while maintaining competitive mass, cost, and volume scores. As shown in Table 3.1, the monoplane with three movable propellers achieves the highest score with a clear margin and is selected for the preliminary design phase.

Key Choice: Drone Design

The drone will be a monoplane with three movable propellers, two in the wings and one in the vertical tail. This option performs well in mass, cost, and control. **Three drones** will be used in the system.

Design Decision: Number of Drones

The number of drones was selected based on an analysis of the dependency of total system mass and energy on the number of drones, as presented in Figure 3.3.

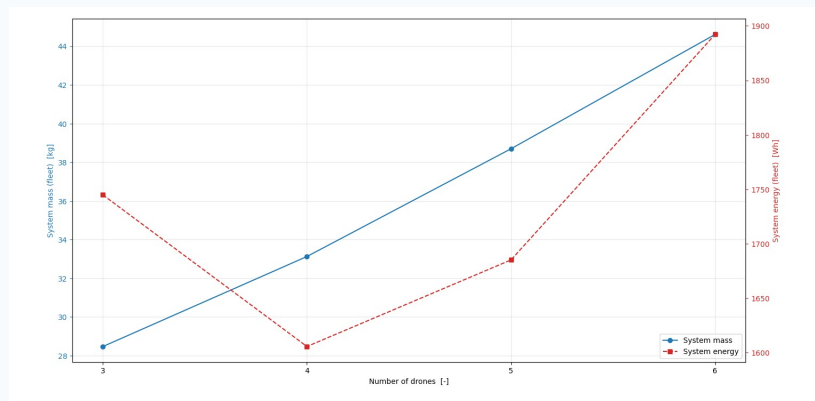


Figure 3.3: Sensitivity analysis of the effects of number of drones on total system mass and energy.

Although increasing the number of drones allows for a lighter design of a single vehicle, it is clear that this saving does not offset the mass increase of adding another drone, because the total mass monotonically increases with number of drones. Additionally, it is expected that the total cost will scale roughly proportionally to the total system mass. This suggests that the number of drones should be minimised. However, the required energy capacity of the system reaches a minimum for the 4-drone configuration. A larger number of drones increases total drag, requiring more energy; with too few drones, the large propellers are less energy efficient. In general, the number of drones needs to be chosen such that mass and energy minimisation are balanced. Hence, three drones were chosen as the optimal configuration, as a system of four drones would weigh 12% more, while only saving 8% of the total energy. Three drones is the minimum number of drones, because redundancy must be ensured in case one of the drones fails.

3.2.2. Payload Carriage Design

For the payload carriage, several design concepts were evaluated using a weighted trade-off analysis. Aerodynamic shapes such as the plane, teardrop, and spheroid performed well in terms of aerodynamic efficiency.

Table 3.1: Trade-off table for drone design options.

Criterion Option	Control Complexity (25%)	Mass (20%)	Cost (20%)	Aerodynamic Performance (20%)	Volume (15%)	Score (/500)
Flying Wing with Two Movable Propellers	[1] Highly coupled lateral and longitudinal dynamics and small stability margins. Unpredictable up/downwash. Moments generated by the tensional loads are hard to control [16].	[4] Main frame is light. Sweep and large elevons require more structural strength and thus weight. No tail and tail boom reduce weight. Large control surfaces and strong control servos add weight [16].	[4] No big cost factors, except that the wing can be manufactured in one piece, reducing part count and costs.	[5] The aerodynamic characteristics of the flying wing are the reason to go for this option. A larger overall lift over drag is achieved by omitting a tail [16].	[4] Size is suitable for the mission. Lower needed aspect ratio and no tail makes the volume compact.	345
Monoplane with Two Movable Propellers	[3] Good stability and controllability for cruise. May struggle with unpredictable forces and up/downwash during non-standard take-off manoeuvre.	[4] Small weight increase from propellers with light movable hinges. Large slender wing is efficiently carried by beams spanning wingtips [16].	[4] Normal configuration with two added servos for the propellers, which do not cost much.	[4] Two propellers in front of the monoplane V-tail configurations will provide efficient aerodynamic characteristics [17].	[3] Long tail and slender wing may need to be modular to meet volume requirement.	360
Monoplane with Fixed Propellers	[5] Pusher and quadcopter configuration is suitable for unpredictable forces and up/downwash. Supports vertical take-off and landing.	[2] The four unused propellers and mounts during cruise add dead mass and drag, increasing battery size and mass.	[2] Five engines and large battery increases cost.	[1] Multiple propellers provide drag in cruise. This significantly reduces the lift-over-drag ratio [18].	[3] Total volume increased due to external rails. Hard to make modular.	270
Monoplane with Three Movable Propellers	[5] Good stability and controllability characteristics suitable for unpredictable forces and up/downwash. The third movable propeller on the tail improves controllability and supports easy vertical take-off and landing.	[4] Three movable propellers with movable hinges add weight. Large slender wing is efficiently carried by beams spanning wingtips.	[4] Normal configuration with three servos for the propellers, which do not cost much.	[3] Third propeller will be in wake of the two front ones, worsening its performance [19]. Furthermore, during vertical take-off, the horizontal tail will be in the wake of the third propeller.	[3] Has long tail and slender wing planform, may have to be made modular to meet volume requirement.	390

However, they generally scored lower in other criteria, including cost and unused volume. In contrast, the net-based solution, despite having the lowest aerodynamic efficiency, scored highly in effective weight due to its low mass, cost due to its simplicity, and volume utilisation because it can adapt to the shape of the payload.

Table 3.2: Trade-off table for payload carriage design options.

Crite- rion Option	Eff. Weight (25%)	Aero Eff. (20%)	Recyclability (20%)	Cost (20%)	Unused Vol. (15%)	Score (/500)
Spheroid	[2] No lift generation, additional structural mass required.	[3] $Cd \approx 0.2$ for $Re > 210^5$	[3] Requires polymer or CNC, recycling limitations, material waste.	[4] Simple geometry enables low-cost manufacturing processes.	[4] Inefficient packing for cubic payloads.	310
Teardrop	[3] Partial lift contribution, reduces net structural load.	[5] $Cd < 0.1$ under typical operating conditions.	[4] Sheet-based manufacturing possible, but limited recyclability of materials used.	[3] Moderate complexity increases manufacturing cost.	[3] Unused aft volume due to shape constraints.	360
Plane	[5] Lift generated by wing reduces payload support requirement.	[4] Aerodynamically optimised surfaces, but residual drag from fuselage and tail.	[3] Complex geometries, mixed materials increase recycling difficulty.	[2] High manufacturing cost due to structural and aerodynamic complexity.	[2] Wing and tail volumes not usable for payload storage.	335
Net	[4] Minimal structural mass, no lift contribution.	[1] $Cd \approx 1.05$ assuming cubic payload geometry.	[5] Highly recyclable, minimal manufacturing waste. ³	[5] Very low cost, commercially available solution.	[5] Adapts to payload shape.	395

As shown in Table 3.2, the net achieved the highest overall score due to its strong performance across all non-aerodynamic criteria. The team evaluated that the gains in weight, manufacturability and recyclability outweigh the gains in aerodynamic performance from other designs.

Key Choice: Payload Carriage Design

The payload carriage will be a net enclosing the payload. This option performs well in manufacturing, recyclability, mass, and cost. It also has minimal unused space for storing payloads.

3.3. Concept Description

The selected concept consists of a swarm of drones connected to a shared payload through cables. The drones have three moveable propellers that serve both for VTOL and forward flight. The payload is enclosed within a net, which serves as the payload carriage system. The number of drones can be adapted depending on the payload requirements. A schematic overview of the concept is shown in Figure 3.4.

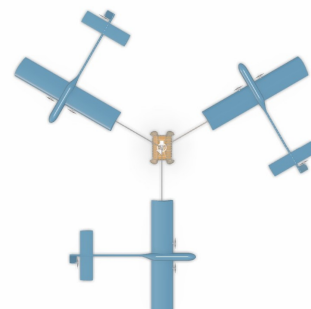


Figure 3.4: System concept description.

4. Functional Analysis

The first step in a design process is defining the functions the system shall perform. Before determining how to achieve the mission, it must be established what it needs to be achieved. These functions encompass the entire life cycle of the product: the design, manufacturing, operation, and maintenance. This ensures that all design decisions remain traceable to a clearly defined set of system objectives. First, the system mission is decomposed into the Functional Breakdown Structure (FBS) in Section 4.1, after which this breakdown is chronologically ordered into a functional mission description in Section 4.2. The functions identified here form the basis for the requirements and subsystems developed in the following chapters.

4.1. Functional Breakdown Structure (FBS)

The first method used to identify and subdivide the functions performed by the projects' systems is the FBS shown in Figure 4.1. It ensures a clear structure by subdividing all functions of the system hierarchically into the lower-level functions that they consist of, thus creating four levels. The highest level, in blue, contains the overarching life cycle, namely the system creation, operation, and maintenance. The second, third, and fourth levels, in green, yellow, and red, contain each parent's subfunctions. This provides a clear overview of the functions the system and its subsystems should perform during their life cycle. Each function also has its own unique code and specifies by which system it will be performed, as described in the figure's legend.

The FBS reveals that the operational phase is the most functionally complex. It encompasses system set-up, take-off, cruise and landing. The cooperative nature of the swarm introduces functions that would not appear in a single drone system, particularly those related to the coordinated manoeuvres.

4.2. Functional Flow Block Diagram (FFBD)

With the functions of the system defined in the FBS, the sequence of the functions is shown in the FFBD in Figure 4.2. This sequential approach of analysing the mission also helps reveal previously overlooked functions, which then can be added back to the FBS.

The sequential relationship between functions is symbolised by solid arrows, while the hierarchical structure is shown by means of dashed arrows. The FFBD also includes logic by means of AND-trees, OR-trees, and conditional statements. AND trees signify functions that must all be performed, in no particular order to fulfil the higher-level function they derive from. OR trees denote collections of functions of which only one is performed. Conditionals determine the subsequent flow of functions depending on the system state.

The FFBD shows that drone failure is a major design consideration of the system. Flight parameters should be monitored continuously to ensure that they are nominal. In case that they are not, a contingency plan has to be in place to prevent total failure of the system.

The maintainability of the system is emphasised, where the course of action is determined by system state that follows from inspection. In the case of a damaged component, the system should allow easy access to components in order to repair or replace them. This will extend the lifetime of the system. The system will only be decommissioned if repair is not possible.

It should be noted that the functions F0 manufacture the system and F2 maintain the system, and their subfunctions are not performed by the system itself, but are instead performed on the system.

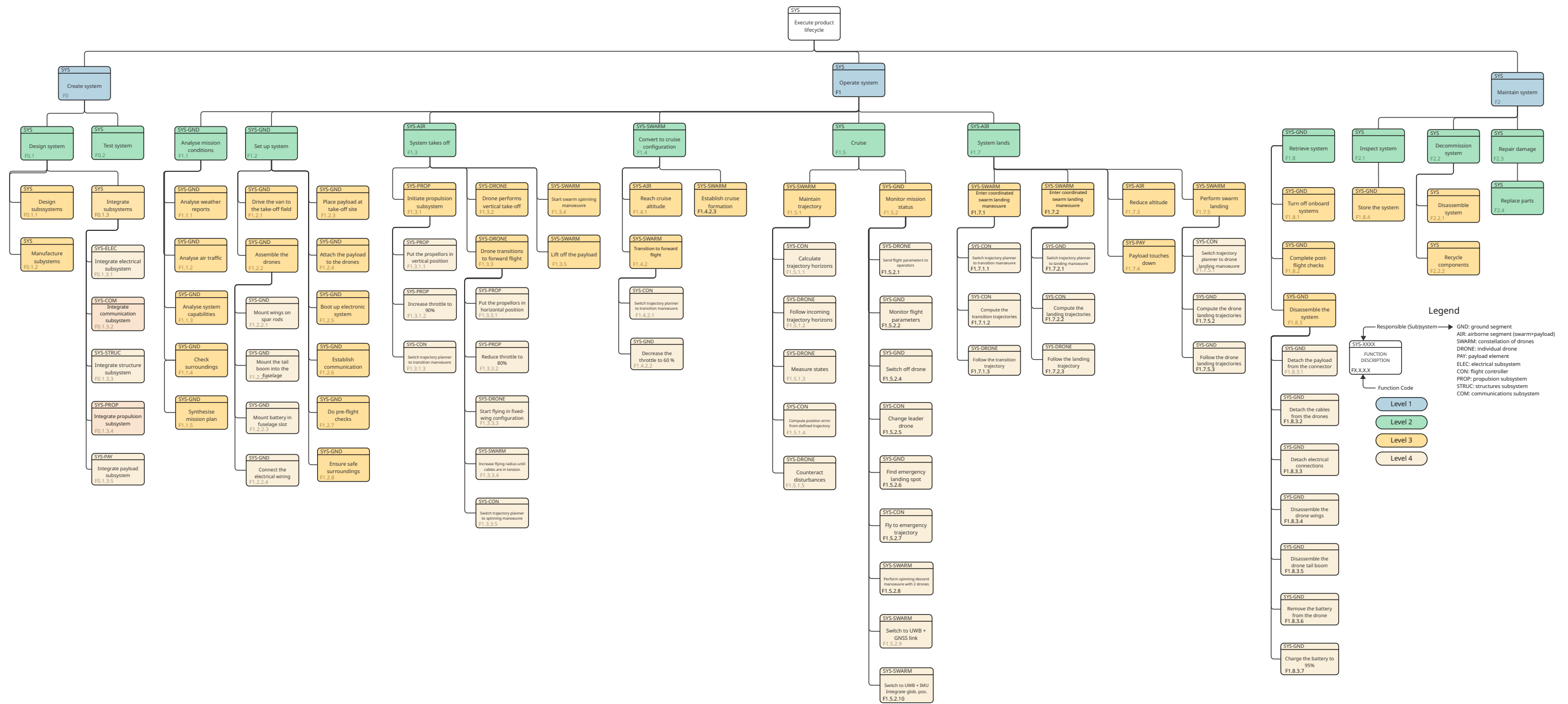


Figure 4.1: Functional Breakdown Structure.

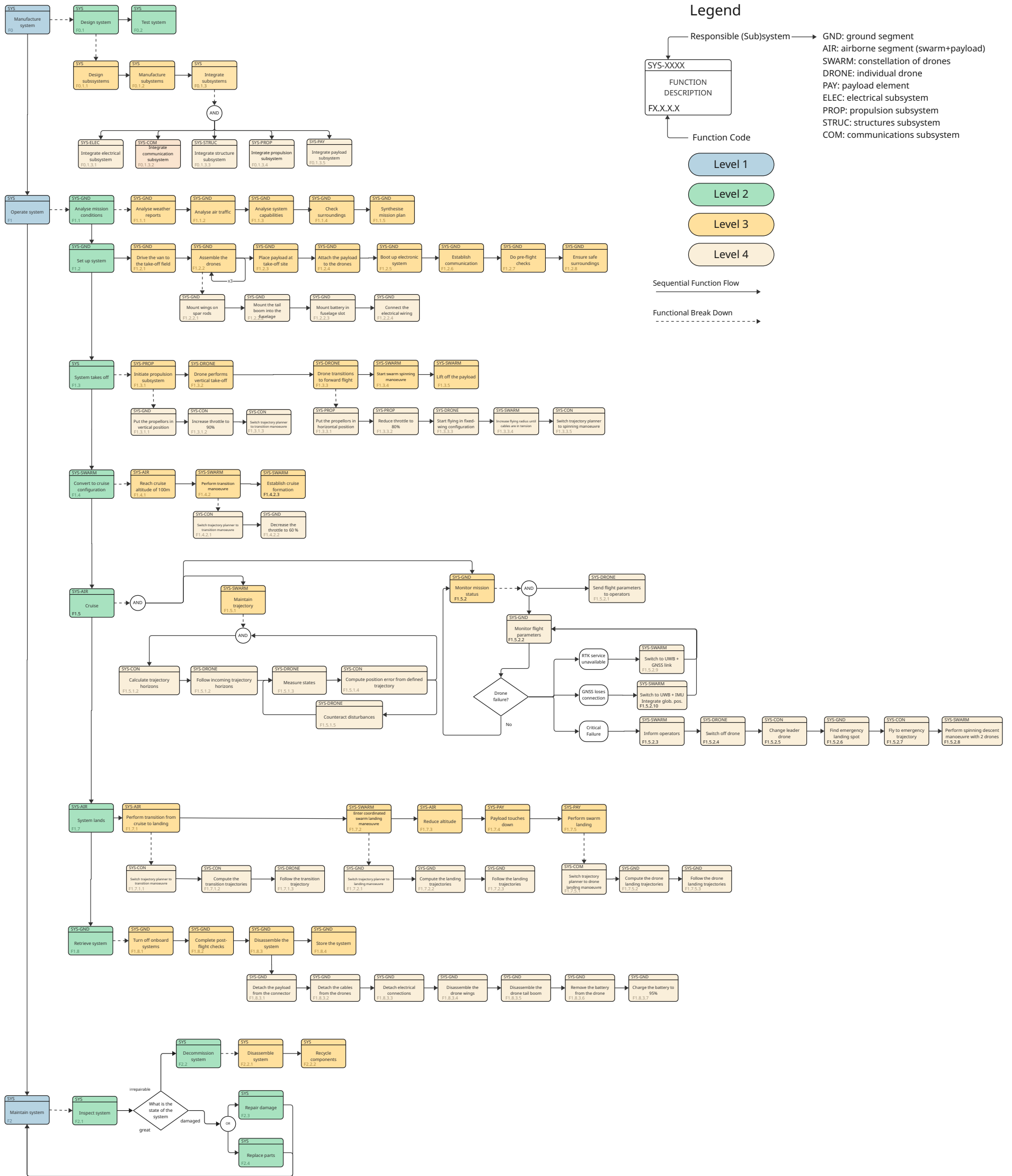


Figure 4.2: Functional Flow Diagram.

5. Technical Risk Assessment

After selecting the design configuration in Chapter 3, the technical risks are expanded to include design-specific risks. These are subdivided into multiple categories to help with the identification and grouping of risks: **PROP** for the propulsion subsystem, **ELEC** for the electricity and power subsystem, **AERO** for aerodynamics, **PAY** for the payload subsystem, **COMM** for the communication subsystem, **STRC** for the structures subsystem, and **CTRL** for the control software subsystem.

Table 5.1: Explanation of the different severities and likelihoods used in the risk assessment.

(a) Likelihood levels.		(b) Severity levels.	
Likelihood (L)	Explanation	Severity (S)	Explanation
Very Low (1)	The event will almost never occur during a system lifetime (<1%).	Negligible (1)	Effect on system is very small and mission can continue as planned.
Low (2)	The event will rarely occur during a system lifetime (<15%).	Marginal (2)	System can continue doing its mission with reduced performance.
Moderate (3)	The event occurs occasionally during a system lifetime (<40%).	Serious (3)	The mission has to be aborted, no damage is done to the system.
High (4)	The event likely occurs during a system lifetime (<65%).	Critical (4)	The mission has to be aborted, and most of the system is preserved.
Very High (5)	The event almost always occurs during a system lifetime (<90%).	Catastrophic (5)	The mission has to be aborted, and most of the system is lost.

Table 5.2 presents the consolidated technical risk register, including the risk description, the responsible team role, with the pre-mitigation likelihood (L) and severity (S) assessment. Table 5.3 introduces the mitigation and contingency plans, with the post-mitigation re-evaluated L and S. The definitions and classifications used for the likelihood and severity levels are provided in Table 5.1. Furthermore, pre- and post-mitigation risk maps were created to visualise the distribution of risks, as shown in Figure 5.1. This report introduces new risks, contingency plans and mitigation strategies that arose with the final hardware design and the integration with the software.

Critical Failure Mode Contingencies

The leader drone is responsible for system coordination. Because every UAV has identical hardware, any unit can assume the leader role, so a drone failure does not compromise the mission, as another drone would take over. When a drone fully fails, it will hang below the payload connection and act as dead weight. To mitigate this risk, the system is designed to sustain the extra load with the remaining two drones. In such an emergency, the pre-computed landing manoeuvre is activated on the remaining drones for a safe system landing.

⁰<https://www.wwf.org.ec/?380761/Recycling-their-own-nets-A-great-challenge-for-artisanal-fishermen> [accessed 08.05.2026.]

Table 5.2: Technical risk register — risk identification and pre-mitigation assessment.

ID	Responsible	Risk Description	Pre-Mit.	
			L	S
PROP01	Propulsion Engineer	Propeller failure due to malfunction or damage, leading to asymmetric thrust and reduced lift on the affected drone.	2	4
PROP02	Propulsion Engineer	Tilting propeller servo or actuator malfunction, reducing or fully locking the thrust vectoring capability of a drone	1	4
ELEC01	Electrical engineer	Power failure due to a manufacturing defect, wiring fault, or damage, resulting in loss of power to propulsion or avionics	1	5
ELEC02	Electrical engineer	Short-circuit in the electrical system, potentially causing loss of control or a complete drone shutdown	1	5
ELEC03	Electronics engineer	Sensor failure due to moisture ingress, software faults, or manufacturing defects, leading to degraded state estimation.	2	3
ELEC04	Electronics engineer	Thermal overload of propulsion motors or onboard electronics, causing power degradation or component shutdown	2	3
ELEC05	Electrical engineer	Battery depletion rate exceeding predictions due to headwinds, heavier-than-nominal payload, or inefficient formation flight	3	4
AERO01	Aerodynamics engineer	Wake interaction from other drones or the payload causing blanking the tail surfaces, inducing a local stall and loss of controllability	2	4
AERO02	Control algorithms engineer	Frequent wind gusts pushing one or more drones past the stall angle, causing partial loss of lift and reduced system controllability	4	5
PAY01	Structures engineer	Payload attachment failure due to underestimated loads or a manufacturing defect, resulting in payload detachment and mission failure	2	5
PAY02	Structures engineer	Unforeseen payload oscillations excited by wind or manoeuvres, reducing overall system controllability	2	4
COMM01	SW systems engineer	Local inter-drone communication loss due to antenna damage or electromagnetic interference, disrupting swarm coordination	1	5
COMM02	Data engineer	Loss of the communication link between mission control and the swarm, removing all supervisory oversight of the mission	1	4
COMM03	SW systems engineer	Single packet loss or momentary communication dropout (~100 ms), caused by mesh latency or brief electromagnetic interference	5	1
COMM04	SW systems engineer	Sustained loss of leader drone communication for more than 1 s, indicating leader hardware or software failure and leaving the swarm without coordination	2	4
COMM05	SW systems engineer	Complete mesh network failure across all nodes for more than 5 s, removing all inter-drone coordination and ground station oversight	1	5
STRC01	Structures engineer	Tail boom structural failure due to underestimated aerodynamic or inertial loads, compromising the airframe integrity of a drone	2	5
STRC02	Structures engineer	Propeller mount failure caused by underestimated dynamic loading or fatigue, leading to loss of propulsion on that motor	2	5

Continued on next page

ID	Responsible	Risk Description	Pre-Mit.	
			L	S
STRC03	HW systems engineer	Excessive cable tension peaks during manoeuvres or gusts, risking rope rupture or attachment point failure	1	5
CTRL01	Trajectory engineer	Cable entanglement caused by relative drone motion, wind disturbances, or asymmetric thrust, compromising swarm manoeuvrability	2	5
CTRL02	Data engineer	Variable or elevated communication latency in swarm coordination, potentially triggering oscillatory or unstable collective behaviour	2	4
CTRL03	SW systems engineer	Instability during the spin-to-forward-flight transition, potentially causing loss of formation stability or a crash	2	5
CTRL04	Control algorithms engineer	Controller divergence due to inaccurate aerodynamic or dynamic models, producing oscillatory or unstable swarm behaviour	2	3

Table 5.3: Technical risk register — mitigation, contingency, and post-mitigation assessment.

ID	Mitigation Plan	Contingency Plan	Post-Mit.	
			L	S
PROP01	Pre-flight propeller health checks and swarm-level load-sharing (n+1 redundancy)	Redistribute thrust across remaining rotors and reallocate swarm load	1	3
PROP02	Pre-flight actuator health checks	Drone performs regular landing instead of vertical	1	3
ELEC01	Battery backup for comms and emergency landing. Pre-flight electrical health checks	Swarm makes an emergency landing	1	3
ELEC02	Electrical isolation design. Pre-flight electrical diagnostics	Redistribute payload load across swarm	1	3
ELEC03	Sensor redundancy and health monitoring. Pre-flight checks	Switch to state estimation using redundant sensors	1	2
ELEC04	Thermal analysis and cooling margin verification	Continue at lower cruise speed or emergency land	1	3
ELEC05	Battery sizing with energy reserve margin	Perform emergency landing at nearest designated zone	2	3
AERO01	Maintain stall margin in control limits. Tighten flight envelope under disturbed flow	Rapid thrust recovery via tilting propellers. Controlled descent	1	2
AERO02	Ensure adequate thrust-to-weight ratio, ensure cruise is not close to stall speed, do not fly at high wind powers	Emergency land the system	2	4
PAY01	Structural safety margins, load verification, and pre-flight inspection	–	1	5
PAY02	Active damping control with thrust margins sized for predicted oscillations and compensation for controller latency.	Switch to a highly damped low-gain control mode	1	3

Continued on next page

ID	Mitigation Plan	Contingency Plan	Post-Mit.	
			L	S
COMM01	Redundant communication links. Autonomous fallback control mode	Switch to autonomous control mode and perform emergency landing	1	4
COMM02	Ensure a reserve link and pre-programmed emergency landing procedure	Perform an emergency landing	1	3
COMM03	Follower drones hold last received setpoint until next packet. Single packet drops are tolerated under nominal operation	No action required	5	1
COMM04	–	Successor drone monitors leader. After 1 s timeout, it assumes leader role.	1	3
COMM05	Dual-antenna on every node to reduce signal blockage. Pre-flight connectivity verification.	Drones maintain UWB-based awareness and execute descent using IMU, GNSS, and barometer.	1	5
STRC01	Structural safety margins, fatigue analysis, and pre-flight checks	Redistribute load across swarm and emergency land	1	4
STRC02	Design for fatigue resistance. Structural pre-flight checks	Redistribute forces across swarm. Perform emergency landing	1	4
STRC03	Validate cable loads in dynamic simulations. Apply safety factors to sizing	Perform emergency landing	1	4
CTRL01	Enforce spacing and cable tension constraints in control law	Reconfigure formation. Reduce speed. Controlled descent if needed	1	4
CTRL02	Validate controller under bounded latency and packet loss	Switch to autonomous mode. Land if instability persists	1	3
CTRL03	Validate transition controller with stability margins and cable load limits	Abort transition and return to spinning flight or hover	1	4
CTRL04	Validate controller robustness against model uncertainties in simulation	Switch to simplified fallback controller	1	3

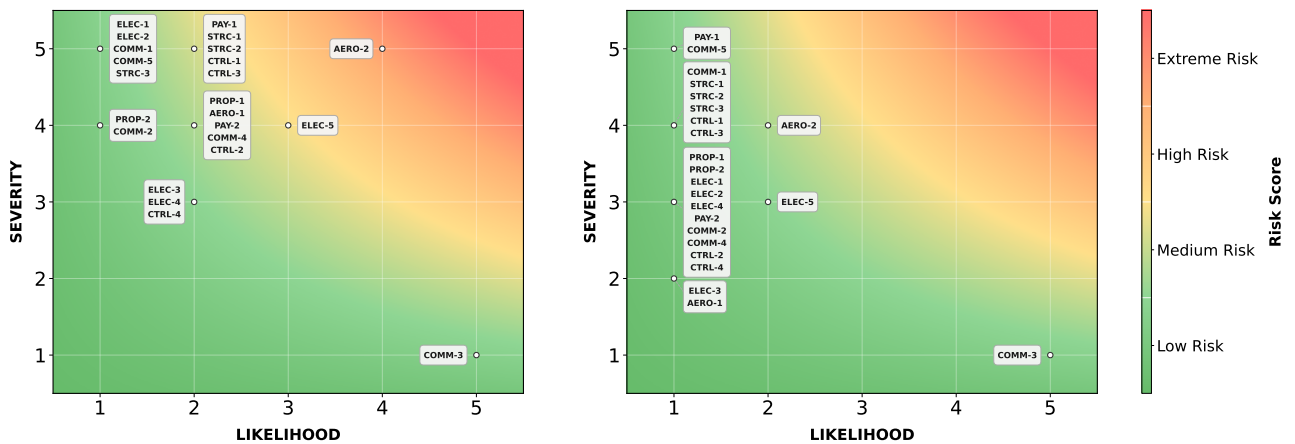


Figure 5.1: Technical risk maps before and after managing.

6. Design Methodology

This chapter explains the team’s approach to designing Dronado. While the following chapters will explain the design of the system linearly, the design of the system was an iterative process, resulting from the many interdependencies of the different subsystems and the manoeuvres. This iterative design process is described in Section 6.1. Additionally, the team’s design considerations for safety and sustainability are presented in Section 6.2 and Section 6.3.

6.1. Design Process

The system consists of four components: the drones, the payload, the trajectory planner, and the individual drone controller. The drone design follows an iterative loop, beginning with a set of stakeholder requirements — range, payload mass, and initial geometric estimates — from which the wing is first sized. With the wing geometry established, the motors and battery are selected, and the battery dimensions in turn drive the fuselage sizing. Aerodynamic analysis then yields the lift and drag distributions across both the wing and fuselage, after which the structural layout and centre of gravity are determined. Finally, the tail surfaces and control surfaces are sized to satisfy stability and control requirements. The wing is then re-sized using the updated mass estimate, and the loop repeats. This process continues until four key parameters converge: the zero-lift drag coefficient, total drone mass, wing area, and centre of gravity location.

Once the drone design has converged, the specifications of the drone, like mass, moments of inertia, and maximum control moments, are input into the trajectory planner. Using hardware specifications and constraints, the trajectory planner finds the optimal trajectories for all drones. If the trajectory planner cannot solve a trajectory due to physical parameters over-constraining the system, for example, the maximum thrust drones can provide, the UAVs are resized to accommodate this increase in thrust or controllability.

Once feasible flight trajectories have been found, the controller finds the necessary control inputs for the drones to follow the trajectories. Once again, if the drones have insufficient performance in thrust or control moments, the drones are resized accordingly. Finally, the entire flight is simulated to verify that the drones can perform the mission. The whole design methodology is shown in Figure 6.1.

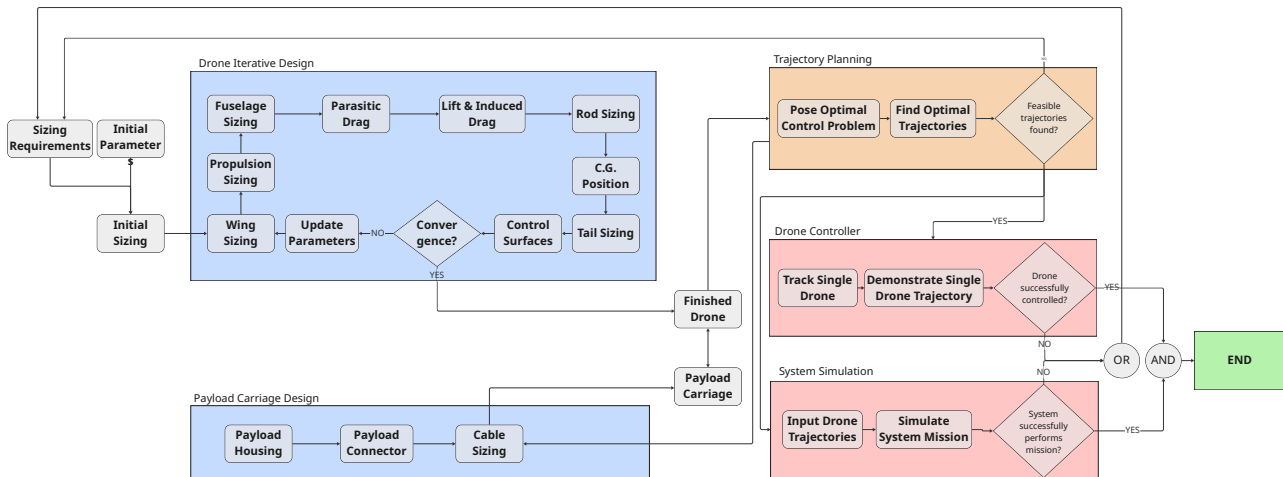


Figure 6.1: Overview of the design logic.

6.2. Design for Safety

Safe operation of the system is a critical design requirement. To support eventual certification, the system must be shown to remain controllable under credible failure scenarios. Identified technical risks are therefore addressed directly within the design through built-in mitigation strategies, primarily based on redundancy. This

section outlines the key redundancy measures and their integration into the design.

6.2.1. One Drone Inoperative Scenario

The loss of a single drone represents a high-risk failure mode described in risks ELEC01, ELEC02, and STRC01 from Chapter 5, particularly during operations over inhabited areas. Concepts relying on in-flight detachment of a failed drone are therefore rejected, as they introduce unacceptable uncertainty in the landing location. Similarly, parachute-based solutions are not considered sufficient due to the lack of precise landing control. Instead, the system is designed to maintain controlled flight with one inoperative drone. This requires each drone to provide sufficient excess thrust to support both the payload and the failed unit during a controlled descent.

Key Choice: One Drone Inoperative Contingency

The system shall remain controllable and execute a controlled descent with one inoperative drone.

6.2.2. One-Engine-Inoperative Scenario

A single engine failure described in risks PROP01 and STRC02 in Chapter 5 must not lead to loss of control or catastrophic system failure. Each drone must therefore remain controllable under one motor failure condition. While mission completion is not required in this case, a safe system-level descent must be achievable. This is ensured by sufficient thrust margin in the remaining motors and adequate control authority to compensate for asymmetric thrust, including lateral force generation to counter induced moments.

Key Choice: One-Engine-Inoperative Contingency

The system shall remain controllable and enable safe descent under a single motor failure per drone.

6.2.3. Drone Design for Redundancy

Redundancy is implemented at the component and subsystem level to reduce the probability of single-point failures described by ELEC03 in Chapter 5. The objective is to prevent loss of critical functions such as communication, control, or power. Wherever feasible, redundancy is achieved either through increased design margins or by incorporating backup components that activate only upon failure of the primary system.

This approach is applied across all major subsystems, including electronics and propulsion. Structural redundancy is inherently addressed through conservative load factors, while propulsion redundancy has already been introduced through the engine inoperative condition.

Key Choice: System-Level Redundancy Strategy

Redundancy is implemented through a combination of design margins and duplicated critical components, ensuring that no single-point failure leads to loss of controllability or mission safety.

6.3. Design for Sustainability

Sustainability is considered in all aspects of the drone's design to minimise its environmental impact during its production, operation and end-of-life. Most importantly, the system is fully battery-powered, and therefore can use renewable components for operations without global emissions. The system is also required to be 60% recyclable, reducing waste and following a circular economy approach to design.

To establish a strong starting point in creating a truly sustainable system, the team arranged a meeting with Dr Benjamin Sprecher, an Assistant Professor at TU Delft who studies how the quantification of environmental impacts can inform sustainable design. Dr Sprecher recommended focusing on recycled parts, recyclability, system lifetime, and maintainability and repairability, because these factors are highly meaningful in creating a sustainable design, and also possible to measure within both the time-frame of 10-weeks and the limited sustainability background of the design team.

The best way that the Dronado project can contribute to sustainability is to opt for sustainable design choices throughout the design project. The Dronado project's immediate plans are technology demonstration, not commercial distribution; therefore, design options will not have a direct impact on a global scale. However, sustain-

able design choices during the project establish a good foundation of sustainability for future applications of the system, which may have more refined and/or scaled versions of the design. When sustainability is a factor in making a decision, this will be denoted by a leaf symbol: .

To track sustainability throughout the design, several indicators are identified. These are most relevant to the design problem and therefore most impactful for achieving a sustainable outcome. They guide design decisions towards improved performance. The indicators are listed in Table 6.1. Each is numbered with the prefix SUS. The importance of each indicator reflects its weighting in the design process.

Table 6.1: Sustainability indicators.

Indicator Number	Indicator	Unit	Importance	Comparison Type
SUS-1	System efficiency	$\text{J kg}^{-1} \text{ km}^{-1}$	High	Quantitative
SUS-2	Recycled parts/materials	%	High	Qualitative/ quantitative
SUS-3	Recyclability of parts/materials	%	High	Qualitative/ quantitative
SUS-4	Lifetime	yr	High	Qualitative
SUS-5	Repairability: how easily can a broken component be fixed or replaced.	-	High	Qualitative
SUS-6	Maintainability: how easily can a component be inspected and upkept	-	High	Qualitative
SUS-7	Sound levels: A-weighted sound exposure level L_{AE} and A-weighted equivalent continuous sound pressure level L_{Aeq}	dB	High	Qualitative
SUS-8	Carbon intensity of battery manufacturing: $\text{CO}_2 \text{ kW}^{-1} \text{ h}$ of the battery's production	$\text{t kW}^{-1} \text{ h}$	Low	Qualitative
SUS-9	Preservation of natural areas	-	Low	Qualitative
SUS-10	Total CO_2 to procure and produce each material.	$\text{kg CO}_2\text{e}$	Low	Qualitative

System efficiency (SUS-1 ) is highly valued as a sustainability metric: a more efficient system requires less energy, reducing both the environmental cost of battery production and replacement as well as the electricity consumed during operation. The team has strong control over this during the design, and it is also of great interest to the stakeholders, so the indicator will greatly drive the design.

Recycled parts per materials (SUS-2 ) and recyclability of parts per materials (SUS-3 ) are important, because they are directly related to virgin material extraction, which carries high environmental and carbon cost. The team has direct control over this through material and supplier selection, making it a design driver rather than a passive indicator.

Lifetime (SUS-4 ), repairability (SUS-5 ), and maintainability (SUS-6 ) are critical, because they dictate how long the system can be used without repair or replacement, in turn requiring less material and energy inputs over the system's life and reducing waste. These indicators are relevant for the system's design because the team can directly control them.

Noise (SUS-7 ) is rated highly as a sustainability metric because it directly affects both local wildlife and human populations near the operating area. It is also a measurable metric, first analytically and then in testing, making it an important indicator of the system's environmental and social sustainability performance.

Natural space preservation (SUS-9 ) relates to the operational space of the system: a larger system requires a larger landing area, and thus may lead to transforming natural spaces into landing areas. This indicator is rated low because its impact on the overall system design is less significant than higher-ranked indicators. However, landing zone selection is an operational decision, so this indicator will be considered during mission planning.

7. Aerodynamic Subsystem Design

After the design methodology was established, the aerodynamic design of the drone is detailed. The drone's aerodynamics is a core discipline, driving both the required propulsive performance and the structural loads the system must withstand. In Section 7.1, the sizing of the wing planform and the airfoil selection is considered. Section 7.2 describes the methodology used to assess the drone's drag. This section is followed by Section 7.3 and Section 7.4, which detail the tail and control surface sizing respectively. Section 7.5 verifies the sizing results by comparing with data from an aerodynamic simulation performed in FLOW5. This section also verifies the drone's stability characteristics. Section 7.6 shows the aerodynamic subsystem's compliance with relevant requirements, presented in Table 7.1. Finally, Section 7.7 proposes recommendations for future work.

Table 7.1: Requirements driving aerodynamic subsystem design.

ID	Requirement
SYS81	The system shall have a stall speed of no more than 14 m s^{-1} .
STK01	The system shall transport a payload of 50 kg at sea-level conditions.
STK02	The system shall achieve a cruise speed of at least 20 m s^{-1} in no-wind sea-level conditions.
STK03	The system shall achieve a range of at least 20 km in no-wind sea-level conditions.
STK17	The system shall fit inside a van for transport to the operating site.
SYS09-NAV13	The drone shall have weathervane stability with a $C_{n_\beta} > 0.05$.
SYS09-NAV14	The drone shall be statically stable ($C_{m_\alpha} < 0$).

7.1. Wing sizing

The wing needs to provide the lift for the drone to fly after transitioning to forward flight. As the drone will spend the majority of the mission in cruise the wing is optimised to fly a 50 kg payload (STK01) at 20 m s^{-1} (STK02). The span is fixed at the maximum value compatible with van transportation assuming a modular design: $b = 3.0 \text{ m}$. This corresponds to the longest continuous wing spar that fits inside a Mercedes Sprinter (STK17), and is structurally advantageous since bending moments are highest at mid-span, making spar continuity desirable at that location. This is favourable as a rectangular planform is chosen, as this is a prototype the drone is designed to be manufactured as easily as possible and sweep and taper do not have significant benefits at low speeds [20].

For the first iteration, an aspect ratio AR of 7.5 is assumed, from which the wing area follows. During subsequent iterations, based on the optimal lift coefficient for cruise $C_{L_{opt}}$ and the mass of the drone which are known, the necessary wing size S_w and aspect ratio AR can be calculated.

Design Decision: Airfoil Selection

The lift coefficient at cruise $C_{L_{cr}}$ is determined by two factors: the most favourable lift coefficient maximising lift-over-drag $\frac{L}{D}$ ratio, leading to a more efficient system (SUS-1 🟢), and the stall speed requirement of $V_{stall} = 14 \text{ m s}^{-1}$ (SYS81). The optimum lift coefficient is found following Voskuijl [21]. Additionally, the cruise lift coefficient needs to be chosen so that it complies with the stall requirement (SYS81):

$$C_{L_{opt}} = \sqrt{C_{D_0} \pi AR e} \quad \text{and} \quad C_{L_{cr}} \leq \left(\frac{V_{cruise}}{V_{stall}} \right)^2 C_{L_{max}}$$

where e is the Oswald efficiency factor, C_{D_0} the parasitic drag coefficient and $C_{L_{max}}$ is the stall lift coefficient. With the cruise lift coefficient $C_{L_{cr}}$, an airfoil that provides maximum $\frac{L}{D}$ at the cruise lift coefficient $C_{L_{cr}}$ can be selected. The selected airfoil should be operating as efficient as possible. It was also found that the stall requirement was quite constraining, forcing the $C_{L_{cr}}$ to be smaller than the optimum lift coefficient $C_{L_{opt}}$. This caused the selection of airfoil with large maximum lift coefficients $C_{L_{max}}$ to be favourable. Following

these considerations, the E423 airfoil was selected due to its high maximum lift coefficient $C_{L_{\max}}$.

The lift behaviour of the design is established by first analysing the airfoil characteristics and then applying the findings to lifting-line theory (LLT) to find three-dimensional wing characteristics. Given the iterative design process, an airfoil is chosen. The airfoil characteristics are computed with the subsonic airfoil development system XFOIL¹, which is integrated in the Python iteration loop by driving the XFOIL executable as a subprocess. This airfoil analysis tool requires the airfoil shape and the Reynolds number, found to be $\approx 4e5$.

The XFOIL implementation returns a linearised 2D section model: a lift-curve slope, zero-lift angle and airfoil moment coefficient. LLT transforms the section characteristics to a 3D finite wing by modelling multiple bound vortex systems at the aerodynamic centre, located at the wing's quarter chord. A sheet of trailing vortices extends from the wingtips to model the induced velocity caused by the finite wing. The induced velocity decreases the effective angle of attack of the wing, thus lowering the wing lift coefficient C_L with respect to the airfoil section lift coefficient C_{ℓ} . The first Fourier coefficient A_1 , as shown by Anderson [22], is used to calculate the wing lift coefficient by $C_L = \pi AR A_1$.

Calculating the Fourier coefficients for different angles of attack yields the wing lift slope coefficient $C_{L_{\alpha}}$. This method is also used for the horizontal stabiliser wing properties. Moreover, LLT also provides an induced drag measure through the Oswald efficiency factor however, the fuselage-wing interference is not taken into account and thus provides a poor measure for the induced drag. Similarly, the LLT does not model the three-dimensional $C_{\ell_{\max}}$ and $C_{m_{ac}}$. For these coefficients, a correction factor dependent on the aspect ratio is implemented for the lift and the moment coefficients, following Raymer [16].

7.2. Drag Estimation

The drag that the drones need to overcome comes from the drones themselves and the payload. For a 50 kg payload and a low density of air transport cargo of 290 kg m^{-3} [23], the payload's largest volume can be estimated to be 0.17 m^3 . Assuming the payload to be a cube, the area of a side of the payload holder is 0.31 m^2 . As the drag of a net is difficult to estimate, the drag coefficient of a cube, which is reported at 1.05 in [24], is considered. This drag contribution is used in the sizing of the drones by allocating its effect proportionally among all the drones.

To estimate the drone's zero-lift drag coefficient, the sizing method presented by Pollet et al. [20] will be used. In this method, the coefficients of each individual component are assumed to be a multiplication of an equivalent flat-plate skin friction coefficient C_f , a shape form factor FF , and their wetted area S_w . An interference factor Q presented by Scholtz [25] is also used. Following Pollet et al. [20], all component contributions are summed and divided by a reference wetted area, in this case the wetted area of the main wing, in:

$$C_{D_0} = \frac{1}{S_w} \sum_{i=1}^{N_{\text{surfaces}}} C_{f,i} FF_i S_{\text{wet},i} Q_i.$$

Following Pollet [20], C_f is found, assuming completely turbulent flow and considering compressibility effects. Using this method the drag contribution of the fuselage, main wing, tail and tail boom are computed. The shape form factors FF are calculated following [16]. The interference factors are computed as described in [25].

7.3. Tail Sizing

Vertical Tail

The vertical tail is sized based on the requirement of $C_{n_{\beta}} > 0.05$ [26], to ensure weathervane stability of the drone. The area is set as the smallest possible area fulfilling that requirement, with the aspect ratio of 4.5 decided based on empirical data from Raymer [16].

Horizontal Tail

To maintain pitch moment equilibrium during cruise, the horizontal tail has to generate negative lift to provide a pitch-up moment. The incidence angle of the horizontal tail is chosen such that no elevator deflection is required to generate this moment during cruise. At the same time, the operating lift coefficient of the horizontal tail is bounded by 40% of the tail's maximum lift coefficient to mitigate the risk of horizontal tail stall described in

¹URL <https://web.mit.edu/drela/Public/web/xfoil/> [accessed 21.05.2026]

risks AERO01 and AERO02 from Chapter 5. This limit ensures that the tail stalls after the main wing, as the wing itself operates at a higher fraction of its $C_{L_{max}}$ of $\frac{0.7816}{1.5951} = 0.49$. This constraint sets a lower bound on the tail area in order for it to provide sufficient moment to ensure cruise moment equilibrium.

7.4. Control Surface Sizing

Controllability of the drone is ensured through the design of its ailerons, elevator and rudder. The attachment of the payload is chosen such that the line connecting it with the centre of gravity is along the line of action of the tension force, to ensure that the payload does not create a moment on the drone during nominal cruise. However, wind disturbances and accelerations during manoeuvres will cause the payload to assume different angles captured by risk PAY02 in Chapter 5. This is considered in the sizing of the control surfaces to retain sufficient control margin against this risk. A worst-case scenario is assumed where the maximum tension observed in the ropes during the mission acts in the horizontal plane, with the moment arm equal to the vertical distance between centre of gravity and the payload attachment point on the drone for the ailerons and the elevator, and the longitudinal distance between these points for the rudder. The full sizing procedure is explained in Table 7.2, with formulas from Márquez et al. [27]. The control surface effectiveness is found from the empirical relation with control surface chord ratio from Al-Shamma and Ali [28]. For each control surface, the maximum deflections and chord ratios prescribed by Sadraey are used [29]. The reason for the latter is that the control surface rod is located more forward in the thicker part of the airfoil, which allows for lighter rods with a higher diameter, which are sized in Section 8.2. The resulting aileron, elevator and rudder span ratios are 0.17, 0.35 and 0.95 respectively.

Table 7.2: Sizing criteria and geometric constraints of aerodynamic control surfaces.

Control Surface	Sizing / Authority Criteria	Geometric Constraints
Wing ailerons	Two independent criteria; governing sets the span ratio: - Required steady roll rate $p \geq p_{req} = 47^\circ/s$ [30] using $p = \left -\frac{C_{l_{\delta_a}}}{C_{l_p}} \delta_{a,max} \frac{2V}{b} \right$ - Payload roll-moment authority $C_{l_{\delta_a}} \delta_{a,max} \geq C_{l_{payload}}$ Most conservative (largest span ratio) requirement is selected.	- Outboard edge fixed at $y/(b/2) = 0.9$ - Inboard edge moved inward until authority requirement is met - Chosen chord ratio $c_a/c_w = 0.3$ - Effectiveness factor τ_a obtained from empirical chord-ratio correlation
Horizontal-tail elevator	Three independent criteria; governing sets the span ratio: - Payload-induced pitching moment $C_{m,payload}$, - Airspeed gust moment demand from $\pm V_{gust}$ speed perturbation - Rear-propeller on top of vertical tail failure moment Required span ratio for each constraint: $\frac{b_E}{b_h} = \frac{C_{m,demand}}{C_{L_{\alpha h}} \eta_h V_h \tau_e \delta_{e,max}}$ Most conservative (largest b_E/b_h) requirement governs.	- Specified elevator chord ratio $c_E/c_h = 0.4$ - Span ratio $b_E/b_h \leq 1$ - Area ratio $S_E/S_h = (c_E/c_h)(b_E/b_h)$ - Effectiveness factor τ_e from empirical chord-ratio polynomial
Vertical-tail rudder	Three independent criteria; governing sets the span ratio: 5 m s^{-1} crosswind side-force equilibrium - Combined yaw-moment authority: 5 m s^{-1} crosswind gust and OEI (one-engine/propeller-inoperative) moment - Payload yaw moment authority Control derivatives: $C_{n_{\delta_r}} = -C_{L_{\alpha v}} V_v \eta_v \tau_r \frac{b_R}{b_v}$, $C_{y_{\delta_r}} = C_{L_{\alpha v}} \eta_v \tau_r \frac{b_R}{b_v} \frac{S_R}{S_v}$ Most conservative (largest b_R/b_v) requirement governs.	- Prescribed rudder chord ratio $c_R/c_v = 0.4$ - Area ratio $S_R/S_v = (c_R/c_v)(b_R/b_v)$ - Span ratio $b_R/b_v \leq 1$ - Effectiveness factor τ_r from empirical chord-ratio polynomial

7.5. Verification and Validation

After the aerodynamic sizing through the methods described previously is completed, the design is verified and validated in various performance and stability analyses in FLOW5². In the performed simulations, the wing and tail surfaces are constructed and meshed in the program, where the fuselage shape is imported from the CAD design, after which it is also meshed in FLOW5. To get the most accurate results, the chosen method for the simulations is the 3D panel method, together with the thick surface interpretation of lifting surfaces. The thick surface method was selected because of its ability to more accurately model using the exact shape of the airfoil, although documentation mentions there are no large differences between the methods³. In the following subsections, the basic aerodynamic performance will be analysed first and will be compared to the characteristics estimated during the sizing. After this, static and dynamic stability characteristics will be determined, as well as the control surface effectiveness, which will also be compared. Lastly, the significance and the accuracy of the simulation results will be discussed.

7.5.1. Aerodynamic performance

The aerodynamic performance curves are shown in Figure 7.1. Note that LLT is also included in the plot because this is the method used in the sizing script, as well as the aerodynamic performance of the drone with extra drag caused by the payload. An important thing not carried over is the presence of the tail propeller, which contributes to the moment of the aircraft. This is why the moment in Figure 7.1 for this simulation seems higher than expected.

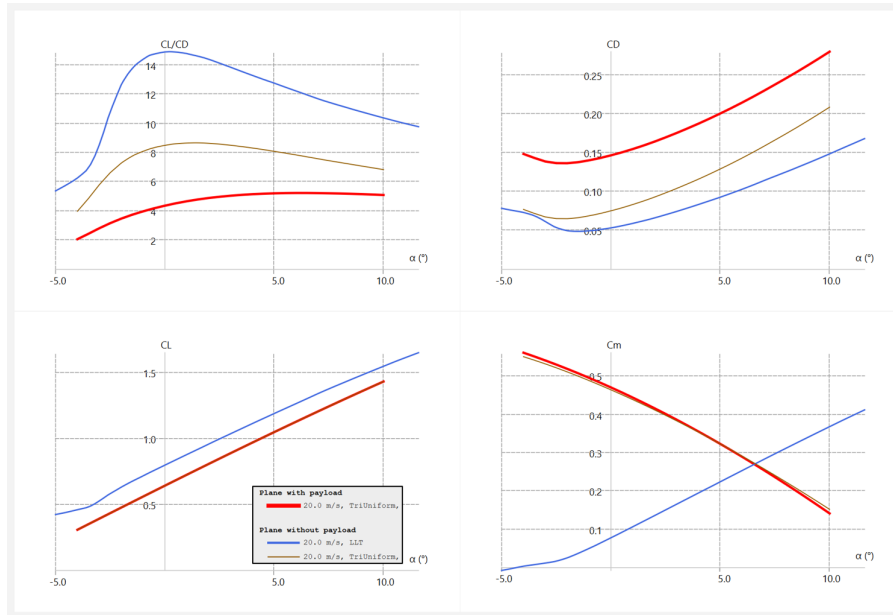


Figure 7.1: Aerodynamic performance curves of single drone.

By comparing both methods at a single point in the flight envelope, $\alpha = 1.7$, the cruise angle of attack calculated through the sizing method, relative over- and underestimation of performances can be explained. The comparison is summarised in Table 7.3. It is observed that the sizing method predicts higher lift and also predicts lower drag coefficients at the cruise lift coefficient $C_{L_{cruise}} = 0.78$, leading to an overall higher gliding efficiency (SUS-1 🍃). This can be partially explained due to the nature of the calculation methods: LLT, also graphed in Figure 7.1 as reference, underestimates drag by ignoring drag provided by the tail, form drag and skin-friction drag, although the latter is later added manually in the sizing script. Moreover, it overestimates lift compared to the simulation, because the negative lift the horizontal tail produces is neglected, but is significant in this drone's design. The 3D panel method with thick surfaces and especially together with viscous interpolation across the boundary layer, provides an accurate way of modelling 3D surfaces [31].

As such, it has to be concluded that the sizing data is validated, but the set requirements cannot be met with this

²<https://flow5.tech/flow5.html> [firstly accessed on 04.06.2026]

³https://flow5.tech/docs/flow5_doc/Analysis/Methods.html [accessed on 15/06/2026]

design. The aerodynamic simulations done in FLOW5 establish a more refined view on the capabilities of the drone with and without the payload, where it is observed that the drag is too high, and the lift is too low.

Table 7.3: Aircraft aerodynamic sizing outputs at cruise conditions at angle of attack $\alpha = 1.7^\circ$.

Parameter	Sizing Results	Simulation Results
Lift coefficients	$C_L = 0.7816$	$C_L = 0.60$
Drag Coefficients	$C_D = 0.055$	$C_D = 0.090$
Cruise Efficiency with payload	$L/D = 6.27$	$L/D = 5.25$
Maximum Efficiency without payload	$L/D = 10.8$	$L/D = 8.68$

7.5.2. Stability

Table 7.4: Non-dimensional stability derivatives.

Param	Value	Param	Value	Param	Value
C_{X_u}	-0.146136	C_{Z_u}	-1.04925	C_{m_u}	0.851905
C_{X_α}	0.170547	C_{Z_α}	-4.76321	C_{m_α}	-1.52981
C_{X_q}	0.229721	C_{Z_q}	-8.58979	C_{m_q}	-24.8673
C_{Y_β}	-0.104449	C_{l_β}	-0.0713623	C_{n_β}	0.110024
C_{Y_p}	0.0187722	C_{l_p}	-0.476645	C_{n_p}	-0.00680969

Table 7.5 compares the stability derivatives obtained from FLOW5 against those from the sizing methods. C_{Y_β} and C_{n_β} are larger and C_{l_p} is smaller in magnitude in the FLOW5 results than in the sizing estimates, indicating that the designed tail will provide greater control authority than initially anticipated. This discrepancy arises because the sizing methods rely on two-dimensional aerodynamic assumptions, whereas FLOW5 accounts for three-dimensional effects. The agreement in sign and the consistent over-prediction by the sizing methods confirm that the tail was sized conservatively.

Table 7.5: Comparison of stability: sizing vs. FLOW5.

Stability	Sizing	FLOW5 Simulation
Static margin (SM)	$0.050 x_{cg}/c$	$0.32 x_{cg}/c$
Side Force due to Sideslip (C_{Y_β})	-0.0836 rad^{-1}	$-0.104449 \text{ rad}^{-1}$
Yaw Moment due to Sideslip (C_{n_β})	0.0500 rad^{-1}	$0.110024 \text{ rad}^{-1}$
Roll Damping (C_{l_p})	-1.0491 rad^{-1}	$-0.476645 \text{ rad}^{-1}$

7.5.3. Control surface effectiveness

The control surface effectivenesses are verified and validated through FLOW5's control analysis method, which allows for an input sequence of control surface angles to be analysed. The comparison between the sizing and the simulation is shown in Table 7.6. In this table is seen that there is a large mismatch in the magnitude of the induced rolling moment of 78% between the sizing and the simulations. This is likely caused by the under-estimation of the 3D spanwise flow present in the DATCOM sizing method used for this aileron. The control effectiveness of the aileron and elevator sizing is overestimated but this can be accounted for by increasing the spanwise length of the ailerons and elevators compared to what was predicted by the sizing script.

Table 7.6: Comparison of control surface effectiveness: sizing vs. FLOW5.

Control Surface	Sizing (rad^{-1})	FLOW5 Simulation (rad^{-1})
Elevator effectiveness ($C_{m_{\delta e}}$)	-0.8766	-0.6417
Rudder effectiveness ($C_{n_{\delta r}}$)	-0.0437	-0.0516
Aileron effectiveness ($C_{l_{\delta a}}$)	-0.2785	-0.0607

7.6. Compliance

Table 7.7: Aerodynamic subsystem compliance matrix.

ID	Compliance	Status
SYS81	The wing is sized to be able to have a stall speed of 14 m s^{-1}	✓
STK01	The wing provides enough lift to carry 50 kg with three drones.	✓
STK02	The wing provides enough lift to cruise at 20 m s^{-1}	✓
STK03	The FLOW5 simulation predicted a reduced L/D ratio. The target 20 km cruise range remains probable but requires further verification.	?
STK17	The wing span was limited to 3 m to fit in the van.	✓
SYS09-NAV13	The weathervane stability $C_{n_\beta} = 0.11$, is above 0.05.	✓
SYS09-NAV14	The drone is statically stable as $C_{m_\alpha} = -1.53$	✓

7.7. Future Recommendations

The FLOW5 simulations in Section 7.5 show that the current design does not meet its own sizing targets: drag is higher and lift is lower than predicted, reducing cruise L/D from 6.27 to 5.25. However, the off-the-shelf components selected in Chapter 18 came out significantly lighter than the 9.8 kg resulting from the sizing script, at 7.8 kg, a 20% reduction, mainly due to the overestimated battery mass. This reduces the required lift and thus the induced drag and power in cruise, partially offsetting the lower L/D. Since the two effects act in opposite directions, the net impact on the 20 km range requirement (STK03) cannot be confirmed without recalculating range using both the FLOW5-derived aerodynamics and the updated component masses together. This recalculation should be prioritised in the next design iteration. At 100 m altitude, gusts above 5 m s^{-1} are common, requiring more control effort to hold formation. Both a rainproof design and gust envelope evaluation should be addressed before finalising the design. A more accurate aerodynamic tool is needed to ensure the tail size and control surfaces are designed correctly, and a more accurate method than LLT is advised for estimating wing lift and drag.

8. Structures Subsystem Design

After the aerodynamic design of the drones has been established, this chapter covers the structural design of the drones to support the aerodynamic loads and house all internal components. The structure will be designed to meet the requirements shown in Table 8.1, starting with the material selection in Section 8.1. Based on the selected material, the drone can be sized in Section 8.2 and the payload in Section 8.3. The structural subsystem's verification is detailed in Section 8.4 and its compliance with relevant requirements, presented in Table 8.1, is given in Section 8.5.

Table 8.1: Requirements driving the structures subsystem design.

ID	Requirement
SYS22-STR01	The drone structure system shall have a mass lower than 3.4 kg.
SYS44-STR02	The fuselage shall allow battery replacement without the use of specialised tools.
SYS20-STR03	The fuselage shall have enough hollow volume to house all central internal drone components.
SYS27-STR04	The drone shall have a wingspan of no more than 3 m.
SYS17-STR05	The wing structure shall withstand 525 N lifting loads without permanent deformation.
SYS44-STR06	The wings shall be mountable on the fuselage without the use of specialised tools.
SYS24-STR08	The total drone structure cost shall be less than 1900 EUR in parts.
STK17-STR09	The drone structure shall be modular.
SYS10-PAY07	The payload connection shall allow independent rotation from the cables.
SYS11-PAY08	The payload connection shall allow for temporary yaw braking.
STK06	The system shall carry the payload as a suspended load during the entire mission.
STK07	The system shall connect the payload to the drones through a suitable physical linkage mechanism.

8.1. Materials Selection

The requirements posed on the total drone mass and cost motivate the selection of materials that are accessible at low cost, allow for inexpensive manufacturing techniques and are lightweight. The existing solutions for hybrid UAVs in a similar weight class can be roughly subdivided into three categories, mainly fully composite structures, high-strength plastic structures or foam structures laminated with a composite skin. The following subsections cover each of these options in more detail and eventually perform a trade-off to find the most suitable configuration for the supporting structure.

8.1.1. Fully Composite Structure

Composite structures are increasingly more often used for UAV structures due to their favourable specific strength and stiffness, which allows for a good structural performance without a high mass penalty¹. Specifically, GFRP is considered here, as it has better properties than most metals and has been used in the aerospace industry before¹. Although CFRP is frequently used in drone design as it is lighter and stronger than most other composites¹, Munalli et al. mention that it is also highly effective at shielding from electromagnetic radiation, which means that it blocks communication [32]. GFRP does not have this property and has been shown to

¹URL <https://www.azom.com/article.aspx?ArticleID=12234> [accessed 16.06.2026]

effectively shield telecommunication equipment without blocking the signal, as shown by Talei-Fard et al [33]. Ashby shows that the stiffness of GFRP varies around 25 GPa, and the density is reported around 1.3 g cm^{-3} [34]. However, manufacturing the GFRP structure is both expensive and time-consuming compared to the other considered techniques. This higher cost originates from both high material costs as well as the need for custom moulds to shape the carbon fibre in complex aerodynamic shapes such as the wing or the fuselage. While traditional CFRP and GFRP materials can be challenging to recycle², Dai et al. mention that both are recyclable to some level [35] (SUS-3 🌱). Thermoplastic FRPs are also a promising easy-to-recycle composite option³ that can be explored to improve the design's economic circularity (SUS-3 🌱).

8.1.2. Polymer Structure

Unreinforced polymers provide a substantially lower performance compared to composites, as they are missing the fibres which contribute most to the strength and stiffness of the material, as mentioned by Salih et al [36]. Mwema and Akinlabi mention that PLA specifically is commonly used in 3D printing, which would be one of the main advantages compared to composite structures, as it allows for easy and cheap manufacturing [37]. As such, for structural components that do not require high load-carrying capabilities, using unreinforced polymers can be a preferable choice. This is also important to be able to make many different prototypes throughout the entire product design phase. Ashby shows that the stiffness of PLA varies around 3 GPa, and the density around 1.2 g cm^{-3} [34]. PLA is a plant-based recyclable material, which can be re-extruded or composted⁴. This contributes to the design's circular-economy goal (SUS-3 🌱).

8.1.3. Foam Structure with Composite Support

This structure would consist of an EPP foam base and a GFRP cover for the wing and CFRP spars and ribs to carry most of the aerodynamic loads. EPP was chosen for its high crash-resistance, cost-effectiveness, and 100% recyclability⁵ (SUS-3 🌱). Additionally, GFRP was chosen for the same reasons as before. CFRP is chosen for its low mass and high stiffness. Previously, it was mentioned that CFRP blocks communication. However, since the spars and ribs will only restrict a small part of the communication's field of view, it was still preferred over GFRP due to its better mechanical properties. Ashby shows that it has a stiffness of around 300 GPa and a density around 1.4 g cm^{-3} [34].

The biggest advantage of the foam structure is a highly simplified manufacturing process, as it can be shaped using a foam cutter⁶. To cut the foam, it is possible to use the foam cutter at TU Delft, costing only 10 EUR⁷. Compared to a full composite structure, no mould is required to apply the composite since the skin can be laid directly onto the foam shape. In addition, the foam structure is highly favourable when it comes to integrating the structural components. Mounting wing spars, ribs and structural booms in the structure can be performed by simply making suitable cutouts in the foam shape and inserting carbon tubes.

Making separate spars and ribs is structurally more efficient than an aerodynamic structure, as they can be optimised for one function rather than two. This means that even though filling the shape with foam would be heavier than an empty structure, for the same strength, the spar and rib combination will be more lightweight than the fully composite structure. EL2 epoxy⁸ was chosen as the laminating resin. A thermoset polymer was chosen since it cures at a temperature of 20° C ,⁹ whereas a thermoplastic would require intense heat to melt into the glass cloth. At these temperatures, the trapped air within the closed cell structure of the EPP foam would expand, causing bloating or melting of the wing and tail geometry.

²URL <https://www.azocleantech.com/article.aspx?ArticleID=1242> [accessed 19.06.2026]

³URL <https://www.metstrade.com/news/sustainability/dispose-recycle-reuse> [accessed 19.06.2026]

⁴URL <https://www.creality.com/blog/is-pla-recycable> [accessed 19.06.2026]

⁵URL <https://www.qdmaifeng.com/EPP-UAV-drone-for-precision-agricultural-crop.html> [accessed 16.06.2026]

⁶URL <https://www.croma-foamcutter.com/en/materials-and-applications/which-materials-can-be-cut/> [16.06.2026]

⁷URL <https://www.tudelft.nl/en/ide/about-ide/facilities/pmb/facilities/> [accessed 16.06.2026]

⁸URL <https://www.easycomposites.co.uk/el2-epoxy-laminating-resin> [accessed 16.06.2026].

⁹URL <https://media.easycomposites.co.uk/datasheets/EC-TDS-EL2-Epoxy-Laminating-Resin.pdf> [accessed 16.06.2026]

8.1.4. Material Trade-Off

The material selection was performed by means of a trade-off, where the equally weighted criteria of mass, cost, and specific stiffness were evaluated. These criteria are selected from the subsystem requirements in Table 8.1. The mass criterion originates from SYS22-STR01 directly. Stiffness originates from both SYS17-STR05 and SYS78-STR07. Finally, the cost criterion follows directly from SYS24-STR08. The weights for these criteria are set to be the same, as their originating requirements are all driving requirements. The trade-off table can be seen in Table 8.2.

The trade-off reveals that the foam core and composite skin material concept is the most favourable. It should be noted that the mass and cost scores are highly qualitative and the scoring is highly context-dependent. For a large-scale manufacturing setting, the high costs of a CFRP-only structure would not be a dominating factor, for example. However, the trade-off reveals an important conclusion - the foam and composite skin structure is the most balanced solution. Both the fully composite and fully polymer structures have unacceptable deficiencies in cost and stiffness, respectively. As such, the foam structure with composite skin emerges as the preferred solution. This option is also suitable for the project's recyclability demands (SUS-3 🌱), with both materials being able to be recycled (see Subsection 8.1.1 and Subsection 8.1.3).

Table 8.2: Material option trade-off.

Material Option	Mass	Cost	Stiffness	Total
Fully Composite (GFRP)	2 (1.3 g cm ⁻³)	1 (high material cost + expensive manufacturing)	3 (25 GPa)	6
Unreinforced Polymer (PLA)	4 (1.2 g cm ⁻³)	4 (very low material cost + cheap manufacturing)	1 (3 GPa)	9
Foam Core + Composite Support	3 (1.3 g cm ⁻³ GFRP + 1.4 g cm ⁻³ CFRP + light foam)	3 (high material cost + cheap manufacturing)	4 (25 GPa GFRP + 300 GPa CFRP)	10

Excellent 4
 Good 3
 Correctable deficiencies 2
 Unacceptable 1

Before any structural components are sized, the general concept for the drone structure is laid out. Though the final stages of the product are intended for commercial use, currently the structural design of the drone is aimed to be manufacturable at a research university scale. The designed system is intended as a prototype, and the first unit produced would serve as a demonstrator. This motivates the importance of a structure that is manufacturable at low cost, while maximising its performance. If the product proves successful, the design concept can be further adjusted to make it suitable for large-scale manufacturing. Sizing of the drone's structure is mostly constrained by the operational requirement STK17-MIS17-SYS27, from which the requirement SYS27-STR04 is derived. This requirement states that the system needs to be transported in a van. This motivated a modular design which facilitates easy storage. A modular design also improves the system's repairability, as a broken subsystem does not necessitate the replacement of the entire drone, but rather a singular component (SUS-5 🌱). Individual components can also be inspected more easily, making a more maintainable design (SUS-6 🌱). To ensure simple manufacturability, the drone is designed in a way that maximises the use of off-the-shelf components.

The main load-bearing structure is designed from CFRP rods connected through CFRP cross clamps. The cross clamps were chosen because they transfer the loads between the tail boom and the wing spars in a more efficient manner than bolted connections, which concentrate the load in a single point. In this structural concept, the wing structure is made up of two circular cross-section spars. In this way, the wing is easily detachable by making the spar rods simply slide out of the wing form. The two-rod wingbox design allows it to resist torsional loads by differential bending. In addition, the wing structure is reinforced with carbon fibre ribs, which double as points of integration for the propellers.

8.2. Drone Structural Sizing

With the selected materials, the structure of the drones can be sized. The main load-bearing structure consists of a total of 7 connected rods: the wing spar, aileron rod, tail boom, horizontal spar, elevator rod, vertical spar, and rudder rod. All of these rods are sized with a hollow cylindrical cross-section. This is because this cross-section is very efficient in both bending and torsion, and also allows for an easy installation in the modular design. The sizing methods for these rods can be seen in Table 8.3. The wing rods are sized for the total wing lift at the maximum structural speed $V_{max} = 30 \text{ m s}^{-1}$ under the one-drone failure lift coefficient, which represents the worst load case where the remaining drones must support the full payload. The velocity follows from the maximum velocity observed in the trajectory planner.

The tail rods are sized for the maximum tail force, computed from the finite-tail $C_{L_{max}}$ at the same structural speed scaled by the dynamic pressure ratio $\eta_h = 0.85$ as mentioned by Oliviero [38]. The vertical tail rods additionally carry the rear propeller thrust as a point load at the tip, acting in the longitudinal plane simultaneously with the aerodynamic side force. The tip deflection limit for all rods is set to 10 % of the relevant reference length as suggested by Al-Shamma and Ali: semi-span for the wing and horizontal tail, full span for the vertical tail, and structural bending arm length for the tail boom [39]. The allowable compressive stress is taken as the compressive strength of the CFRP, $\sigma_{allow} = 570 \text{ MPa}$, with a safety factor of 1.5 applied to all loads. It should be noted that the resulting rod dimensions from the sizing procedure in Table 8.3 are the minimal allowable dimensions. In reality, the rods are bought off the shelf, which means that they would have a larger thickness and outer diameter, and would thus be stronger.

Table 8.3: Failure modes and geometric constraints of CFRP structural rods.

Component	Failure Modes	Geometric Constraints
Wing spar rod	Sized for the more critical of: • Tip deflection $\delta \leq \delta_{max}$ (Euler–Bernoulli, uniformly distributed load) • Compressive bending stress $\sigma \leq \sigma_{allow}$ at the outer fibre Load: total wing lift at structural speed V_{max} under one-drone failure lift coefficient.	• Rod length = wing span • Outer diameter $\leq 80\%$ of local section height at max-thickness x/c • If outer diameter is capped, wall thickness is increased to maintain structural margin
Wing aileron rod	Same independent criteria as spar rod: • Tip deflection limit • Compressive bending stress limit Load: total wing lift at structural speed V_{max} under one-drone failure lift coefficient.	• Rod length = aileron span • Outer diameter $\leq 80\%$ of local section height at aileron hinge $x/c = 1 - c_{ail}/c_w$ • Thinner aft section governs; t_{wall} increased if outer diameter is capped
Tail (boom) rod	Two criteria, governing one sets the diameter: • Tip deflection $\delta \leq \delta_{max}$ under L_{tail} (Euler–Bernoulli, point load at tip) • Superimposed bending + torsion: von Mises criterion $\sigma = \sqrt{\sigma_b^2 + 3\tau^2} \leq \sigma_{allow}$ Bending load due to L_{tail} and torque due to maximum rudder side force.	• Rod length = tail boom length • Tail boom length + fuselage nose length $\leq 3 \text{ m}$ to fit inside van

Continued on next page

Table 8.3: Failure modes and geometric constraints of CFRP structural rods. (Continued)

Component	Failure Modes	Geometric Constraints
Horizontal tail spar rod	Same independent criteria as wing spar rod; load is L_{tail} : • Tip deflection limit • Compressive bending stress limit	• Rod length = horizontal tail span • Outer diameter $\leq 80\%$ of section height at HT max-thickness x/c
Horizontal tail elevator rod	Same independent criteria as wing spar rod, same load L_{tail} : • Tip deflection limit • Compressive bending stress limit	• Rod length = elevator span • Outer diameter $\leq 80\%$ of section height at elevator hinge $x/c = 1 - c_{elev}/c_t$ • Thinner aft section governs
Vertical tail spar rod	Two loads act simultaneously: • Propulsive thrust at tip (longitudinal plane) • Aerodynamic side force from gust + rudder deflection (lateral plane) Governing criterion is the more critical of: • Tip deflection under RSS of thrust and side-force equivalent point load • Compressive bending stress under RSS of thrust and side-force bending moments	• Rod length = vertical tail span + tail boom diameter • Outer diameter $\leq 80\%$ of section height at VT max-thickness x/c • Root chord $c_{root,vt} = S_v/b_v$ used for section height
Vertical tail rudder rod	Same independent criteria as VT spar rod; same simultaneous loads: • Tip deflection under thrust + side-force load • Compressive bending stress under RSS of thrust and side-force bending moments	• Rod length = rudder span + tail boom diameter • Outer diameter $\leq 80\%$ of section height at rudder hinge $x/c = 1 - c_{rud}/c_v$ • Aft section thinner than spar location; outer diameter cap governs

The size of the fuselage was determined based on the size of the internal components. All internal components can be fit inside a box of dimensions $129.2 \text{ mm} \times 129.9 \text{ mm} \times 724.0 \text{ mm}$. This box already includes a spacing factor of 1.15 on each of the sides to make sure no components are right on the edge. Around this box, a cylinder can be fitted with a diameter of 183.2 mm. In front of this cylinder, an elliptical nose was placed to reduce the pressure drag. Behind the fuselage, a tapered tail was attached to further decrease the pressure drag. The tail follows a raised cosine. This is because a raised cosine can smoothly transition from the cylinder to the tail boom while being parallel to both edges. A visualisation of the geometry can be seen in Figure 8.1.

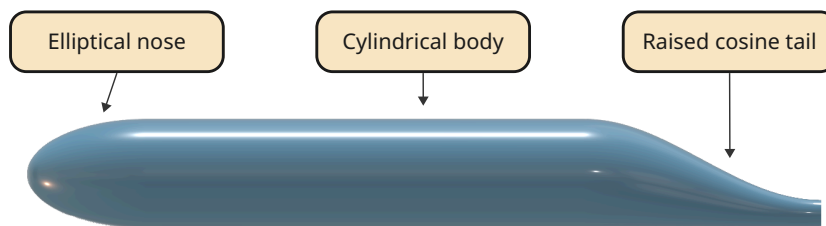


Figure 8.1: Fuselage geometry.

Because the rods are the main load-bearing components in the fuselage, they should be connected such that they can function as a single frame. The tail boom is considered the base of the frame, as it is the component closest to the floor. The wing rods will be connected to the tail boom through the use of cross-clamps. These are made to connect perpendicular rods, which makes them ideal for this, as they also allow the wing rods to be removed for transport. The horizontal and vertical tail rods will be connected through holes in the back of the tail boom. The rods will then be secured through the use of an adhesive, making the tail one solid part. Additionally, four CFRP ribs are used: two on either side of the fuselage and two in the left and right wings, respectively. The ribs in the wings are positioned at the location of the propellers to help introduce the thrust force to the main supporting structure. The combined tensions and bending stresses, resulting from propeller thrust and wing lift respectively, remain well below the material's allowable limit at both the fuselage and motor stations. Therefore, the rib thickness is limited by the minimum thickness of CFRP plate commercially available. Schematic representations of these component connections can be seen in Figure 8.2.

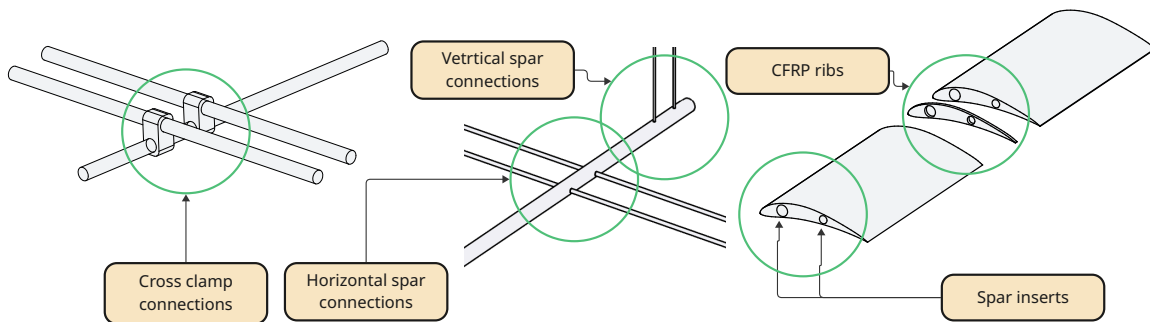


Figure 8.2: Structural concept of the drone (drawing not to scale).

To house the internal drone components such as the battery, sensors, communication module, etc., the fuselage is partially hollowed out to fit these parts. To make sure that all internal components of the drone are easily accessible, a latch will be made on the top of the fuselage. This latch is a rectangular cutout of dimensions 300 mm × 120 mm. These dimensions are based on the size of the battery, as this is the largest component.

Based on the calculated dimensions from this sizing procedure, commercially available parts can be selected where possible. In case this is not possible, the materials are taken into account. These parts are summarised in Table 8.4. The EPP foam block based on the dimensions of the wing and the fuselage. Three separate blocks that fit around the fuselage, and both half-wings are added up, resulting in the cost as listed in the table. The mass, however, was calculated based on the foam density and computed part volumes. For the rods, commercially available parts were found with the smallest available thickness and outer diameter, which are both larger than or equal to the calculated values. The cost of the ribs was decided based on a rectangular patch of carbon fibre that fits around the rib profile. The mass was again calculated using the CFRP density and part volume. The rod connectors were chosen such that both the tail boom and the wing rods can fit inside. Finally, the glass cloth and resin were selected based on the double of the combined area of all aerodynamic lifting surfaces. It should be noted that 5 glass cloths are bought and included in the cost, but the fifth one will not be used fully and thus only accounts for 410 g in the mass budget. It is important to note that no mounting plates for the battery and electronics are considered here, as they are negligible in both mass and cost, because they can be 3D-printed at low cost.

Table 8.4: Structural parts summary.

Component	Cost (€)	Mass (kg)	Quantity
EPP foam ¹⁰	143.95	0.938	1

Continued on next page

¹⁰URL <https://www.epp-versand.de/> [accessed 16.06.2026]

Component	Cost (€)	Mass (kg)	Quantity
Wing spar rod ¹¹	127.18	0.441	1
Wing aileron rod ¹²	118.82	0.498	1
Tail (boom) rod ¹³	161.33	0.720	1
HT rods ¹⁴	14.05	0.033	2
VT rods ¹⁵	4.19	0.005	2
Carbon plate ¹⁶	54.22	0.011	1
Rod connectors ¹⁷	17.98	0.140	3
100g 2x2 Twill Woven Glass Cloth (1000mm) ¹⁸	4.00	0.100	4.1
EL2 Epoxy Laminating Resin ¹⁹	15.35	0.410	1
Total Structure	731.27	3.957	–

Key Choice: Drone Structures Subsystem

The final structural design of the drones consists of seven connected hollow rods and four ribs made from CFRP, a fuselage and wing base made from EPP, and a GFRP wing laminate. Of the seven CFRP rods, two are in the main wing, two in the horizontal tail, two in the vertical tail, and one connects the tail to the fuselage. Each rod has been sized for the maximum aerodynamic forces it could experience during flight. Additionally, the vertical tail is sized for the forward thrust of the rear propeller.

8.3. Payload Structural Sizing

The net containing the payload and the cables connecting the payload have to be sized for the loads that they will experience during the mission. Furthermore, the carabiner clips connecting them have to be selected.

8.3.1. Net Selection

A polyester webbing cargo net of 1.5 m by 1.5 m²⁰ is chosen to carry the payload, as it is large enough to contain the cube-shaped payload with sides of ≈ 0.56 m computed in Section 7.2. The net has a payload carrying capacity of 2.5 tons, which is more than sufficient to carry the 50 kg payload. It is chosen for its ease of use, allowing compliance with the 40-minute set-up requirement. The net can simply be spread flat before loading the payload in the centre, after which the corners are gathered, and the net can be lifted using a lifting hook. Furthermore, the webbing structure made out of only polyester allows for simpler recycling²¹ (SUS-3 🌱). The recyclability will be detailed in Chapter 24.

¹¹URL <https://www.carbonwebshop.com/carbon-fiber-tubes/industrial-performance-tubes/industrial-performance-tube-30x28x3000mm/> [accessed 21.05.2026]

¹²URL <https://www.carbonwebshop.nl/carbon-fiber-buizen/industrial-performance-buizen/industrial-performance-buis-25x22x3000mm/> [accessed 12.06.2026]

¹³URL <https://www.carbonwebshop.com/carbon-fiber-tubes/industrial-performance-tubes/industrial-performance-tube-35x32x3000mm/> [accessed 16.06.2026]

¹⁴URL <https://www.hyperflight.co.uk/products.asp?code=CARBON-TUBE-10MM> [accessed 12.06.2026]

¹⁵URL <https://www.hyperflight.co.uk/products.asp?code=CARBON-TUBE-5MM> [accessed 12.06.2026]

¹⁶URL <https://www.carbon-composite.com/en/Carbon-Plate-0.3mm/CP003-4> [accessed 12.06.2026]

¹⁷URL <https://cicloscorredor.com/en/p/potencia-mtb-merida-expert-trial-35d-negro> [accessed 16.06.2026]

¹⁸URL <https://www.easycposites.eu/100g-22-twill-woven-glass-cloth> [accessed 12.06.2026]

¹⁹<https://www.easycposites.co.uk/el2-epoxy-laminating-resin> [accessed 21.05.2026]

²⁰URL <https://www.securefixdirect.com/polyester-webbing-cargo-net-1m---4m-hoisting-sling-loading-safety-21169-p.asp> [accessed 16.06.2026]

²¹<https://szoneierfabrics.com/what-is-polyester-made-of/> [accessed 16.06.2026]

8.3.2. Cable Selection

Three 18-metre cables connect the payload carriage to the drones. Based on a simulation of the drone formation performed in Chapter 15, the maximum tension experienced in any single cable at any point during the mission is 850 N or 86.7 kg force. Furthermore, this simulation confirmed that high stiffness and damping are desirable to reduce payload spring dynamics.

The selected rope is the Prorope 16-carrier braided polyester rope with 8 mm diameter²². Polyester is chosen for its ease of recyclability (SUS-3 ) , falling within the same category as the net. Furthermore, it is weatherproof, maintaining its strength in exposure to UV as well as rain, essential for continuous outdoor operation (SUS-4 ) . Prorope publishes an in-house tested breaking strength of 1037 kg for this diameter rather than a catalogue estimate for the others. However, since the ropes will have to be knotted, they will retain 50 % of their strength²³. This results in a breaking strength of 518.5 kg or 5086 N. Therefore, the safety factor is $\frac{5086}{850} = 5.98$. This is higher than the general rule for the working coefficient of ropes of 5²⁴. As a mono-material braided polyester rope, it falls into the same recyclability category as the net.

The standard formula for axial stiffness is

$$k = \frac{EA}{L} \quad (8.1)$$

where E is Young's modulus of the material, A is the cross-sectional area, and L is the length. Orcaflex, a standard tool for cable dynamics, provides the following relation for the axial stiffness of polyester fibre ropes²⁵:

$$EA = 1.09 \cdot 10^6 d^2$$

where EA is given in kN and d is in metres. For the chosen diameter of 8 mm:

$$EA = 1.09 \cdot 10^6 \cdot 0.008^2 = 69.76 \text{ kN} = 69760 \text{ N}$$

Using Equation 8.1, $k = \frac{EA}{L} = \frac{69760}{18} = 3876 \text{ N/m}$. The viscous damping coefficient c is calculated from the damping ratio ζ and the system critical damping coefficient:

$$c = 2\zeta\sqrt{km} \quad (8.2)$$

where $m = \frac{50}{3} \approx 16.7 \text{ kg}$ is the payload mass attributed to each cable. The damping ratio is estimated from the loss factor $\tan \delta$ of the polyester (PET) fibre material via the standard relation for lightly damped systems²⁶:

$$\zeta = \frac{\tan \delta}{2} \quad (8.3)$$

The loss factor $\tan \delta$ of drawn PET fibre under axial loading at room temperature is estimated as approximately 0.02, based on measurements by Morton and Hearle [40]. Although these measurements were performed at 110-300 Hz, DMA measurements on PET at 0.3-10 Hz confirm that $\tan \delta$ is frequency-independent in the glassy state well below $T_g \approx 120^\circ\text{C}$ ²⁷. The mass carried per cable is $\frac{50}{3} \approx 16.7 \text{ kg}$. The resulting natural cable frequency of $\omega_n = \sqrt{k/m} = \sqrt{3876/16.7} \approx 15.2 \text{ rad s}^{-1}$ (2.4 Hz) is within this range. The damping ratio then becomes:

$$\zeta = \frac{0.02}{2} = 0.01$$

²²URL <https://prorope.com/products/polyester-touw-gevlochten-in-wit-en-zwart-1-5-mm-t-m-12-mm?variant=45604379558156>

²³URL <https://www.marlowropes.com/news/rope-strength-and-how-retain-it/> [accessed 16.06.2026]

²⁴URL <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0042> [accessed 16.06.2026]

²⁵URL <https://www.orcina.com/webhelp/OrcaFlex/Content/html/Ropewire,Axialandbendingstiffness.htm> [accessed 17.06.2026]

²⁶URL <https://www.comsol.com/blogs/damping-in-structural-dynamics-theory-and-sources> [accessed 16.06.2026]

²⁷URL <https://www.tainstruments.com/pdf/literature/TA423.pdf> [accessed 16.06.2026]

The resulting damping ratio using Equation 8.2 is:

$$c = 2 \cdot 0.01 \sqrt{3876 \cdot 16.7} = 5 \text{ N s/m}$$

8.3.3. Payload Connector

The rotation of the payload and drones must be decoupled to ensure that the payload does not begin spinning when the drones fly in a circle around it during the take-off manoeuvre. Additionally, to prevent uncontrolled payload rotation, a braking mechanism is required as stated in requirements SYS10-PAY07 and SYS11-PAY08. Figure 8.3 shows the designed payload connector. The connector features a swivel with two threaded parts: a hook is attached on one side to connect the cables from the drones, while a threaded rod is inserted on the other side, to which a brake calliper mounting plate is welded. A 3D-printed electronics housing, discussed in Section 10.3, is mounted at the opposite end of the threaded rod. A bicycle brake is selected for the braking mechanism, as such brakes are designed to dissipate the momentum of humans, who are significantly heavier than the 50 kg payload. Carabiner clips are used to connect the net to the payload connector as well as the cables to the drones and the payload connector. The selected clips are made out of stainless steel²⁸, a fully recyclable material²⁹. They have a working load of 120 kg each, more than sufficient to carry the payload.

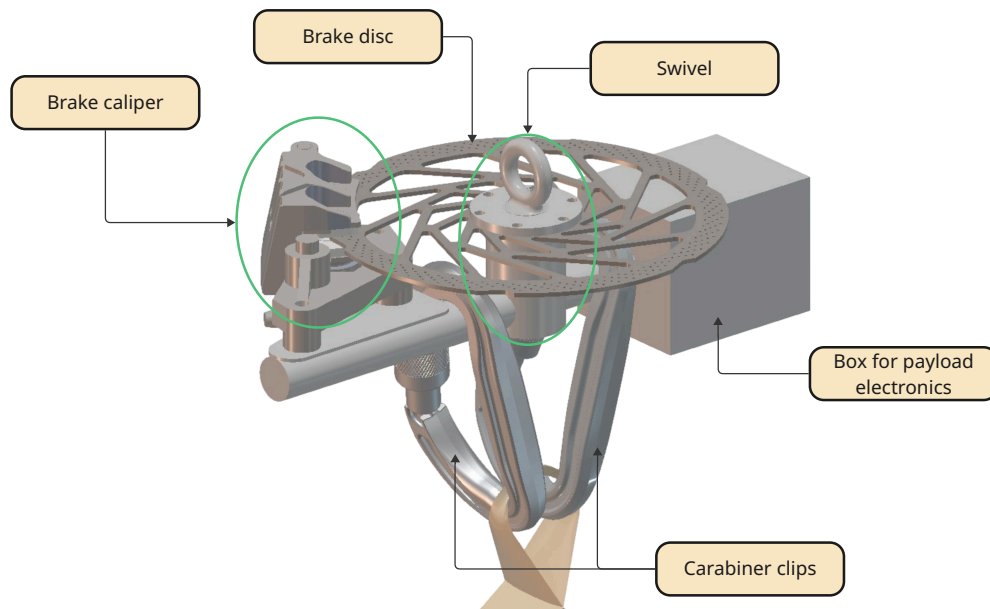


Figure 8.3: Payload Connection

Key Choice: Payload Connector

A payload connector has been designed that can decouple the rotation of the payload and the drones, featuring a brake that can dissipate unwanted rotation of the payload.

8.4. Verification

The requirements SYS44-STR02, SYS44-STR06, SYS10-PAY07, and SYS11-PAY08 can all be verified through demonstration once the drone system has been built. Additionally, requirements SYS20-STR03, SYS27-STR04, and STK17-PAY09 can then be verified through inspection. Finally, SYS17-STR05 can be verified through testing in the TU Delft aircraft hall. SYS17-STR05 can be verified using the whiffletree to simulate a distributed bending load on a half cantilever beam. The test can be performed using a CFRP rod with the same outer diameter and thickness as the selected one. However, to simulate the half cantilever bending, the rod should be at least

²⁸URL <https://www.steelropes24.com/Snap-Hook-with-Eyelet-and-Thread-Stainless-Steel-DIN-5299-Form-C/DS10061.1> [accessed 16.06.2026]

²⁹URL <https://www.okonrecycling.com/industrial-scrap-metal-recycling/stainless-steel/stainless-steel-recyclable/> [accessed 16.06.2026]

1650 mm long. This encompasses half of the actual rod length plus 150 mm to clamp the rod. Then a load of half of the total lift force (333.41 N) should be applied for testing. Finally, SYS22-STR01 and SYS24-STR08 can be verified directly from Table 8.4. This table shows that the total structural cost is 731.27 EUR, which is far below the requirement of 1900 EUR. However, the total structural mass is 3.957 kg, which is 16.4 % over the requirement of 3.4 kg. However, this is not necessarily an issue as the most important mass budget is for the total drone mass. Hence, if the other subsystems come out to be more lightweight than their requirements, the total drone mass could still meet the 10 kg requirement. The future verification procedures are summarised below.

Verification: Future Structural Verification Tasks

The mass and cost have been verified from the component selection. Battery replacement, wing mounting, cable rotation, and yaw braking shall be verified through demonstration. Additionally, component housing, wingspan, and modularity can be verified through inspection. Finally, the load-carrying capability shall be verified through whiffletree testing in the aircraft hall at TU Delft.

8.5. Compliance

Table 8.5: Structures subsystem compliance matrix.

ID	Compliance	Status
SYS22-STR01	The total structure mass is 16 % above the limit value	✗
SYS44-STR02	As discussed previously, hollowed-out compartments and a latch are provided in the fuselage to comply with this requirement	✓
SYS20-STR03	The fuselage has been sized based on internal components	✓
SYS27-STR04	The span was a geometric constraint when sizing the wing rods	✓
SYS17-STR05	The CFRP rods have been sized for the worst case lift (666.82 N per rod)	✓
SYS44-STR06	The wings are designed such that the rods can be inserted and the foam wings can be attached without the use of tools	✓
SYS24-STR08	The total system cost is significantly below the required value	✓
STK17-STR09	The drone structure was designed with rods so the wing spars and foam wing can easily slide on and off.	✓
SYS10-PAY07	The swivel from Subsection 8.3.3 in the payload connector allows for independent rotation of the drones and the payload.	✓
SYS11-PAY08	The brake from Subsection 8.3.3 in the payload connector allows for temporary braking.	✓
STK06	The system can successfully carry the payload throughout the mission	✓
STK07	A suitable linking mechanism is designed to connect the payload and the swarm	✓

9. Propulsion Subsystem Design

The propulsion system provides the thrust required for the drone to sustain flight. With the aerodynamic drag established in Section 7.2, the motor, propeller, and battery can be selected. This chapter first sizes propellers in Section 9.1, followed by the motor selection process in Section 9.2. Battery sizing is subsequently addressed in Section 9.3. The results are validated against eCalc in Section 9.5 and compliance for relevant requirements, presented in Table 9.1, is shown in Section 9.6. Recommendations for future work are provided in Section 9.7.

Table 9.1: Requirements driving propulsion subsystem design.

ID	Requirement
SYS82	The drone shall have a thrust-to-weight ratio of at least 2.
SYS22-PROP01	The propulsion subsystem shall have a mass less than 4.8 kg.
SYS39-PROP03	The propulsion system noise level shall not exceed 55 dB at 100 metre distance from the drone.
SYS02-PROP04	The propulsion subsystem of each drone shall provide at least 40 N thrust at 20 m s^{-1} airspeed.
SYS74-PROP05	The propulsion subsystem shall operate in nominal conditions over the battery's voltage range.
SYS18-PROP06	The drone shall remain controllable following the failure of any single propulsion unit.
STK05	The drones shall lift vertically during take-off.

9.1. Propeller Sizing

The sizing of the propulsion system is initiated by evaluating the thrust required for the three main flight phases - climb, cruise and vertical take-off, where climb velocity and required lift coefficient can be found based on a maximum excess power condition. Additionally, for the vertical take-off manoeuvre, the moment equilibrium of the thrust was considered. Because one of the propellers is located at the vertical tail of the drone and two of the propellers are located at the leading edge of the wing. Hence, depending on the position of the centre of gravity, the propellers need to provide different amounts of thrust, adding up to the take-off thrust.

$$T_{\text{cr}} = \frac{D_{\text{cr}}}{n_{\text{props}}} \quad \text{and} \quad T_{\text{cl}} = \frac{D_{\text{cl}} + \dot{h}m_{\text{load}}g_0/V_{\text{cl}}}{n_{\text{props}}} \quad \text{and} \quad T_{\text{to}} = \left(\frac{T}{W}\right) m_{\text{dr}}g_0.$$

Algorithm 1 Iterative Propeller Sizing

```

1:  $n_{\text{current}} \leftarrow n_0$ 
2:  $n_{\text{prev}} \leftarrow n_0 + 2\varepsilon$ 
3: while  $|n_{\text{current}} - n_{\text{prev}}| > \varepsilon$  do
4:    $n_{\text{prev}} \leftarrow n_{\text{current}}$ 
5:   Load propeller data  $\{C_T(J), C_P(J)\}$  for  $n_{\text{current}}$ 
6:    $J \leftarrow V_{\text{cr}}/(n_{\text{current}}D)$ 
7:   while  $|C_T(J) \rho n_{\text{current}}^2 D^4 - T^*| > \varepsilon_T$  do
8:      $J \leftarrow J + \Delta J \cdot \text{sign}(T^* - C_T(J) \rho n_{\text{current}}^2 D^4)$ 
9:    $J^* \leftarrow J$ 
10:   $n_{\text{current}} \leftarrow V_{\text{cr}}/(J^*D)$ 
return  $(n_{\text{current}}, J^*, C_T(J^*), C_P(J^*))$ 

```

Based on the required thrusts found, the propeller sizing was performed using an iterative procedure, which allowed for a rapid evaluation of multiple propeller options. This loop is illustrated in Algorithm 1. In turn, a propeller which operates at high efficiency in the cruise phase could be chosen, while also ensuring sufficient performance in other flight phases. With this procedure, the effect of propeller size on the design characteristics could be studied to inform the propeller choice.

Design Decision: Propeller Selection

The propeller diameter influences the complete design in a complex manner, and its effect on the design was not obvious in the design exploration phase. To determine a propeller diameter, a sensitivity analysis was done by changing the propeller diameter used for the design. The resulting systems were compared based on mass and energy required for flight, shown in Figure 9.1.

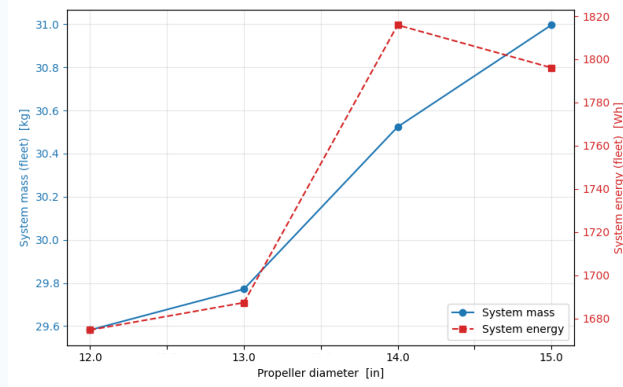


Figure 9.1: Sensitivity analysis for propeller diameter

The results show that both total mass and energy consumption increase with propeller diameter. This trend is primarily driven by the heavier motors required to drive larger propellers, which in turn necessitates a larger wing to generate sufficient lift. The resulting increase in drag demands greater thrust during cruise, reducing propulsive efficiency and requiring a larger battery, a snowball effect that compounds across the entire design. Although propeller efficiency at cruise improves with diameter, this gain is insufficient to offset the mass penalty introduced by the motors. It should also be noted that propeller diameter influences numerous interdependent design parameters simultaneously, meaning its overall effect cannot be fully captured by a small set of metrics alone. The 11-inch propeller is not shown as the propeller could not provide sufficient lift for the VTOL manoeuvre of the drone. Finally, the 12-inch diameter propeller is chosen.

In line with improving system efficiency (SUS-1 🌱), the propeller was optimised for cruise efficiency, resulting in a relatively high pitch. While low-pitch propellers are preferred for hover [41], the VTOL phase is not thrust-critical in this design, as the force required to lift the payload is provided by the wing. The high-pitch propellers can therefore achieve the hover performance required by operating at higher RPM when the cables are slack and only the vehicle load is carried. This is a considerable strength of the presented design, since no dedicated, additional propellers are needed for VTOL. Now the CAM CARBON 12x8 propeller is chosen.

9.2. Motor Sizing and Selection

With the propeller parameters decided, the motors can be sized to provide the required thrust at different flight conditions. As a first estimate that provides an order of magnitude of the required motor KV rating, the following relation is used

$$KV = \frac{60n}{V_b f_{thr}}, \quad (9.1)$$

which gives a $KV = 670$, when a throttle setting of 0.9 is chosen for the most restrictive VTOL flight phase to provide a T/W of two which will not be achieved in typical operations. Although this equation considers the unloaded motor case and thus is not fully representable of real operating conditions, it gives an idea of the required KV rating and a starting point for the motor choice. Based on that rating, an off-the-shelf motor can

be chosen, and it can be verified that it provides the required performance.

To verify the performance of the motor, the required current and voltage must be found at the previously chosen operational points of cruise, climb and hover. The current and voltage required for a given flight phase can be computed respectively from

$$I = \frac{\tau}{K_t} + I_0, \quad V = IR_w + V_{\text{emf}}.$$

Starting with the estimated KV , an off-the-shelf motor was chosen to check whether the required performance can be realised. The obtained voltage and currents required in different flight phases are presented in Table 9.2

It is clear from the table that a 700 KV motor would not be a feasible solution, since the required current is largely above the allowable maximum value of 43 A. A likely cause of this is the fact that the propellers were chosen to maximise the efficiency of flight in fixed-wing cruise mode. In turn, very high current needs to be drawn. This suggests that motors with a lower KV are required, which operate at lower currents for the same RPM. In that way, hovering can still be achieved, while optimising the entire system for the dominating cruise phase and not using dedicated propellers for VTOL. However, lowering the current requires an increase in voltage to achieve the same output power level. This led to considering two other motor models rated at lower KV values.

Table 9.2: Motor operating point summary for candidate motors.

	Cruise	Climb	Hover	T/W=2	Max. allowable	Cruise	Climb	Hover	T/W=2	Max. allowable
	<i>TR 42-50A 700KV¹</i>					<i>VCI 4218 350KV²</i>				
V [V]	13.6	18.1	15.8	21.8	33.07	19.5	33.5	29.5	39.5	48
I [A]	38.6	61.2	47.4	78.0	43.0	25.2	31.0	22.9	38.5	73.5
Throttle [-]	0.57	0.75	0.66	0.9	1	0.44	0.75	0.66	0.89	1

It is clear that the lower KV rating allows for a balanced voltage and current drawn at different flight phases. In particular, for the VCI motor the cruise current approaches the 10% – 30% range of total current, which leaves considerable margin for more restrictive flight phases. The high efficiency at cruise and a considerable margin of 18% to peak current in the most restrictive VTOL phase motivate the choice of the VCI 4218 motor. The lower KV motor choice dictates that the battery needs to be rated 12S to provide sufficient voltage. The mass of the motor was estimated for the iteration with weight estimation obtained from [42]. Once the motor has been selected an ESC has been found to be able to provide the maximum current.

9.3. Battery Sizing and Selection

Design Decision: Battery Selection

Before the required battery capacity can be computed, the battery type needs to be chosen. The commonly used batteries in UAVs are Li-Po and Li-ion batteries [43]. Although Li-ion batteries typically offer a higher energy density, Li-Po batteries offer a higher C-rate, which for a certain battery capacity leads to higher maximum current. As hybrid UAVs often require operating at high RPM, which requires drawing high currents, Li-Po batteries are a more common choice. This led to the choice of the Li-Po battery for the designed system.

After the battery and voltage have been decided as 12S 44.4 V, the battery can be sized. The required battery capacity can be computed by considering the power required over all mission phases. Another important consideration is the depth of discharge (DoD) which is the percentage of the battery used in each operational cycle. As increased DoD significantly increases battery degradation a DoD of 80% is advised [44] to promote system lifetime (SUS-4 ). Next to the increased battery life this DoD provides an energy margin in case of a drone

failure. The necessary capacity of the battery is calculated as

$$C_{\text{bat}} = \frac{P_{\text{cruise}} t_{\text{cruise}} + P_{\text{climb}} t_{\text{climb}}}{\text{DoD } V_{\text{bat}}} \cdot 3.6 \quad (9.2)$$

After all considerations, the MG UAV Solid-State LiPo battery³ is selected, with its parameters listed in Table 9.3. The chosen battery capacity of 13 000 mA h slightly exceeds the required 12 500 mA h, representing the next commercially available size. It is further verified that the maximum continuous discharge current of the battery exceeds the peak current demand of the motor. The mass of the battery was estimated for the iteration with weight estimation obtained from [42].

Table 9.3: Battery parameters.

Number of cells	Voltage	Capacity	Discharge rate	Maximum current	Mass
12S	44.4 V	13 000 mA h	10C	130 A	1.746 kg

9.4. Sound Signature

The propeller tonal noise was estimated using Gutin's loading-noise formula. For the q -th blade-passing harmonic, the root-mean-square acoustic pressure at the observer is given by

$$p_q = \frac{qn\omega}{2\sqrt{2}\pi cL} \left(-T \cos \beta + \frac{cQ}{\omega R^2} \right) J_{qn} \left(qn \sin \beta \frac{V}{c} \right).$$

All symbols used are explained in the table of symbols. The first five harmonics were used during the calculations as the fifth harmonic already had less than 0.1% of the pressure of the first harmonic. For the observer angle and distance the observer was assumed to be right below the drone at cruise altitude causing $\beta = 90^\circ$ and $L = 100$ m. The sound pressure level of each harmonic was then calculated from

$$SPL_q = 20 \log_{10} \left(\frac{p_q}{p_{\text{ref}}} \right)$$

where the reference acoustic pressure is $p_{\text{ref}} = 20 \times 10^{-6}$ Pa. Finally considering the three different propellers the sound of the three propellers are added up, which results in 54.9 dB at 100 meters. The road traffic noise levels in Europe are reported to be 55 dB according to the WHO⁴. The drone thus aims to produce less than 55 dB of sound during cruise at cruise altitude when flying over residential areas. This ensures a satisfactory sound level for the system during operations (SUS-7 .

9.5. Verification and Validation

Verification/Validation: Using eCalc for the Propulsion Subsystem

To validate the propulsion subsystem sizing method, eCalc is used. The maximum current, voltage, RPM at hover, and thrust-to-weight ratio obtained from eCalc are compared with those from the sizing model described in this section, and the results are presented in Table 9.4. A lithium polymer battery with the closest available capacity of 12 A h was selected. For the motor, the Xnova 4030 was chosen as the closest available match to the sized motor, sharing the same KV rating of 350 KV. Its no-load current of 1 A and internal resistance of 0.37Ω compare well with the sized motor values of 1.1 A and 0.4Ω , respectively.

³URL <https://rcdrone.top/products/mg-uav-solid-state-battery-6s-12s-14s-13000mah-10c-for-heavy-load-long-endurance-uavs?variant=48186552320224> [accessed 12.06.2026]

⁴URL <https://www.who.int/europe/news-room/fact-sheets/item/noise> [accessed 12.06.2026]

Table 9.4: Motor performance comparison at maximum throttle: model vs. eCalc.

Parameter	Model	eCalc	Δ (%)
Current at max thrust (A)	38.48	45.88	−16.1
Voltage at max thrust (V)	39.75	40.98	−3.0
RPM at max thrust	13375	13251	+0.9
T/W	2.07	2.06	+0.5

The values estimated by the sizing model are in good agreement with the eCalc results. The largest discrepancy is observed for the maximum current at full throttle, which is underestimated by 16.1 %. While this is a notable underestimation, the value remains well within the operating envelope of the selected motor and battery, which have maximum current ratings of 73.5 A and 130 A, respectively. Furthermore, eCalc itself reports an accuracy of ± 10 %, which accounts for a significant portion of the observed discrepancy. All remaining parameters show close agreement with the sizing model and fall well within the operational limits of the selected components. Finally, eCalc confirms that the thrust-to-weight ratio exceeds two, validating the sizing model output. Additionally, eCalc reports that the temperature at maximum operating conditions will be 62 °C, which is a safe operating temperature.

9.6. Compliance

Table 9.5: Propulsion requirements.

ID	Requirement	Status
SYS82	The thrust-to-weight ratio was validated to be 2.07 with eCalc.	✓
SYS22-PROP01	The final subsystem mass is 2.8 kg.	✓
SYS39-PROP03	The drone produces 54.9 dB at 100 meters	✓
SYS02-PROP04	The propulsion subsystem can provide 45.9 N thrust at 20 m s ^{−1} airspeed.	✓
SYS74-PROP05	The validation shows that the propulsion subsystem operates in nominal conditions over the battery's voltage range.	✓
SYS18-PROP06	Even in the case of one motor failure the remaining two motor can provide 120 N of thrust which is enough to cruise and land.	✓
STK05	The drone has a T/W of 2, meaning enough trust is provided for VTOL	✓

9.7. Recommendations

The battery sizing presented in the design assumes nominal operating conditions, but in practice, several real-world effects can reduce the available energy and power output. For example, cold weather is a well-known concern for lithium-polymer cells. At low temperatures, the internal resistance of the cells increases and its usable capacity decreases by 15% when temperature drops to approximately −10 °C [45]. Given that mission profiles can involve operation at a range of altitudes, exposing the battery to lower temperatures, this phenomenon is directly relevant. Insulating the battery compartment or using waste heat from the ESCs are common mitigation strategies, but none has been considered at this stage.

Furthermore, during high-power flight phases such as climb, the battery must deliver nearly 5 kW. As the battery depletes, voltage sag becomes more pronounced [46], reducing the voltage available to the motors, consequently lowering their maximum RPM and thrust. This means that the propulsion system may not be able to provide enough thrust near the end of the mission than predicted by sizing calculations with constant battery voltage. Future work should evaluate battery performance and incorporate battery discharge characteristics to verify adequate behaviour throughout the mission.

10. Electrical Subsystem Design

The electrical subsystem handles all signal processing, sensing, communication, actuation, and power distribution across the three segments of the system: the drones, the payload connection, and the ground station. Each segment carries its own set of electronics tailored to its role, from full flight control and trajectory execution on the drones, to sensor fusion and communication on the payload, to mission monitoring on the ground. This chapter first identifies the subsystem requirements that drive the electronics selection, then maps these to concrete hardware choices in Section 10.1. Component lists for UAVs, payload, and ground segments are shown in Section 10.2, Section 10.3 and Section 10.4. The electrical internal layout is presented in Section 10.5. Section 10.6 demonstrates compliance with relevant requirements, listed in Table 10.1, and future recommendations are addressed in Section 10.7. Note that choices related to the communication architecture are treated separately in Chapter 11.

Table 10.1: Subsystem requirements driving electronics and sensor selection.

ID	Requirement
NAV01	The navigation subsystem shall measure angular rates with an accuracy of $\pm 0.1^\circ \text{ s}^{-1}$.
NAV02	The navigation subsystem shall measure accelerations with an accuracy of $\pm 0.01 \text{ m s}^{-2}$.
NAV03	The navigation subsystem shall measure relative positions with an accuracy of $\pm 0.10 \text{ m}$.
NAV04	The navigation subsystem shall measure heading with an accuracy of $\pm 1^\circ$.
NAV05	The navigation subsystem shall provide relative inter-drone positions at a rate of at least 10 Hz .
NAV06	Each drone shall measure cable tension with an accuracy of $\pm 5 \text{ N}$ over a range of 0 N to 500 N .
NAV07	Each drone shall measure the relative wind direction in two axes with an accuracy of $\pm 1^\circ$.
NAV08	The navigation subsystem shall provide barometric altitude estimates with an accuracy of $\pm 1 \text{ m}$.
NAV09	The navigation subsystem shall provide airspeed measurements with an accuracy of $\pm 0.5 \text{ m s}^{-1}$.
STK11	The system shall be powered by batteries.

Together, these requirements define the minimum sensing and positioning performance the electronics must deliver. NAV01 and NAV02 set the accuracy floor for inertial sensors, NAV04 constrains the heading reference, and NAV03 demands decimeter-level relative positioning, ruling out standalone GNSS and necessitating an relative positioning solution. NAV05 through NAV07 drive the selection of the relative positioning, cable tension, and wind sensing hardware, while NAV08 establishes the barometric altitude baseline used during vertical manoeuvres, and NAV09 provides an airspeed measurement accuracy.

10.1. Component Selection Rationale

Each requirement in Table 10.1 maps to one or more hardware choices. This section justifies these mappings at a high level; the full component lists and wiring are presented in the sections that follow. All components are commercially available, making these replaceable and thus the system more easily repairable (SUS-5 ). First, Table 10.2 summarises the resulting sensor accuracies alongside their sources.

Table 10.2: Sensor accuracies.

Component	Measurement	Accuracy ($\pm$)
GNSS	Absolute position	1.5 m^1
	Relative position	$0.01 \text{ m} + 1^\circ^2$

Continued on next page

Component	Measurement	Accuracy ($\pm$)
Compass	Heading angle	1° ³
UWB module	Relative distance	10 cm ⁴
IMU	Angular rates	0.5% ⁵
	Accelerations	0.5% ⁵
Barometer	Altitude	0.1 m ⁶
Load cell	Tension	0.25 N ⁷
Rotary encoder	Angle of attack/sideslip	0.1° ⁸
Pitot Tube	Airspeed	1% (0.3 m s^{-1}) ⁹
	Temperature	2°C ⁹

Attitude and Inertial Sensing (NAV01, NAV02)

The Pixhawk 6X Mini flight controller carries three redundant ICM-45686 IMUs, each providing three-axis gyroscope and accelerometer data. The ICM-45686 specifies a sensitivity error of $\pm 0.5\%$ for both. At a typical flight controller bandwidth of 100 Hz, the resulting RMS noise is approximately $0.038^\circ \text{s}^{-1}$ and 0.007 m s^{-2} , both well within the NAV01 and NAV02 thresholds. Triple redundancy allows the flight controller to cross-check readings and reject faulty units.

Global and Relative Positioning (NAV03, NAV05)

Standalone GNSS provides only metre-level accuracy, far short of the $\pm 0.10 \text{ m}$ required by NAV03. This is addressed through a moving-baseline RTK configuration: each drone carries a Holybro H-RTK F9P module as a rover, while the leader drone's F9P is configured as a moving base station that broadcasts corrections over the mesh network. In RTK fixed mode, the F9P achieves a relative position accuracy of $0.01 \text{ m} + 1 \text{ ppm}$, enabling centimetre-level relative positioning without ground infrastructure. Note that the global position of the system as a whole remains at standalone GNSS accuracy (approximately 1.5 m to 2.5 m), since no fixed ground base provides absolute corrections. For formation control, however, only relative accuracy matters.

To complement RTK under high-dynamics or degraded satellite conditions, each drone and the payload also carry a Nooploop LinkTrack P-A UWB module with a specified ranging accuracy of $\pm 10 \text{ cm}$. The four UWB ranges among drones and payload fully define the formation triangle geometry. The UWB modules support update rates of up to 200 Hz, well above the 10 Hz floor set by NAV05.

The navigation design follows a layered degradation strategy, where the loss of any single positioning source does not result in an immediate loss of formation awareness. Under nominal conditions, the primary source is the moving-baseline RTK solution, with UWB ranging running in parallel as a cross-check during brief RTK fix losses. If RTK corrections are lost entirely, each drone still has its own standalone GNSS fix at approximately

¹URL https://cdn.sparkfun.com/assets/d/e/2/8/b/ZED-F9P_datasheet.pdf [accessed 15.06.2026]

²URL https://content.u-blox.com/sites/default/files/ZED-F9P_ProductSummary_UBX-17005151.pdf [accessed 15.06.2026]

³URL https://www.saelig.com/supplier/isentek/ist8301c_datasheet_v10_20130712.pdf [accessed 16.05.2026]

⁴URL https://ftp.nooploop.com/software/products/uwb/doc/LinkTrack_Datasheet_V2.1_en.pdf [accessed 15.06.2026]

⁵URL <https://invensense.tdk.com/en-us/products/6-axis/icm-45686> [accessed 15.06.2026]

⁶URL <https://nl.farnell.com/seeed-studio/101020068/barometer-sensor-arduino-raspberry/dp/4007687> [accessed 16.06.2026]

⁷URL <https://www.ato.com/micro-load-cell-s-type-1kg-to-50kg> [accessed 15.06.2026]

⁸URL <https://witmotion-sensor.com/products/jy-me01-high-precision-18-bit-resolution-absolute-encoder-digital-rotation-angle-sensor> [accessed 15.06.2026]

⁹URL <https://holybro.com/products/high-precision-dronecan-airspeed-sensor-dlvr?variant=44438283714749> [accessed 15.06.2026]

1.5 m accuracy, which can be fused with UWB ranges and IMU propagation to maintain a degraded but usable position estimate, sufficient to hold formation and initiate a safe landing. In the worst case, where both GNSS and UWB are unavailable, the system falls back to IMU propagation, barometric altitude, magnetometer heading, and cable tension readings. Since an emergency landing requires only a short-duration descent, the drift accumulation of these sensors is expected to remain within acceptable bounds. This strategy also extends to single-drone failure: the remaining two drones and the payload still form three nodes with three pairwise UWB ranges, three GNSS fixes, and three IMU readings, fully resolving the formation triangle.

Heading (NAV04)

The Holybro H-RTK F9P Helical module integrates an IST8310 three-axis magnetometer alongside the GNSS receiver, providing a heading reference independent of gyroscope drift with a specified accuracy of $\approx \pm 1^\circ$ after calibration. This eliminates the need for a separate compass board and simplifies the wiring within each drone.

Cable Tension (NAV06)

Each drone carries a micro S-type load cell at the cable attachment point, read through a NAU7802 24-bit I2C ADC. The load cell specifies a combined error of $\pm 0.05\%$, corresponding to ± 0.25 N, which is well within the ± 5 N threshold of NAV06. The NAU7802 communicates directly with the Pixhawk over I2C, eliminating the need for a separate microcontroller. These measurements allow the flight controller to account for cable forces, estimate payload position when not available, and detect anomalies such as cable slack or overload.

Wind Direction (NAV07)

Two JY-ME01 absolute rotary encoders are mounted with a 3D-printed wind vane assembly on each drone, measuring the relative wind direction in two axes. From these readings, the onboard computer senses angle of attack and sideslip, needed for computing aerodynamic forces during both the spinning and forward-flight phases. The encoder offers a 0.001° resolution, but the practical flow angle accuracy is limited by vane dynamics and aerodynamic effects rather than the sensor itself. The system is nevertheless expected to meet the $\pm 1^\circ$ requirement of NAV07.

Barometric Altitude (NAV08)

The Pixhawk 6X Mini integrates two onboard barometers, which provide redundant pressure measurements for altitude estimation. Their relative pressure accuracy of approximately ± 0.12 hPa corresponds to an altitude accuracy of roughly ± 0.1 m, comfortably meeting the ± 1 m threshold of NAV08. Dual redundancy allows the flight controller to cross-check readings and reject outliers caused by transient pressure disturbances.

Airspeed (NAV09)

Each drone carries a Holybro DroneCAN DLVR differential pressure sensor connected to a pitot tube (PT40 variant). The DLVR specifies an accuracy of less than 1% across its 2500 Pa range, with a resolution of 0.6 Pa. At the nominal cruise dynamic pressure of approximately 245 Pa (corresponding to 20 m s^{-1} at sea level), this translates to an airspeed error of roughly $\pm 0.3 \text{ m s}^{-1}$, within the $\pm 0.5 \text{ m s}^{-1}$ required by NAV09. This measurement complements the wind vane encoders (NAV07), which provide direction only.

Communication

All nodes in the system share a unified Doodle Labs Mesh Rider Mini radio operating on the 2.4 GHz band, forming a mesh network. The communication architecture rationale and topology are described in full detail in Chapter 11.

10.2. UAV Electronics

A core design decision is that all three drones carry identical electronics and follow the same manufacturing plan. This choice simplifies production, logistics, and, most importantly, enables dynamic leader failover.

The system adopts a leader-follower architecture. One drone assumes the leader role and is responsible for sending formation setpoints to the other two follower drones, which execute their own low-level attitude and position control. In the current design stage, all drones are pre-loaded with the optimal trajectory computed by the trajectory optimiser described in Chapter 13. The leader distributes the corresponding reference setpoints

over the mesh network during flight. In a future implementation, the leader would perform live trajectory planning onboard, using real-time state feedback from all drones and the payload.

To simplify the manufacturing procedure and to aid the scalability of the system, all drones will have the leader capability, but the payload carriage will house only the attitude sensors and will not perform any live computation. The initial leader drone is connected to the payload through the mesh. In case this drone were to lose communication with the other components in the system, one of the other drones is designated in advance as a successor to ensure a smooth transition between roles.

To determine when the successor drone should take over, failure criteria must be established. The Doodle Labs radio module has a typical latency of 10 ms to 20 ms. A timeout threshold of 100 ms is considered safe to account for message contention and occasional dropouts; during this period, the affected drone holds its last commanded state and attempts to recover the connection. If communication is restored within this window, normal operation resumes. If communication is not restored after 1 s, the initial leader drone is considered to have failed. A successor is then designated based on drone health status, and initiates the safe-landing procedure at the nearest safe space to decrease the risk of a fatal crash. The failed drone remains suspended from the cable throughout this process. This directly satisfies STK09 (see Chapter 13), which requires that the failure of a single drone shall not lead to a crash of the complete system.

Table 10.3 summarises the electronic components carried by each drone, covering flight control, sensing, communication, and power management. All listed costs and masses reflect the total per drone, i.e. the unit value multiplied by the quantity shown. A dash (—) in the max power column indicates a passive or non-power-consuming component, such as an antenna or power distribution board.

Table 10.3: Electronic components carried by each UAV.

Type	Component	Qty.	Power [W]	Mass [g]	Cost [EUR]
<i>Computing & Control</i>					
Flight controller	Pixhawk 6X Mini ¹⁰	1	2.5	58	247
Onboard computer	Raspberry Pi 5 (8 GB) ¹¹	1	12	60	172
<i>Positioning</i>					
GNSS / compass	Holybro H-RTK F9P Helical ¹²	1	0.5	49	255
UWB module	Nooploop LinkTrack P-A ¹³	1	0.2	5	79
<i>Sensing</i>					
Load cell	Micro S-type load cell ¹⁴	1	0.05	60	200
Rotary encoder	JY-ME01 absolute encoder ¹⁵	2	0.5	22	62
Pitot tube	DroneCAN Airspeed Sensor PT40 ¹⁶	1	0.5	39	95
<i>Communication</i>					
Mesh radio	Doodle Labs Mini OEM ¹⁷	1	5	34	1273

Continued on next page

¹⁰URL <https://holybro.com/products/pixhawk-6x?variant=44399078768829> [accessed 15.06.2026]

¹¹URL <https://www.amazon.com/Raspberry-Pi-8GB-SC1112-Quad-core/dp/B0CK2FCG1K> [accessed 15.06.2026]

¹²URL <https://holybro.com/products/h-rtk-f9p-helical> [accessed 15.06.2026]

¹³URL <https://www.nooploop.com/linktrack/> [accessed 15.06.2026]

¹⁴URL <https://www.ato.com/micro-load-cell-s-type-1kg-to-50kg> [accessed 15.06.2026]

¹⁵URL <https://witmotion-sensor.com/products/jy-me01-high-precision-18-bit-resolution-absolute-encoder-digital-rotation-angle-sensor> [accessed 15.06.2026]

¹⁶URL <https://holybro.com/products/high-precision-dronecan-airspeed-sensor-dlvr?variant=44438283714749> [accessed 15.06.2026]

¹⁷URL <https://uaxtech.com/products/doodle-labs-mini-oem-mesh-rider-radio> [accessed 15.06.2026]

Type	Component	Qty.	Power [W]	Mass [g]	Cost [EUR]
Antenna	Singularity 2.4 - SMA (omnidir.) ¹⁸	2	—	19	43
<i>Power & Actuation</i>					
ESC	Hobbywing XRotor Pro 50 A ¹⁹	3	1	84	168
Power distributor	Matek FCHUB-12S ²⁰	1	—	21	25
Voltage converter	Matek Micro BEC 6–30 V ²¹	1	—	1	4
<i>Interfaces</i>					
Serial converter	CP2102 USB-to-TTL ²²	2	0.5	9	10
Load-cell interface	NAU7802 I2C amplifier ²³	1	0.01	3	5
Total			~25	~470	~2640

The electronics mass per drone is approximately 470 g, roughly 5% of total drone mass, leaving sufficient margin for other subsystems. The dominant cost drivers are the Doodle Labs Mesh Rider radio and the Holybro RTK GNSS module, which together account for over half of the per-drone electronics cost. The total three-drone electronics expenditure amounts to $3 \times 2640 \text{ EUR} \approx 7920 \text{ EUR}$, representing nearly half of the 20 000 EUR system budget (STK14). All prices reflect unit costs at time of writing and exclude shipping, import duties, and handling fees.

An overview of the wiring of the components on the drone can be found in Figure 10.1. Electronics are subdivided into different sizes, proportional to the current and power transmitted.

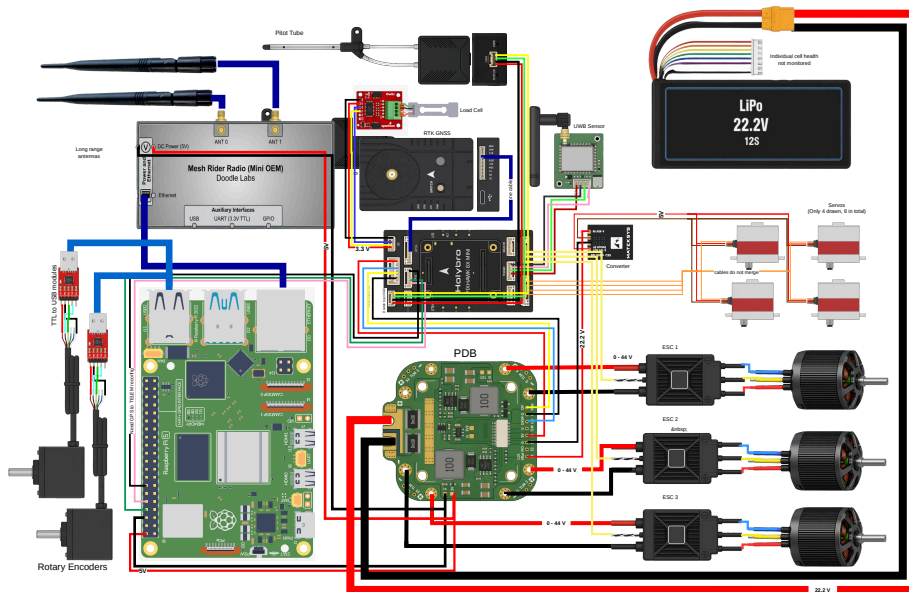


Figure 10.1: Wiring diagram for each UAV electronics.

¹⁸URL <https://truerc.com/71973-singularity-24-sma> [accessed 15.06.2026]

¹⁹URL <https://druav.com/products/2pcs-hobbywing-xrotor-pro-50a-esc> [accessed 15.06.2026]

²⁰URL <https://www.mateksys.com/?portfolio=fchub-12s> [accessed 15.06.2026]

²¹URL <https://www.mateksys.com/?portfolio=mbec6s> [accessed 15.06.2026]

²²URL <https://www.123-3d.nl/123-3D-USB-naar-TTL-serieel-converter-CP2102-UART-i2012.html> [accessed 15.06.2026]

²³URL <https://www.adafruit.com/product/4538> [accessed 15.06.2026]

10.3. Payload Electronics

The payload connection houses a lighter set of electronics compared to the drones, as it carries no flight controller, no ESCs, and no actuation hardware. Its primary roles are to provide its own position and attitude estimates to the swarm, to participate in the UWB ranging geometry, and to relay status and health data over the mesh network. A Raspberry Pi 5 (1 GB variant) handles sensor fusion and communication locally, while three redundant ICM-45686 IMUs and two BMP085 barometers provide attitude and altitude estimates independently of the drones. The triple-redundant sensor layout mirrors the Pixhawk approach used on the drones and allows sensor voting to reject faulty readings. This also ensures mitigation of risk ELEC03 in Chapter 5. A TCA9548A I2C multiplexer manages bus addressing for the identical sensors. The payload is powered by a dedicated 1S LiPo cell, keeping its power supply independent of the drone buses. Table 10.4 lists all payload components.

Table 10.4: Electronic components carried by the payload.

Type	Component	Qty.	Power [W]	Mass [g]	Cost [EUR]
<i>Computing</i>					
Onboard computer	Raspberry Pi 5 (1 GB) ²⁴	1	9	60	50
<i>Positioning</i>					
GNSS / compass	Holybro H-RTK F9P Helical ¹²	1	0.5	49	255
UWB module	Nooploop LinkTrack P-A ¹³	1	0.2	5	79
<i>Sensing</i>					
IMU	ICM-45686 ²⁵	3	<0.1	6	15
Barometer	BMP085 pressure sensor ²⁶	2	<0.1	20	38
I2C multiplexer	TCA9548A ²⁷	1	<0.01	1	6
<i>Communication</i>					
Mesh radio	Doodle Labs Mini OEM ¹⁷	1	5	34	1273
Antenna	Singularity 2.4 - SMA (omnidir.) ²⁸	2	—	19	43
<i>Power</i>					
Battery	4000 mAh 3.7 V 1S LiPo ²⁹	1	—	72	13
Voltage Converter	3.7 V to 5 V ³⁰	1	—	15	4
Total			~15	~280	~1780

The payload electronics total approximately 280 g and 1780 EUR. The mass is dominated by the Raspberry Pi 5, the RTK module, and the communication subsystem. By equipping the payload with its own Mesh Rider radio, it now communicates with the drones over the same mesh network rather than relying on a separate short-range

²⁴URL <https://www.tme.eu/nl/details/sc2162/raspberry-pi-minicomputers/raspberry-pi/raspberry-pi5-1gb/> [accessed 15.06.2026]

²⁵URL <https://invensense.tdk.com/products/motion-tracking/6-axis/icm-45686/> [accessed 15.06.2026]

²⁶URL <https://nl.farnell.com/en-NL/seeed-studio/101020068/barometer-sensor-arduino-raspberry-dp/4007687> [accessed 15.06.2026]

²⁷URL <https://www.adafruit.com/product/2717> [accessed 15.06.2026]

²⁸<https://truerc.com/71973-singularity-24-sma> [accessed 15.06.2026]

²⁹URL https://www.reichelt.com/nl/nl/shop/product/li-ion-accu_soldered_333287_4000_mah_3_7_v_-373551?PROVID=2809 [accessed 23.06.2026]

³⁰URL https://www.alibaba.com/product-detail/DC-DC-Boost-Converter-3V-3_62019843043.html [accessed 23.06.2026]

and potentially fragile link. The combined system electronics cost across all four nodes (three drones and the payload) amounts to approximately $3 \times 2640 \text{ EUR} + 1780 \text{ EUR} = 9700 \text{ EUR}$, consuming roughly 50% of the 20 000 EUR budget set by STK14.

An overview of the wiring of the electronics stored in the payload connection can be found in Figure 10.2.

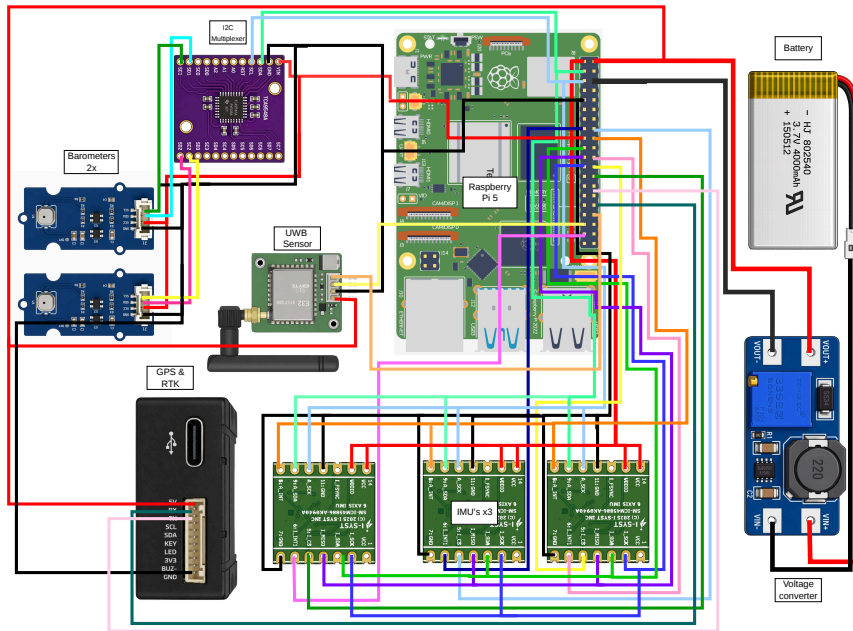


Figure 10.2: Wiring diagram for the electronics in the payload connection.

10.4. Ground Station Electronics

The ground station is the simplest electronic segment of the system. Its role is to provide the operators with real-time telemetry from the drones and payload and to broadcast high-level mission commands such as waypoint updates or abort instructions to the swarm.

The station consists of a Doodle Labs Mesh Rider Mini radio connected to a laptop running the ground control software. By using the same Mesh Rider hardware as the drones and the payload, the ground station joins the mesh network as a regular node, and can receive telemetry and send commands to any airborne unit without a dedicated long range link. Table 10.5 lists the ground station components.

Table 10.5: Electronic components at the ground station.

Type	Component	Qty.	Mass [g]	Cost [EUR]
Mesh radio	Doodle Labs Mini OEM	1	34	1273
Antenna	Singularity 2.4 - SMA (omnidir.) ³¹	2	19	43
Total			~55	~1320

The ground station electronics cost amounts to approximately 1320 EUR (radio and antennas). The operator laptop is excluded from the system cost budget, as it is a general-purpose device that is not consumed or dedicated to the system. Any standard laptop capable of running open-source ground control software is sufficient, and operators are expected to supply their own. Including the ground Mesh Rider, the total Doodle Labs expenditure across all five nodes amounts to $5 \times 1273 \text{ EUR} = 6365 \text{ EUR}$, making it the largest cost item in the electrical subsystem.

10.5. Internal Layout

Now that the necessary electronic components have been chosen they all need to be connected and placed. Additionally as discussed in Chapter 8 and requirement STK17-STR09 the design is made to be modular. The cable routing should therefore allow for quick connection and disconnection of the wings from the fuselage while connecting the motors and servos on the wing. The component layout and cable routing in the drone is shown in Figure 10.3.

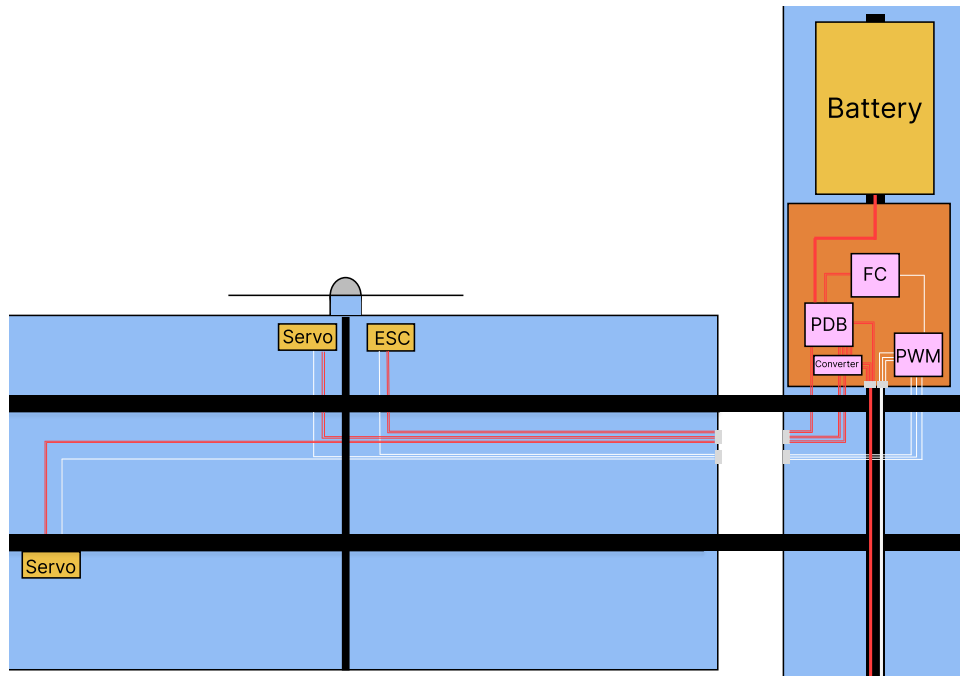


Figure 10.3: Cable routing for each UAV electronics.

The positions of the battery and wing spars were established during the drone sizing process to locate the centre of gravity appropriately for stable flight. This sizing left a volume above the wingbox and forward of the battery, indicated in orange, available for the remaining components. The main electrical components — the flight controller and PDB (see Section 10.2) — are housed in this region and indicated in pink.

The ESCs are mounted on the wings rather than in the fuselage, as they generate significant heat during operation; the wing-mounted position promotes passive cooling through the oncoming airflow during flight.

Electrical cables are routed from the fuselage through the wing structure to the control servos, ESC, and motors. To facilitate modularity and ease of assembly, electrical connectors are introduced at the wing root, as indicated in grey in Figure 10.3. Two connectors are provided per wing: one carrying power to all wing-mounted components, shown in red, and one carrying signal cables, shown in white.

Cabling to the servos and motor located in the tail is routed through the interior of the tail boom, then distributed through the horizontal and vertical tail surfaces to their respective actuators and motor.

10.6. Compliance

Table 10.6: Electrical subsystem requirements compliance.

ID	Evidence	Status
NAV01	The ICM-45686 gyroscope has an RMS noise of $0.038^{\circ} \text{ s}^{-1}$ at 100 Hz bandwidth. Triple-IMU fusion this reduces to $0.022^{\circ} \text{ s}^{-1}$, well within the $\pm 0.1^{\circ} \text{ s}^{-1}$ threshold.	✓

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ID	Evidence	Status
NAV02	The ICM-45686 accelerometer has an RMS noise of 0.007 m s^{-2} at 100 Hz bandwidth, within the $\pm 0.01 \text{ m s}^{-2}$. Additional triple-fusion margin.	✓
NAV03	The moving-baseline RTK fixed mode achieves $0.01 \text{ m} + 1 \text{ ppm}$ relative accuracy, supplemented by UWB ranging at $\pm 0.10 \text{ m}$. Both within the $\pm 0.10 \text{ m}$ threshold.	✓
NAV04	The IST8310 magnetometer integrated in the H-RTK F9P provides heading accuracy of approximately $\pm 1^\circ$ after calibration, meeting the $\pm 1^\circ$ threshold.	✓
NAV05	The Nooploop LinkTrack P-A supports update rates up to 200 Hz, and the RTK solution provides updates at 10 Hz. Both exceed the 10 Hz minimum rate.	✓
NAV06	The micro S-type load cell has a combined error of $\pm 0.05\% \text{ FS} = \pm 0.25 \text{ N}$, well within the $\pm 5 \text{ N}$ threshold over the 0 N to 500 N range.	✓
NAV07	The JY-ME01 rotary encoders provide an absolute accuracy of $\pm 0.1^\circ$ with 18-bit resolution, exceeding the $\pm 1^\circ$ requirement by an order of magnitude.	✓
NAV08	The two barometers integrated in the Pixhawk 6X Mini provide a relative altitude accuracy of approximately $\pm 0.1 \text{ m}$, well within the $\pm 1 \text{ m}$ threshold. Dual redundancy enables cross-checking of readings.	✓
NAV09	The Holybro DLVR pitot sensor specifies less than 1% error, yielding approximately $\pm 0.3 \text{ m s}^{-1}$ at cruise speed, within the $\pm 0.5 \text{ m s}^{-1}$ threshold.	✓
STK17-STR09	The drone structure wing cabling was made that the wing can easily slide on and the connector between the spars will connect the cabling to the fuselage as discussed in Figure 10.3.	✓
STK11	Batteries are used for powering both the propulsion and the electronics.	✓

10.7. Recommendations

Onboard the drones and the payload, sensors take measurements of the acceleration, angular rates, wind speed, cable tensions, etc. However, inaccuracies come with them, and it is important to consider their effect as they are implemented. Commercially available components often list their accuracies as specifications, and these can be used as a reference for the error that each component will have. For example, an IMU such as the ICM-45686 on the Pixhawk 6X Mini specifies its gyroscope bias and accelerometer noise density, which can then be modelled as additive noise in the simulation. To assess if the control system can tolerate these inaccuracies, Gaussian noise is introduced in the simulation. Preliminary results indicate that the system remains stable under small noise levels, although a more detailed sensitivity analysis across the full flight mission is recommended for future work.

Real-world sensors introduce other challenges besides this stationary noise that might not be captured by the datasheet specifications alone. First, sensor latency means that the measurements arrive with a small and non-zero delay, after which the quantity measured changes. For faster inner loops, even a few milliseconds delay can degrade controller performance. In the design, this challenge is addressed by keeping the most latency sensitive measurements (angular rates and accelerations from the IMU) on the same board as the flight controller, minimising the delay introduced by communication.

Second, even identical sensor models exhibit variation in bias or scale factor, causing the readings to drift over time. A ground calibration procedure before each flight is therefore planned to align these offsets across all three drones.

Finally, different sensors operate at different update rates, and vibrations from the rotors and aerodynamic loads can further corrupt accelerometer and barometer readings. An Extended Kalman Filter can be incorporated to handle the varying update rates by applying each correction as it arrives without requiring a common clock. For vibrations, soft-mounting the flight controller and low-pass filtering are standard mitigations, even though the cutoff frequency would require careful tuning.

11. Communication

Communication between the drones and with the ground station is crucial for the mission's success. Section 11.1 presents the link budget to verify link closure over the 20 km mission range. Next, Section 11.2 presents the communication diagram of the system that describes the architecture of the system. Section 11.2 demonstrates the compliance with relevant requirements, listed in Table 11.1.

Table 11.1: Requirements driving communications design.

ID	Requirement
SYS26-COM01	The onboard computer shall transmit at least 12 kB s^{-1} to the ground station.
SYS26-COM02	The telemetry datalink shall transmit data over a distance up to 20 km during cruise.

11.1. Communication Link Budget

The communication link budget of the drones and the ground station to find the required antenna gain is done through analytical calculations and communication requirements.

A robust communication architecture is critical to ensure proper coordination of drones in a swarm [47]. To ensure that the received signal is strong enough, Equation 11.1 [48] can be used to calculate the received signal power. This power must then be larger than the sensitivity of the receiving communication module to achieve a clear communication link.

$$P_r = P_t + G_t + G_r - L_p - L_m \quad (11.1)$$

In Equation 11.1, P_r signifies the received power, P_t the transmitted power, G_t the transmission gain, G_r the receiver gain, L_p the free space loss, and L_m the miscellaneous losses. The selected Doodle Labs Mini OEM Mesh Rider Radio has a transmission power of 31 dBm¹ or 1 dB, which can be used as P_t . Next, the free-space losses can be calculated using Equation 11.2.

$$L_p = \left(\frac{4\pi d}{\lambda} \right)^2 [48] = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) \quad (11.2)$$

Here, d signifies the distance between the transmitter and receiver. A worst-case distance of 20 km is considered, as specified by requirement SYS26-COM1 from Table 11.1. λ signifies the wavelength of the signal. This can be calculated using the speed of light and the signal frequency, $\frac{c}{f}$. For a frequency of 2.4 GHz ², this results in a free space loss of 126.07 dB.

Multiple sources of miscellaneous losses are considered here: cable losses, body blockage losses, polarisation mismatch losses, air-to-air fading margins and atmospheric attenuation. The first of these loss sources can be estimated by taking an RG316 cable³ of 10 cm. For this specific cable, the loss is 0.143 dB at a frequency of 2.4 GHz ⁴. Body blockage losses are taken as 35 dB in the worst-case scenario for fixed-wing drones [49]. Next, polarisation mismatch losses can be assumed to be 1.5 dB [50]. Then, the fading loss can be taken from Lyu et al [51]. The maximum small-scale fading depth was found to be 14.05 dB, and is hence taken as the worst case here [51]. The largest standard deviation of the shadow loss is also taken as 2.7 dB [51]. The other large-scale contribution is ignored here, as it is already accounted for with the L_p term. The atmospheric attenuation losses

¹URL <https://uaxtech.com/products/doodle-labs-mini-oem-mesh-rider-radio>[12.06.2026]

²URL <https://uaxtech.com/products/doodle-labs-mini-oem-mesh-rider-radio>[12.06.2026]

³URL <https://www.elecbee.com>[accessed 12.06.2026]

⁴URL <https://thedxshop.com/coax-loss-calculator/>[accessed 12.06.2026]

can be estimated based on the method provided by Anderson et al., who mention that at a rain rate of 100 mm h^{-1} , the rain attenuation at 2.4 GHz is only 0.03 dB km^{-1} [52]. Cloud attenuation is 0.05 dB km^{-1} , and attenuation due to atmospheric gasses is 0.02 dB km^{-1} [52]. Manola et al. mention that the highest recorded rainfall in the Netherlands is 21 mm h^{-1} , which is significantly below the 100 mm h^{-1} from Anderson et al., showing that the estimates are conservative [53] [52]. This results in a total atmospheric attenuation of 0.1 dB km^{-1} or 2.0 dB over the length of the 20 km mission. Lastly, pointing losses are also ignored as omnidirectional antennas are used for communication.

Assuming that the same architecture will be used for both transmission and reception, the required antenna gain can be calculated using the previously determined values and a reception sensitivity of -167 dBm ⁵ or -197 dB using Equation 11.1. This yields a minimum required antenna gain of -8.269 dB . Doodle Labs provides a list of recommended antennas for this specific radio module⁶. From this list, the omnidirectional antenna with the lowest acceptable gain and operating frequency of 2.4 GHz was chosen. This is the Singularity 2.4 - SMA antenna from TrueRC with a gain of 1.9 dBic and a weight of 9.45 g⁷. A summary of all contributions is shown in Table 11.2.

Table 11.2: Link budget summary.

Parameter	Contribution
P_t	1 dB
G_t	1.9 dB
G_r	1.9 dB
L_p	126.07 dB
L_{cable}	0.143 dB
$L_{\text{body blockage}}$	35 dB
$L_{\text{polarisation mismatch}}$	1.5 dB
$L_{\text{small-scale fading}}$	14.05 dB
$L_{\text{shadow fading}}$	2.7 dB
$L_{\text{atmospheric attenuation}}$	2 dB
L_m	55.393 dB
P_r	-176.663 dB
Reception Sensitivity	-197 dB
Margin	20.337 dB

It is important to note that the previous calculations were performed for the communication between the current leader drone and the ground station. The same communication link will be used for short-range communication between drones. However, this link will have a lower free-space loss, since it is performed over shorter distances, and a lower shadow-fading loss, since the communication occurs mostly at an altitude of 100 m, where there are few obstacles. This means that the sizing of the drone-to-ground link is the most constraining.

Key Result: Sufficient Communication Budget

Table 11.2 shows that a sufficient margin of 20.337 dB remains after taking into account both free space losses and miscellaneous losses in the communication link. Additionally, Table 11.2 shows that this margin can be achieved with a relatively small antenna gain of 1.9 dB. This is possible due to the high sensitivity of the mesh radio module of -197 dB .

⁵URL <https://icmaychip.com/he/product/rm-2450-12m3/8431379.html>[accessed 13.06.2026]

⁶URL <https://kb.doodlelabs.com/recommended-antenna-matrix>[accessed 13.06.2026]

⁷URL <https://truerc.com/71973-singularity-24-sma>[accessed 15.06.2026]

11.2. Communication Diagram

The communication flow diagram in Figure 11.1 shows the data exchanged between subsystems within each segment and across segments. The system is organised into four segments: the ground segment, the leader drone, the follower drones (two of them), and the payload.

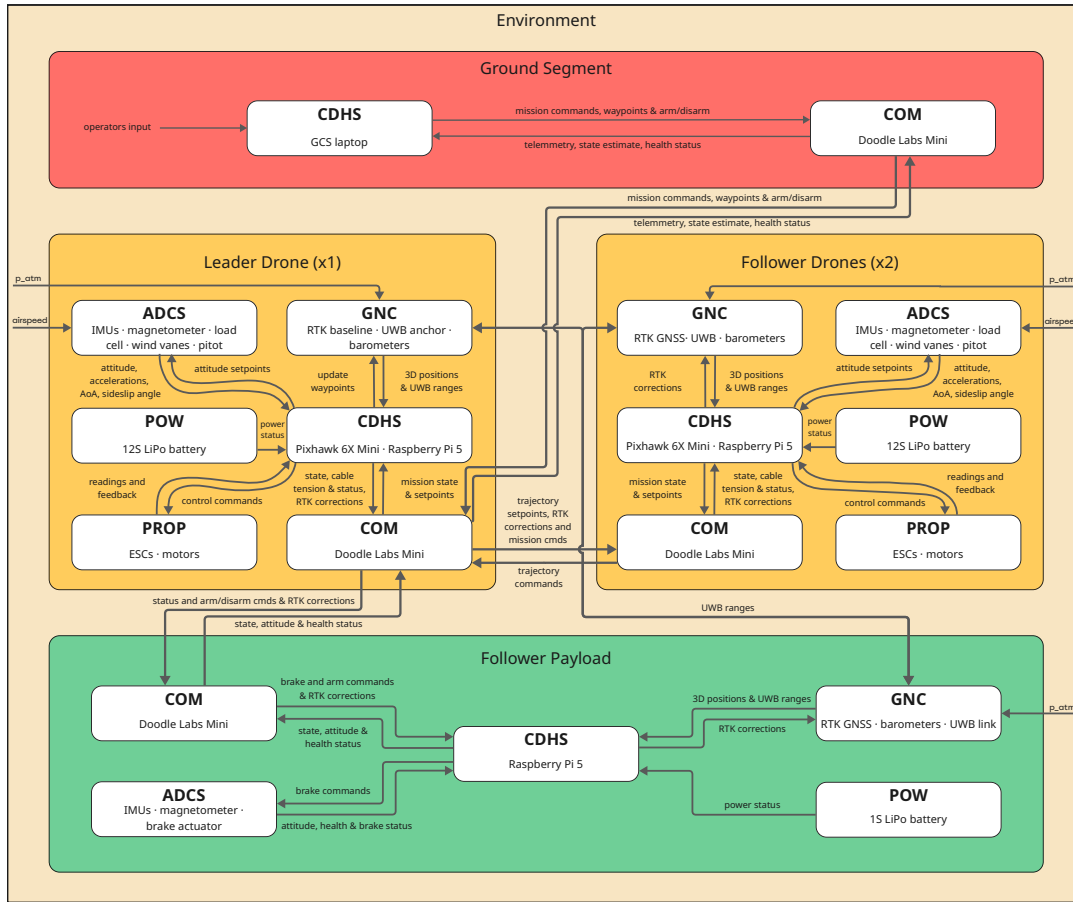


Figure 11.1: Communication Flow Diagram

In initial design iterations, the communication architecture followed a star topology centred on the payload, using multiple dedicated radio types for different links. This introduced a single point of failure at the payload hub and scaled poorly, as adding a drone required adding another dedicated radio to the central node. The final design replaces this with a unified mesh network in which all five nodes carry the same Doodle Labs Mesh Rider Mini radio and participate as equal peers. The remainder of this section describes the resulting architecture.

The leader drone is the central node of the system. Its command and data handling subsystem (CDHS) coordinates the entire swarm. The leader generates RTK corrections from its GNSS moving baseline receiver and broadcasts them to the follower drones and the payload, enabling centimetre-level relative positioning between them. This drone also has the full mission profile loaded and is in charge of sending trajectory setpoints and mission commands to each follower drone. To ensure smooth coordination of the swarm, it is important to consider communication latency. For swarm communication, a common latency goal is 10 ms⁸. The selected Doodle Labs radio module has a latency between 1.5 ms and 10 ms⁹, which makes it suitable for this application. Additionally, the module has been successfully used in the DroneSeed drone swarm¹⁰, further supporting its merit in this system.

Within each drone, CDHS acts as the central brain hub, as all subsystems communicate through it. The ADCS

⁸URL <https://inferensys.com/guides/autonomous-drone-navigation-and-fleet-coordination/how-to-architect-a-low-latency-communication-network-for-swarm-coordination> [accessed 17.06.2026]

⁹URL <https://doodlelabs.com/product/mini/#common-used> [accessed 17.06.2026]

¹⁰URL <https://doodlelabs.com/case-studies/droneSeed/> [accessed 17.06.2026]

subsystem supplies attitude measurements, accelerations and aerodynamic angles to CDHS, which returns attitude setpoints to close the control loop. The GNC subsystem provides position, UWB ranges, altitude, and cable tension to CDHS, which in turn forwards RTK corrections back to GNC. Actuator commands are handed by CDHS to the propulsion subsystem, which returns ESC telemetry. All external communication goes through the COM subsystem, which broadcasts data over the short and long range links.

Follower drones are identical to the leader in terms of hardware. Their Raspberry Pi 5 remains in standby during nominal operation and activates only upon leader failure, at which point the promoted drone assumes the full leader role: it takes over RTK base broadcasting, UWB anchor designation, trajectory coordination, and crucially, becomes the primary point of contact for the ground station. Because all drones carry the same Mesh Rider radio and are equal nodes on the mesh network, no reconfiguration of the communication links is required. The ground station simply continues communicating with the swarm through the mesh, which automatically routes traffic to the new leader. This software-defined role assignment provides a smooth failover path without any hardware reconfiguration.

It is important to note that the main supporting structure of the drones is made from carbon fibre rods. Carbon fibre has the property that it blocks electromagnetic waves and hence communication. To account for this, each node is connected to two omnidirectional antennas placed on the left and right sides of the drone body. This placement also provides spatial diversity, improving link reliability during the spinning manoeuvre when drone orientation changes rapidly. This will prevent the signal path from passing through the carbon fibre frame and blocking the signal, while still enabling communication with all components in the system.

The payload segment is intentionally light. Its CDHS fuses IMU angular rates and accelerations, GNSS position, barometric altitude and UWB ranges to derive attitude and position estimates locally, and relays state and health status back to the leader over the mesh network. The payload carries its own Doodle Labs Mesh Rider radio, making it a full peer on the mesh and eliminating the single point of failure previously associated with a dedicated short-range link. The brake actuator is governed by the ADCS subsystem as it controls the payload spin rate like a reaction wheel.

The ground segment joins the mesh network via its own Doodle Labs Mesh Rider Mini, with no separate telemetry radio required. The GCS laptop sends mission commands, waypoints, and arm/disarm instructions to the leader, and receives full telemetry, state estimates and health status from it in return.

Key Result: System Communications

Figure 11.1 demonstrates how the various roles communicate to act as one interconnected system with low latency to achieve effective swarm communication. To improve the reliability of the communication link, the received power could be measured during a test flight to determine the total link losses more accurately.

11.3. Compliance

Table 11.3: Communication compliance matrix.

ID	Compliance	Status
SYS26-COM01	The radio module can send data at 80 Mbps or 10 MBps.	✓
SYS26-COM02	The free space loss is evaluated for 20 km with a 20.337 dB margin.	✓

Key Limitation: Line of Sight

It should be noted that due to the curvature of the Earth, the maximum line of sight of the communication architecture is 35.70 km for a ground station at 0 m altitude with the system at 100 m altitude. This is larger than the considered range, and thus doesn't form a problem at this point. However, if the range were increased, increasing the ground station elevation or switching to satellite communication should be considered.

12. Guidance and Control Overview

The primary objective of the software developed in this project is to autonomously coordinate the multi-UAV swarm to successfully fulfil the mission. This chapter describes the team's approach to achieving this, explaining the problem complexity in Section 12.1, detailing the design approach in Section 12.2, and describing the simulation built by the team in Section 12.3. Reference frames are illustrated in Section 12.4.

12.1. Problem complexity

Current state-of-the-art development for drone control is done for single-aircraft systems [54]. However, this system consists of several connected aircraft under very high loads, making it a highly coupled system [55]. Because of this coupling, traditional aircraft control strategies are not directly applicable in this project [12]. For this project, careful planning of the drone's motion is needed to prevent drone collision and successfully control the payload [56]. Additionally, the flight controller must be specifically designed to handle heavy and constantly changing forces and moments [57]. It must tolerate the high loads exerted by the shared payload without losing control or causing the system to become unstable. Furthermore, the system faces the challenge of cable tension dynamics [1]. If a cable is loose during flight and then suddenly pulls tight, it creates a spike force that can instantly destabilise a drone or break the cable itself [54]. The software must therefore ensure that the cables maintain continuous and safe tension throughout the entire mission to prevent this.

12.2. Design Approach

To manage the complexity of the system, a divide-and-conquer design philosophy is employed, separating the software architecture into two distinct modules: the trajectory planner and the flight controller. The trajectory planner is responsible for calculating the complete flight trajectories for all three drones. It takes the physical limits of the hardware and the target payload trajectory as inputs, and then generates a synchronised, collision-free trajectory for the entire swarm. These calculated trajectories are then fed as waypoints into the flight controller. The controller acts on this data, transforming the trajectory waypoints into low-level commanded actuator signals, that the physical drones can use to track the trajectory.

These two modules are kept separate to isolate and simplify the engineering challenges of each part. The trajectory development focuses entirely on formulating the mathematical constraints and objective functions required to create feasible, collision-free paths. Meanwhile, the controller development focuses strictly on hardware integration and control loop design to ensure flight stability. Although both parts will eventually be highly integrated and tightly coupled within the final system, they are currently kept decoupled. This separation ensures simplicity during the development phase and allows for a clearer, more independent analysis of each subsystem.

Key Result: Software Development Division

Trajectory planning and drone controller are kept separate during the design phase for development simplicity. They will be integrated in the final system.

12.3. Simulation

The trajectory planner generates feasible trajectories based on a mathematical model of the system and a set of optimisation objectives. However, the assumptions used during trajectory generation may not fully capture the dynamics and disturbances encountered during real operation. To evaluate the quality and robustness of the generated trajectories, they are therefore validated in a simulation environment.

The simulation incorporates higher-fidelity system dynamics, including payload motion, cable behaviour, and external disturbances, to evaluate the performance of the generated trajectories under more realistic conditions. By executing the planned trajectories within this environment, it is possible to assess mission feasibility while verifying compliance with hardware limitations. Performance metrics, such as inter-drone separation distances, are monitored to identify potential issues and evaluate overall system performance. The resulting insights are

then used to iteratively refine the team's design, adjusting optimisation weights and constraints, creating a feedback loop between design and system validation, keeping the design team in the loop.

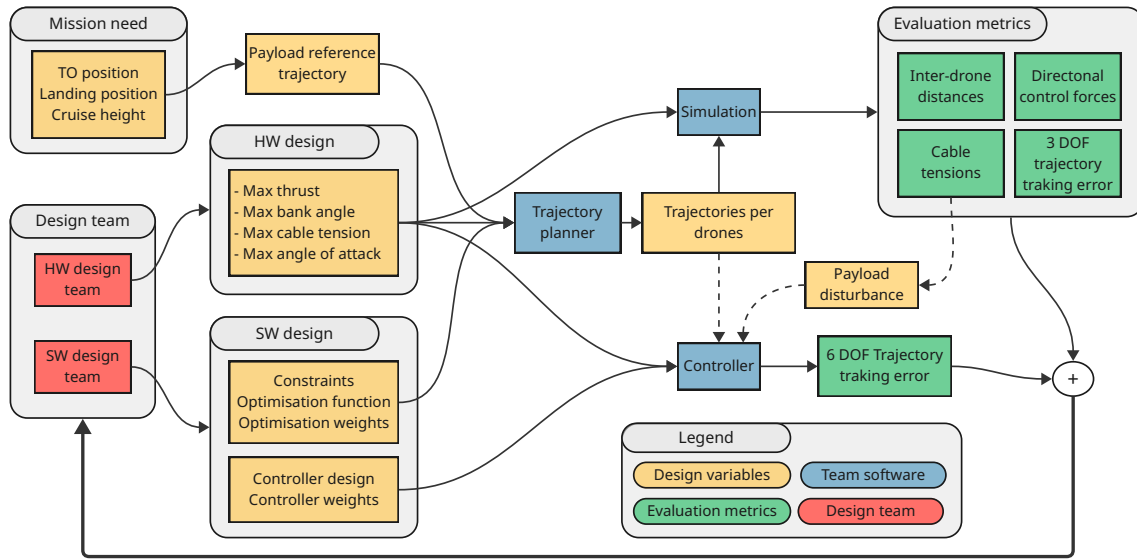


Figure 12.1: Software components and their interactions.

12.4. Reference Frames

The drone and global reference frames are shown in Figure 12.2. The aerodynamic reference frame is used for planning the drone's motion. The x axis aligns with the aerodynamic velocity vector, the z axis points down and lies in the drone's plane of symmetry, and the y axis completes the right-handed coordinate frame.

The body frame is used for controlling the drone. The x (forward) axis points to the drone's nose, the z axis points down and lies in the drone's plane of symmetry, and the y axis completes the right-handed coordinate frame. With the strapdown IMU making measurements in the body frame, this frame is a convenient choice [58, pp. 177-219].

Note that sideslip is assumed to be zero, hence the y axes of the body and aerodynamic frames are aligned.

The global reference frame is used for the swarm's motion. Its axes follow the East, North, and Up (ENU) axes, with the z axis pointing up perpendicularly to the ground, and the x and y axes parallel to the ground.

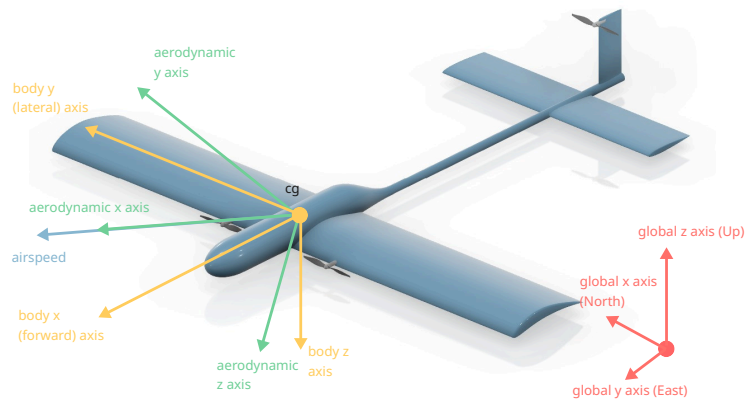


Figure 12.2: Reference frames: aerodynamic frame (green), body frame (green), and global frame (red).

13. Trajectory Optimisation Framework

This chapter develops the trajectory optimisation software capable of generating optimal trajectories for each one of the UAVs. First, Section 13.1 gives an overview of this software module. Then, Section 13.2 describes in detail the modelling used for the UAVs, cables and payload. This makes possible the definition of the Optimal Control Problem in Section 13.3, and further description of the solver used can be found in Section 13.4. A sensitivity analysis on the weights, modelling parameters and initial conditions, together with weight tuning, is developed in Section 13.5. Results and assumptions are detailed in Section 13.6 and Section 13.7. Compliance with relevant requirements, presented in Table 13.1, is demonstrated in Section 13.8. Challenges and future recommendations are given in Section 13.9.

Table 13.1: Requirements relevant to the trajectory planner.

ID	Requirement
STK08-MIS08-SYS14	The system shall coordinate the motion of all drones during payload transport.
STK08-MIS08-SYS15	The system shall distribute the payload load among the drones during cooperative flight.
STK09-MIS09-SYS17	The system shall remain controllable after the failure of one drone.
STK18-MIS18-SYS59	Mission planning shall be done in 25 minutes.
STK32	The system shall enable modular scaling of payload capacity through the addition of aerial vehicles.

13.1. Trajectory Planner Overview

The trajectory planner is the high-level optimisation module responsible for calculating the trajectories for each one of the UAVs, including the coordination of the motion of the swarm during the mission. The operator provides the number of drones, mission range, payload mass, and target cruise altitude through an operator interface. This highlights the flexibility and scalability of the system. Based on these inputs and predefined payload trajectories, UAV parameters, cable parameters, mission constraints, and cost-function weights, the planner can compute the complete mission optimised trajectory for each one of the drones. These trajectories will be pre-computed and saved in the Raspberry Pi 5 in all drones. The leader drone will host the trajectory planner and communicate the individual trajectories to the other drones, so each UAV follows its pre-defined path. By using the drone-controller, drones can adjust their trajectories to collectively transport the payload.

The goal of the trajectory planner is to provide a first demonstration of the feasibility of the mission while optimising the UAVs' trajectories required to realise it. For this reason, the trajectory of the payload is pre-defined, and the UAV trajectories are optimised around it. This way the planner can determine if the drones are able to cooperatively transport the payload through the reference trajectory finding automatically their optimal configuration without prescribing it.

The planner computes dynamically feasible UAV states and control histories while satisfying the vehicle, cable, and mission constraints. The solution is optimised with respect to the selected multi-objective cost function. However, as it will be later discussed, the problem is non-convex, and the result should be interpreted as a locally optimal feasible trajectory rather than a guaranteed global optimum [59].

Related work has investigated cooperative transportation of payload using multirotor UAVs [55] and trajectory planning based on cable-suspended loads [13]. However, this chapter addresses the problem of coordinating multi-hybrid fixed-wing UAVs together carrying a suspended payload through cables, between different mission

phases, handling transitions between spinning and coordinated cruise flight, and to tune and optimise the phase-specific weights for the cost functions. To the authors' knowledge, this exact problem has never been addressed before, and this is what shows the novelty of the work.

Figure 13.1 shows the full mission profile generated by the trajectory planner. The following sections will analyse the modelling steps, problem formulation, solver description, sensitivity analysis, and weight tuning process to generate this mission trajectory as well as the final results analysing more detailed plots for the trajectories. The VTOL lift-off and landing require little horizontal space, helping to preserve natural flora (SUS-9 🌿).

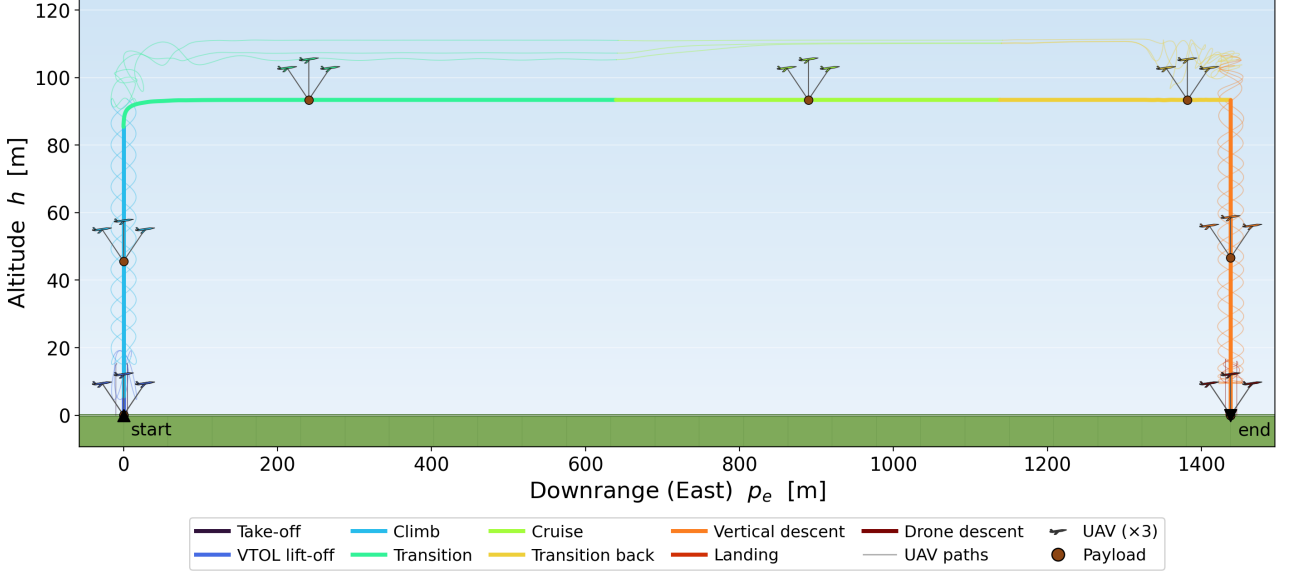


Figure 13.1: Overview of the trajectory for all mission phases generated by the trajectory planner with the tuned weights. The cruise phase was set to 500 m for computational efficiency and figure clarity, although it can be easily adjusted to the full 20 km mission range.

13.2. Modelling of Collaboratively Carrying Multi-Hybrid UAV Systems

The system is modelled as three coupled subsystems: the UAV dynamics, the cable mechanics, and the payload dynamics. Together, these define the equality constraints implemented in the optimal control problem introduced in Section 13.1.

13.2.1. UAV Dynamic Model

The motion of each UAV is modelled as a three-degree-of-freedom point mass for simplicity. p_e and p_n are the position components towards the eastward and northward direction, respectively, while h gives altitude. For each i th UAV, the state vector $\mathbf{x} \in \mathbb{R}^6$ is defined as

$$\mathbf{x}_i = \begin{bmatrix} V_i & \gamma_i & \chi_i & p_{e,i} & p_{n,i} & h_i \end{bmatrix}^\top,$$

where V_i is the airspeed, γ_i is the flight-path angle, χ_i is the course heading angle, defined positively according to the right-hand rule in the aerodynamic frame and $(p_{e,i}, p_{n,i}, h_i)$ is the point mass position in the inertial frame. The control input vector $\mathbf{u}_i \in \mathbb{R}^4$ collects the thrust magnitude, angle of attack, bank angle, and cable tension,

$$\mathbf{u}_i = \begin{bmatrix} T_i & \alpha_i & \mu_i & T_{C,i} \end{bmatrix}^\top.$$

Building on the three-degree-of-freedom model from [11], the nonlinear model is extended to capture the cable tensions induced by the suspended load, under the assumption of 0° sideslip angle. To model the VTOL transition to forward flight, a rotor tilt angle $\delta_t \in [0, \pi/2]$ is introduced, where $\pi/2$ corresponds to the cruise configuration and $\delta_t = 0$ to hover. This assumption is applied only during the transition from VTOL to the

forward-flight phase; in the cruise and climb-up phases, the thrust angle δ_t is treated as constant at $\pi/2$. Among the different 3-DoF models for a fixed-wing aircraft, the aerodynamic-frame model is the minimal model that includes airspeed-dependent aerodynamics, and tracks the states the controller uses.

The nonlinear equations of motion for each UAV, extended from [11], dropping the i th subscript for clarity, are shown in Equation 13.1.

$$\begin{aligned} \dot{p}_e &= V \sin \chi \cos \gamma & \dot{V} &= \frac{1}{m} \left[\sum_{t=1}^3 T_t \sin(\delta_t - \alpha) - D - mg \sin \gamma + T_{C,V} \right] \\ \dot{p}_n &= V \cos \chi \cos \gamma & \dot{\gamma} &= \frac{1}{mV} \left[\left(L + \sum_{t=1}^3 T_t \cos(\delta_t - \alpha) \right) \cos \mu - mg \cos \gamma + T_{C,\gamma} \right] \\ \dot{h} &= V \sin \gamma & \dot{\chi} &= \frac{1}{mV \cos \gamma} \left[\left(L + \sum_{t=1}^3 T_t \cos(\delta_t - \alpha) \right) \sin \mu + T_{C,\chi} \right] \end{aligned} \quad (13.1)$$

The aerodynamic forces of lift and drag are modelled according to the hardware design with:

$$L = \frac{1}{2} \rho V^2 S C_L \quad \text{and} \quad D = \frac{1}{2} \rho V^2 S (C_{D_0} + k C_L^2)$$

where the dynamic pressure is calculated with cruise velocity, while the UAV parameters are the same as those defined in Chapter 7. Moreover, the tension forces are decomposed from the inertial frame, denoted with superscript E , to the body aerodynamic frame, denoted with superscript B , by means of the rotation matrix R_{BE} as shown in Equation 13.2.

$$\mathbf{T}_C^B = R_{BE}(\gamma, \chi) \mathbf{T}_C^E = \begin{bmatrix} \cos \gamma \cos \chi & \cos \gamma \sin \chi & \sin \gamma \\ -\sin \gamma \cos \chi & -\sin \gamma \sin \chi & \cos \gamma \\ -\sin \chi & \cos \chi & 0 \end{bmatrix} \begin{bmatrix} T_{C,x} \\ T_{C,y} \\ T_{C,z} \end{bmatrix} \quad (13.2)$$

where $\mathbf{T}_C^B = [T_{C,V}, T_{C,\gamma}, T_{C,\chi}]^\top$.

13.2.2. Cable Dynamics

The cables are modelled as rigid, massless, tension-only links. This approximation removes cable elasticity from the model, while preserving the geometric coupling between each UAV and the payload, following common trajectory-optimisation formulations for cooperative UAV load transport [12]. The massless idealisation follows from the small cable-to-load ratio, each 18m cable weights $\approx 1.25\text{kg}$, about $\approx 6.25\%$ of its per-load share. On the other hand, the rigid idealisation treats the cables as inextensible links. This assumption is standard in cooperative aerial transport trajectory optimisation [55], and was validated by [60], whose rigid-massless cable model proved more robust for estimation than a flexible-cable alternative. Cable elasticity is recovered through a spring-damper model in the simulation-based validation in Chapter 15. The cable force is applied as an equal-and-opposite action-reaction pair according to

$$\mathbf{T}_{C_{\text{pay}},i}^E = -\mathbf{T}_{C_{\text{UAV}},i}^E = T_{C,i} \hat{\mathbf{u}}_i^E.$$

For each cable, let $\hat{\mathbf{u}}_i$ denote the unit vector, expressed in the global reference frame, from the payload to the i th UAV, for $i = 1, \dots, N_{\text{UAV}}$, used to orient the magnitude of the cable tension $T_{C,i} \in \mathbb{R}_{\geq 0}$.

13.2.3. Payload Dynamics Model

The payload is modelled as a point mass subject to gravity, aerodynamic drag, opposing the velocity vector of the payload, cable-tension forces, and, when in contact with the ground, a normal reaction force N . Its resultant

force, in the ENU inertial frame defined in Subsection 13.2.1, is shown in Equation 13.3.

$$\mathbf{F}_{\text{pay}}^E = (-m_{\text{pay}}g + N) \mathbf{e}_z - \frac{1}{2}\rho\|\mathbf{v}_{\text{pay}}\|^2 S_{\text{pay}} C_{D0} \hat{\mathbf{v}}_{\text{pay}} + \sum_{i=1}^{N_{\text{UAV}}} T_{C,i} \hat{\mathbf{u}}_i^E. \quad (13.3)$$

The payload dynamics follow Newton's second law, yielding a nonlinear second-order system in position, where $\dot{\mathbf{p}}_{\text{pay}}, \mathbf{v}_{\text{pay}} \in \mathbb{R}^3$.

$$\dot{\mathbf{p}}_{\text{pay}} = \mathbf{v}_{\text{pay}}, \quad \dot{\mathbf{v}}_{\text{pay}} = \frac{\mathbf{F}_{\text{pay}}}{m_{\text{pay}}}. \quad (13.4)$$

During free flight, the ground reaction is zero. For ground-contact phases, N is constrained to be non-negative and bounded by the payload weight, $0 \leq N \leq m_{\text{pay}}g$, so that the ground can only exert an upward normal force.

13.3. Finite-time Optimal Control Problem

Once the coupled dynamics of the collaborative lifting system are defined, the Optimal Control Problem (OCP) can be formulated, with the relative cost function and path constraints implemented in the nonlinear programming (NLP) formulation.

13.3.1. OCP formulation

To pose the optimal control problem over the entire system, the N_{UAV} states and the payload state vectors are stacked into a single state vector, with the corresponding inputs stacked similarly:

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}_1^\top & \cdots & \mathbf{x}_{N_{\text{UAV}}}^\top & \mathbf{p}_{\text{pay}}^\top & \mathbf{v}_{\text{pay}}^\top \end{bmatrix}^\top \quad \mathbf{U} = \begin{bmatrix} \mathbf{u}_1^\top & \cdots & \mathbf{u}_{N_{\text{UAV}}}^\top \end{bmatrix}^\top \quad (13.5)$$

which follow the dynamics $\dot{\mathbf{X}} = \mathbf{f}(\mathbf{X}, \mathbf{U})$ assembled from Subsection 13.2.1 and Equation 13.3. The simplified notation allows to write the OCP, with a cost function J , subject to inequality path constraints $\mathbf{h}(\mathbf{X}_{k+1}, \mathbf{U}_k) \leq 0$. The problem is discretised over N_t nodes, with a $\Delta t = 0.05$ s, and the backward Euler time-stepping method [61] is used to enforce the equality constraint in the NLP.

$$\begin{aligned} & \min_{\substack{\mathbf{X}_0, \dots, \mathbf{X}_{N_t} \\ \mathbf{U}_0, \dots, \mathbf{U}_{N_t-1}}} J(\mathbf{X}, \mathbf{U}) \\ & \text{subject to } \mathbf{X}_0 = \mathbf{X}_{\text{init}}, \\ & \quad \mathbf{X}_{k+1} = \mathbf{X}_k + \Delta t \mathbf{f}(\mathbf{X}_{k+1}, \mathbf{U}_k), \\ & \quad \mathbf{h}(\mathbf{X}_{k+1}, \mathbf{U}_k) \leq 0, \quad k \in \{0, \dots, N_t - 1\}. \end{aligned} \quad (13.6)$$

13.3.2. Cost Function

The cost function introduced in Subsection 13.3.1 is a function of the current system state vector $\mathbf{X}_k$, and system input vector $\mathbf{U}_k$. Building upon the work by Sun et al., the cost function from a quadrotor platform is modified to implement a cost on the derivative of the per-UAV states $\mathbf{x}_i$ and control inputs $\mathbf{u}_i$ with finite differences, as shown in Equation 13.7. Here, $\|\mathbf{x}\|_{\mathbf{W}}^2 = \mathbf{x}^\top \mathbf{W} \mathbf{x}$ denotes the weighted squared norm, where $\mathbf{P}$, $\mathbf{Q}$, $\mathbf{R}$, $\mathbf{T}$, and $\mathbf{E}$ are symmetric positive semi-definite weighting matrices. Moreover, the cost function rewards the sharing of cable tension and power between the swarm. To enforce the correct arrangement of the N_{UAV} , a formation cost function J_{form} is included to penalise deviations from the set cruise shape after climb transition. Finally, J_{lean} is used to slow down the landing to ensure a smooth manoeuvre. Each component of the cost function is evaluated over the prediction horizon and summed over all discretisation nodes.

$$\begin{aligned} J = \sum_{k=0}^{N_t-1} & \left(\|\mathbf{p}_{\text{pay},k} - \mathbf{p}_{\text{pay},k}^{\text{ref}}\|_{\mathbf{P}}^2 + \sum_{i=1}^{N_{\text{UAV}}} \left(\|\mathbf{x}_{i,k+1} - \mathbf{x}_{i,k}\|_{\mathbf{Q}}^2 + \|\mathbf{u}_{i,k+1} - \mathbf{u}_{i,k}\|_{\mathbf{R}}^2 \right. \right. \\ & \left. \left. + \|T_{C,i,k} - \bar{T}_{C_k}\|_{\mathbf{T}}^2 + \|P_{i,k} - \bar{P}_k\|_{\mathbf{E}}^2 + J_{\text{form},i,k} \right) + J_{\text{lean},k} \right) \end{aligned} \quad (13.7)$$

A relevant component of Equation 13.7 is the payload tracking objective, which rewards the OCP for keeping the payload point-mass close to its predetermined reference path. The weighting matrix $\mathbf{P}$ is a diagonal matrix, defined as $\mathbf{P} = p \mathbf{I}$, with $p \in \mathbb{R}_{\geq 0}$ a scalar weight and $\mathbf{I} \in \mathbb{R}^{3 \times 3}$, for the position on the global reference frame.

Moreover, the cost function penalises high rates of change in the system states and control inputs through a first-order finite difference scheme. The matrices $\mathbf{Q}$, $\mathbf{R}$ weight each of the differences and normalise them by their relative maximum allowable range, to reduce the cost function to the same order of magnitude. The weighting matrix $\mathbf{Q}$ acts only on the dynamic substates (V, γ, χ) of each UAV, as shown in Equation 13.8.

$$\mathbf{Q} = \text{diag}\left(\frac{W_{\Delta V}}{(V_{\max} - V_{\min})^2}, \frac{W_{\Delta \gamma}}{(2\gamma_{\max})^2}, W_{\Delta \chi}, 0, 0, 0\right) \in \mathbb{R}^{6 \times 6} \quad (13.8)$$

The heading state variable χ is wrapped with $\sin^2(\cdot)$, which is intrinsically bounded to $[0, 1]$ and respect the 2π -periodicity of χ avoiding the discontinuity at $\pm\pi$. Similarly to $\mathbf{Q}$, the control input rate weighting matrix $\mathbf{R}$ can be written as shown in Equation 13.9.

$$\mathbf{R} = \text{diag}\left(\frac{W_{\Delta T}}{(T_{\max} - T_{\min})^2}, \frac{W_{\Delta \alpha}}{(\alpha_{\max} - \alpha_{\min})^2}, \frac{W_{\Delta \mu}}{(2\mu_{\max})^2}, \frac{W_{\Delta T_C}}{T_{C,\max}^2}\right) \in \mathbb{R}^{4 \times 4}. \quad (13.9)$$

Furthermore, the cost function includes per-UAV penalties on cable tension and power disparity distribute the power usage equally and reduce overall energy consumption. Apart from reducing operating costs, this also links to system efficiency (SUS-1 ) in Section 6.3. The average power and thrust at timestep k is computed by averaging over the swarm values:

$$\bar{T}_{C_k} = \frac{1}{N_{\text{UAV}}} \sum_{i=1}^{N_{\text{UAV}}} T_{C_{i,k}}, \quad \bar{P}_k = \frac{1}{N_{\text{UAV}}} \sum_{i=1}^{N_{\text{UAV}}} T_{i,k} V_{i,k}.$$

while the matrices $\mathbf{T}$, $\mathbf{E}$ are one-dimensional matrices given the scalar values of the tension and power per UAV, as shown in Equation 13.10.

$$\mathbf{T} = \frac{W_{\bar{T}}}{T_{C,\max}^2} \in \mathbb{R}^{1 \times 1}, \quad \mathbf{E} = \frac{W_{\bar{P}}}{(T_{\max} V_{\max})^2} \in \mathbb{R}^{1 \times 1}. \quad (13.10)$$

Finally, the form and lean components of the cost function in Equation 13.7 penalise the aggressive manoeuvres associated with the climb-to-cruise and cruise-to-descent transitions. The first transition in the mission requires the swarm to enter a cruise energy-efficient formation. The swarm is encouraged to adopt this formation by prescribing a nominal cruise offset from the payload for the i th drone, defined as $\boldsymbol{\rho}_{i,k} \equiv \mathbf{p}_{i,k} - \mathbf{p}_{L,k}$. The cost thus reads:

$$J_{\text{form}} = W_{\text{form}} \sum_{k=0}^{N_t-1} \sigma_k \frac{\|\boldsymbol{\rho}_{i,k} - \boldsymbol{\rho}_{i,k}^*\|^2}{L_c^2},$$

where $\boldsymbol{\rho}_i^*$ denotes the imposed offset, L_c is the cable length, and $\sigma_k \in [0, 1]$ is a smoothstep gate that ramps the anchor on over the transition window $[t_0, t_1]$. This function is used to slowly raise the weight of the cost function to avoid sharp input changes to minimise the cruise offset.

On the other hand, during the transition back to spinning, to help the solver find a way to decelerate the payload, the drone's rotation axis around the payload is encouraged to be tilted by an angle. The same smoothstep function used in the transition to cruise is implemented in the landing phase. This results in encouraging tilting back the resultant tension acting on the payload, thus slowing it down, which is implemented through the following cost function:

$$J_{\text{lean}} = W_{\text{lean}} \sum_{k=0}^{N_t-1} \sigma_k \left\| \frac{\bar{\mathbf{r}}_k}{\|\bar{\mathbf{r}}_k\|} - \hat{n}_{\text{ref}} \right\|^2 \quad (13.11)$$

where $\hat{n}_{\text{ref}}$ is the desired (backward-tilted) lean direction and $\bar{\mathbf{r}}_k = \frac{1}{N_{\text{UAV}}} \sum_{i=1}^{N_{\text{UAV}}} \boldsymbol{\rho}_{i,k}$ is the mean UAV offset

from the payload.

13.3.3. Constraints

The nonlinear program enforces constraints on UAV states, control inputs, cable geometry, inter-UAV separation, cable tension, and formation handedness. These constraints ensure that the computed trajectory remains dynamically feasible and respects the physical limitations of the aircraft-payload system. The numerical values for each one of the parameters constraining these limits can be found in Table 13.2.

Control and State Bounds: For every UAV i and node k , different control bounds are enforced as constraints:

$$\begin{aligned} T_{\min} &\leq T_{i,k} \leq T_{\max} \\ T_{i,k} V_{i,k} &\leq P_{\max} \\ \alpha_{\min} &\leq \alpha_{i,k} \leq \alpha_{\max} \\ -\mu_{\max} &\leq \mu_{i,k} \leq \mu_{\max} \end{aligned}$$

The state bounds are:

$$\begin{aligned} V_{\min} &\leq V_{i,k} \leq V_{\max} \\ -\gamma_{\max} &\leq \gamma_{i,k} \leq \gamma_{\max} \end{aligned}$$

Note that the power constraint assumes a small angle of attack, and only becomes useful for forwards flight as, for hovering, power is still being used despite airspeed being 0. In that case, the thrust constraint takes over.

Cable Constraints: Cables are modelled as inextensible ropes with nominal length L_c and a taut-band tolerance ε_L :

$$(L_c - \varepsilon_L)^2 \leq \|\mathbf{p}_{i,k}\|^2 \leq (L_c + \varepsilon_L)^2 \quad (13.12)$$

This constraint results in a hollow sphere in the feasible set of 3-dimensional positions of the UAVs. A hollow sphere is a non-convex set [62], because a line segment can be traced, all points of which may not belong to the feasible set. This makes the domain of the cost function non-convex, thus making the OCP non-convex. This means global optimality is not guaranteed.

Cables can only carry tension, and each UAV must remain at or above the payload:

$$0 \leq T_{C,i,k} \leq T_{C,\max} \quad (13.13)$$

$$h_{i,k} \geq h_{\text{pay},k} \quad (13.14)$$

Here, $T_{C,i} \geq 0$ is the cable tension magnitude, treated as an optimisation variable.

Collision and Entanglement Avoidance: Every pair of UAVs (i, j) with $i < j$ must maintain a minimum separation at every node to avoid collisions:

$$\|\mathbf{p}_{i,k} - \mathbf{p}_{j,k}\|^2 \geq d_{\min}^2 \quad (13.15)$$

To prevent cable crossings, the normalised scalar triple product of the three cable vectors $\mathbf{d}_i^k = \mathbf{p}_i^k - \mathbf{p}_L^k$ is bounded away from zero:

$$\sigma \frac{\mathbf{d}_1^k \cdot (\mathbf{d}_2^k \times \mathbf{d}_3^k)}{L_c^3} \geq \epsilon_{\text{ent}} \quad (13.16)$$

where $\sigma \in \{+1, -1\}$ is the chirality sign determined from the initial formation offsets, and $\epsilon_{\text{ent}} = 0.05$. This represents the normalised volume formed by the three cables, and prevents a cable from crossing the plane formed by the other two, which would result in entanglement.

Control-Angle Acceleration Limits: Control-surface authority imposes limits on the angular rates of α (pitch, driven by elevator) and μ (roll, driven by ailerons), computed via centred finite differences at interior nodes $k \in \{1, \dots, N-2\}$:

$$\ddot{\theta}_{\min} = \frac{q_{\min} S \bar{c} C_{m,\min}}{I_{yy}} \leq \frac{\alpha_i^{k+1} - 2\alpha_i^k + \alpha_i^{k-1}}{\Delta t^2} \leq \ddot{\theta}_{\max} = \frac{q_{\min} S \bar{c} C_{m,\max}}{I_{yy}} \quad (13.17)$$

$$\left| \frac{\mu_i^{k+1} - 2\mu_i^k + \mu_i^{k-1}}{\Delta t^2} \right| \leq \ddot{\phi}_{\max} = \frac{q_{\min} S b C_{l,\max}}{I_{xx}} \quad (13.18)$$

where $q_{\min} = \frac{1}{2} \rho V_{\min}^2$ is the dynamic pressure evaluated conservatively at $V_{\min}$.

Table 13.2: State and control limit values used in the NLP. All the constraints in fixed-wing UAV are also used in the tilt-rotor VTOL mode, except the minimum airspeed which is set to 10^{-4} so VTOL can start rest.

Fixed-Wing UAV Mode			Tilt-Rotor VTOL Mode		
Parameter	Symbol	Value	Parameter	Symbol	Value
Min. airspeed	$V_{\min}$	14 m/s	Min. VTOL airspeed	$V_{\min, \text{VTOL}}$	1.0×10^{-4} m/s
Max. airspeed	$V_{\max}$	30 m/s	Min. thrust per propeller	$T_{\min}$	0 N
Max. flight-path angle	$\gamma_{\max}$	45°	Max. thrust per propeller	$T_{\max}$	61.0 N
Min. thrust	$T_{\min}$	0 N	Max. power per motor	$P_{\max}$	1867 W
Max. thrust	$T_{\max}$	183.1 N	Min. rotor tilt angle	$\delta_{\min}$	0°
Max. power	$P_{\max}$	5602 W	Max. rotor tilt angle	$\delta_{\max}$	90°
Min. angle of attack	$\alpha_{\min}$	-15°	Max. rotor tilt rate	$\dot{\delta}_{\max}$	$720^\circ/\text{s}$
Max. angle of attack	$\alpha_{\max}$	8°	Max. angle-of-attack rate	$\dot{\alpha}_{\max}$	$10^\circ/\text{s}$
Max. bank angle	$\mu_{\max}$	35°	Max. bank-angle rate	$\dot{\mu}_{\max}$	$10^\circ/\text{s}$
Min. UAV separation	$d_{\min}$	6 m	Max. deceleration	$a_{\text{decel}, \max}$	3 m/s^2
Max. cable tension	$T_{c, \max}$	750 N			
Nominal cable length	L_c	18 m			
Cable length tolerance	δ_L	0.1 m			

13.4. Nonlinear Programming Solver

The trajectory optimisation problem described in Section 13.1 results in a finite-dimensional Nonlinear Program (NLP). The optimisation problem is modelled using CasADi [63] framework and solved using IPOPT [64]. IPOPT was selected because the trajectory planning problem is formulated as a smooth nonlinear program. Its interior-point formulation allows equality and inequality constraints to be enforced directly [64]. Furthermore, the use of IPOPT in CasADi has been widely adopted for UAV trajectory optimisation [5]. An important remark is that the NLP formulated is non-convex, as justified in Subsection 13.3.3, for this reason the solution found by the optimiser will be locally optimal and does not guarantee to be globally optimal.

13.4.1. IPOPT Settings

A summary for the IPOPT settings used can be found in Figure 13.3. First, the maximum number of iterations defines the largest number of nonlinear solver iterations allowed before IPOPT terminates [65]. A sufficiently high value is required because some receding-horizon windows are tightly constrained. This setting gives IPOPT enough iterations to move from the initial guess toward a feasible solution.

Table 13.3: Main IPOPT settings used for the fixed-wing trajectory optimisation.

Setting	Value
Maximum iterations	2000
Acceptable tolerance	10^{-6}
Acceptable iterations	15
Convergence tolerance	10^{-8}
Barrier parameter strategy	Adaptive

Secondly, the acceptable tolerance and acceptable iteration settings values provide an additional termination criterion [65]. If the solver remains within the acceptable tolerance for a specified number of consecutive iterations, IPOPT stops solving. Thirdly, a low convergence tolerance was set to reduce numerical variability between runs and obtain consistent solution across different computers. Finally, the barrier parameter strategy was set to adaptive. IPOPT handles inequality constraints through a barrier formulation. The barrier parameter controls how strongly the optimiser is kept away from the boundary of the feasible region during the iterations [64]. The adaptive strategy allows IPOPT to update this parameter automatically, based on the progress of the optimisation.

Solver Limitations

One of the limitations of IPOPT is that it does not tune or adapt the weights its cost functions contain for the optimisation. The weights are fixed inputs that determine the scalar objective function, and IPOPT then minimises this objective subject to the imposed dynamics and constraints. Therefore, later tuning is required to get a smooth and feasible trajectory. This process will be explained in detail in Subsection 13.5.1.

A limitation of the current IPOPT implementation is that it is not suitable for real-time onboard control. In this work, IPOPT solves the NLP problem iteratively, and the resulting computation time is above the control sampling time. Therefore, *Dronado* currently will use the trajectory planner as a pre-computed trajectory installed into the drones. This will be explained more in detail later in Section 17.1.

13.4.2. Receding Horizon Control

The trajectory planner uses a receding-horizon optimisation strategy, following the general principle described by Kwon and Han [66, pp. 4]. Instead of solving the complete mission trajectory in one large optimisation problem, the planner solves a smaller finite-horizon problem. The trajectory is discretised with a fixed time step Δt , each optimisation window spans a physical duration of $N_h \Delta t$. From this optimised window, only the first portion of the solution is committed, corresponding to N_{apply} nodes. The horizon is then shifted forward, and the next optimisation window is solved using the previously committed trajectory as the initial condition. The values used for these parameters are given in Table 13.4.

Table 13.4: Receding-horizon discretisation parameters used in the trajectory planner.

Parameter	Symbol	Value
Time step	Δt	0.05 s
Horizon length	N_h	50 nodes
Applied nodes per solve	N_{apply}	5 nodes

13.4.3. Initial Conditions and Warm Starting

Switching between mission phases and horizon windows requires defining how previous states and control inputs are continued through the optimisation. Two different approaches were followed: when switching between mission phases, initial conditions are passed on as hard constraints. When switching between horizons, the uncommitted solution to the previous horizon is used as an initial guess for the next one, known as a warm start. This greatly increases the convergence rate for IPOPT as the guess already meets all of the set constraints, and the solver does not need to use iterations to just find a feasible solution.

Regarding phase initial conditions, after each phase finishes, the final node solution is stored and passed to the next phase as a hard constraint. Initial conditions pass on final UAV states, payload position, payload velocity, cable tensions and controls. They are enforced as equality constraints so the IPOPT is forced to meet these states and controls.

In relation to the warm starts, for each optimisation window the code stores the full solution and the next window is initialised using the previous solution shifted forward. This gives IPOPT a starting guess that is already close to the expected next solution [67]. Since the previous window already satisfied similar dynamics and constraints, the shifted solution is usually close to feasible, helping IPOPT converge faster and more reliably.

13.5. Sensitivity Analysis

Having defined the optimisation problem and all the tools that will be used to solve it, it is necessary to tune the parameters implemented for solving the NLP. First, a sensitivity analysis was performed on the weights of the cost functions. This was used for weight tuning. When optimal weights were found, a sensitivity analysis was performed on relevant modelling parameters and initial conditions.

13.5.1. Weights Sensitivity and Tuning

The different mission goals, formulated as cost functions, need to be balanced through weighting parameters. These weights will vary between phases, depending on the specific priorities. As explained in Section 13.4, these weights need to be tuned. This section will explain in detail how sensitivity analysis was performed on this weights to find the most influential ones for each mission phases and how tuning was performed.

Weight Sensitivity Analysis

Initially, a set of weights was manually tuned to obtain feasible trajectories with reasonable payload tracking error. This allowed to define the cost functions of all mission phases and inspect if they were working correctly. After having defined all mission phases, the solver settings, the cost functions and an initial set of non-optimal weights, it was time for tuning the weights.

These preliminary weights were used as baseline to run a sensitivity analysis on each one of them. One by one the weights were varied for each one of the mission phases using factors of 0.1 and 10. This perturbation size of an order of magnitude was selected because many weights are small, making smaller changes unlikely to produce visible changes in the optimised trajectory.

For each perturbed solve, four physical performance metrics were evaluated: payload tracking RMSE, maximum cable tension, maximum propulsive power, and maximum thrust. Weight changes were plotted against these metrics in four separate tornado plots [68] for each one of the mission phases. These sensitivity results were used to identify the weights with the strongest influence on the mission metrics. Only these weights were retained for the tuning stage, reducing the search dimension and avoiding optimisation over parameters with little measurable effect. Figure 13.2 serves as illustration of one of the tornado plots used for this analysis.

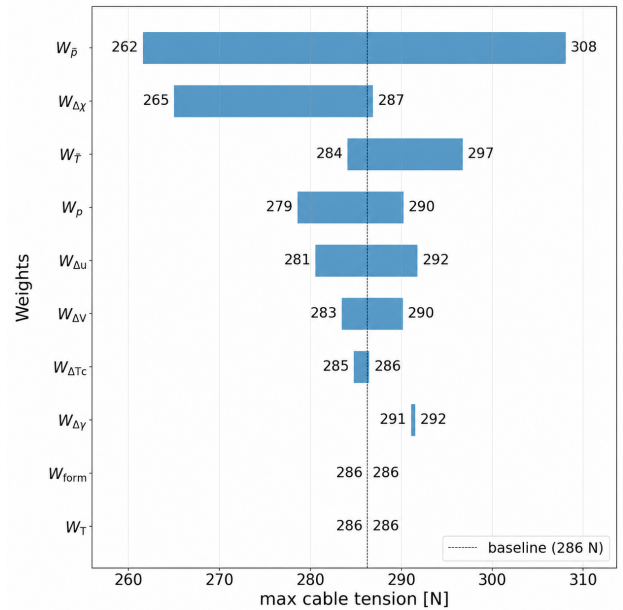


Figure 13.2: Tornado plot showing the effect of one-at-a-time weight perturbations on maximum cable tension during cruise. Left bars indicate a tenfold weight reduction and right bars indicate a tenfold increase.

Weight Tuning

The selected weights were then tuned using Latin Hypercube Sampling [69] combined with Pareto filtering [70]. For each mission phase, 50 to 100 candidate weight combinations were generated within predefined bounds that constrained weight values to be $(1e^{-4}, 1e^{-1})$. Latin Hypercube Sampling was used to generate the different values for each one of the weights, ensuring a balanced choice of weight values between samples [69].

Each candidate was evaluated by solving the corresponding trajectory optimisation problem, computing and saving the physical performance metrics from the resulting trajectory. A candidate was considered dominated if another candidate performed no worse in all selected objectives and strictly better in at least one [70]. Infeasible solves were excluded from the Pareto front. The physical performance metrics, implemented as Pareto

objectives and were chosen to represent the main trade-offs in the trajectory design: payload tracking RMSE, power spread, and control-input variation. The Pareto front contains the non-dominated weight sets for which no objective could be improved without degrading any other objective [71].

Figure 13.3 shows an example of one of the seven Pareto fronts generated for each one of the mission phases. Each axis represents one Pareto objective. Orange points correspond to non-dominated Pareto-optimal candidates, while grey points represent dominated candidates. This plot helps identify feasible weight sets with the best trade-offs between the selected objectives.

The selection for the optimal weight was performed based on a priority-weighted Minimum-Manhattan-Distance [72]. First, each objective was normalised across the Pareto points and depending on their ranking of importance for the Pareto objectives, they were given a weight of: 0.5, 0.33 or 0.17 (from most to least important objective). With this the Minimum-Manhattan-Distance was calculated [72], which found the global knee point of the Pareto front, highlighted in the Pareto plots as a red diamond.

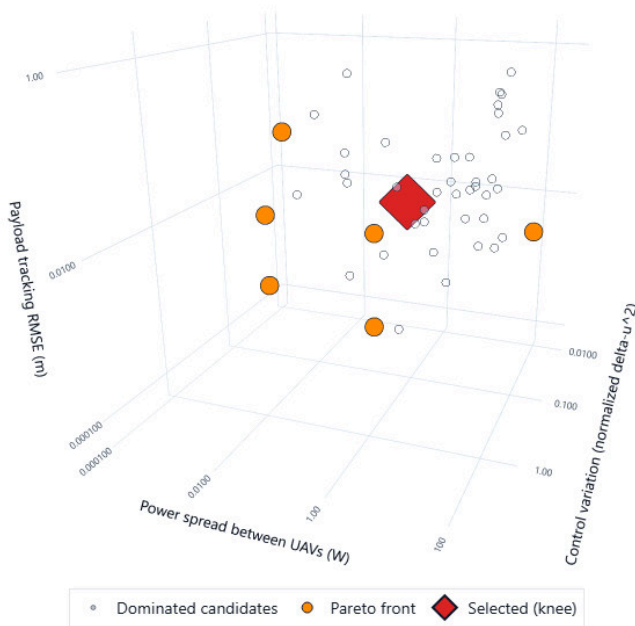


Figure 13.3: Pareto front generated for the vertical-descent mission phase.

Table 13.5 summarises the order of priority of each one of the objectives for the different mission phases. Importance levels are required, since some phases such as transition to spin-down need to prioritise a lot more the control variation than payload RMSE to get smooth controls. For cruise, power spread is prioritised since having a balanced power demand between UAVs will prevent one drone running out of battery faster than the others, improving endurance of the system. Similarly, priorities are defined for each one of the mission phases. It was observed that treating Pareto objectives as equal importance or improperly defining the order of priority leads to non-smooth manoeuvres, drones diverging and increases in the payload tracking RMSE. These priorities help define phase-specific preference of objectives. This allowed us to find the optimal weights for each one of the mission phases, summarised in Table 13.6 and Table 13.7.

Table 13.5: Priority ranking used to select final weights from the Pareto front.

Phase	First Priority	Second Priority	Third Priority
Cruise	Power spread	Payload RMSE	Control variation
Transition to cruise	Payload RMSE	Control variation	Power spread
Transition to spin-down	Control variation	Power spread	Payload RMSE
Climb and Descent	Payload RMSE	Thrust margin	Cable tension
VTOL and Landing	Smooth controls	Cable tension	Payload RMSE

Key Result: Final Weights

Table 13.7 summarises the final tuned weights obtained for each mission phase after completing the sensitivity analysis and Pareto tuning process.

Table 13.6: Normalised cost-function weights for VTOL and landing phases. Dashes indicate inactive terms ($W = 0$).

Phase	$W_{\Delta u}$	$W_{\Delta T_C}$	$W_{\Delta \chi}$	W_{climb}	W_N	W_{tilt}
VTOL	$2 \cdot 10^{-4}$	—	—	$4 \cdot 10^{-1}$	$5 \cdot 10^{-3}$	$6 \cdot 10^{-1}$
Landing	$2 \cdot 10^{-1}$	$6 \cdot 10^{-1}$	$2 \cdot 10^{-2}$	—	$1 \cdot 10^{-1}$	$8 \cdot 10^{-2}$

Table 13.7: Normalised cost-function weights for fixed-wing mission phases. Dashes indicate inactive terms ($W = 0$). The vector $W_{\Delta u}$ applies to thrust, angle of attack, and bank angle. Tran. 1 refers to the transition that goes from spin-up to cruise; Tran. 2 refers to the transition that goes from cruise to spin-down

Phase	W_p	$W_{\Delta u}$	$W_{\Delta T_c}$	$W_{\Delta \gamma}$	$W_{\Delta \chi}$	$W_{\Delta V}$	W_{form}	$W_{\bar{P}}$	$W_{\bar{T}}$	W_{lean}
Climb	$5 \cdot 10^{-1}$	$1 \cdot 10^{-3}$	$7 \cdot 10^{-4}$	$4 \cdot 10^{-2}$	$1 \cdot 10^{-3}$	$4 \cdot 10^{-1}$	—	—	—	—
Tran. 1	$1 \cdot 10^{-1}$	$3 \cdot 10^{-1}$	—	$3 \cdot 10^{-1}$	—	$4 \cdot 10^{-2}$	$1 \cdot 10^{-2}$	—	$2 \cdot 10^{-1}$	—
Cruise	$2 \cdot 10^{-1}$	$1 \cdot 10^{-1}$	$2 \cdot 10^{-2}$	$2 \cdot 10^{-1}$	$2 \cdot 10^{-1}$	$4 \cdot 10^{-1}$	—	$3 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	—
Tran. 2	$2 \cdot 10^{-1}$	$4 \cdot 10^{-1}$	$8 \cdot 10^{-3}$	$8 \cdot 10^{-2}$	$4 \cdot 10^{-3}$	$3 \cdot 10^{-1}$	—	—	—	$2 \cdot 10^{-2}$
Descent	$9 \cdot 10^{-1}$	$6 \cdot 10^{-2}$	—	$1 \cdot 10^{-2}$	$6 \cdot 10^{-4}$	—	—	—	$2 \cdot 10^{-4}$	—

After selecting the tuned weights, the full mission was re-run and compared with the manually tuned baseline. This verification assessed whether the selected weights improved the desired mission metrics while preserving feasibility and acceptable trajectory behaviour. Figure 13.4 shows four relevant parameters used to compare the two cases. For the manual and the tuned trajectories, the histories for the three drones are shown using different colours for each one of the drones. In these plots cruise was performed just for 500m, this was done to save computational time and keep the comparison easier to visualize. This distance is a configurable parameter in the code and can be increased as needed, including to the intended 20km objective.

Verification: Tuned Weights

The tuned mission improved overall control smoothness of the trajectory. Looking at the climb phase, the manual baseline flies at the stall speed and maximum angle of attack for most of it. Furthermore, for total thrust and bank angle there is a sudden spike towards the upper limit. The tuned case instead climbs with an airspeed mostly around $18 - 20 \text{ ms}^{-1}$ and angle of attack below 5.4 deg. This is due to the tuned weights keeping a more aerodynamic margin, as they optimise for smooth control variations.

For the transition to cruise, shapes for tuned and manual plots are very similar, the order of the drones after the transition changes to avoid the crossing that can be observed at the beginning on cruise for the bank angle between UAV 1 and UAV 2, which generates spikes at the beginning of the cruise section for the manual case. The tuned trajectory has all parameters nearly steady for the cruise and only a smooth decrease of bank angle is observed, which will be later analysed in Section 13.6.

The transition to descent manoeuvre shows the greatest improvement. This manoeuvre requires fast changes in the shown parameters, but the tuned case managed to smooth these changes significantly. The manual baseline consistently reaches the limiting values for all parameters, it almost reaches the airspeed limit, hits the angle of attack bounds very often, and produces thrust spikes up to the thrust limit. The tuned trajectory does not reach the airspeed limit and reaches the top limit for the angle of attack but reduced significantly the sharp oscillations. Similarly, the thrust and bank angle plots show that sharp oscillations are very reduced, reaching a lot less the limits. The main reason for this improvement was the high priority given to the control variation objective when calculating the knee point of the Pareto front (see Table 13.5). The tuned transition back therefore provides smoother trajectory that is feasible, as it all parameters stay below the maximum bounds.

The descent phase has a similar profile for airspeed and angle of attack, however, the manually tuned trajectory reached angle of attack and bank angle limits. Both cases reduce the total thrust to zero for the

vertical descent, gliding is the preferred manoeuvre. For the take-off and landing similar trends can be observed for both cases.

These findings verify that the tuned trajectory improves the smoothness and reduces the times the trajectory reaches the maximum limits for the parameters, compared with the manual trajectory. A more detailed analysis for the manoeuvres of the tuned case is provided later in Section 13.6.

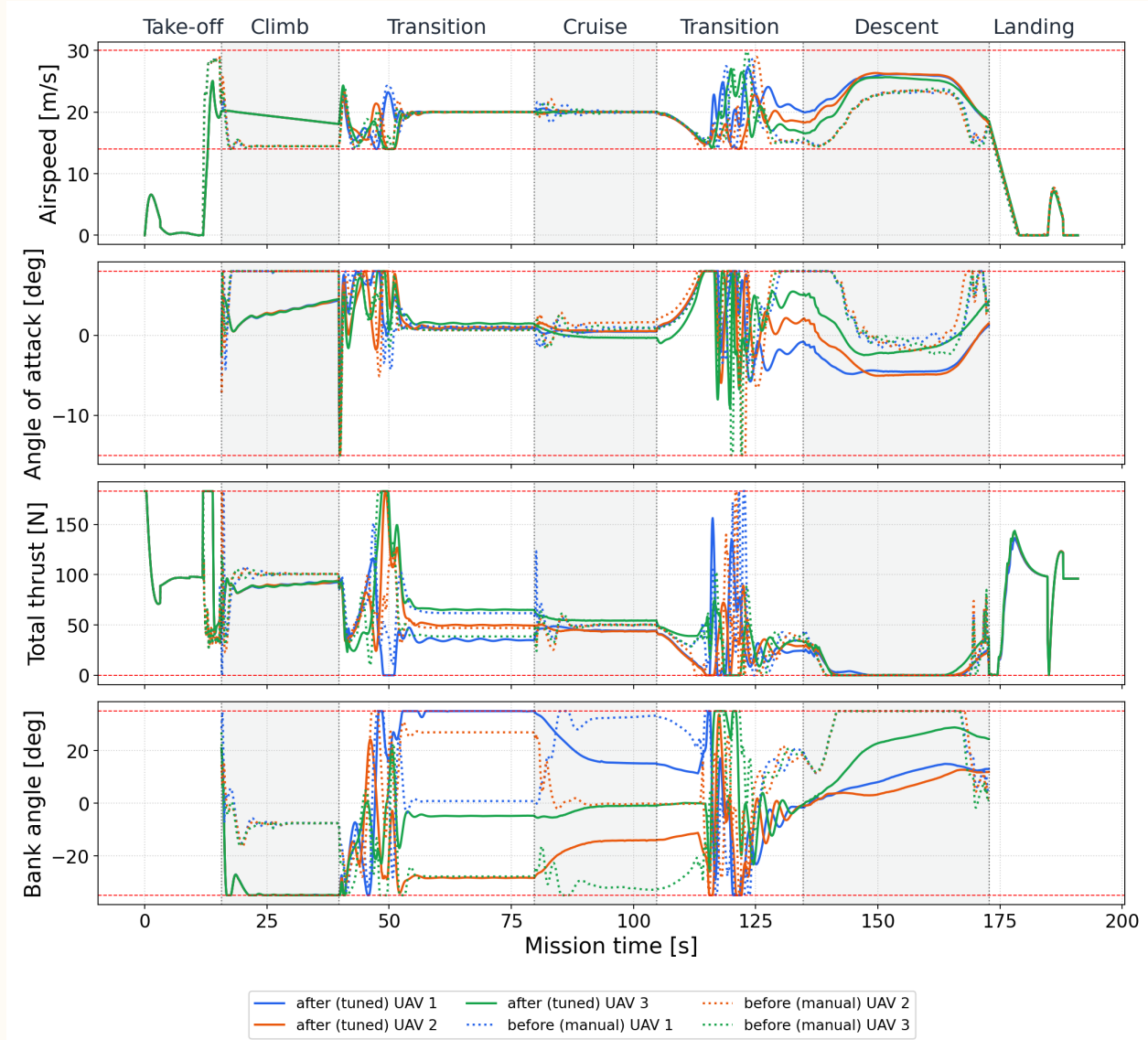


Figure 13.4: Comparison between the manually tuned baseline and the final Pareto-selected weight configuration for the airspeed, angle of attack, thrust and bank angle. Including in red dashed line the limiting values for these parameters.

Verification: Physical Constraints

Figure 13.4 shows that state constraints are met throughout the mission, except for the airspeed during the vertical take-off, as it should not be implemented when hovering. This verifies that the trajectory planner generates trajectories that follow the physical constraints of the system.

13.5.2. Sensitivity on Resultant Weights

During the tuning process it was observed that small changes to the weights resulted in great variations in the trajectories computed. Therefore, a sensitivity analysis will be performed on the optimised weights to assess the robustness of the simulation into greater detail.

Each one of the mission phases was run by varying the tuned weights by an order of magnitude up and down. Tornado plots were generated to identify the three most influential weights. These weights were then refined at additional factors: 0.1x, 0.2x, 0.5x, 2x, 5x, 10x. For every run, four performance metrics were recorded: payload tracking RMSE, maximum cable tension, maximum thrust, and maximum propulsive power.

Figure 13.5 summarises, for each mission phase and metric, the largest normalised variation produced by any tested weights. It can be observed how the transition, climb, and vertical descent are the most sensitive phases, with the payload tracking RMSE of the transition peaking with a 1216% of sensitivity from the baseline case. The climb phase also shows a relatively large RMSE sensitivity. The vertical descent phase experiences the largest increase in maximum propulsive power and maximum thrust.

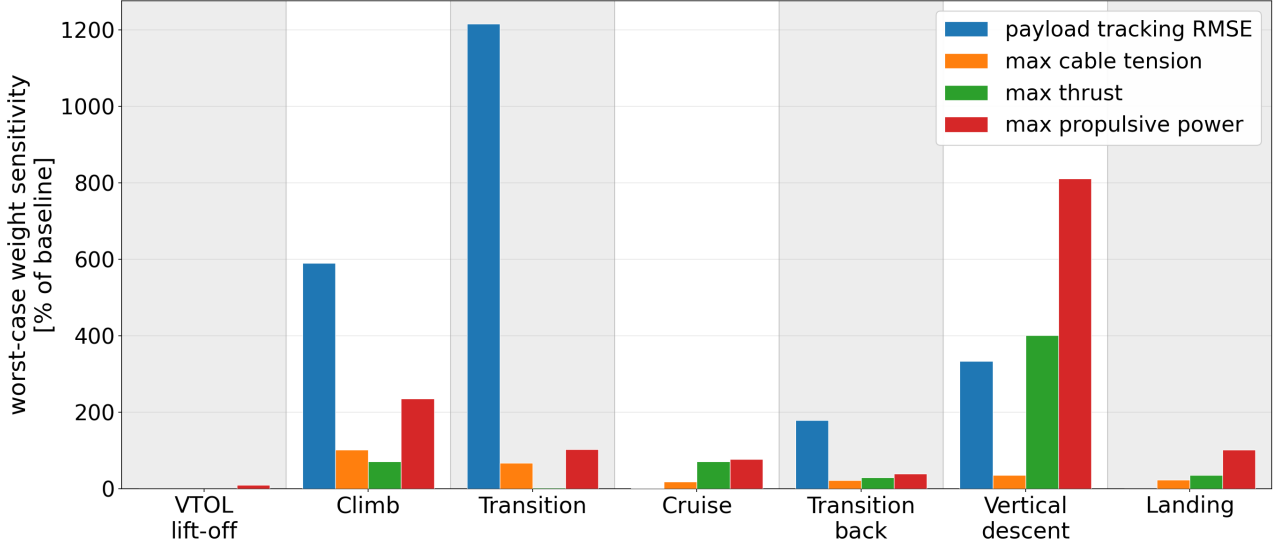


Figure 13.5: Cross-phase robustness summary for changes in the weights for the cost functions.

To assess which one of the specific weights caused the sensitivities observed in the bar plot, heat maps were generated for each performance metric. Each heat map shows the normalised swing of one metric, relative to the tuned baseline, when each cost weight is perturbed by an order of magnitude [73]. The normalised swing is calculated as the difference between the maximum and minimum value of the metric over all tested weights multiplied by their factors, divided by the baseline metric value:

$$S = \frac{J_{\max} - J_{\min}}{J_{\text{baseline}}} \times 100$$

Figure 13.6 is the heat map generated for the payload RMSE tracking error. This map shows that $W_{\Delta\gamma}$ is the weight that increases the normalised swing by 1216% for the transition, 591% for climb and 334% for the vertical descent. These three phases have in common that are the only ones where the drones undergo spinning vertical motion. This sensitivity can be explained by looking at equation: $\dot{h} = V \sin(\gamma)$. Gamma, the UAV flight-path angle, directly determines the vertical component of the motion of the drones. Changes in gamma will greatly affect the vertical positioning of the payload and the cable-tension distribution.

The heat maps for maximum thrust and maximum power showed that $W_{\Delta\gamma}$, $W_{\Delta\chi}$, W_p and $W_{\Delta u}$ have the greatest influence in the vertical-descent phase, other phases are not very sensitive. Specially for thrust, these weights increase the normalised swing by around 400% for the descent phase. The reason for this behaviour is that small changes in these weights can affect how aggressively the optimiser corrects payload position and cable geometry. The vertical-descent phase is very sensitive to this since it has very low thrust and power demand but a tight force-balance requirement.

For maximum cable tension $W_{\Delta\gamma}$ has the greatest influence for both the climb, increasing the swing by 102%, and transition, increasing the swing by 56%. In both phases the flight path angle determines how smoothly

vertical motion is introduced or removed, perturbing this parameter will change the timing and smoothness of the load and therefore the cable tension.

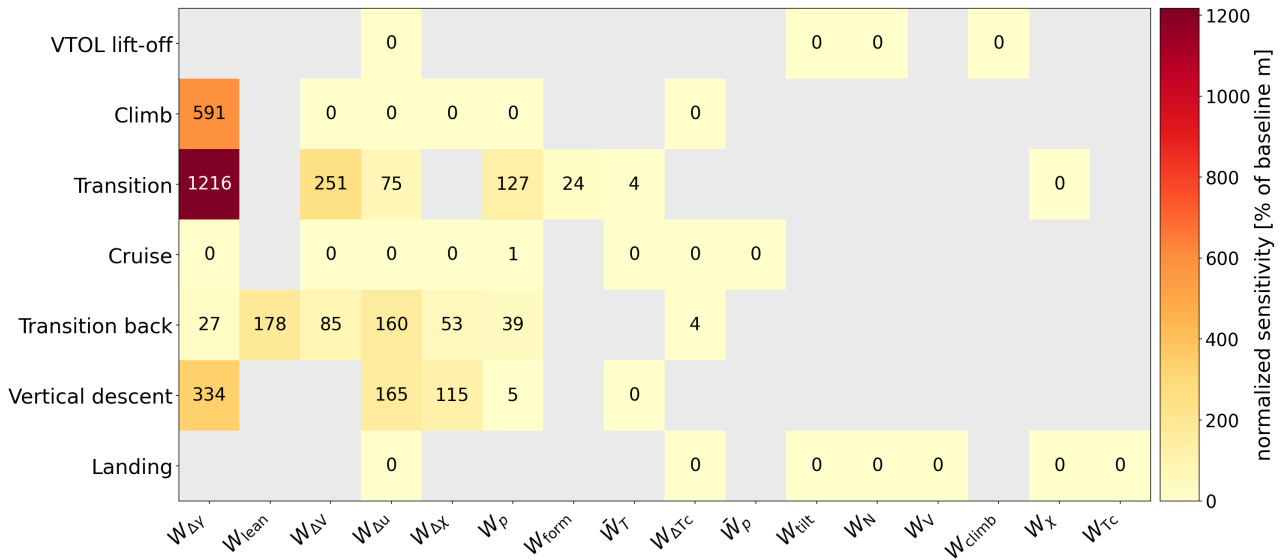


Figure 13.6: Heat map for the payload tracking RMSE for all mission-phases. Weights are ordered from largest to lowest influence on the normalised swing.

Key: Sensitivity to changes in tuned weights

The analysis highlights the high sensitivity of the trajectory planner to changes in the tuned weights, specially for the transition, vertical descent and climb phases. $W_{\Delta\gamma}$ emerged as the weight inducing most sensitivity for the four metrics examined. The heat-maps show that the tuned trajectory is not a robust set of weights, but a locally effective tuning for the current mission setup. Future versions of the trajectory planner should not only minimise performance metrics, but aim for robustness to small perturbations in the weights.

13.5.3. Model Parameter Sensitivity

Having tuned the weights for the full mission profile, the robustness of the model parameters should be assessed. Ten percent variations were given to the system parameters more susceptible to change in realistic operation scenarios. The parameters together with the justification for their choice are:

- **Payload area:** The payload reference area is highly uncertain, because a net is used as payload container. The area will vary depending on payload geometry and orientation. Furthermore, the exposed area may vary during flight due to payload motion.
- **Payload mass:** The trajectory planner is currently optimised for a payload plus carriage mass of 60 kg. However, the transported mass will vary between missions and will be one of the operator inputs before the mission.
- **UAV zero-lift drag coefficient:** The UAV C_{D0} was estimated during the aerodynamic design process. Due to the assumptions described in Chapter 7, this value may deviate from the final aerodynamic performance. Its effect on trajectory feasibility and performance is therefore investigated.
- **Cable length:** The cable length was selected to satisfy the take-off area constraint and the minimum inter-UAV separation requirement. Since this parameter directly affects the formation geometry and cable forces, its influence on the trajectory performance metrics is evaluated.
- **Maximum thrust:** The maximum available thrust constrains the achievable acceleration, climb performance, and manoeuvre feasibility. Since propulsion performance may differ from the estimated value, the robustness of the trajectory planner to variations in available thrust is assessed.

The four scalar metrics used to assess robustness of the trajectory planner for each one of the parameters previously described are the maximum cable tension, maximum propulsive power, maximum thrust and payload

tracking RMSE. It was observed that VTOL and landing phases are not very affected by variations in weights and the modelling parameters, therefore, this sensitivity study of the modelling parameters focuses on the fixed-wing phases.

To assess the sensitivity of the mission phases on the parameters previously mentioned with the metrics, each parameter was varied one at a time and each phase was run independently. A maximum variation of $\pm 20\%$ for each one of the five parameters was evaluated, multiplying each one of them by $[0.8, 0.9, 1.0, 1.1, 1.2]$ factors. For each phase and each metric, the worst case over the parameters was plotted in a graph, displayed in Figure 13.7. The plotted quantity is normalised, as a percentage of the baseline values.

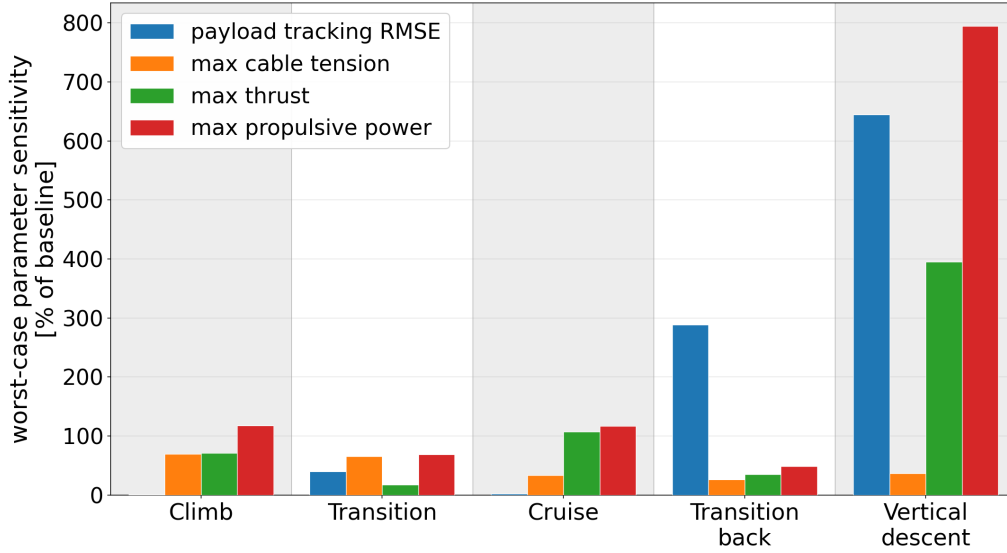


Figure 13.7: Summary of the robustness for each one of the fixed-wing mission phases when varying the modelling parameters: payload area, payload mass, UAV zero-lift drag coefficient, cable length and maximum thrust.

The graph shows that vertical-descent is the phase most sensitive to variations in the modelling parameters, followed by the transition-back. To assess which modelling parameters contributed the most to the observed sensitivity, heat maps were generated for each performance metric. In the heat maps, each cell corresponds to one mission phase and one perturbed parameter. The value inside of each cell is the normalised swing, which is the difference between the maximum and minimum value of the metric over all tested scaling factors, divided by the baseline metric value, as it was previously explained for the weight sensitivity.

Figure 13.8a shows the heat map for payload tracking RMSE. Darker cells indicate parameters that make the phase more sensitive to the metric being evaluated. This first plot shows that cable length and C_{D0} of the UAV are generating a sensitivity increase of 645% and 620% respectively in payload tracking RMSE for the vertical-descent phase. This is because this phase requires a force balance between cable geometry and aerodynamic drag. A change in cable length will modify the suspension geometry, directly affecting the tension required to support the payload. C_{D0} will affect the thrust and altitude needed to maintain the descending formation. Therefore, changes in these two variables will directly influence the payload tracking RMSE.

For the transition-back phase, the payload tracking RMSE gets mostly affected by changes in the maximum thrust with a 288% normalised swing. The main goal of this phase is to decelerate the payload from cruise to hovering condition, which will be limited by the thrust UAVs can produce. Therefore, this will be the parameter affecting the most if the drones can actually follow the reference trajectory.

Figure 13.8b shows the heat map generated to assess which parameters affected the most the maximum cable tension. Cable length, payload reference area, and payload mass were identified as the parameters with the greatest influence on the results for all mission phases. This is physically consistent, as these parameters directly affect the cable dynamics. The normalised swing variations in this heat-map are a lot lower than the ones previously examined for the payload tracking RMSE.

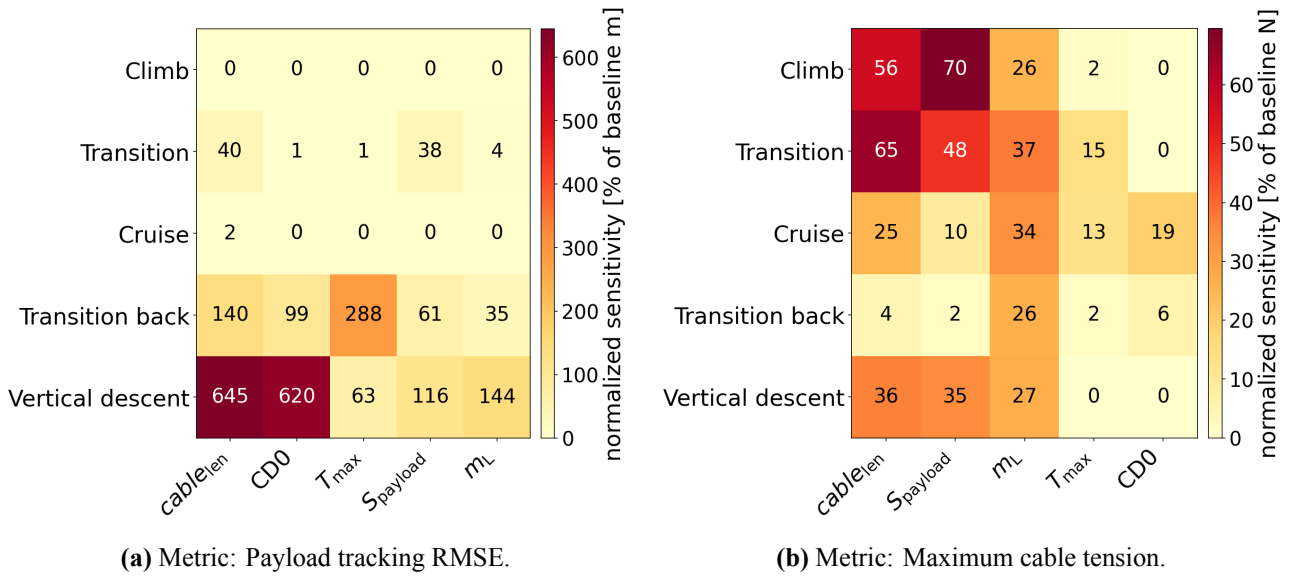


Figure 13.8: Heat map comparing the sensitivity in percentage from the baseline for changes in the modelling parameters for fixed-wing mission phases. Modelling parameters appear in the order from highest to lowest influence.

Similarly, two more heat maps were generated to assess parameter impact on maximum propulsive power and maximum thrust. In both cases, the vertical descent phase showed the highest sensitivity, with values around 700% and 350% for power and thrust respectively. The largest normalised variations were mainly caused by changes in cable length, payload area, and payload mass. Cable length is very influential, since it directly affects the vertical component of the tension available to support the payload. The payload reference area and mass will also affect the aerodynamic force acting on the payload during descent. For this reason, variations in these parameters make vertical descent the most sensitive phase for maximum power and thrust.

Key: Sensitivity to changes in modelling parameters

The analysis highlights the high sensitivity of the trajectory planner to changes in the modelling parameters, specially for the vertical descent and transition back phases. The cable length emerged as the parameter inducing most sensitivity for the four metrics examined. The heat-maps show that the tuned trajectory is locally effective tuning for the current mission setup, but is not robust to variations in modelling parameters. Future versions of the trajectory planner should not only minimise performance metrics, but aim for robustness to small perturbations in these parameters.

13.5.4. Initial-Conditions Sensitivity

The last step in the sensitivity study is to analyse the robustness of each one of the mission phases to small perturbations in the initial hand-off conditions. For each mission phase, the baseline case was computed using as initial condition the last state of the previous phase. From this baseline case, 20 Monte Carlo samples were generated by applying zero-mean Gaussian perturbations to the following variables: payload position, payload velocity, UAV airspeed, and UAV heading. Each one of these variables had a different standard deviation in their Gaussian distribution to reflect their different physical units and expected uncertainty levels:

Table 13.8: Gaussian perturbations used in the Monte Carlo simulations.

Perturbed quantity	Gaussian distribution
Payload position	$\Delta x_L, \Delta y_L, \Delta z_L \sim \mathcal{N}(0, 0.30^2)$
Payload velocity	$\Delta \dot{x}_L, \Delta \dot{y}_L, \Delta \dot{z}_L \sim \mathcal{N}(0, 0.15^2)$
Drone velocity	$\Delta V_i \sim \mathcal{N}(0, 0.30^2)$
Drone heading	$\Delta \chi_i \sim \mathcal{N}(0, 3^2)$

For the payload position and payload velocity, the Gaussian distributions are independently drawn. As an example, the payload position disturbance is:

$$\Delta p_L \sim \mathcal{N} \left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0.09 & 0 & 0 \\ 0 & 0.09 & 0 \\ 0 & 0 & 0.09 \end{bmatrix} \right) \quad (13.19)$$

The chosen standard deviations represent small but meaningful hand-off uncertainties for each one of the variables. They are large enough to perturb the trajectory beyond numerical noise, but small enough compared to larger overall dimensions such as cable length of $18m$. Furthermore, a fixed random seed was used so the perturbations were repeatable.

Each one of these perturbed-initial conditions cases were solved independently and the following plots were evaluated: payload tracking hand-off compared with the tracking error, maximum cable tension comparison with the baseline along time, maximum thrust error against time, and the time it takes to recover from hand-off perturbation. The following paragraphs will summarise the main findings for the mission phases found to be the most sensitive.

The greatest sensitivity to initial conditions was found to be in the transition-back mission phase. Figure 13.9 shows how the tracking error evolves over time for different hand-off values for both cruise and transition-back. Both phases manage to reduce the error very low in the first 2.5 s of the trajectory, which means the optimiser quickly corrects the initial position offset. However, for the transition back, small differences in velocity, heading, cable tension and formation geometry may still remain. At around second 7.5 the payload reference requires a strong deceleration, those remaining differences amplify during this demanding manoeuvre. It can be observed that the tracking error rises sharply up to values over 1 m. At around second 21, after the system managed to break it can be observed that the tracking error converges back to the reference. This behaviour may be influenced by the previous priority order chosen for tuning the weights in Table 13.5. For the transition back the weights were optimised for minimising control variation and power spread mostly, payload error was only categorised as a third-order priority.

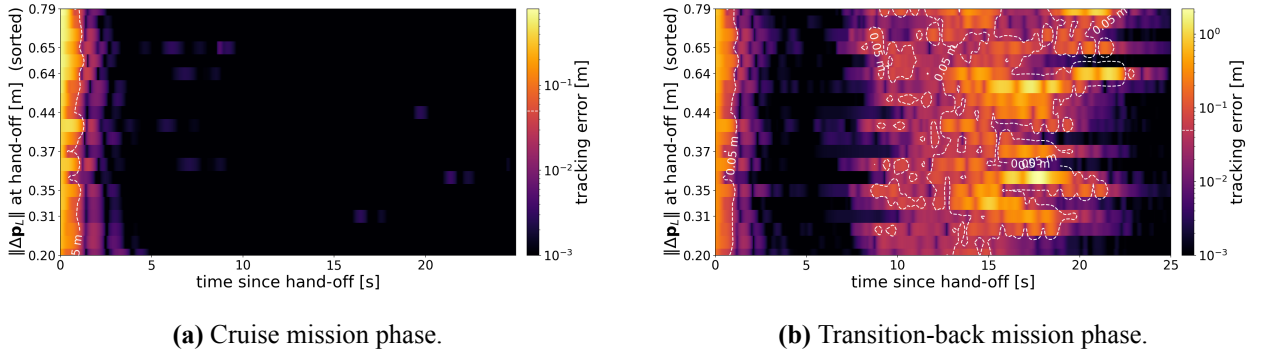


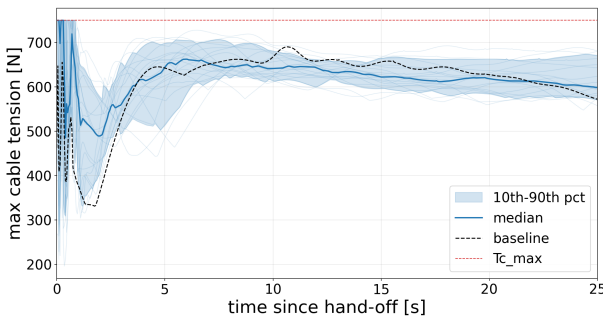
Figure 13.9: Payload tracking error as a function of time for all the considered initial conditions with their correspondent hand-off. Two mission phases are shown: cruise and transition-back.

Another metric used to assess the impact of changes in initial conditions for each one of the mission phases was the maximum cable tension over time. Which looks for the single highest cable tension reached by any one drone at any timestep during this phase. Figure 13.10 shows these plots for the four mission phases which had the greatest impact. First, for the climb (Figure 13.10a) and vertical-descent (Figure 13.10b) a similar phenomenon occurs. For both of them the median of the perturbed cases peaks towards the maximum cable tension allowed within the first 2 seconds of the phase, when the baseline case had a much lower maximum cable tension. Both phases perform similar motion, one moves the payload up the other down. They are load-critical vertical phases, where initial-condition disturbances require immediate cable-force corrections. At the beginning of these phases the payload is still stabilising for a later more smooth descent or ascent, for this reason,

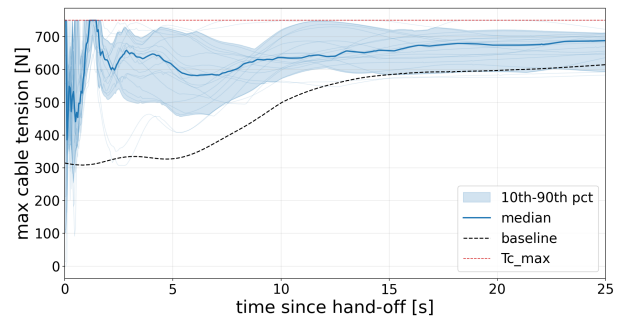
varying the initial conditions for these phases will make the optimiser correct this mismatch by applying large cable forces. After correcting this it can be observed how the perturbed cases end up following a similar trend to the one of the baseline.

The transition to cruise tension graph (Figure 13.10c) it shows that the baseline case peaks to the maximum allowed cable tension, while the perturbed cases remain in much more acceptable cable tensions. This may be related with the hand-off from the climb phase, where the baseline must preserve the previous phase's final cable tension and control values. However, the perturbed cases are not forced to maintain the cable-tension from cruise, they are free to chose to have an acceptable cable tension. These less constrained cases result in a much more smooth maximum cable tension profile, however, future sensitivity study should preserve inherited cable tensions when perturbing the initial state for a more realistic assessment of robustness.

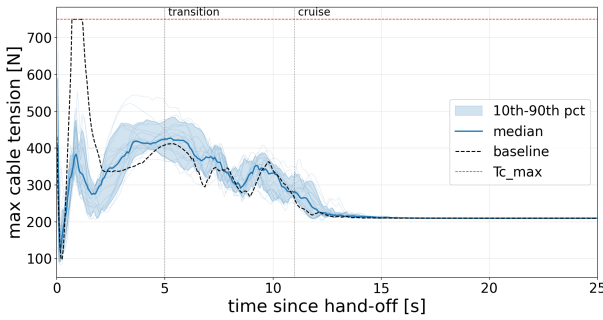
For the transition-back mission phase (Figure 13.10d), cable tensions are higher for perturbed cases, which was expected and they become close to a similar range to the one of the baseline line after the first 10 seconds of the phase. This mission phase shows a robust behaviour for initial conditions.



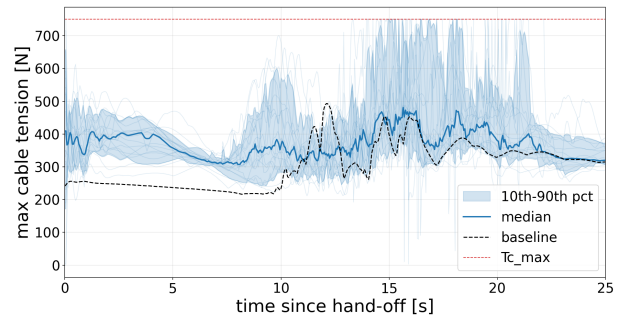
(a) Climb mission phase.



(b) Vertical-descent mission phase.



(c) Transition-to-cruise mission phase.



(d) Transition-back mission phase.

Figure 13.10: Cable tension over time for the baseline and perturbed cases in four mission phases: climb, vertical descent, transition to cruise, and transition back.

Lastly, the time of recovery from the hand-off perturbations was assessed for all mission phases. All mission phases showed the trend of larger time to recover for larger hand-off perturbations, as Figure 13.11b exemplifies. The only exception for this pattern was observed in the transition-to-cruise phase.

As Figure 13.11a shows for 18 out of the 20 Monte Carlo simulations the time to recover was very similar, even if the hand-off perturbation was larger. Furthermore, for two outliers with intermediate hand-off took more than 12 seconds to recover. However, these cases reduce the hand-off error within approximately one second. The reason for this is the definition of recovery. A case is only counted as recovered when the tracking error drops below 0.05 m and stays below until the end of the phase. These outliers had a tracking error of 0.065 and 0.057 m, which is only slightly above the threshold. For this reason, these cases should be interpreted as mild transients rather than major failures in the transition phase. The rest of the points robustness to initial conditions may occur due to a similar reason to the one mentioned for the maximum tension plots. In the transition-to-cruise phase the maximum cable tension is not inherited from the previous phase, therefore the time to recover

is really low since the phase is less constrained that it should be.

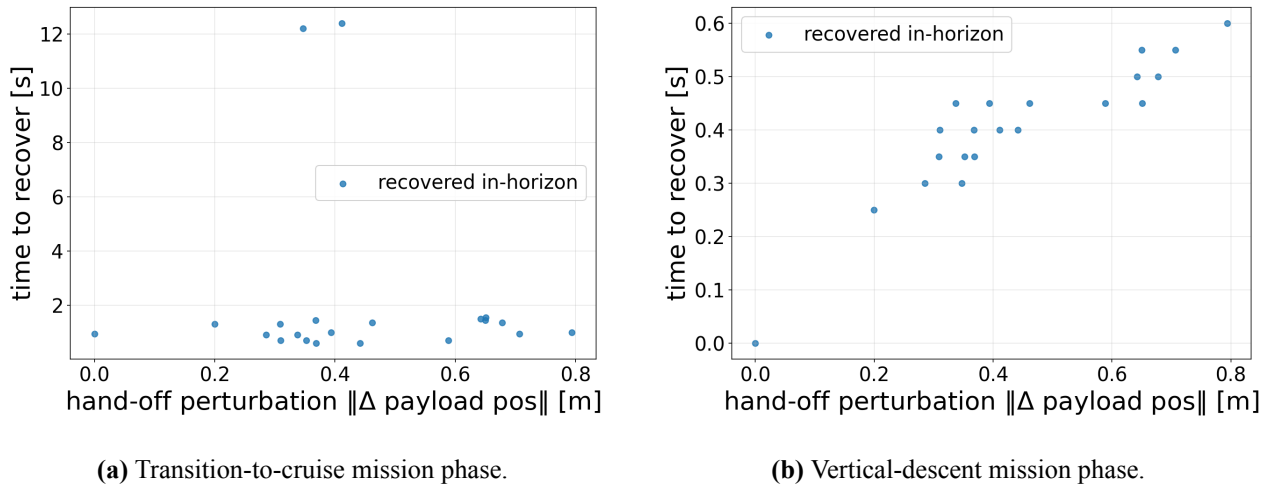


Figure 13.11: Scatter plot showing the time it takes to recover as a function of the hand-off perturbation for two mission phases: transition-to-cruise and vertical-descent.

13.6. Results

The following sections will explain in detail the trajectories generated by the tuned optimiser for each one of the mission phases, trying to find reasonable explanations for the physical trends observed.

Mission Phase Durations

Figure 13.1 summarised in one plot all the trajectories generated for each one of the mission phases. Table 13.9 gives a detailed list of the times the drones will take to complete each one of the phases. The times in this table are computed for a cruise range of 20 km and a cruise payload altitude of 95 m.

Table 13.9: Mission phase flight durations.

#	Mission phase	Duration
1	Take-off	11.90 s
2	VTOL lift-off	3.80 s
3	Climb	24.0 s
4	Transition	40.0 s
5	Cruise	1000 s

#	Mission phase	Duration
6	Transition-back	30.0 s
7	Vertical descent	38.1 s
8	Landing	12.0 s
9	Drone descent	6.25 s
Total mission		≈ 1166 s

Transition from Hovering to Forward Flight and Spinning Vertical Climb

Now that the weights have been tuned and the robustness of the optimiser is verified, the resultant trajectories can be interpreted. After taking off vertically, the UAVs need to tilt their propellers and make use of their wings to fly forward and start lifting the payload.

Figure 13.12a shows the resulting trajectories from the optimiser, where the dot represents the starting point and the star the end point. From this, it can be seen that, when the drones initially lose altitude as they tilt the propellers, they also move outwards. This is because of the cable length constraint, which forces them to lie on a sphere with cable length as radius around the payload. Once they gain sufficient speed and the thrust is aligned with the nose of the aircraft, it regains altitude and begin to move around the payload to start lifting it.

Once the UAVs have fully transitioned into forward flight, the payload needs to be lifted upwards to achieve the cruise altitude. Figure 13.12b, shows the trajectory drones followed during this phase. The drones were not forced to spin through any constraints or cost functions, but rather to just make the payload follow its reference. The trajectory planner showed, consistently with a range of weights and initial conditions, that the optimal trajectory for the UAVs in order to lift the payload vertically up is to spin around it. This is a remarkable

conclusion as it validates the proposed mission profile, which includes a spinning climb as the most efficient way for the UAVs to lift the payload vertically.

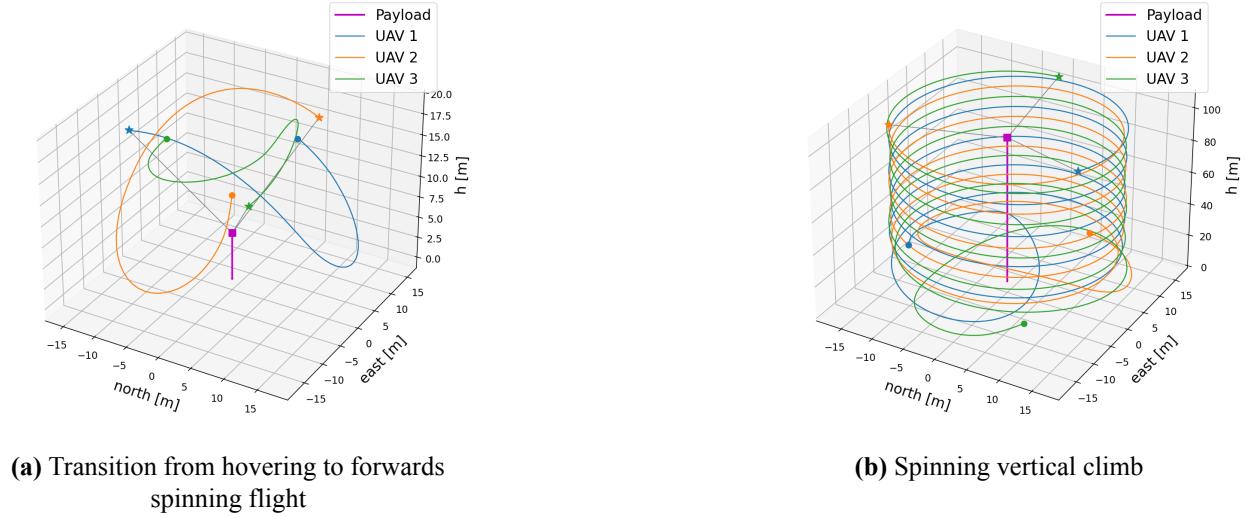


Figure 13.12: 3D trajectories of the UAVs to reach cruise altitude

Key Result: Vertical Climb

The optimiser identified spinning climb to be the optimal way to lift the payload vertically, without this behaviour being explicitly enforced by the constraints costs.

Transition to Cruise

The transition from spinning climb to cruise is a complex manoeuvre, as the UAVs need to collaboratively lift the payload, accelerate it to cruise speed, all while finding their cruise formation. To analyse the trajectories, the behaviour of the payload needs to be understood, as its motion drives the system through the payload tracking cost function. Figure 13.13 shows the forwards cable tension component, it can be seen how the resultant tension along the cruise heading acting on the payload closely matches the reference acceleration obtained by differentiating the reference payload trajectory twice. That means the drones collaborate such that the forward component of the resultant is always aligned with the cruise heading.

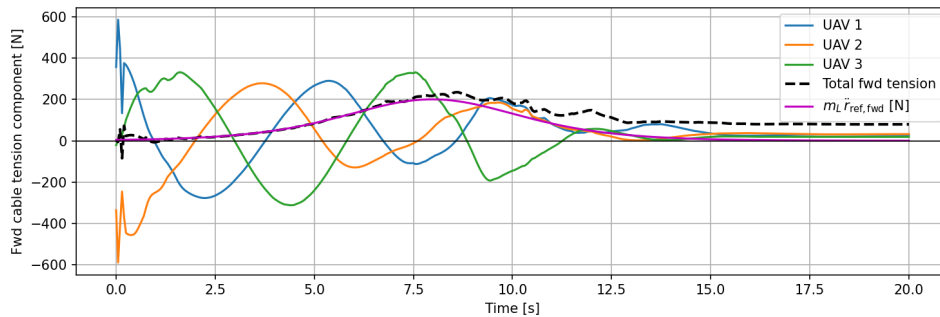


Figure 13.13: Tension along payload cruise heading from each UAV, their addition, and the target forward force on payload derived from payload reference trajectory for the transition manoeuvre

When the payload needs to accelerate forward, the oscillations of all three UAVs have a positive offset in Figure 13.13, given that the magnitude of the peaks is larger than that of the valleys. This is due to the fact that, since the drones are spinning around the payload, when one is going in front of the payload, it drops its altitude to align the tension with the heading (shallower angle with respect to the horizontal) as seen in Figure 13.14. When it goes behind the payload, it regains altitude so that it does not pull the payload back while providing support to lift it, as tension is more vertically aligned. Thus showing how the drones are constantly

collaborating to both lift the payload while accelerating it along its reference trajectory. In addition to that, in Figure 13.13, it can be seen how the reference acceleration deviates from the resultant forward tension once it has gained some speed. This is due to the drag force starting to have an effect on the motion of the payload too.

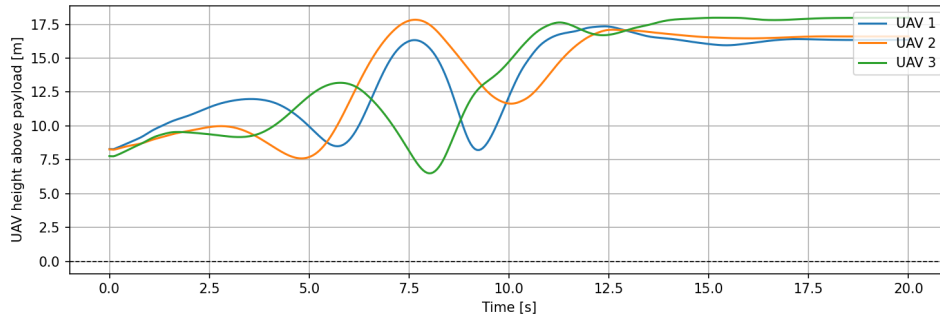


Figure 13.14: Height above the payload for each UAV for the transition to cruise

In order to see the full picture, the states and controls need to be analysed, which also reflect the oscillatory nature of the motion. Intuitively, when the UAVs drop to pull the payload forward, their speed should increase as potential energy is traded for kinetic. However, the opposite is the case here, as airspeed in Figure 13.15 and height above the payload in Figure 13.14 have practically no phase difference, rather than the expected 180° . For the thrust in Figure 13.16, which could explain this apparent discrepancy, regions of minimum thrust correspond to maximum airspeed and vice versa. So the changes in airspeed are not explained by the thrust.

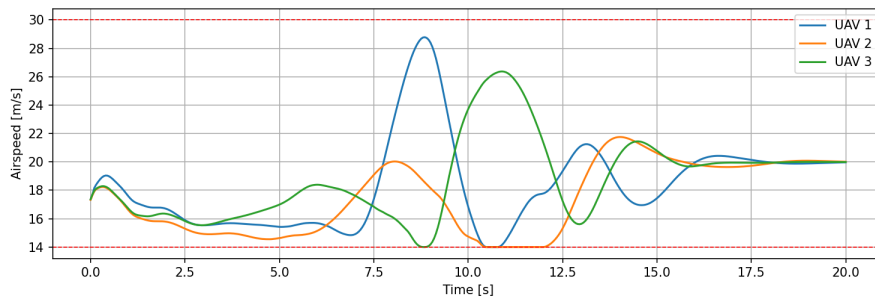


Figure 13.15: Airspeed for each UAV for the transition to cruise

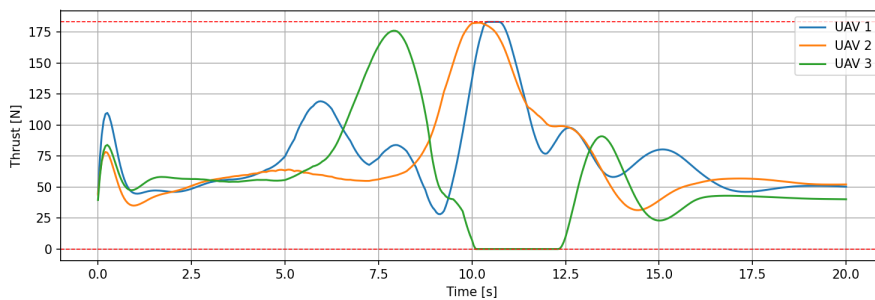


Figure 13.16: Thrust for each UAV for the transition to cruise

Looking at the equations of motion in Equation 13.1, the only thing that could still cause the airspeed to behave like this is the component of the cable tension acting along the airspeed axis of the UAV. Indeed, when this component of the tension in Figure 13.17 is compared to the airspeed plot in Figure 13.15, regions of increasing airspeed correspond to regions of maximum forward tension on the UAV. What the former plot suggests is that the path of the drones around the payload is not fully circular, but rather elliptical, where the cable tension does not always act perpendicular to the drones motion. This results in a deceleration of the drone when it is "overtaking" the payload, which propels it forwards by stealing momentum from the drone. The opposite happens when the drones fly backwards past the payload (still in front, but moving opposite to the payload's

motion), they accelerate by using the tension, which also brings the payload forward. This could also be an explanation for the drones dropping and rising, as the payload will be able to extract more momentum from a dropping drone, as it tries to gain kinetic energy.

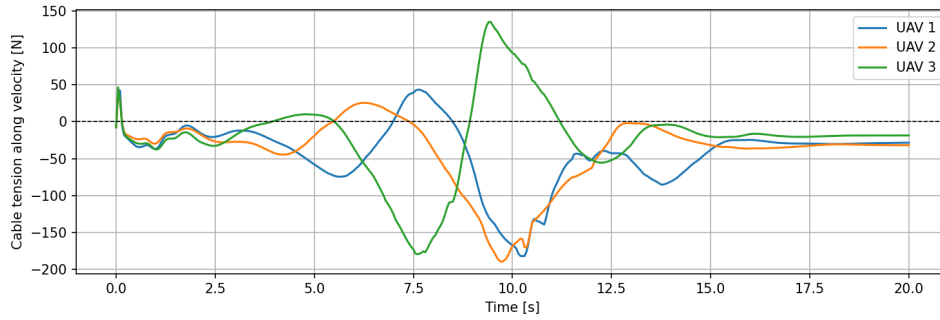


Figure 13.17: UAV cable tension along their airspeed vector for the transition manoeuvre

It is perhaps useful to visualise their behaviour by looking at the top view of the manoeuvre in Figure 13.19 and the top view relative to the payload in Figure 13.18. The relative view shows the UAVs spin in circles around the payload, but due to the motion of the payload, they result in the absolute trajectory in Figure 13.19. A conclusion could be drawn that the speed of the drones relative to the payload remains constant as they form the circle around it, but this is not true. As discussed previously, the drones decelerate as they "overtake" the payload and accelerate as they go behind it, so this difference is enhanced relative to the payload if it is moving forward. Therefore, in order to keep the circular shape seen in Figure 13.18, they also need to be turning faster when they are behind the payload than when they are in front. This is backed by Figure 13.20, which shows peaks in the bank angle that correspond to the UAVs being behind the payload (higher altitude in Figure 13.14).

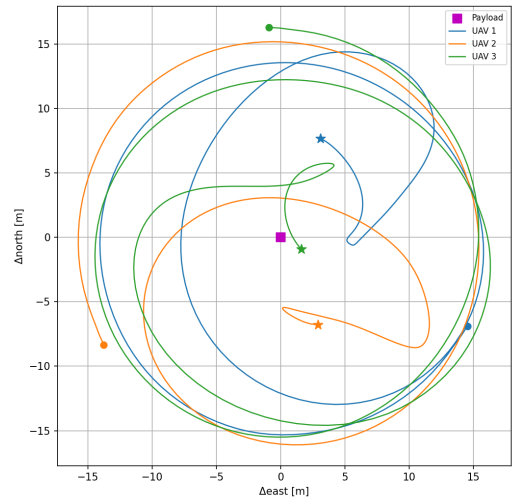


Figure 13.18: Top view relative to the payload of the trajectory for the transition to cruise

Validation: spinning UAVs with forwards-moving payload

At the start of the transition to cruise, when the drones have not fully transitioned but are still moving the payload forwards, the top view in Figure 13.19 shows the same elliptical shape as the spinning fixed-wing UAVs trajectories with straight forwards payload motion presented by Girardello et al [2].

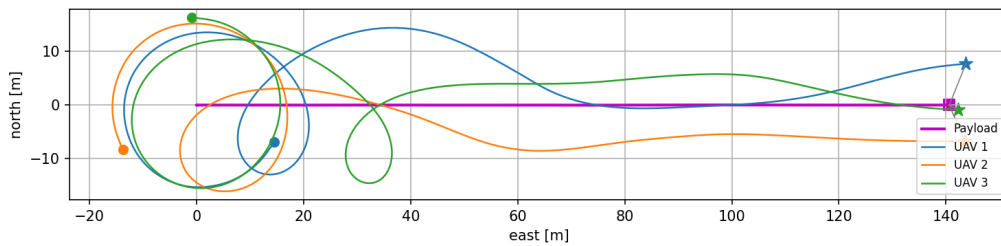


Figure 13.19: Top view of the trajectory for the transition to cruise

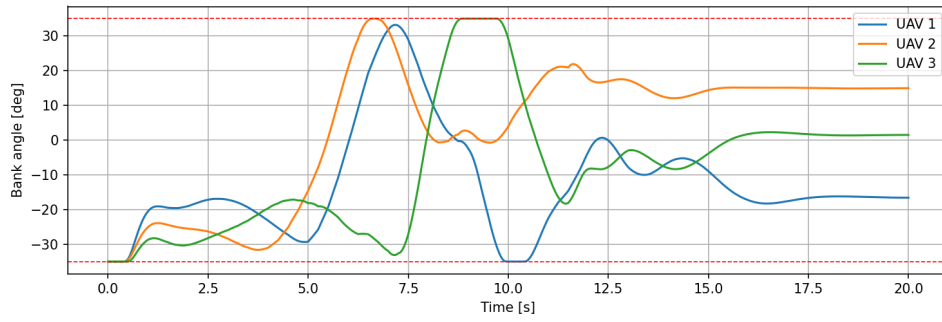


Figure 13.20: Bank angle for each UAV for the transition to cruise

Overall the strategy that optimiser has chosen consists of 2 key aspects. First, it tilts the plane of rotation of the drones, such that the tension of the drones in front is used for accelerating the payload forwards (by aligning the tension with the horizontal plane), and the tension of the ones in the back is used to counter the weight (by aligning it vertically). Secondly, the rotation is stretched to form an ellipse and strategically give and take momentum from the drones, in such a way that the payload is also accelerated.

Finally, when the formation weight starts to rise and the payload has gained a significant speed, the drones end the transition and each follow the reference formation, finalising their transition to cruise. The implementation of the formation weight is deemed necessary as, when it is not present, the UAVs finish the transition with one drone at a significantly lower altitude, with the other 2 carrying all the weight. Even though the energy weight should force them to collaboratively carry the payload, the optimiser only reduces this cost in the chosen horizon of 2.5 s. It therefore lacks long term vision to equalise the load, as the energy required to get to the optimal formation over the horizon is larger than the one to keep the imbalance. The implementation of the formation cost is thus needed for a proper transition to cruise.

Cruise

Once the transition to cruise has been finalised, the optimiser starts solving with the cruise weights. The 3d trajectory in Figure 13.21 shows that the left and right UAVs move closer to the middle drone.

This result can be explained from the choice of priorities for the weight tuning in Figure 13.5.1. Power spread is chosen as the top priority, which results in a cooperative behaviour, penalising differences in power usage. This minimises the consumed energy throughout the mission (SUS-1 🌱). The way the optimiser does this is precisely by pulling the drones closer together. The bank angle is hence reduced, so less lift is needed to keep holding the payload up (more vertically aligned). Given that the speed is given by the payload reference cruise speed of 20 m s^{-1} , the angle of attack can be reduced which in turn reduces drag and the power required to cruise. The trajectory planner therefore finds the energy optimal cruise formation.

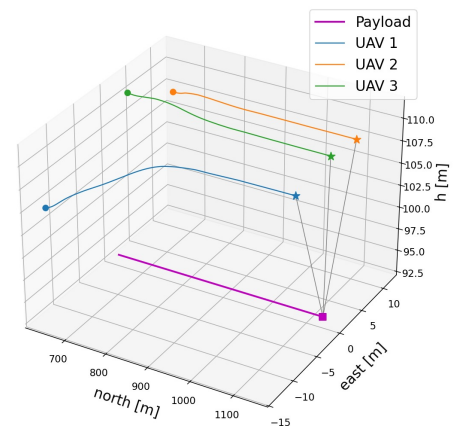


Figure 13.21: 3D trajectories of UAVs for cruise

Transition from to cruise to spinning descent

Another particularly interesting manoeuvre to analyse is the transition from cruise back to spinning. As discussed in Subsection 13.5.4, this phase was especially sensitive, and therefore, as seen in Figure 13.22, the heading-wise reference acceleration was held for longer but for a smaller magnitude, to make the manoeuvre less aggressive.

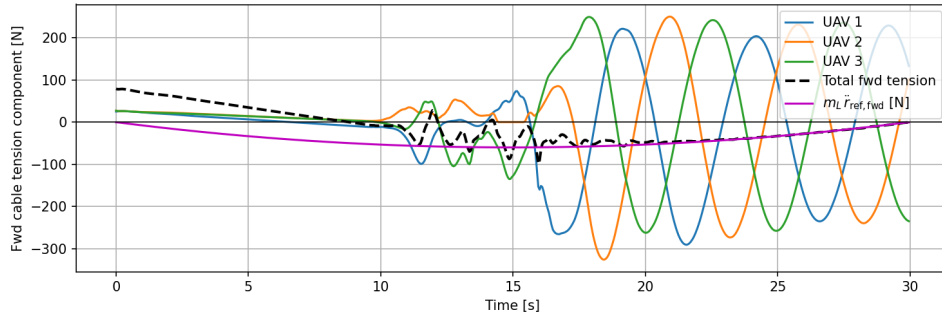


Figure 13.22: Tension along payload cruise heading from each UAV, their addition, and the target forward force on payload derived from payload reference trajectory for the transition back manoeuvre

By looking at Figure 13.23, towards the end, the similarity with the transition to cruise is evident, as the trademark elliptical turns of changing size as the payload decelerates also appear. The UAVs also form circles relative to the payload. Up until this point, it seems the transition back from cruise is just a mirrored version of the transition to cruise. Nonetheless, discrepancies are observed when comparing Figure 13.24 to Figure 13.25. While for the transition to cruise the UAVs airspeed decreased as their altitude dropped, the opposite is the case here. This is likely due to the lower magnitude of the deceleration required, approximately 50 N (acceleration times payload mass) in Figure 13.22 compared to 200 N in Figure 13.13. For this manoeuvre, the payload does not need to decelerate as aggressively, so it chooses not to steal momentum from the drones as they drop, as just aligning the tension with the (negative) cruise heading direction already proves to be sufficient.

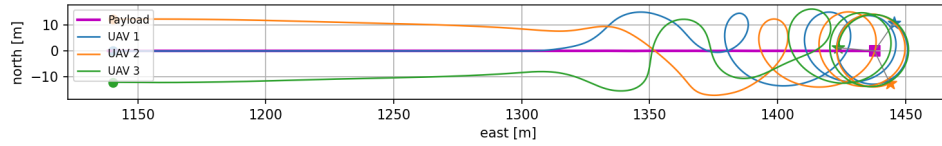


Figure 13.23: Top view of the trajectory for the transition back from cruise

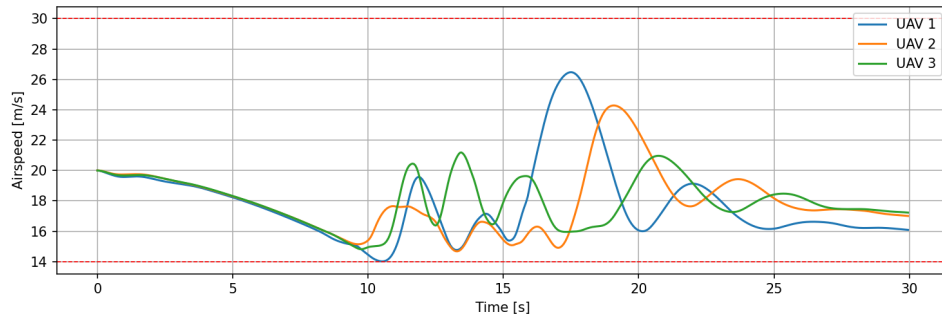


Figure 13.24: Airspeed for each UAV for the transition back from cruise

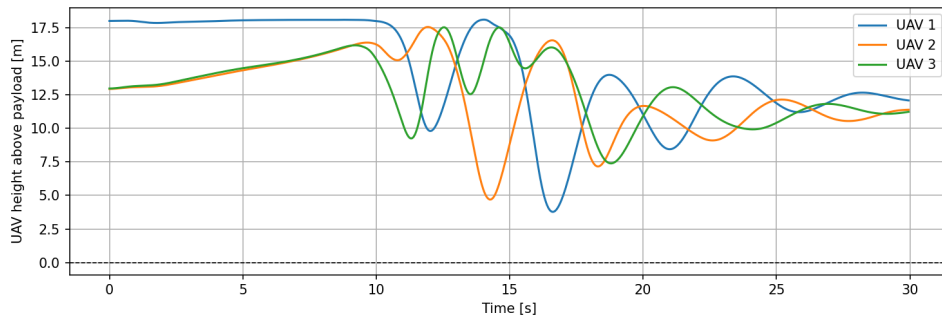


Figure 13.25: Height above the payload for each UAV for the transition back from cruise

From approximately 15 s onwards the transition back is essentially a mirrored version of the transition to cruise. But the behaviour before that is where it differs. This is the case because the optimiser requires the UAVs to decelerate the payload while they are in cruise formation. Their most natural response for that is to slow down with the payload while increasing drag by increasing the angle of attack as seen in Figure 13.24 and Figure 13.26. Only when they hit the state limits on both sides around 10 s do they try to find another way to slow the payload down. Figure 13.22 shows the region from this point until 15 s, when the UAVs start purely spinning, is the most inaccurate. This is because the optimiser struggles to find a stable way to sustain the deceleration, thus the quicker oscillations. At 15 s the optimiser finds the spinning and easily ends the manoeuvre with the mirrored transition to cruise.

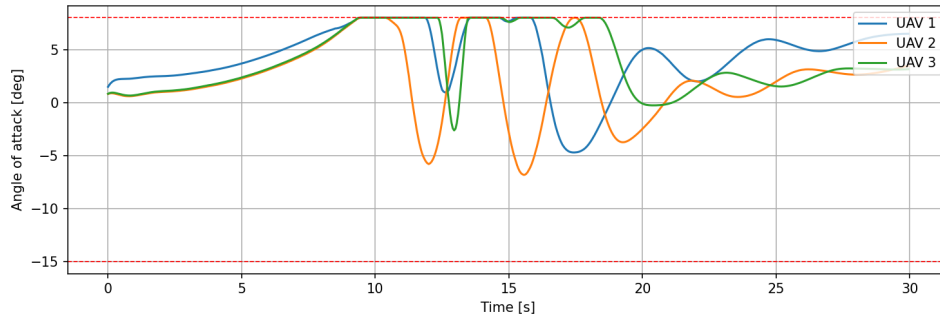
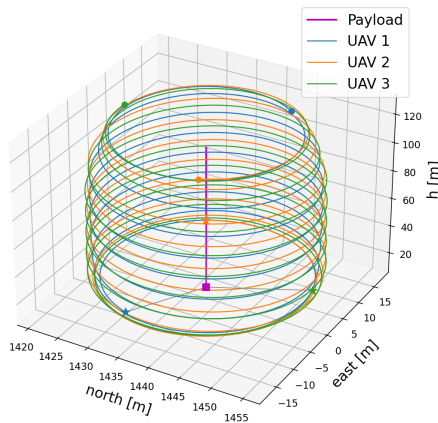


Figure 13.26: Angle of attack for each UAV during the transition back manoeuvre

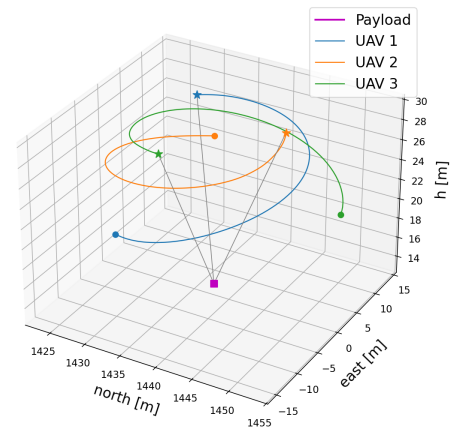
Spinning vertical descent and transition back to hovering

After the UAVs have managed to slow the payload down and spin in place, they start the descent. As shown in Figure 13.27a, the result is almost identical to the spinning vertical climb but reversed. An interesting result is that the thrust is set to zero throughout the whole manoeuvre. This means that the drones are able to perform it by just gliding down, which helps by reducing the battery usage required for each mission (SUS-1 🍀).

After the payload has made contact with the ground, they need to stop spinning and go back to hovering, so they can initiate their landing. As seen in Figure 13.27b, the UAVs increase their altitude as their propellers tilt up, given also that they do not need to lift the payload any more. The turn radius is also reduced as their airspeed decreases, and their altitude increases. It was observed that, in order to slow down, the UAVs increase their angle of attack and propeller tilt to the maximum, as this results in the highest backwards force. It also results in the increase in altitude which helps as well, by trading kinetic with potential energy .



(a) Spinning vertical descent



(b) Transition from forwards spinning flight to hovering

Figure 13.27: 3D trajectories of the UAVs during descent and landing transition.

Cable Entanglement Avoidance

It is challenging to draw any conclusions on cable entanglement from the plots presented until now. Hence, to ensure the compliance of the trajectory planner with the cable entanglement constraint, the normalised scalar triple product is plotted throughout the entirety of the mission.

Verification: Cable Entanglement

Figure 13.28 shows the product has a constant sign and does not violate the margin throughout the mission. Two exceptions are seen at the very start and end of the mission. This happens when the UAVs and the payload all lie on the ground, where the volume formed by the cables is 0, but they are far from entanglement. This points to the conclusion that the trajectories generated by the planner never lead to cable entanglement. Note that the margin is precisely reached during cruise. This makes sense as the drone formation tends to lie in the same plane, and is not a problem as long as the margin is not crossed.

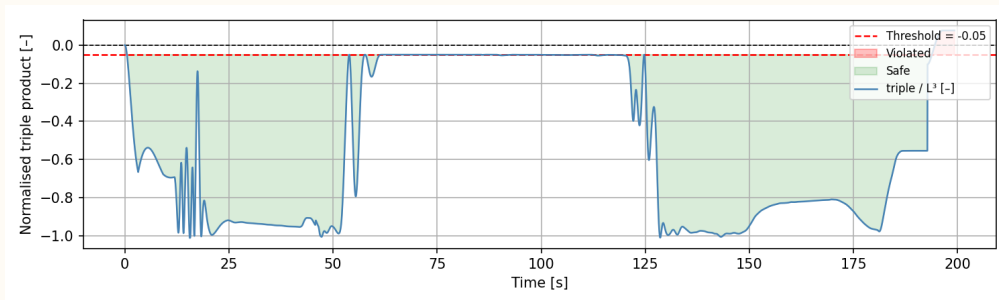


Figure 13.28: Normalised scalar triple product of relative positions of UAVs to the payload

Two Drones Case

To assess the robustness of the trajectory planner to the possibility of carrying two drones, the variable defining the number of drones was set to 2 to check if it would be possible to perform an emergency landing. Figure 13.29 shows the trajectory the planner found to be the optimal with the tuned weights. It is therefore possible to perform emergency landings with only two UAVs, where the payload trajectory remains well controlled. The drones correctly performed the cruise, transition, spin-down, landing and drone descent, while carrying the 60 kg payload, accounting for the extra 10 kg from the failed drone.

Verification: Two-UAV Emergency Landing

The trajectory planner verifies that, within the assumptions of the implemented model, a feasible emergency-landing trajectory can be generated for the two-UAV case:

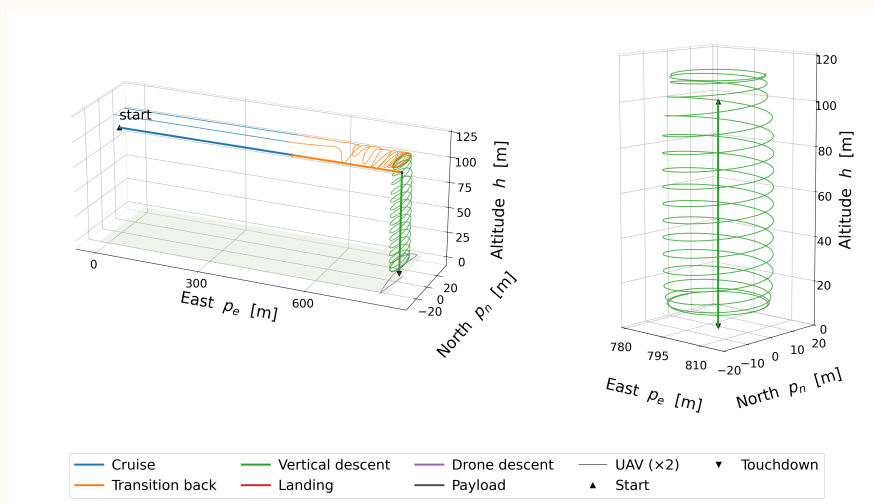


Figure 13.29: Trajectory for the two drones case from cruise to drone touchdown

13.7. Assumptions Summary

Table 13.10: Trajectory planner assumptions.

ID	Assumption	Effect
A-TRAJ-1	Sideslip is 0 at all times	Fails to consider necessary control surface deflections to coordinate turns and additional drag. Introduces error in double derivative constraint for the roll angle ($\ddot{\mu} = \ddot{\phi}$)
A-TRAJ-2	Each UAV is modelled as a 3-DoF point mass.	No rotational degrees of freedom are implemented, which ignores external moments acting on the drones and rotational dynamics.
A-TRAJ-3	The payload trajectory is predefined and fixed.	The real energy optimal trajectory is not found for the whole system, just for the drones for that given payload reference.
A-TRAJ-4	Thrust angle is constant for fixed-wing phases (no rotation of propellers).	Restrict possible manoeuvres that could leverage this extra degree of freedom for the system, like reducing stall speed.
A-TRAJ-5	The payload is modelled as a point mass.	Aerodynamic moments acting on the payload are ignored so yaw braking cannot be included.
A-TRAJ-6	The cables are rigid, massless connections	Ignores cable tension response to elongation and thus any spring-dampener dynamics.
A-TRAJ-7	Collision avoidance is simplified to minimum UAV-to-UAV distance.	Simplifies clearance volume to a sphere, ignoring different constraints for horizontal and vertical distances, as well as consideration of the direction of motion.
A-TRAJ-8	Cable entanglement is determined using the scalar triple product.	Overconstrains the motion of the cables, because the cable that is attached in the middle of the bearing to the payload connection is not allowed to cross the plane formed by the other two, even though it would not entangle in reality.
A-TRAJ-9	The OCP is discretised using backward Euler with fixed time step.	Solution's accuracy is proportional to the time step, requiring a small step and thus higher computational time to achieve accurate solutions.
A-TRAJ-10	The full mission is solved using receding-horizon windows.	The trajectory planner only ensures an optimal trajectory over the chosen horizon, which can lead to myopic decisions that prioritise short-term over long-term optimality
A-TRAJ-11	Obstacles are neglected.	Planned solution might differ from the real one due to real-life obstacles. Future trajectory planning will be performed online and will therefore consider this.
A-TRAJ-12	The atmosphere is assumed still and uniform (wind, gusts, turbulence, etc).	Planned trajectories may approach operational limits which could be temporarily surpassed aerodynamic perturbations
A-TRAJ-13	Obstacles are neglected.	Planned solution might differ from the real one due to real-life obstacles. Future trajectory planning will be performed online and will therefore consider this.
A-TRAJ-14	Only angle of attack rate is affected by the pitch rate	Flight path angle changes are ignored for the constraint on maximum and minimum double derivative for the pitch angle which leads to small inaccuracies

13.8. Compliance

Table 13.11: Trajectory planner compliance matrix.

ID	Means of compliance	Status
STK08-MIS08-SYS14	Section 13.6 explained in detail how the trajectory planner coordinates all drones.	✓
STK08-MIS08-SYS15	Table 13.5 put as one of the top priorities even thrust and velocities between drones to transport the payload. It was later verified in Section 13.6.	✓
STK09-MIS09-SYS17	Figure 13.29 shows that two drones could perform an emergency landing with their corresponding trajectories.	✓
STK18-MIS18-SYS59	Running the complete mission with the trajectory planning takes around 15 mins.	✓
STK32	By adding extra drones to the swarm the payload carrying capacity and optimum increases, see Figure 3.3, where manoeuvres are also working.	✓

13.9. Challenges and Future Recommendations

Regarding the sensitivity analysis, the following relevant recommendations can be addressed:

- **Modelling of the bodies:** Advance towards a 6DoF model, including aerodynamic derivatives; include cable damping, mass and elasticity.
- **Manoeuvres definition:** Optimise the trajectory of the payload together with the UAVs; verify robustness of the trajectory planner to other manoeuvres such as fast turns during cruise.
- **Weight tuning process:** In future work, all cost-function weights should be tuned, rather than only the most influential ones, to obtain smoother and more accurate trajectories. The weights should also be made time-dependent, allowing them to adjust with time within one same mission phase.
- **Observed sensitivity of the tuned weights:** For the payload tracking RMSE, the transition-to-cruise and climb phases were found to be the most sensitive, mainly due to $W_{\dot{\gamma}}$. Therefore, $W_{\dot{\gamma}}$ should be retuned using a robustness-based criterion rather than only the payload tracking error. The selected value should lie on a flat region of the response curve, where small perturbations produce similar RMSE values. For maximum power and maximum thrust, the vertical descent phase was the most sensitive, with increases of 810% and 425% from the baseline, respectively. This was mainly caused by $W_{\dot{\gamma}}$, $W_{\dot{\chi}}$, W_{track} , and $W_{\Delta u}$. The vertical-descent weights should be tuned using a robustness criterion that also includes peak thrust and peak power.
- **Model parameter sensitivity:** The vertical descent phase was excessively sensitive for all assessed criteria. The most influential parameters were: cable length; payload drag coefficient C_{D0} ; payload reference area; payload mass. Cable length should be optimised over the full trajectory. In the current analysis, only its sensitivity was assessed, but it was found to be the most influential parameter in all four generated heat maps. So further optimisation will be very beneficial. Furthermore, the payload drag coefficient C_{D0} should be revised to ensure that the selected value is accurate, since it strongly affects the sensitivity results. For missions with different payload masses or reference areas, the weights may need to be re-optimised at the beginning of the mission to adapt the planner to the specific payload characteristics.
- **Initial-condition sensitivity:** The transition-back phase was excessively sensitive to initial-condition perturbations. To reduce this sensitivity, its duration should be increased and the deceleration demand should be reduced. Another fix is to not force transition-back to immediately track the nominal path if the payload starts slightly offset. Cable tension should be imposed as a forced input or constraint during the transition-to-cruise phase to obtain more realistic results.

14. Drone Flight Controller

After the trajectory of each drone is calculated by the trajectory planner, each drone needs its own controller in order to follow this trajectory. This chapter describes the drone flight controller. Because the drones are identical, each drone has the same controller. The controller is detailed in Section 14.1 and its PyBullet implementation is explained in Section 14.2. Section 14.3 showcases the controller's performance in a number of tests. Section 14.4 shows the drone controller's compliance with relevant requirements, which are listed in Table 14.1. Future recommendations are given in Section 14.5.

Table 14.1: Requirements relevant to the drone flight controller.

ID	Requirement
SYS30-NAV02	The drone shall deviate a maximum of 3 m due to wind gusts.
STK05-MIS05-SYS09	The system shall maintain stability during all flight phases.
STK01-MIS01-SYS01	Each drone shall be able to carry a load of 20 kg at sea-level conditions.
SYS14-NAV11	The drone controller shall ensure the planned trajectory is followed with an accuracy of 3 m.

14.1. Cascaded PID Controller

A cascaded PID controller is selected for the control of individual drones. A driving factor for this choice was the simplicity of PIDs, allowing the team to have sufficient time to develop the hardware, trajectory planner, and simulation environment within the DSE time frame, instead of creating a more complex controller. Additionally, Li et al. [4] explain that cascaded PIDs are a widely accepted fixed-wing UAV control architecture.

Design Decision: Drone Flight Controller Selection

A cascaded PID controller is selected for its simplicity and wide use in fixed-wing UAVs [4].

Transformations between reference frames are made using quaternions. DAISCH¹ explains quaternions to be commonly used in aerospace IMU applications and to be advantageous over using Euler angles due to their lack of gimbal lock, computational efficiency, smooth interpolation, and numerical efficiency.

The flight controller's block diagram is detailed in Figure 14.1. It takes reference trajectories of the global x, y, and z axes as inputs for the drone to follow. Yaw is used as an input to decompose x and y information (global frame) into forward and lateral information (body frame), using the global coordinates to forward coordinates and global coordinates to lateral coordinates block diagrams of Figure 14.1. Errors in position and velocity along the x and y axes are included, to control both position and smoothness of flight.² Additional gains also allow the lateral and forward errors to be weighed differently. The controller then employs outer loop PIDs to resolve global errors:

- **Forward error PID.** This minimises the difference in current and reference forward position and velocity of the drone.
- **Lateral error PID.** This minimises the difference between current and reference sideways position and velocity of the drone.
- **Altitude error PID.** This minimises the difference between current and reference altitude, using the global z error.

¹URL <https://daischsensor.com/understanding-quaternions-in-imu-technology/> [accessed 12.06.2026]

²URL <https://maxicrane.com/blogs/news/differences-between-velocity-mode-and-position-mode-in-motion-control> [accessed 15.06.2026.]

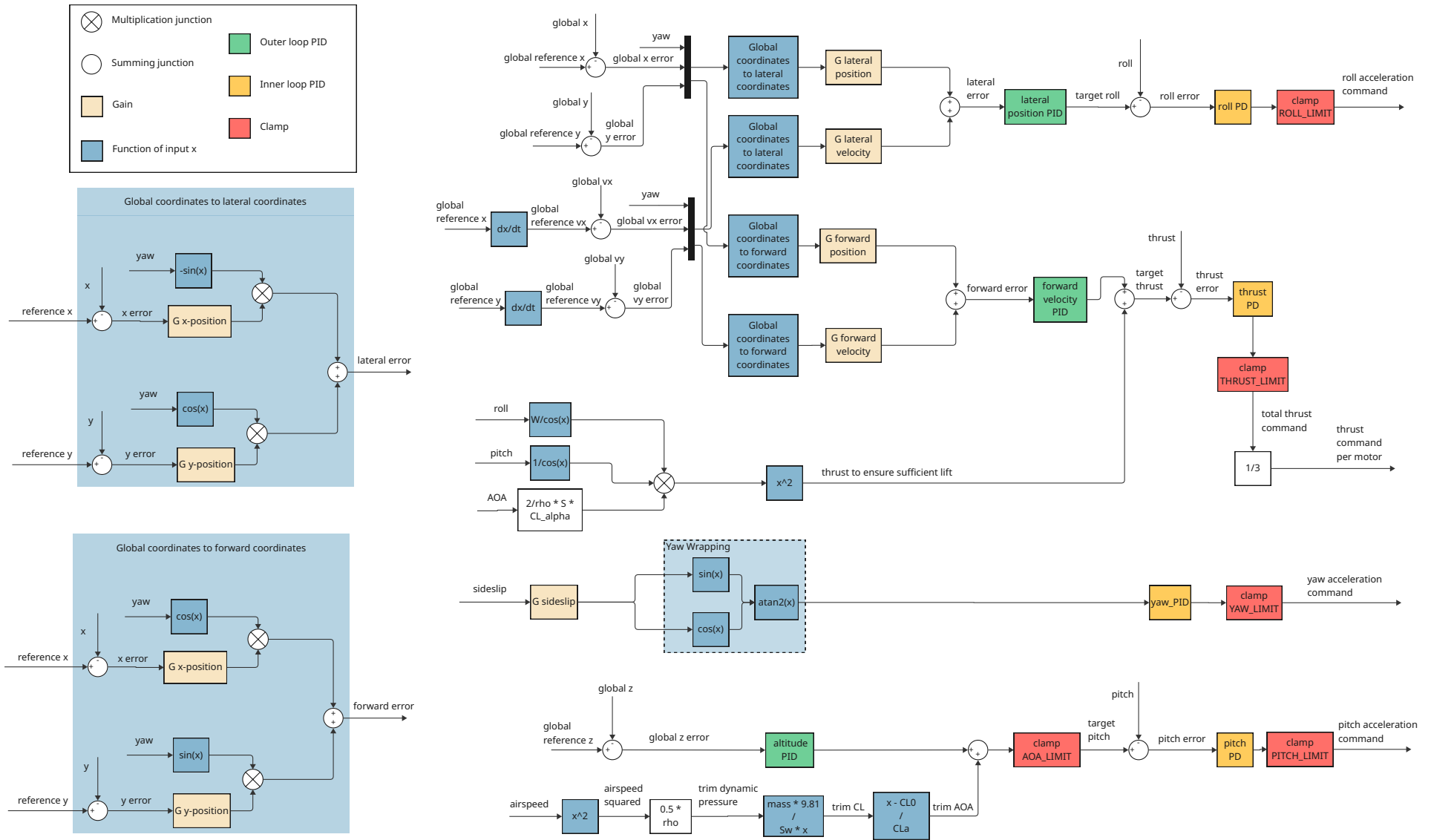


Figure 14.1: Drone controller: a cascaded PID.

The drone is operating in a coupled environment. For example, altitude can be increased by increasing lift, which can in turn be increased through increasing speed through thrust or angle of attack through pitch. Furthermore, required thrust and pitch are interdependent, as increases in pitch decrease the thrust acting in the forward direction, and increases in thrust increase the lift, decreasing the required pitch for altitude changes.

The drone uses a decoupled response approach to its environment: roll is used to correct lateral errors, pitch to correct altitude errors, and thrust to correct forward errors. This decoupled approach is feasible, because the forward velocity and altitude PIDs can compensate for each other's commands. The decoupled approach is also desirable, being simple to implement and understand, and thus easier to tune and verify [74].

With pitch and thrust being used to control only altitude/forward position directly, the direct combination of these control outputs are not utilised. Nardiello³ explains that this is an appropriate decision at low angles of attack at fast airspeeds, but not for high angle of attack manoeuvres such as landing, which require the command outputs to be assigned in reverse. This can be easily implemented in the drone controller by assessing the drone's flight regime through airspeed and/or angle of attack measurements, in turn using pitch/thrust for altitude/forward velocity control. This is not shown in the block diagram (Figure 14.1) nor the PyBullet simulation described in Section 14.2, due to time limits of the DSE. It should still be noted that pitch and thrust indirectly affect each other, as both impact airspeed and are dependent on airspeed.

Design Decision: Pitch for Altitude Control and Thrust for Forward Velocity Control

The PyBullet simulation (and the corresponding block diagram in Figure 14.1) implements a drone flight controller detailed for high airspeed, low angle of attack manoeuvres, i.e. operations at cruise velocity. This justifies using pitch for altitude control and thrust for forward velocity control³. This decision is appropriate for the goal of validating the drone design within the DSE time frame.

The pitch required to achieve trimmed flight is added to the altitude PID's target pitch, to ensure that the drone flies with enough lift during steady flight. Similarly, the velocity required to maintain sufficient lift to counteract drag is added to the forward PID's target velocity, to ensure that the drone flies with sufficient lift for steady flight. This includes compensations for banking and pitching manoeuvres, during which components of lift act out of the vertical axis, and therefore velocity must be increased to maintain enough lift to counteract weight.

A proportional yaw controller opposes sideslip. Yaw wrapping⁴ is used to ensure that the yaw never exceeds $\pm\pi$ rad and that the controller smoothly transitions between $\pm\pi$ rad.

The controller's inner loop applies PIDs for the four control outputs: roll, pitch, yaw, and thrust. Integral terms for these controls are set to zero, so as to not integrate the previously-derived values from the outer loop PIDs. As such, the inner loop consists of PDs. The roll, pitch, and yaw PDs minimise the difference between current and target roll, pitch, and yaw angles respectively, and each output the corresponding angular acceleration command. Each command is then clamped to not exceed the limit imposed by the maximum deflections and effectiveness of the ailerons, elevators, and rudders. The thrust PD minimises the difference between current and target thrust, and outputs the corresponding thrust command to each motor. This is clamped to not exceed the maximum thrust per motor.

To avoid saturation, anti-windup logic is applied for the outer loop PIDs. If a control surface is saturated, a term proportional to the difference in the saturated command and command is subtracted from its integral term⁵:

$$u_{integral} = \begin{cases} \int K_I e \, dt, & \text{if the control output does not saturate.} \\ \int K_I (e - K_{aw}(sat(u) - u)) \, dt, & \text{if the control output saturates.} \end{cases}$$

In this way, the control surface is kept close to its saturation limit until it is no longer saturated⁵. The integral term corrects steady-state errors to the extent permitted by the control surface, while preventing the accumulation of integral error that cannot be realised during saturation, and thus also delays when the error starts to decrease⁵.

³URL <https://pilotworkshop.com/tips/pitch-or-power/> [accessed 11.06.2026.]

⁴URL <https://nl.mathworks.com/help/map/ref/wraptopi.html> [accessed 15.06.2026.]

⁵URL https://ocw.mit.edu/courses/16-30-feedback-control-systems-fall-2010/8c33eb306938cac6cd73e701a86a5b32_MIT16_30F10_lec23.pdf [accessed 11.06.2026.]

Key Choice: Drone Flight Controller

Each drone flight controller is a cascaded PID, controlling forward error with thrust, lateral error with roll, and altitude error with pitch. Sideslip is corrected with yaw. The outer loop controls are forward speed error, lateral position error, and altitude position error PIDs. The inner loop controls are the roll, pitch, yaw, and thrust PDs. The inner loop controls command the control outputs in a decoupled manner.

14.2. PyBullet Implementation

The drone controller was built in a six-degree-of-freedom environment using PyBullet, a Python module for the simulation of physics and dynamics⁵. Table 14.2 summarises the forces and moments included.

Table 14.2: The forces and moments considered for the drone flight controller’s implementation in PyBullet.

External Forces and Moments	Control Forces and Moments	Moments Resulting from Control Forces
• Lift • Pitching moment from tail lift • Pitching moment from wing lift • Pitching moment at aerodynamic centre • Drag • Weight • Air resistance to rotational motion	• Rolling moment • Pitching moment • Yawing moment • Thrust force	• Roll damping moment • Pitch damping moment • Yaw damping moment • Pitching moment from rear propeller’s thrust

Gains were tuned using an autotuning script to minimise the cost function

$$J = \sum_{t=0}^T (|e_x(t)| + |e_y(t)| + |e_z(t)|),$$

that is, the sum of the position errors in each axis. This optimisation problem was solved using differential evolution. Shaji⁶ explains this to be a heuristic approach, where initial candidate solutions are evolved through random mutation. A grid of the solution space was searched, allowable for the amount of gains to tune⁷ and because the tuning only has to be performed once, therefore can be reasonably computationally-expensive⁸.

It should be noted that the cascaded PID controller has high sensitivity to its initial conditions, and care must be taken to ensure the initial position, velocity, and orientation of the drone are suitable for the trajectory. It is also important that the trajectories used for testing the controller are possible for the drone to fly, with appropriate translational and rotational speeds.

The results of implementing the drone controller in PyBullet for a circular trajectory are shown in Figure 14.2. This trajectory also includes a constant climb rate, and therefore mimics the spinning up manoeuvre. This is a gentler trajectory than the one described by the trajectory planner, with a larger radius. Unfortunately, the team was unable to fully test this trajectory due to the time constraints of the DSE. This more aggressive manoeuvre requires cable tension to provide centripetal force, and thus requires cable force modelling.

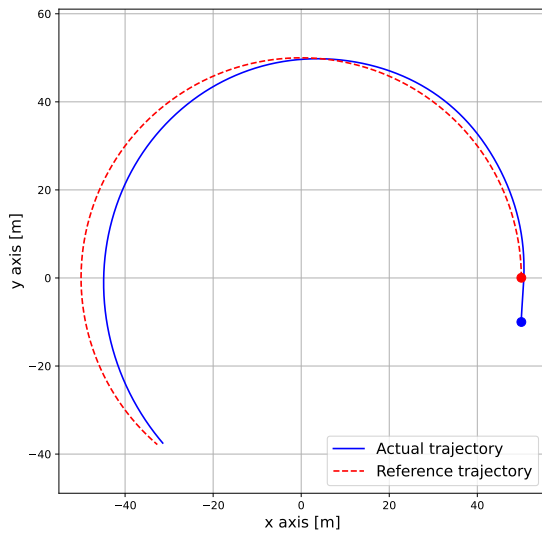
Figure 14.2 shows that the controller can follow a trajectory while remaining in stable flight. The drone starts before the reference trajectory in the y axis, but catches up to it, showing the drone can recover from forward position errors. The drone overshoots the trajectory at first, and then undershoots it. This is likely partly due to a deviation from ideal initial conditions at the beginning of the flight. Figure 14.2b showcases the coupled forward error and altitude error discussed in Section 14.1: phugoid motion is seen along the z axis.

⁵URL <https://pypi.org/project/pybullet/> [accessed 10.06.2026.]

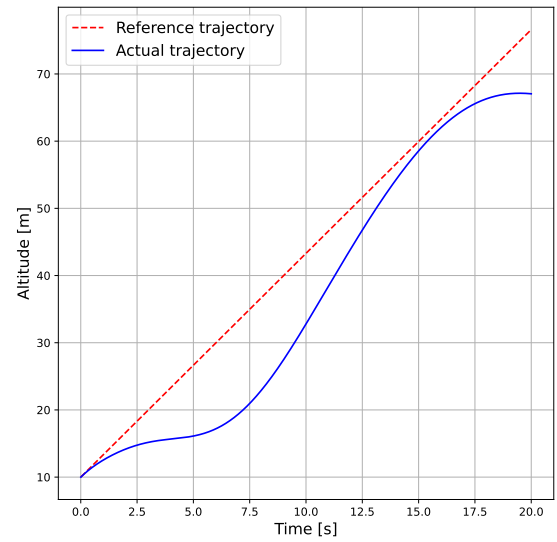
⁶URL https://medium.com/@reshma_shaji/differential-evolution-what-it-is-and-how-does-it-work-81d3415c2367 [accessed 11.06.2026.]

⁷URL <https://neurosnap.ai/blog/post/understanding-grid-search-as-an-optimization-algorithm-in-machine-learning/643748be49872f3862f39aed> [accessed 15.06.2026.]

⁸URL <https://medium.com/@cjl2fv/an-intro-to-hyper-parameter-optimization-using-grid-search-and-random-search-d73b9834ca0a> [accessed 15.06.2026.]



(a) Planar tracking.



(b) Altitude tracking over time.

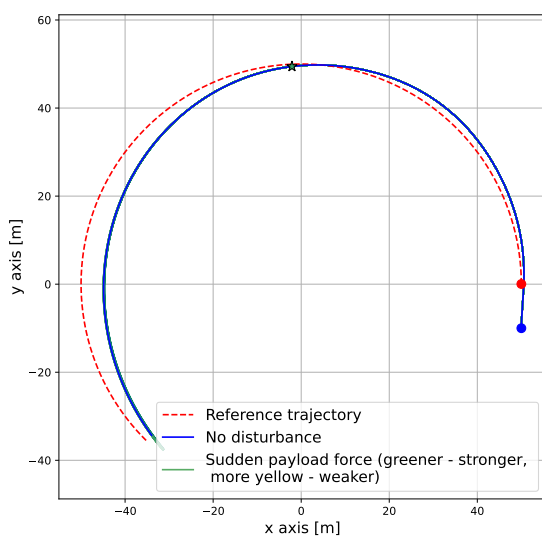
Figure 14.2: The drone controller's trajectory tracking.

Validation: Stability and Controllability of an Individual Drone

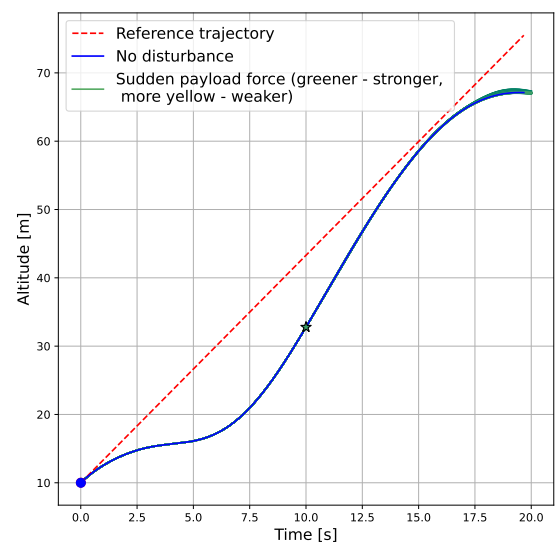
The PyBullet drone flight controller validates the drone design, showing that each individual drone is stable and able to follow a trajectory. This is intended as an early validation tool for the current stage of the design process. It is expected that more comprehensive simulations as well as real-life flight tests will be conducted to further validate the drone's stability and controllability.

14.3. Drone Controller System Testing

Figure 14.3 shows the controller's reaction to wind gusts ranging from ± 5 N in the global x, y, and z axes. These values overestimate the drag force resulting from a 10 m s^{-1} wind gust. The wind gusts are modelled as a step function lasting 0.1 s starting at 10 s, indicated by a star in Figure 14.3a. The drone is minimally impacted by the wind gusts, with some small deviations from the original path occurring from 17.5 s to 20 s. This verifies that the drone can recover from wind gusts. It should be noted that the drone typically continues to undershoot the reference trajectory, indicating that the cascaded PID requires further tuning.



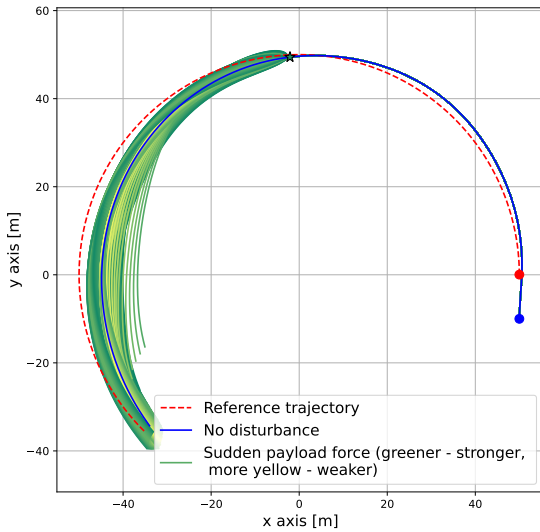
(a) Planar tracking.



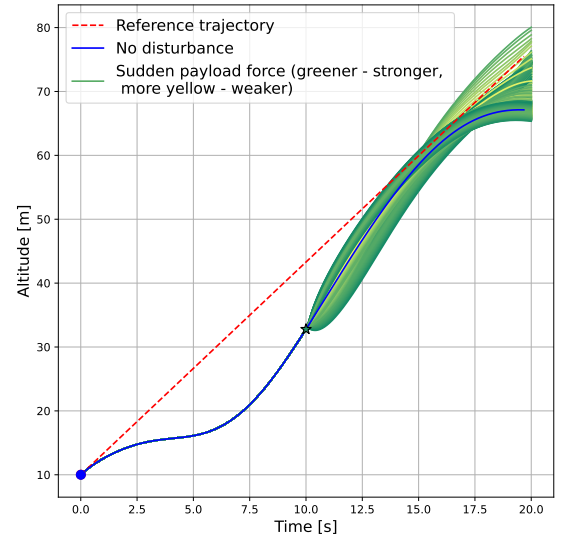
(b) Altitude tracking over time.

Figure 14.3: The drone controller's trajectory tracking with a wind gusts, occurring at the star.

Figure 14.4 shows the controller's reaction to sudden payload movements, ranging from 0 N to 600 N in the global z axis and ± 600 N in the global x and y axes. These values are taken from the simulation of the swarm, where the payload tension is averaged to be less than 700 N. It is evident that the drone recovers from these sudden “jerks” in the payload's motion. Interestingly, the trajectory continues to undershoot the reference trajectory for all payload forces, again indicating a tuning error.



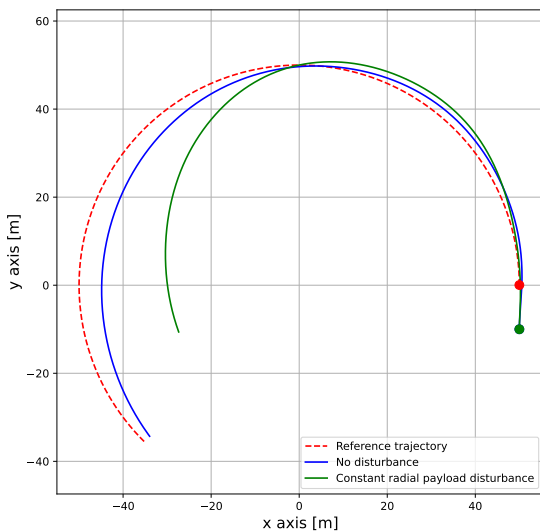
(a) Planar tracking.



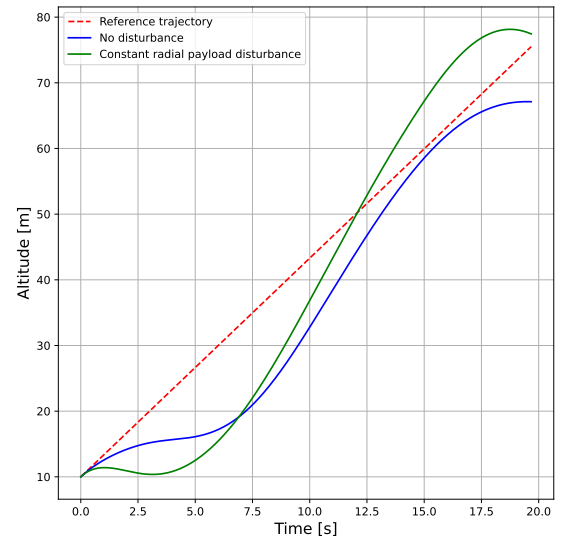
(b) Altitude tracking over time.

Figure 14.4: The drone controller's trajectory tracking with sudden payload movements, occurring at the star.

Figure 14.5 shows the controller's motion with a constant radial force, resulting from the payload tension. A smaller radius results, proving the importance of the payload's force on each drone, and the feasible trajectories that result. This inward force will allow each drone to follow the more aggressive manoeuvre commanded by the trajectory planner, with a smaller radius. The drone also can achieve the climb rate with the payload, initially undershooting and then overshooting the reference altitude to overcome the additional force.



(a) Planar tracking.



(b) Altitude tracking over time.

Figure 14.5: The drone controller's trajectory tracking with constant radial payload tension.

Validation: Stability and Controllability of an Individual Drone Subject to Disturbances

The PyBullet drone flight controller validates that the drone can recover from wind gusts and forces mimicking jerky payload movements, as well as fly with a constant radial force mimicking the constant payload tension.

14.4. Compliance

Table 14.3: Drone controller compliance matrix.

ID	Means of compliance	Status
SYS30-NAV02	Figure 14.3b shows that the drone has minimal deviations due to wind gusts.	✓
STK05-MIS05-SYS09	The drone is able to fly within its roll, pitch, and yaw limits while remaining stable.	✓
STK01-MIS01-SYS01	Figure 14.5a demonstrates that the drone can carry a cable-suspended payload, including during climb.	✓
SYS14-NAV11	While the drone has a maximum error larger than 3 m, with more time spent tuning gains and TECS pitch and thrust control, the drone will follow trajectories within this limit.	✗

14.5. Future Recommendations

While the cascaded PID approach is simple and feasible, future drone flight controllers could consider implementing a controller that is better equipped for the coupled pitch and thrust flight of a fixed-wing UAV. One control law that could be used is Total Energy Control System (TECS), explained by Spark et al. [75] to be a control law based on principles of energy exchange. Spark et al. shows that TECS decouples forward speed and altitude control, such that thrust controls total energy and pitch controls kinetic and potential energy exchange. Spark et al. compared PID and TECS through simulation, finding TECS to have less altitude overshoot, illustrating the advantage of implementing TECS.

Key Choice: Future Steps for the Drone Flight Controller

Each drone flight controller should implement a Total Energy Control System (TECS) for altitude and forward error control, to overcome the coupling between these commands. This will reduce overshoot and phugoidal motion that the PID controller produces as a result from the coupling. The cascaded PID control for roll will remain.

15. Simulation-Based Validation

This chapter presents the simulation environment developed to evaluate the trajectory planner under higher-fidelity conditions than those assumed during trajectory generation. Section 15.1 motivates the simulator and defines its goals. Section 15.2 describes the software architecture. Section 15.3 presents the physics model used, including the assumptions made. Section 15.4 presents the results of running the planner’s generated trajectories through the simulator, analysing cable tensions and system oscillations under more realistic conditions. Section 15.5 demonstrates the compliance of relevant requirements, which are listed in Table 15.1. Section 15.6 discusses future recommendations.

Table 15.1: Requirements relevant to the Dronado simulation developed by the team.

ID	Requirement
SYS14-NAV07	The path planner shall maintain drone separation above 7 m between drone CGs during flight operations without wind gusts.
SYS14-NAV15	The path planner shall generate collision-free trajectories for 3 to 5 drones across all flight phases, respecting the performance constraints of every drone.
SYS09-NAV12	The drone controller shall ensure drone stability during all nominal operational phases.

15.1. Simulation Goals

The trajectory optimiser operates under a simplified system model that prioritises development simplicity over physical fidelity. Cables are modelled as rigid, the payload is represented as a single point mass, and no external disturbances are considered. While these simplifications are necessary to keep the optimisation problem understandable, they omit dynamics that are present in the real system and that may significantly affect mission feasibility.

The simulation environment is developed to address this gap, introducing spring-damper cable dynamics, wind disturbances, and a double-pendulum payload model in which the connector and the 50 kg payload are modelled as two separate masses linked by a cable. The overarching goal of the simulator is to validate that the planned trajectories are feasible under more realistic conditions than those assumed during optimisation. Four metrics are used to evaluate performance: tracking error per drone, control forces, cable tensions, and inter-drone distance. The last of these is the most critical for safety, since it represents the collision risk.

Validation: Trajectory

The simulation validates whether trajectories generated under simplified assumptions remain feasible under more realistic physics.

15.2. Simulation Architecture

The simulation is implemented in Python, chosen for its suitability for agent-based development, rich scientific and visualisation libraries, and familiarity to the development team.

The architecture is built around four classes: `Drone`, `Cable`, `Payload`, and `DroneController`, each responsible for maintaining and updating its own state. `DroneController` is owned by the `Drone` class, reflecting the physical reality that each drone operates its own controller independently. This agent-based decomposition keeps the system modular, making the simulation easier to extend or modify in future iterations.

These objects are initiated and coordinated by a central file, which drives the simulation loop at a fixed time step. At initialisation, reference trajectories per drone are loaded from a CSV file and used both to set the

initial positions of all agents and as the tracking targets for the controllers throughout the simulation. In the main loop, the physics module computes all external forces acting on the system: weight, aerodynamic forces, cable tension, and normal forces on the floor. Each drone's controller computes an force in 3D using a PID controller, with saturation limits per direction to reflect the physical thrust constraints of a fixed-wing drone. These forces are then combined into a net force per agent, which is used to update the states, integrated forward in time. After the loop completes, the recorded output variables are passed to visualisation functions for further inspection. The code flow is illustrated in Figure 15.1.

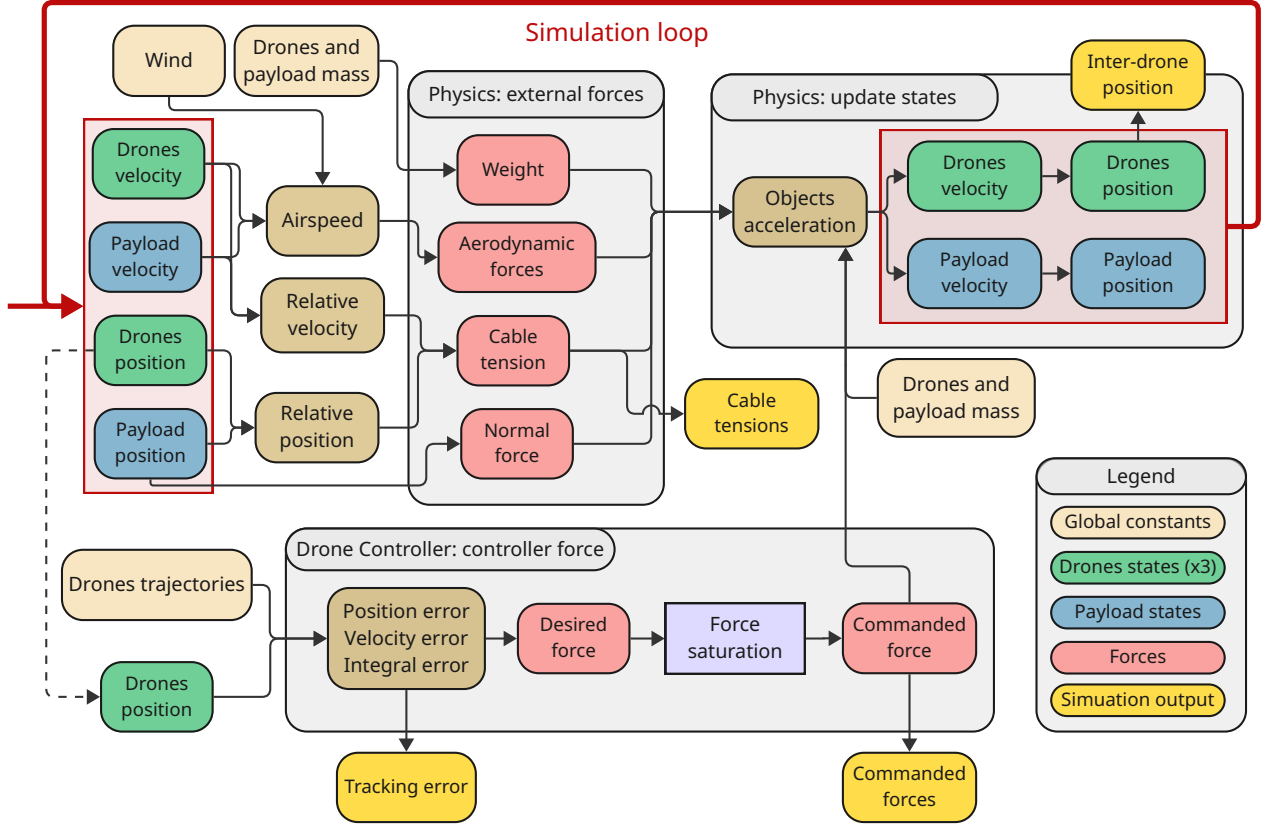


Figure 15.1: Simulation data flow

15.3. Simulation Physics Model

The simulation implements several physical models across three areas: dynamics, environment, and control. In the next paragraphs these areas will be explained.

Dynamics

Each drone and the payload are modelled as point masses with 3 degrees of freedom, capturing translational motion in three dimensions. This level of fidelity is sufficient for assessing trajectory feasibility and inter-agent safety, while not needing to incorporate complex rotational dynamics.

The drones and payload are connected by spring-damper cables. Each cable applies a tensile force only when taut, producing no force in compression. The tensile force has two components: a spring term proportional to the cable extension, and a damping term proportional to the relative velocity along the cable axis, which has an energy dissipation effect without requiring flexible-body formulation. The formulation for the tension in the cable T_c is given by

$$\mathbf{T}_c = \begin{cases} -k (\|\mathbf{r}\| - L_0) \hat{\mathbf{r}} - d (\mathbf{v}_{rel} \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}}, & \|\mathbf{r}\| \geq L_0 \\ \mathbf{0}, & \|\mathbf{r}\| < L_0 \end{cases}$$

where k is the cable stiffness, c is the damping coefficient, L_0 is the cable unstretched length, $\mathbf{r}$ is the relative

position vector of the connected elements, and $\mathbf{v}_{rel}$ their relative velocity vector [76].

Environment

The aerodynamic model accounts for lift and drag forces acting on each drone. In addition, four wind models are available to introduce atmospheric disturbances: a constant wind vector, a random gust model in which gusts of fixed duration are triggered stochastically at each time step, a sinusoidally oscillating wind, and a turbulence model. For our system, the turbulence model and constant wind modelling are the most relevant.

The turbulence is modelled as a zero-mean Ornstein-Uhlenbeck processes, one per spatial axis. Given a simulation time step Δt , each axis is updated via the exact discrete transition [77]

$$\mathbf{w}_{k+1} = e^{-\Delta t/\tau} \mathbf{w}_k + \sigma \sqrt{1 - e^{-2\Delta t/\tau}} \boldsymbol{\eta}_k, \quad \boldsymbol{\eta}_k \quad (15.1)$$

where $\mathbf{w}_k$ is the wind vector at step k , τ is the correlation time controlling how slowly the wind varies, σ is the standard deviation of the wind speed, and $\boldsymbol{\eta}_k$ is a random vector at each time step.

Control

Control is handled by a PID controller that tracks the imported per-drone reference trajectories. Because the drone dynamics are modelled as a 3-DoF point mass, the controller outputs a resultant force vector directly rather than attitude commands. To increase controller fidelity, force limits are enforced in the drone's body frame, defined by the current velocity direction, with separate saturation limits applied to the forward, lateral, and upward components to reflect the asymmetric force authority of a fixed-wing platform. The forward limit is set to the maximum thrust force of the hardware design. The lateral limit is derived from the lift generated at cruise speed, assuming a maximum bank angle of 30° , since a fixed-wing aircraft can only generate lateral force by rolling. The upward limit is set to 1.5 times the cruise lift force, approximating the additional normal force a drone could generate by increasing its angle of attack which cannot be captured directly in a 3-DoF model but is accounted for through this ceiling.

Assumptions

These models introduce a set of simplifying assumptions, listed with their expected effects in Table 15.2.

Table 15.2: Simulation assumptions.

ID	Assumption	Effect
A-SIM-1	Fixed time-step numerical integration is used.	Introduces integration error. Reliability degrades for dynamics whose characteristic frequencies approach the inverse of the time step.
A-SIM-2	Model parameters are known and constant.	Eliminates parameter uncertainty; results are only valid where parameter variation is negligible.
A-SIM-3	Constant aerodynamic coefficients.	Valid only within the linear aerodynamic regime.
A-SIM-4	Gravitational acceleration is constant.	Negligible effect below 1 km [78].
A-SIM-5	Battery discharge is not modelled.	Simulation is not valid for missions approaching battery limits.
A-SIM-6	Rotational dynamics are not modelled.	Attitude coupling and actuator saturation due to attitude control cannot be assessed.
A-SIM-7	Drones and payload are modelled as point masses.	Neglects geometry-dependent effects and cable attachment offset.
A-SIM-8	Cables are massless linear spring-damper elements.	Valid for cable lengths and loads within the elastic regime [76].

Continued on next page

ID	Assumption	Effect
A-SIM-9	Wind modelled as a change in effective velocity. No aerodynamic interaction between drones.	Wake and downwash effects neglected. Results are unreliable when drones operate close, where aerodynamic interference between drones becomes non-negligible.
A-SIM-10	Sensor measurements are not modelled.	Results are unreliable for assessing closed-loop performance under realistic sensing conditions.
A-SIM-11	Drone thrust is commanded directly with no actuator dynamics.	Unreliable for transient manoeuvres requiring rapid thrust changes.

15.4. Simulation Results

Discrepancies between the simplified models used during trajectory design and the higher-fidelity simulation environment expose limitations and inform iterative improvements to both the trajectory planner and the control strategy. The results presented in this section are a direct consequence of the physics gap inherent in the design process.

15.4.1. No-Wind Conditions

Observed Issues and Design Iterations

Initial simulation runs under no-wind conditions revealed several issues emerging from the interaction between the cable flexibility model and the trajectory design.

The first issue identified was the effect of cable flexibility on inter-drone separation. With cable tensions of approximately 500 N and a stiffness of 1000 N m^{-1} , the resulting elongation is around 0.5 m. Combined with strict hardware limits, this caused the inter-drone distances to drop below the safety threshold. This is particularly concerning during the transition manoeuvres, where the trajectories rely on tight turns and the drones are already close. These simulations revealed that any deviation from the planned trajectory significantly increases the risk of collision, a scenario the trajectory planner does not explicitly account for, as it only enforces absolute inter-drone distance constraints.

Cable flexibility also introduced system-level oscillations. The high accelerations during the transition phase cause energy to be stored in the cables, which is subsequently released during cruise as oscillations parallel to the flight direction. These are eventually damped by aerodynamic drag and remain on the order of 1 m to 3 m relative to the drone positions. More concerning are the oscillations arising during the transition from cruise to spin-down, where strong payload deceleration drives large cable tensions and energy accumulation. In this phase, oscillation amplitudes reach 5 m to 10 m. The primary concern here is the lack of payload position control, which introduces significant uncertainty in the landing footprint. However, inter-drone distance plots over the same interval remain large with little to no risk of inter-drone collision.

Key Result: Coupling Dynamics Simulation

Cable flexibility introduces risks not captured by the rigid-cable trajectory planner:

- inter-drone separation violations due to cable elongation and tight turns
- large payload oscillations during phase transitions

inter-drone separation violations due to cable elongation, and large payload oscillations during deceleration. Trajectory feasibility must therefore be evaluated against the flexible-cable dynamics, particularly during the transition phases..

These problems were communicated to the design team, which subsequently revised the trajectory design to mitigate the observed issues.

Finally, a controller concern came from the inclusion of the double-pendulum payload dynamics. Initially, this introduced large deviations from the planned path. However, appropriate tuning of the force controller gains eliminated the severe oscillations. As noted in Section 14.2, the controller is highly sensitive to the assigned weighting parameters, and this sensitivity is compounded by the fact that the optimal weights vary with the

system dynamics. Tuning the controller for a single drone and assuming transferability to the full multi-drone system is not sufficient. The controller must be tuned for the fully coupled system, since an otherwise valid configuration can become dynamically infeasible when the coupled dynamics are not accounted for during the tuning process.

Simulation Results

After the above-mentioned issues were mitigated through design iterations, the no-wind simulation results are presented below.

In general, the drones track the reference trajectories well throughout most of the flight envelope. A large tracking error spike remains visible at the transition from cruise to spin-down, however, as discussed above, the trajectory was modified such that errors of this magnitude do not pose a collision risk, as confirmed by the inter-drone distances during this phase. The payload deceleration-induced oscillations are also still present during spin-down, though their amplitude has been reduced to 2 m–3 m, significantly less severe than the 5 m–10 m observed prior to the design iterations. Some minor residual oscillations are visible during other flight phases, which could likely be reduced with further control gain tuning. These residual oscillations are also reflected in the control force profiles. The diagram further shows that, despite some peaks, the controller is able to track the trajectory with relatively modest control inputs throughout the manoeuvre.

Finally, the cable tensions remain slightly above the planned value of 700 N, reaching a peak of approximately 850 N, but remain well within the structural failure threshold of 5600 N.

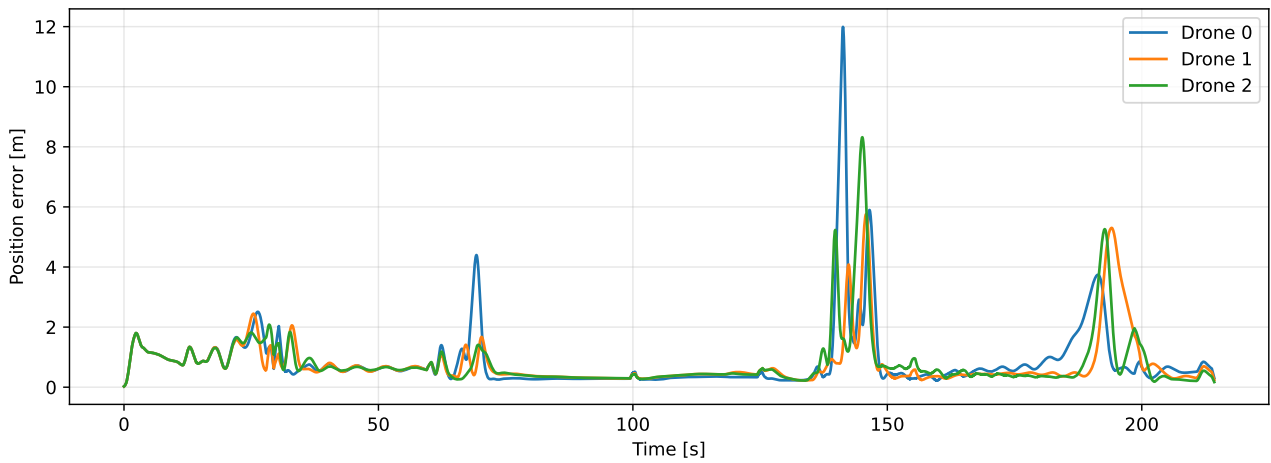


Figure 15.2: Trajectory tracking error in simulation under no-wind conditions.

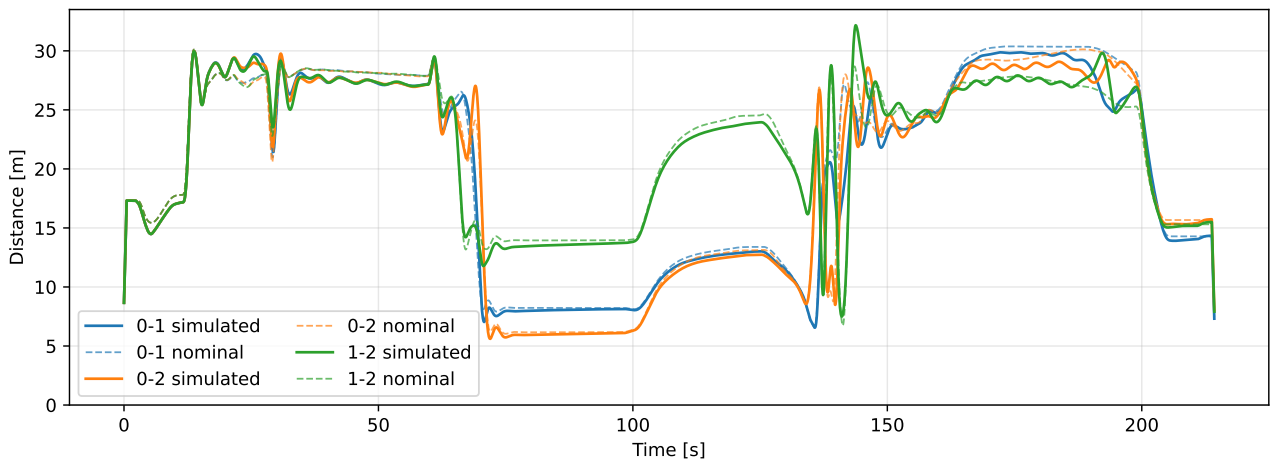


Figure 15.3: Inter-drone distances in simulation under no-wind conditions.

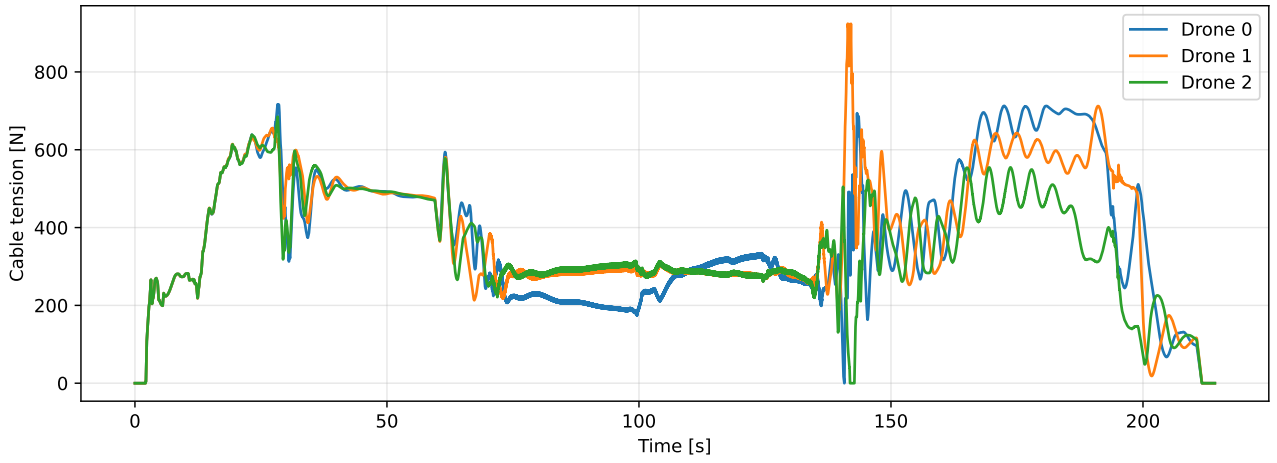


Figure 15.4: Cable tensions in simulation under no-wind conditions.

Wind conditions

Under wind conditions, before the trajectory redesign, several of the issues observed in the no-wind case were significantly exacerbated, with inter-drone distances dropping below 0.5 m. Following the redesign, the system is capable of maintaining a safe inter-drone distance despite of the increased tracking error due to the wind.

Two representative cases from the range of experiments conducted are presented here. The first is a constant crosswind of 10 m s^{-1} perpendicular to the cruise direction. The second is a turbulent wind field generated according to the model presented in Equation 15.1, with parameters $\tau = 2$ and $\sigma = 3$, which produced a peak wind speed of 12 m s^{-1} during the simulation. The results for both cases are shown in Figure 15.5 and Figure 15.6. The strength of the wind was increased until the drone distance dropped below 4 m, which resulted in $\sigma = 6$ and a maximum recorded wind speed of 27 m s^{-1} .

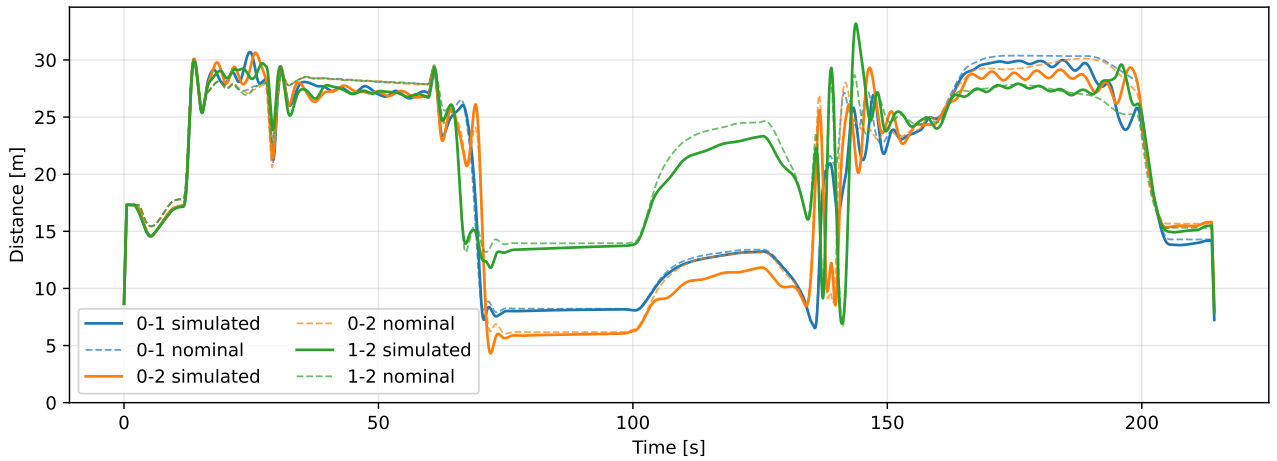


Figure 15.5: Inter-drone distances under constant crosswind of 10 m s^{-1} .

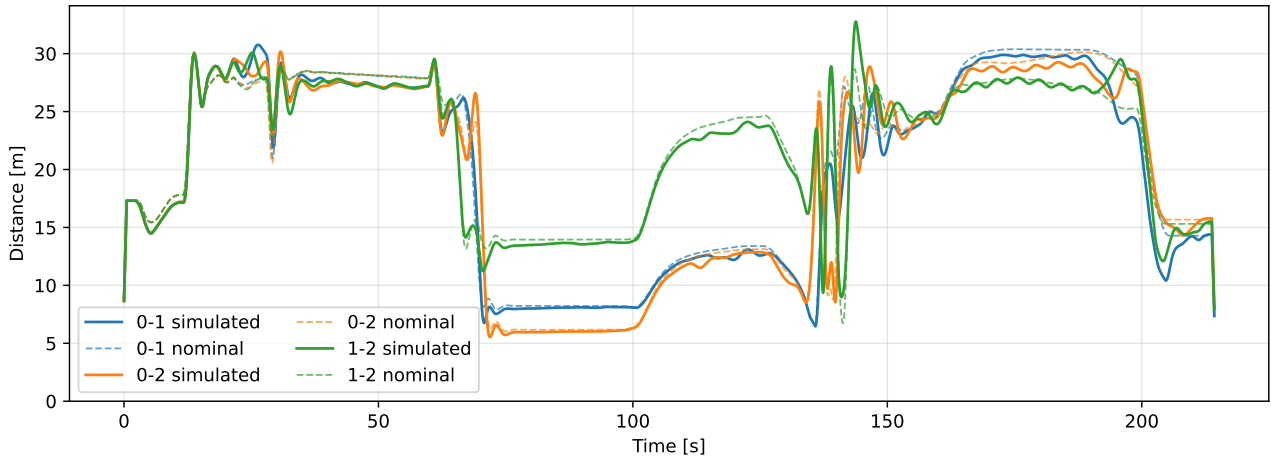


Figure 15.6: Inter-drone distances under turbulent wind conditions with peak wind speed of 12 m s^{-1} .

15.5. Compliance

Table 15.3: Trajectory planner validation results.

ID	Requirement	Status
SYS14-NAV07	Inter-drone separation remains above 6 m throughout all nominal flight phases in both no-wind and wind conditions, as confirmed by the distance plots in Section 15.4.	✓
SYS14-NAV15	The trajectory planner generates collision-free trajectories for the full drone swarm across all flight phases, respecting individual drone performance constraints, under both no-wind and wind conditions.	✓
SYS09-NAV12	The drone swarm remains stable throughout all nominal operational phases.	✓

15.6. Future Recommendations

Two main directions are identified for future development of the simulation environment.

The first is an increase in simulation fidelity. The current model does not account for rotational dynamics of the drones, which represents the most immediate extension. Beyond this, additional disturbance and modelling elements can be progressively incorporated, including sensor measurement noise and an Extended Kalman Filter (EKF) for state estimation, energy consumption modelling, and propeller RPM dynamics among others. Each of these additions would narrow the physics gap and increase confidence in the simulation results.

The second direction is integration with the rest of the software, including trajectory planner and controller. Adding the trajectory planner onto the simulator would allow onboard computing capabilities to be assessed under realistic conditions. Integration with the controller would enable end-to-end testing of the full system autonomy. Together, these integrations would allow the complete system design to be validated in a single simulation environment. However, this increased scope also introduces significant software complexity, and careful interface design between subsystems will be necessary to keep the integrated simulator maintainable.

16. Verification and Validation

Verification and validation are an essential part of any engineering project. Verification confirms that the system has been built correctly according to its requirements, and validation ascertains that the system has been built to the client's expectations.

This chapter explains how verification and validation were carried out throughout the DSE time frame. As this is conducted at many stages throughout the design process, an overview is given. The commercially available and custom software tools used were evaluated with the methodology detailed in Section 16.1. Requirements were verified following the strategy detailed in Section 16.2. The system was validated adhering to the approach described in Section 16.3. Any tasks that could not be performed within the DSE time frame, for example because they required real-world testing, are indicated by .

16.1. Software Tools and Models

The verification and validation efforts are not only limited to the developed system, but also encompass the tools and models used during the design process. This is crucial to ensuring that the results are trustworthy and reliable, and can be confidently presented to the stakeholders. An important distinction is that the tools developed by the team require a much more in-depth verification effort than existing off-the-shelf software solutions.

16.1.1. Commercial Software

Verification

The main software tools were simulation tools for aerodynamic design: XFOIL and XFLR5. These share a common operational pipeline that can be roughly divided into the following steps: importing the geometrical model, meshing, choosing an appropriate model and solver, and visualising and interpreting the results. As such, a common verification framework was followed:

1. **Geometry verification.** Ensuring that the geometrical model was correctly imported into the simulation software, checking whether boundary geometry is correctly labelled.
2. **Mesh quality check.** Quantifying the mesh quality based on established metrics (skewness, shape distribution, etc.).
3. **Convergence monitoring.** Ensuring that the error progresses without unwanted oscillations or divergence.
4. **Test of solver on a benchmark case.** Whenever possible, checking the chosen solvers accuracy for a simpler test case where an analytical solution or experimental data are available.
5. **Boundary condition compatibility.** Checking whether the simulation results comply with prescribed boundary conditions.
6. **Conservation properties.** Checking whether expected conservation properties (energy, mass) are fulfilled.
7. **Mesh convergence study.** Verifying whether the error decreases at an expected rate with mesh or time step refinement.
8. **Check order of magnitude of results against simpler methods.** Whenever possible, checking the order of magnitude of the results against the results coming from a tool of lower fidelity.
9. **Visual inspection of results.** Visualising the results and ensuring that observed trends match the expected behaviour.

Validation

The validation process established whether the predictions made using the software tools were applicable and within an acceptable error range within the parameter domain of the considered problem. As such, the main

assumptions and their implications were considered per software tool.

XFOIL implements a potential flow panel method with an integral boundary layer formulation [79]. It can predict viscous flow behaviour, and the compressibility effects can be predicted reliably up to sonic conditions using the Karman-Tsien correction. A limitation of the software is that it does not predict the behaviour of separated flow. As such, it is only reliable up to stall.

XFLR5 implements a potential flow panel method in three dimensions. However, it does not implement any additional modelling of viscous and boundary layer effects. The viscous drag is only estimated based on interpolating two-dimensional viscous drag from XFOIL results, which XFLR5 calls. This means that only its order of magnitude can be predicted. This leads to systematic underestimation of viscous drag and thus an overestimate of aerodynamic efficiency. As viscous effects are not reliably predicted, XFLR5 was only used for low Reynolds flows¹.

For each software tool, analysis was performed using the following steps:

1. Document the parameter regime of the planned simulation.
2. Check whether the simulation tool is feasible to use for the chosen regime.
3. If possible, find literature supporting simulation tool performance on comparable test case.
4. Establish an acceptable error level.
5. If available, compare order of magnitude of results against simpler model.
6. Quantify the error in the result.

16.1.2. Custom Software Tools

Verification

The verification effort for software tools developed from the ground up is considerably more than for commercial software, which has already been extensively tested. The steps used to perform verification for the code followed the hierarchy of unit, subsystem and system-level tests.

Unit Tests

- **Verification of implementation consistency with the underlying mathematical formulation.** Code implementations are validated by comparing the implemented logic against the analytical models and equations from which they are derived. An example is the verification of Hooke's law implementation within the cable dynamics model.
- **Verification of mathematical implementations through analytical hand calculations.** Done with emphasis on validating nominal, limiting, and edge-case conditions. Examples include evaluating the cable model under zero elongation, near-zero length, static equilibrium, and varying angular and extension conditions.
- **Verification that parameter variations result in physically consistent and expected system responses.** An example is confirming that increasing cable elongation produces a corresponding increase in cable tension.

Subsystem Tests

- **Verification of physically consistent coupled behaviour.** Outputs of each subsystem are assessed against expected physical trends and engineering intuition. Examples include the relationship between payload mass and required wing area, or between cable dimensions and drone-payload separation distance.
- **Verification of boundary-condition preservation.** The integrated simulation is tested to ensure that subsystem interactions do not violate predefined physical or operational limits, such as actuator deflection bounds, structural constraints, or cable stress limits.

¹URL <https://www.flow5.tech/xflr5/xflr5.html> [accessed 21.05.2026]

- **Integration visualisation and geometry inspection.** Visualisation tools are used to qualitatively verify that the integrated system geometry, relative positioning, and mesh or discretisation resolution conform to the specified model parameters and assumptions.
- **Sensitivity analysis of integrated behaviour.** The robustness of subsystems is evaluated by varying selected parameters and assessing whether the overall behaviour remains stable and physically plausible. Examples include controller performance under parameter perturbations or changing environmental conditions.

System Tests

- **Sensitivity analysis of system-level behaviour.** Done through variation of key parameters to assess the robustness and stability of the integrated simulation under changing conditions.
- **Solver convergence verification.** Ensure numerical stability and consistency of the simulation results with varying solver settings, discretisation levels, or integration time steps.

Validation

For custom codes written in the scope of the project, the validation process must also be performed. This process can differ from the one established for the external software tools, because the planned software will have much wider applicability than only aerodynamic simulation. The validation process must clearly establish the physical scenarios in which the software gives applicable predictions and how reliable these predictions are.

The validation of the final version of the software is not be feasible in the scope of the DSE, since there is not sufficient experimental data available for comparable systems. The validation process for a certain software component can be carried out in the following steps:

1. Establish assumptions for the implemented physics model.
2. Define the validation domain.
3. Quantify the error introduced by the assumptions.
4. Quantify uncertainty introduced by the assumptions.
5. Establish an acceptable error level.
6. Establish an error metric for the comparison with benchmark data.
7. Compute error between code result and benchmark data.
8. Perform statistical analysis on error variability.

16.2. System Verification

This section is concerned with verifying all requirements. These can be verified in a number of ways, namely, inspection, analysis, simulation, and testing. Requirements were verified following the V-model, starting from subsystem requirements, then system requirements, mission requirements, and finally stakeholder requirements. Some requirements may be verified in multiple ways, depending on the stage of the design. Many requirements were verified through analysis and simulation during the DSE time frame, which is concerned with system design. All requirements will be verified by inspection or testing after the DSE is complete , when the project progresses from design to manufacturing.

16.2.1. Inspection

Some requirements can be verified simply through inspection. These include simple mass and dimension measurements as well as measurements to confirm commercially-purchased components meet specifications. Inspection methods can include weighing, measuring dimensions with a ruler/protractor, and using a power meter.

16.2.2. Analysis

Requirements relating to system thrust, power, mass, and dimensions were verified by analysis, with calculations or mathematical models predicting whether the requirement met its specification. This involved the use of hand

calculations, physics-based models, common engineering theory for structures, etc. These requirements will be verified in real-world tests to establish confidence in the system.

16.2.3. Simulation

Requirements relating to system aerodynamics, control and stability, path planning, and operations were verified by simulation. This approach is cost-effective and risk-free, providing a safe environment to prove design concepts in the Dronado system. These requirements will be verified in real-world tests to establish confidence in the system.

16.2.4. Test

When possible, each requirement should be verified by testing, as this verification method best represents real-world conditions and thus demonstrates the highest level of confidence. All test facilities detailed below are available to students at TU Delft, and therefore to the design team.

Some testing procedures may require certification of personnel and/or certification of the system. Tests also have additional costs associated with possible crashes and subsequent repairs. This varies for different crash severities. These aspects affect time and cost budgets, and require further conversation with the client before proceeding.

Indoor Testing for Electronics, Telecommunications, and Structural Systems

Electrical and power requirements require minimal equipment for testing, such as a multimeter. This can be found in TU Delft's Aerospace Faculty's Instrumentation Lab or MAVLab and can be used for free by TU Delft staff and students. These facilities do not have waiting times and can be utilised during working hours by the design team with no waiting period.

Telecommunication requirements do not require specialised equipment for testing, and therefore no specific testing facility. Most requirements can be tested in any space. However, SYS26-COM02 requires a distance of 20 km to verify that the operators can establish a datalink for the system in cruise. This can be done by two members of the team travelling 20 km apart to separate the onboard computer from the ground station.

Most of the structural and mechanical requirements can be verified at TU Delft's Aerospace Faculty's Mechanical Testing Lab. This facility does not have waiting times, and can be utilised during working hours by the design team with no waiting period.

Indoor Testing for Individual Drones

The control of individual drones can be tested in TU Delft Aerospace Faculty's CyberZoo, an indoor test location of size 10 m by 10 m by 7 m and equipped with an Optitrack (indoor GPS) system.² Individual drones should first be tested in the CyberZoo to verify their stability and control in hover. Once this has been achieved, their performance in a wind tunnel can be verified. Testing should not be conducted immediately in a wind tunnel, as the waiting period is longer and the availability is more restricted, limiting the testing schedule.

Dr.ir. Ewoud Smeur explained that the CyberZoo is free for TU Delft staff and students. This facility has limited waiting time, but is frequently in use. Thus, organisation with other users must be organised. Therefore, regular testing is possible at the CyberZoo, making it suitable for primary testing of individual drones.

Wind Tunnel Testing for Individual Drones and Payload

Many requirements related to the aerodynamic performance, control and stability of individual drones can be tested in a wind tunnel. While testing these parameters for the whole system in a wind tunnel would also be beneficial, wind tunnels accessible to the team are not large enough to test the whole system. Testing should be done in TU Delft's Open Jet Facility, a low-speed wind tunnel of size 8 m by 13 m with a maximum velocity of 35 m s^{-1} .³ This facility is large enough to separately test individual drones and the payload, and provides enough airspeed to test the 20 m s^{-1} stakeholder requirement STK02.

²URL <https://www.tudelft.nl/lr/organisatie/afdelingen/control-and-operations/facilities/drone-facilities/cyberzoo> [accessed 18.05.2026.]

³URL <https://www.tudelft.nl/lr/organisatie/afdelingen/flow-physics-and-technology/facilities/low-speed-wind-tunnels/open-jet-facility> [accessed 18.05.2026.]

Dr.ir. Ferdinand Schrijer, the Scientific Director of TU Delft's Aerospace Engineering Faculty's Flow Physics and Technology Department⁴ detailed that commercial rates for access to the Open Jet Facility are around 5000 EUR per day (without technical assistance). Standard test campaigns range from one day to two weeks, and require at least a few weeks of preparatory work. Additionally, the Open Jet Facility is fully booked until the beginning of February 2027. It should be noted that this facility is free for TU Delft staff and students. Due to the limited availability and significant preparatory time, the control and stability characteristics should be tested in the CyberZoo. However, due to the size of the drone, testing the fixed-wing flight characteristics is not feasible in the CyberZoo. As such, the CyberZoo only facilitates testing the hover flight mode. The fixed-wing flight will need to be tested at a larger, outdoor site. The requirements tested at the wind tunnel should only focus on wind conditions and aerodynamic performance, as testing other requirements is not feasible with the time available to use the facility. Furthermore, testing can be organised with another research group, such that each team can test during the other team's downtime.

System Ground Testing 🏠

Most requirements should be tested in real-life conditions. In this way, the requirements can be verified in conditions most similar to operating conditions. In collaboration with Unmanned Valley Valkenburg, TU Delft can conduct outdoor tests in Valkenburg.⁵ This is a 25 ha outdoor space, the largest UAS test field of the Netherlands, and it provides a large enough area to test the full Dronado system in real-life conditions.⁶

Dr.ir. Ewoud Smeur described that Valkenburg costs 500 EUR per month for twelve test slots, each lasting two hours. Valkenburg must be reserved one day in advance, and typically is available on short notice. This makes this testing facility accessible for testing, but tests should be particularly planned to limit costs. Still, Valkenburg will be the main testing facility of the entire Dronado system.

16.3. System Validation: Customer Assurance

In addition to verifying that the system was designed correctly, it must be confirmed that the correct system was designed for the client, i.e. that the design is validated. To achieve this, weekly meetings were held with the client to discuss concerns and receive continuous feedback. This enabled the team to make timely adjustments to the design, rather than having to make major redesigns once the final design is already defined.

To prove that the final design fulfils the client's wishes, the team will hold a meeting with the client to formally present the final design. This consists of an overview of the entire design, detailed design of subsystems, subsystem integration, simulations of manoeuvres, and evidence that the design is feasible. The design's limitations, operational constraints, requirements, functions, performance, abilities, costs, scheduling, risks, compliance with regulations, testing plan, and compliance with sustainability factors 🌱 will also be communicated in detail. The client's satisfaction is the first step of validating the design. The satisfaction of other stakeholders, such as customers of the system, is also important, as is testing to ensure that Dronado performs its delivery task as expected.

This approach follows the V-model, where smaller components are validated in weekly meetings before the final system is validated in the final presentation. This is a time- and resource-effective method of validation which avoids costly redesign.

⁴URL <https://www.tudelft.nl/en/ae/organisation/departments/flow-physics-and-technology/facilities/people> [accessed 18.05.2026.]

⁵URL <https://www.tudelft.nl/lr/organisatie/afdelingen/control-and-operations/facilities/drone-facilities/valkenburg> [accessed 18.05.2026.]

⁶URL <https://unmannedvalley.nl/> [accessed 18.05.2026.]

17. Critical Design Analysis

The 10-week time frame of the DSE allows for simulations of the Dronado system, but it does not allow for the actual prototyping and flying of the system. As such, it is important to critically assess the design and how it could be realised into a physical system. This chapter details the two main challenges: onboard computational effort and time constraints presented in Section 17.1 and legal considerations in Section 17.2. Section 17.3 also addresses compliance with relevant requirements, presented in Table 17.1.

Table 17.1: Requirements relevant to system certification.

ID	Requirement
STK10	The system shall achieve an acceptable ground risk for operation over populated areas according to applicable EASA standards.
STK22	The system shall comply with applicable aviation regulations for unmanned aerial operations.
STK23	The system shall comply with applicable requirements for operation over populated areas.
STK24	The system shall comply with applicable wireless communication regulations.
STK25	The system shall comply with applicable sustainability regulations.

17.1. Onboard Computational Effort and Time Constraints

The trajectory planner developed within the DSE demonstrates the feasibility of an optimisation-based control approach for calculating individual drone trajectories. As explained in Chapter 13, the trajectory planner computes entire trajectories for each drone using a receding-horizons control strategy with the CasADi optimiser on a laptop equipped with an Intel Core i7 CPU. While these precomputed trajectories can be used to successfully transport the system, they do not allow for obstacle avoidance of aerial obstacles such as power lines and birds. Additionally, the trajectory planner does not take into account time delays for receiving state data, nor does it impose a computing budget comparable to the selected flight computer. Hence, the implementation of the trajectory planner needs to be considered in more detail.

One option is to keep the trajectory planner onboard the system, utilising the onboard computer of a drone to compute all trajectories. This allows for fast exchange of sensor data, leading to quick system responses using the most up-to-date data. This leads to more precise trajectories as well as faster reactions to perturbations. On the other hand, the onboard flight computer only has a small computing budget that needs to be modified for the trajectory planner's high computing demands. The trajectory planner's optimisation algorithm will need to be made more efficient, and possibly less effective, to satisfy this.

Another option is to move the trajectory planner to the ground station, where the system sends data to the ground station, and the ground station processes this information and sends back individual drone trajectories. The ground station has much more computing capacity than the onboard computers, allowing for a faster and/or more accurate result. However, it has slower access to real-time data, explained in Section 11.1. With higher latency, the ground station might need to estimate the system states of the drone and payload instead of using directly measured values, due to the delay-induced mismatch between measurement time and actual system state. Higher latency might also limit throughput data, leading to constraints on the number of states the trajectory planner could use in its optimisation process¹.

¹URL <https://www.fortinet.com/resources/cyberglossary/latency> [accessed 12.06.2026]

Another issue with having the ground station perform trajectory planning is that the system is susceptible to communication blocks, for example, from electromagnetic signal interference of high-voltage power lines or obstacles such as trees or buildings blocking the ground station's line-of-sight². By considering the Earth's curvature, at a 20 km range, the vertical line-of-sight drops by 30 m, further complicating the communication link. If the communication between the ground station and aerial system were to be severed, some degree of autonomous control would need to be in place to handle this. This would necessitate controller development that might be similar to an onboard trajectory planner controller, taking the design back to the previous option.

Design Decision: Onboard or Ground Computing for the Trajectory Planner

An onboard trajectory planner has more up-to-date data to generate more precise trajectories and respond to obstacles quickly. However, it has limited computing resources to run optimisation-based control for individual drone trajectories.

A ground station-based trajectory planner suffers from lag and more restricted data rates, impeding the system's precise trajectory generation and quick response to obstacles. Communication failure would necessitate a controller similar to the onboard trajectory planner. Conversely, it has a much larger computing budget for optimising trajectories.

While a potential ground station trajectory planner would have more computational power, for now an onboard flight computer is selected to remain as the trajectory planner, since the shortcomings in this option's computing budget can be accommodated. Its advantages in using the most up-to-date information also establish this option as the best for trajectory generation and collision avoidance. To achieve on-board real-time computing, both the efficiency of the trajectory planner's optimiser (see Section 13.9 and the computing power of the onboard computer must be addressed.

Sun [1] demonstrated real-time multi-aerial collaborative carrying with quadcopters was possible. He successfully showed real-time computing of individual drone trajectories, where a laptop with an Intel Core i7- 13700H acted as the trajectory planner and communicated trajectories to each drone using WiFi. He used a receding horizon approach and the ACADOS optimiser with a similar cost function as in Subsection 13.3.2. As fixed-wing UAVs are less manoeuvrable than quadcopters, they have more states, and more constraints are imposed on the fixed-wing UAVs of this project [20]. Antony [80] explains that computational time increases exponentially with the number of states and constraints. Therefore real-time computing becomes more challenging for Dronado's swarm of fixed-wing UAVs, in comparison to Sun's swarm of quadcopters with less states and constraints. As such, while Sun's successful real-time collaborative payload-carrying demonstration is promising for the feasibility of real-time trajectory computing for collaborative payload-carrying swarms, it does not confirm that fixed-wing UAVs will have the same performance as quadcopters for this application. However, he was able to calculate real-time trajectories for a maximum of nine drones without exceeding his computing budget: this is six more drones than the three drones of Dronado's swarm, and therefore encouraging for the Dronado system.

Madabushi et al. [81] demonstrated online computation of trajectories for three fixed-wing UAVs using receding-horizon NMPC, with hardware experiments showing collision avoidance between obstacles and drones. Similarly to the trajectory developed in Chapter 13, this paper also makes use of a multi-objective cost for tracking, energy, smoothness, etc. This paper supports the feasibility of online fixed-wing trajectory computation by solving the optimisation problem with SNOPT [82], an alternative NLP solver to the current IPOPT being used in the trajectory planner (Section 13.4). Furthermore, their implementation uses Hermite-Simpson integration [83], while the current trajectory planner makes use of backward Euler, explained in Section 13.3. However, their planner method differs from this work, since they use decentralised planing, un-coupled vehicles and there are no cables present. This paper serves as evidence that online fixed-wing NMPC is feasible and alternative numerical choices, such as SNOPT and Hermite-Simpson may be considered for future improvements.

The trajectory planner of Chapter 13 computed 50 nodes in 2.5 s, and used five nodes before finding a new horizon. Each optimisation commits 0.25 s of the trajectory, which means the onboard computer would need to solve each NLP in less than 0.25 s and ideally with an extra margin. Figure 17.1 shows the CPU time to solve windows for each one of the mission phases. The time is around 1.2 s, with the VTOL phase around 2.2 s, and

²URL <https://help.dronedeploy.com/hc/en-us/articles/13808173367447-Why-does-my-drone-controller-lose-connection-during-flight> [accessed 12.06.2026]

some outliers showing much higher computational time. This graph demonstrates the unfeasibility for real-time computing, and therefore changes to the trajectory planner are necessary.

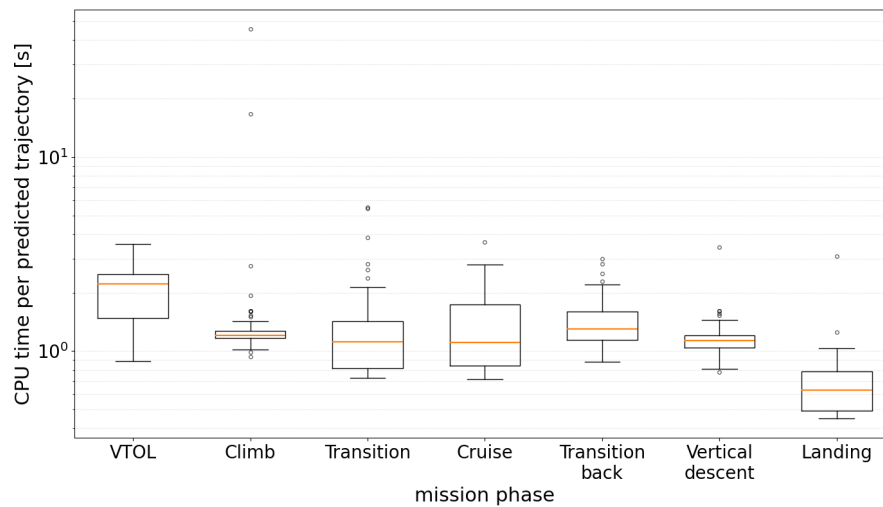


Figure 17.1: CPU time for each window solved by the trajectory plane per mission phase. All optimisation runs were performed on a laptop equipped with a 13th Gen Intel Core i7-13700H CPU. This was run for the case with three UAVs, with 50 horizon nodes. The vertical axis is in the logarithmic scale.

One improvement would be to use non-equidistant rather than linearly-spaced segments for the receding horizons, as done by Sun [1]. In this way, the nearest futures of trajectory predictions are weighed more heavily in the optimising function and increased in fidelity [1]. Further information is included to assist with long-term planning, but it does not dominate the optimising function. A smaller horizon can also be selected, using less nodes. Non-equidistant segments ensure that the horizon length is sufficiently large without sacrificing short-term fidelity [1]. A smaller horizon reduces computational effort, helping to achieve the computational budget.

Another improvement would be to utilise `acados` rather than `CasADi`. `acados` is a software package for solving nonlinear programs using an optimal control problem (OCP) structure⁵. `acados` is described to be optimised for high-frequency control loops⁵, which is suitable for predicting trajectories with sufficient speed. Furthermore, swarm trajectories have been successfully computed using `acados`, for example Sun’s [1] multi-aerial collaborative carrying (for a maximum of nine drones), Adajania et al.’s [56] quadrotor swarm in cluttered environments (for a maximum of twelve drones). This successful experimental proof of centralised planning of drone swarms establishes `acados` as a promising optimiser package for the Dronado system.

With more efficient trajectory horizons and the use of `acados`, the computational load of the trajectory planner will decrease. This addresses the current issue of the trajectory planner exceeding the computing budget for future development of the Dronado system.

Currently, obstacle avoidance is not planned. Additional sensors will need to be added to each drone to make this possible, such as a laser scanner, sonar, radar, LiDAR, or camera [84], impacting mass, cost, and power. Computing efforts will also increase. Quantifying this increase depends greatly on the sensor and obstacle-avoidance approach chosen [85]. With the Dronado system expecting to encounter few obstacles, a computationally inexpensive obstacle avoidance algorithm can be selected. For instance, Basnet et al. [86] demonstrates low computational-cost when using time-of-flight sensors for obstacle avoidance.

The trajectory planner's receding horizons control strategy is also appropriate for real-time obstacle avoidance, as obstacles can be taken into account with each new horizon. An onboard trajectory planner is best-suited for obstacle avoidance, as it has a faster response time than a ground station-based trajectory planner.

⁵URL <https://docs.acados.org/> [accessed 15.06.2026.]

Key Choice: Onboard Computing for the Trajectory Planner

The onboard trajectory planner is kept for the system design, because the trajectory planner's computational demands can be reduced to meet the limited computing budget. Solutions like a smaller horizon with non-equidistant segments and usage of an acados optimiser can achieve this.

17.2. Legal Considerations and Certification

Operating a multi-drone cargo system in European airspace requires compliance with a strict EASA regulatory framework [87]. No-fly zones, altitude ceilings, and restricted areas around airports, critical infrastructure and safe emergency landing sites must be integrated into the route planner.

Certification is a major open challenge [88]. Current EASA type certification standards are designed for single aircraft: No established regulations for cooperative multi-drone cargo configurations can be found yet. Precedents from the drone light show industry show that coordinated swarm approvals are possible³, but extending these to heavier systems with suspended payloads would require substantial additional work [60]. This problem would be worsened with expanding outside European markets and the subsequent coordination with foreign regulatory authorities. As such, this task is outside of the scope of the DSE.

Flight over populated areas is particularly constrained under EASA's specific category [88] due to the ground risk posed by a 50 kg payload. As the system will be targeted at remote place delivery operations, explained in Chapter 2, population density maps to route around densely inhabited zones could be a practical mitigation strategy [88]. The feasibility should be further examined for the long-term project viability.

Additionally, there are strict regulations surrounding the utilisation of radio frequencies. Some bandwidths are forbidden to use, for example for military purposes [89]. These prohibited frequencies are avoided by operating in the 2.4 GHz band, which makes these regulations met.

The sustainability regulations concern the systems environmental footprint, which is assessed in Chapter 24, as well as the sound pollution the system produces. The latter has been preliminary calculated to be below the level of regular truck in Section 9.4. Performance in both sustainability categories look promising, but shall ultimately be verified in the prototyping phase

Finally, cybersecurity risks must be considered too. The system's reliance on GNSS, mesh radio, and telemetry links makes it vulnerable to spoofing and jamming [90]. Mitigations such as cross-checking GNSS against UWB and IMU measurements, encrypted frequency communications and autonomous safe-landing procedures on communication loss should be addressed in a dedicated risk assessment as the design is further refined [90].

17.3. Compliance

Table 17.2: Drone controller compliance matrix.

ID	Means of compliance	Status
STK10	No unmitigated large ground risks are present, but system yet to be certified and tested	✗
STK22	No unmitigated large aerial operation risks are present, but system yet to be certified and tested	✗
STK23	No unmitigated large risks involving populated areas are present, but system yet to be certified and tested	✗
STK24	System does not operate on forbidden radio frequencies	✓
STK25	Preliminary calculations estimate the system to be largely sustainable, but system is yet to be certified and tested	✗

³URL <https://eudroneport.com/blog/drone-shows-get-right-permits/> [accessed 10.06.2026.]

18. Resource Allocation

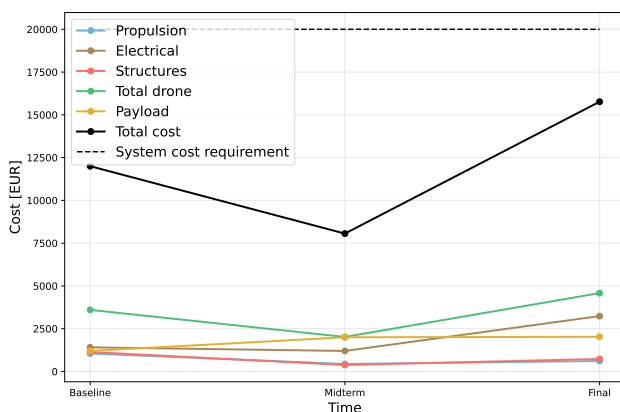
Resource allocation ensures that key resources remain within a certain threshold. This requires continuous evaluation, with uncertainties of each subsystem's resource use decreasing over time, leading to progressively more accurate predictions. This chapter explains the technical budget and its evolution of the driving resources of Dronado: cost and mass. Budgetary requirements are listed in Table 18.1 and their compliance is addressed in Table 18.4.

Table 18.1: Requirements relevant to system budgets.

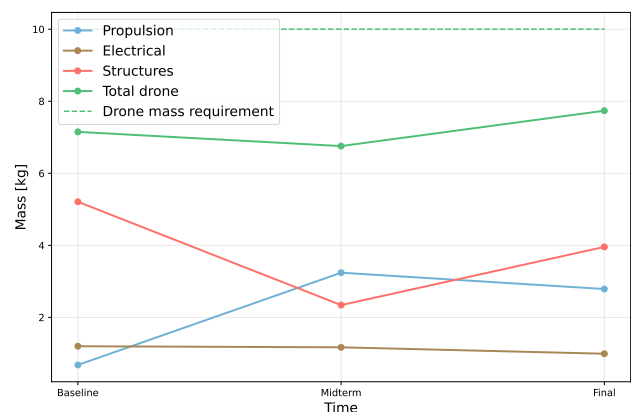
ID	Requirement
STK12	Each individual drone shall have a total maximum mass of 10 kg.
STK14	The total system parts cost shall be less than 20 000 EUR.
STK30	The system shall use commercially available components where technically feasible.
STK31	The system shall minimise reliance on single-source suppliers for mission-critical components.

Figure 18.1 shows the evolution of the cost and mass budgets over time, with the dashed black and red lines indicating the total allowable cost and total allowable drone mass respectively. It is clear that cost stayed within budget throughout the project, maintaining a sufficient margin. The total cost decreased between the baseline and midterm, showing that the initial cost estimate was more conservative. It increased between the midterm and the final, demonstrating a more detailed cost breakdown. Subsystem costs varied less, but generally increased from the midterm to the final.

Furthermore, the drone also stayed within its mass budget throughout the project, maintaining a sufficient margin. The structures and propulsion subsystems changed the most over time, while the electrical mass budget stayed mostly constant. Total drone mass stayed relatively constant, and always below 8.000 kg. Lighter drones make the system more efficient, as less mass has to be propelled by the propulsion system (SUS-1 🌱).



(a) Cost budget over time.



(b) Mass budget over time.

Figure 18.1: Evolution of cost and mass budgets over time.

Table 18.2 and Table 18.3 show the bill of materials for each drone and the entire system. The mass of each drone is 7.737 kg, allowing a 2.263 kg margin for developing the drone after the DSE. Similarly, the total cost for building the system is 15,768.14 EUR, giving a remaining 4,231.86 EUR contingency. It should be noted that 5 glass cloths are bought and included in the cost, but the fifth one will not be used fully and thus only

accounts for 410 g in the mass budget. Furthermore, the carbon plate will be cut into four ribs with the listed total mass, but the cost of the full plate is used.

Table 18.2: Single UAV bill of materials.

Component	Mass [kg]	Cost [€]	Qty.	URL
Propulsion				
MG UAV Solid-State LiPo Battery 13000mAh 12S	1.746	361.00	1	https://rcdrone.top/products/mg-uav-solid-state-battery-6s-12s-14s-13000mah-10c-f-or-heavy-load-long-endurance-uavs [accessed 21.05.2026]
VCI 4218 350KV FPV Motor	0.320	70.48	3	https://iflight-rc.eu/nl-nl/products/vci-4218-350kv [accessed 16.06.2026]
CAM Carbon Power-Prop 12x8	0.0273	12.90	3	https://natterer-modellbau.de/CAM-Carbon-Power-Prop-12x8 [accessed 21.05.2026]
Propulsion subtotal	2.788	611.14		
Structural System				
EPP Foam	0.938	143.95	1	https://www.epp-versand.de/ [accessed 16.06.2026]
Wing Spar Rod	0.441	127.18	1	https://www.carbonwebshop.com/carbon-fiber-tubes/industrial-performance-tubes/industrial-performance-tube-30x28x3000mm/ [accessed 21.05.2026]
Wing Aileron Rod	0.498	118.82	1	https://www.carbonwebshop.nl/carbon-fiber-buizen/industrial-performance-buizen/industrial-performance-buis-25x22x3000mm/ [accessed 12.06.2026]
Tail Boom Rod	0.720	161.33	1	https://www.carbonwebshop.com/carbon-fiber-tubes/industrial-performance-tubes/industrial-performance-tube-35x32x3000mm/ [accessed 16.06.2026]
HT Rods	0.033	14.05	2	https://www.hyperflight.co.uk/products.asp?code=CARBON-TUBE-10MM [accessed 12.06.2026]
VT Rods	0.005	4.19	2	https://www.hyperflight.co.uk/products.asp?code=CARBON-TUBE-5MM [accessed 12.06.2026]
Carbon plate	0.044	54.22	1	https://www.carbon-composite.com/en/Carbon-Plate-0.3mm/CP003-4 [accessed 12.06.2026]
Rod Connectors	0.140	17.98	3	https://cicloscorredor.com/en/p/potencia-mtb-merida-expert-trial-35d-negro [accessed 16.06.2026]
100g 2x2 Twill Woven Glass Cloth	0.100	4.00	4.1	https://www.easycomposites.eu/100g-22-twill-woven-glass-cloth [accessed 12.06.2026]
EL2 Epoxy Laminating Resin	0.410	15.35	1	https://www.easycomposites.co.uk/el2-epoxy-laminating-resin [accessed 21.05.2026]
Structural subtotal	3.957	731.27		
Avionics / Electrical				
Servos	0.053	74.95	8	https://wetronic.nl/savox-SC-1256TGplus-digitale-servo-titanium-gear-20kg_nl [accessed 16.06.2026]

Continued on next page

Component	Mass [kg]	Cost [€]	Qty.	URL
Micro BEC 6–30V to 5V/9V-ADJ	0.001	4.00	1	https://www.mateksys.com/?portfolio=mbec6s [accessed 12.06.2026]
Matek FCHUB-12S Power Distributor	0.021	25.00	1	https://www.aliexpress.com/p/tesla-landing/index.html?scenario=c_ppc_item_bridge&productId=1005009122292994 [accessed 12.06.2026]
Pixhawk 6X Mini	0.058	247.00	1	https://holybro.com/products/pixhawk-6x [accessed 15.06.2026]
USB–TTL Converter (CP2102)	0.002	5.00	2	https://www.123-3d.nl/123-3D-USB-naar-TTL-serieel-converter-CP2102-UART-i2012.html [accessed 12.06.2026]
Singularity 2.4 SMA Antenna	0.0095	21.50	2	https://truerc.com/71973-singularity-24-sma [accessed 15.06.2026]
ESC Hobbywing XRotor Pro 50A	0.028	56.00	3	https://druav.com/products/2pcs-hobbywing-x-rotor-pro-50a-esc [accessed 12.06.2026]
Micro Load Cell (S-type)	0.060	200.00	1	https://www.ato.com/micro-load-cell-s-type-1kg-to-50kg [accessed 15.06.2026]
NAU7802 I ² C ADC Amplifier	0.003	5.00	1	https://www.adafruit.com/product/4538 [accessed 15.06.2026]
JY-ME01 Absolute Rotary Encoder	0.011	31.00	2	https://witmotion-sensor.com/products/jy-me01-high-precision-18-bit-resolution-absolute-encoder-digital-rotation-angle-sensor [accessed 15.06.2026]
DroneCAN Airspeed Sensor DLVR (PT40)	0.039	95.00	1	https://holybro.com/products/high-precision-dronecan-airspeed-sensor-dlvr [accessed 15.06.2026]
H-RTK F9P Helical GNSS + Compass	0.049	255.00	1	https://holybro.com/products/h-rtk-f9p-helical [accessed 15.06.2026]
Raspberry Pi 5 (8 GB)	0.060	172.00	1	https://www.amazon.com/Raspberry-Pi-8GB-SC1112-Quad-core/dp/B0CK2FCG1K [accessed 15.06.2026]
UWB Nooploop Link-Track P-A	0.005	79.00	1	https://www.nooploop.com/linktrack/ [accessed 15.06.2026]
Doodle Labs Mesh Rider Mini OEM	0.034	1273.00	1	https://uaxtech.com/products/doodle-labs-mini-oem-mesh-rider-radio [accessed 15.06.2026]
Wiring (total)	0.109		1	
Avionics subtotal	0.992	3237.60		
Single UAV Summary				
Total UAV	7.737	4580.01		

Table 18.3: Full UAV swarm system bill of materials (3 UAVs and shared payload).

Component	Mass [kg]	Cost [€]	Qty.	URL
UAV Swarm				
Single UAV	7.737	4580.01	3	(see Table 18.2)
UAV Swarm subtotal	23.211	13740.03		
Payload System				

Continued on next page

Component	Mass [kg]	Cost [€]	Qty.	URL
I2C Multiplexer (TCA9548A)	0.001	3.50	1	https://www.tinytronics.nl/en/communication-and-signals/io-converters/i2c-multiplexer-tca9548a [accessed 12.06.2026]
ICM-45686 IMU	0.002	5.00	3	https://invensense.tdk.com/products/motion-tracking/6-axis/icm-45686/ [accessed 15.06.2026]
BMP085 Barometer	0.001	19.00	2	https://nl.farnell.com/en-NL/seeed-studio/101020068/barometer-sensor-arduino-raspberry/dp/4007687 [accessed 16.06.2026]
UWB Nooploop Link-Track P-A	0.005	79.00	1	https://www.nooploop.com/linktrack/ [accessed 15.06.2026]
H-RTK F9P Helical GNSS + Compass	0.049	255.00	1	https://holybro.com/products/h-rtk-f9p-helical [accessed 15.06.2026]
Raspberry Pi 5 (1 GB)	0.060	50.00	1	https://www.tme.eu/nl/details/sc2162/raspberry-pi-minicomputers/raspberry-pi/raspberry-pi5-1gb/ [accessed 15.06.2026]
4000 mAh 3.7 V 1S LiPo Battery	0.072	13	1	https://www.reichelt.com/nl/nl/shop/product/li-ion-accu_soldered_333287_4000_mah_3_7_v_-373551?PROVID=2809 [accessed 23.06.2026]
3.7 V to 5 V Voltage Converter	0.015	4	1	https://www.alibaba.com/product-detail/DC-DC-Boost-Converter-3V-3_62019843043.html [accessed 23.06.2026]
Doodle Labs Mesh Rider Mini OEM	0.034	1273.00	1	https://uaxtech.com/products/doodle-labs-mini-oem-mesh-rider-radio [accessed 15.06.2026]
Singularity 2.4 SMA Antenna	0.0095	21.50	2	https://truerc.com/71973-singularity-24-sma [accessed 15.06.2026]
Polyester Webbing Cargo Net	2.980	98.35	1	https://www.securefixdirect.com/polyester-webbing-cargo-net-1m---4m-hoisting-sling-loading-safety-21169-p.asp [accessed 12.06.2026]
Steel Carabiner Clip	0.020	3.80	8	https://www.steelropes24.com/Snap-Hook-with-Eyelet-and-Thread-Stainless-Steel-DIN-5299-Form-C/DS10061.1 [accessed 12.06.2026]
Polyester Cables (18 m runs)	1.249	26.10	3	https://prorope.com/products/polyester-touw-gevlochten-in-wit-en-zwart-1-5-mm-t-m-12-mm [accessed 12.06.2026]
Avid BB5 Mechanical Brake System	0.338	47.56	1	https://hollandbikeshop.com/en-gb/sram/avid/avid-disc-brake [accessed 16.06.2026]
Payload subtotal	7.488	2028.11		
System Summary				
Total System	30.699	15768.14		

Table 18.4: Components compliance matrix.

ID	Means of compliance	Status
STK12	Single drone weight is 7.737 kg.	✓
STK14	The total system cost is 15,768.14 EUR.	✓
STK30	All components are widely commercially available.	✓
STK31	All components are widely commercially available.	✓

19. Performance Analysis

The primary function of the designed system is transporting cargo in an efficient manner. As such, the performance metrics used to assess the system centre around quantifying the various aspects of what it means to efficiently transport a payload.

The first analysis performed on the system is the assessment of how the energy consumption changes with payload mass for varying fleet sizes, shown in Figure 19.1. The energy required to carry the payload is expressed in energy per distance (Wh km^{-1}) and is evaluated at a cruise speed of 20 m s^{-1} for fleet sizes ranging from three to six drones.

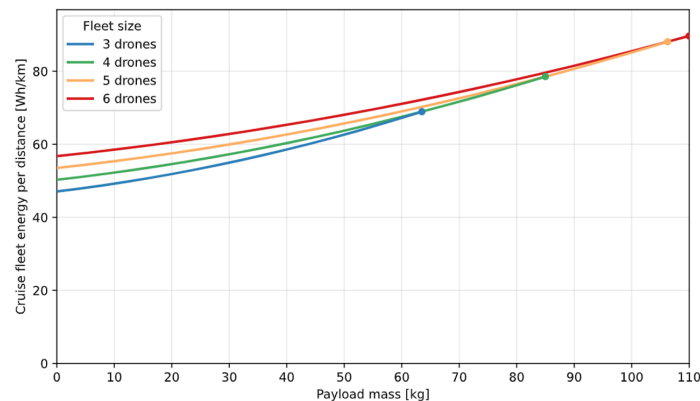


Figure 19.1: Payload efficiency sweep showing how the energy consumption changes with payload for the different fleet sizes.

It can be seen that more energy is required to carry heavier payloads. Furthermore, the energy per kilometre increases more steeply for smaller fleet sizes, such that beyond a certain payload mass it becomes more efficient to distribute the load across a greater number of drones (SUS-1 🍃). This behaviour stems from the quadratic drag polar, which causes both drag and energy consumption to grow quadratically with the additional lift required per drone. The propellers also become less efficient when operating above their cruise thrust setting, further amplifying the energy penalty at higher payload fractions (SUS-1 🍃).

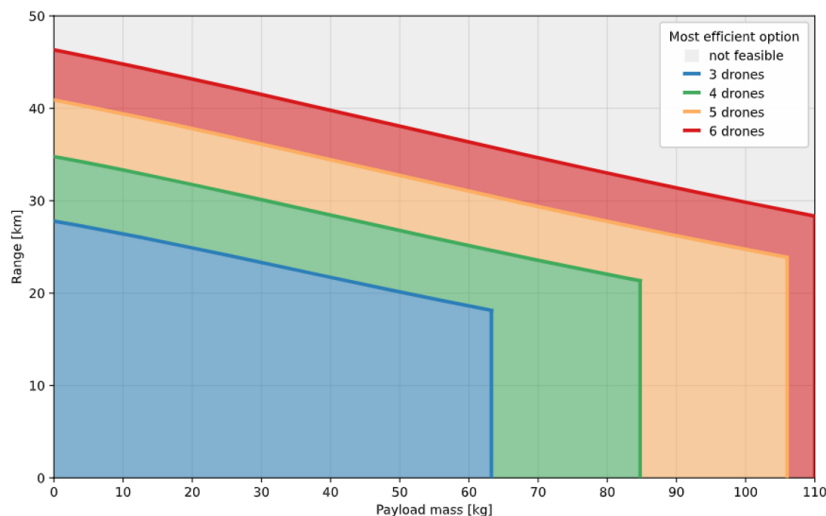


Figure 19.2: Best fleet size as a function of payload mass and required range. The coloured regions show the lowest-energy feasible number of drones, while the grey region indicates combinations that cannot be flown with the available battery, lift or thrust limit.

Building on this, Figure 19.2 shows how the mission range varies with payload mass and identifies the lowest-energy feasible fleet size for each combination. The range is determined by computing the drag required to sustain 20 m s^{-1} flight at each payload mass, and the configuration requiring the fewest drones while remaining within battery, lift, and thrust limits is then selected. It can be seen that three drones are indeed the most efficient configuration for the design point of 50 kg over 20 km (SUS-1 🍃). The three-drone fleet can carry up to 64 kg efficiently, though the achievable range at that payload is reduced to 18 km. Figure 19.2 thus shows the most efficient drone configuration for every payload mass and delivery range.

The system performance should also be assessed across different flight phases. The drone is designed with the goal of maximising efficiency in cruise flight. This is the most lengthy trajectory phase, and thus helps the system to improve its efficiency (SUS-1 🍃). It must also be ensured that the performance in climb and hover phases happens at an acceptable power level and can be realised within the constraints of standard propulsion hardware. In Table 19.1 the performance in different flight phases is quantified.

Table 19.1: Propulsion system performance summary across flight phases.

Flight Phase	RPM	Total Thrust	Shaft Power	Throttle
Cruise	8550	46 N	1200 W	0.58
Climb (best ROC)	11300	95 N	3000 W	0.76
Hover (T/W=1)	10000	90 N	2200 W	0.66
VTOL manoeuvre (T/W=2)	13375	180 N	4500 W	0.90

Key Result: Drone Propulsive Performance

An important conclusion that can be drawn from Table 19.1 is that the power drawn in the hover phase is nearly four times larger than that in cruise. This showcases the important characteristic of the design, which is the fact that the propellers are optimised purely for cruise. As such, the hover flight phase is very demanding on the motors and should only be used to allow the drones to take off from a limited space. The operations of the system should always be planned to allow the drones to transition to forward flight as soon as possible. This also ensures the system is using less energy for operations (SUS-1 🍃).

20. Final System Description

After having described the design for the Dronado system in detail, this chapter highlights the main design parameters and shows the connections between the hardware and software components of the system. First, Section 20.1 gives an overview of what the system does and how different modules are connected. Secondly, the physical system and software are described in Section 20.2 and Section 20.3 respectively. Finally, Section 20.4 summarises the main system parameters and Section 20.5 demonstrates the system's compliance with the overarching stakeholder requirements listed in Table 20.1.

Table 20.1: Overarching stakeholder requirements.

ID	Requirement
STK04	The system shall enable cooperative transport of a payload using multiple hybrid drones.
STK19	The system shall operate safely within defined atmospheric conditions.
STK20	The design shall be completed within the 10-week DSE period.
STK21	The design shall be documented according to applicable DSE report and review standards.
STK34	The system shall be able to take off from a field.

20.1. Integrated System Overview

Dronado is a cooperative cargo-transport system, composed of a swarm of three fixed-wing UAVs, connected through 18 m cables to the 50 kg payload through a payload connector, which includes some sensing equipment and a braking mechanism used to stop payload rotation during the mission. The payload is carried inside a net. The physical configuration of the system is shown in Figure 20.1.

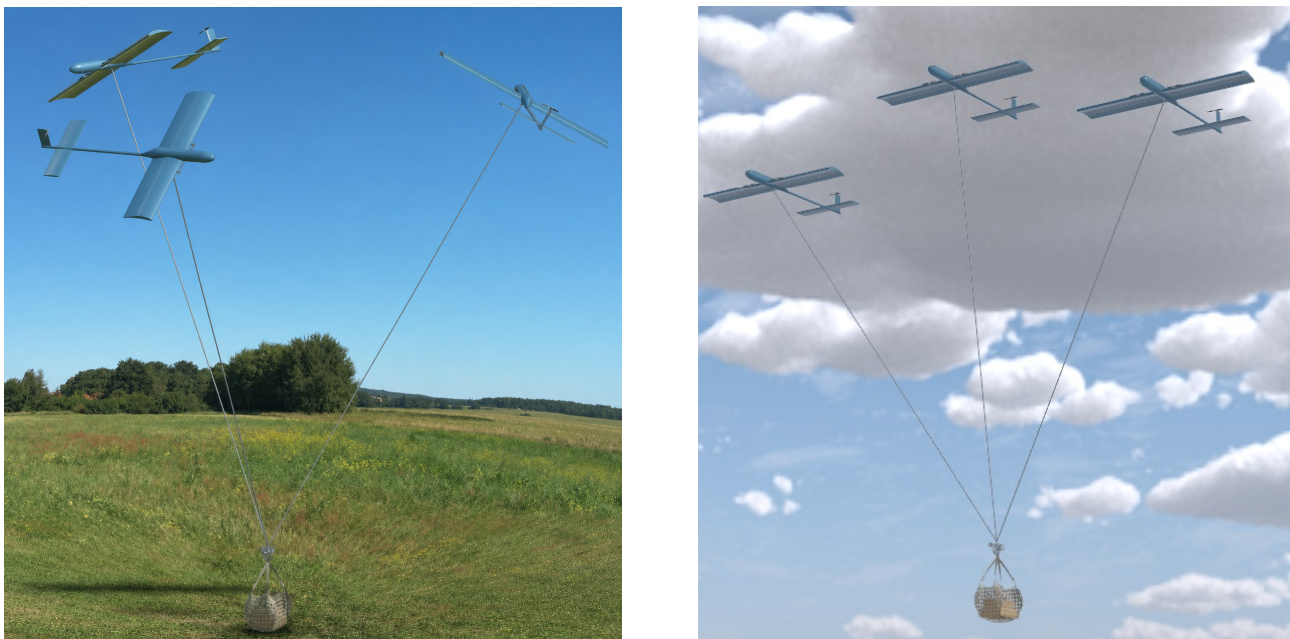


Figure 20.1: Physical overview of the Dronado system, showing the take-off manoeuvre on the left and cruise configuration on the right.

At system level, Dronado can be divided into three main segments: the airborne, the payload, and the ground

segment. The airborne segment consists of the structures and propulsion of the UAVs, their onboard sensors, communication hardware, drone controllers, and the trajectory planner. The payload segment consists of the net, cables, and connector, containing the payload sensors. The ground segment consists of an operator interface through which the operator can determine the mission range, cruise altitude, number of drones, and perform an emergency landing, while also keep receiving mission information and monitoring it.

For each operation, the operator needs to send the mission parameters to the trajectory planner through the user interface. With this, the trajectory planner can compute an optimal path for each one of the UAVs in the swarm. These trajectories are commanded by the leader drone, sending the other UAVs their required trajectories. The path of each one of the drones is tracked using an individual controller in each one of the UAVs. The controller will send commands to the control surfaces actuators to correct deviations from the trajectory.

Figure 20.2 summarises the hardware and software interfaces. The diagram shows the difference between physical connection, signal flows and power distributions for all the mentioned segments. The displayed UAV architecture is repeated for all drones, while the trajectory planner is hosted by the leader drone.

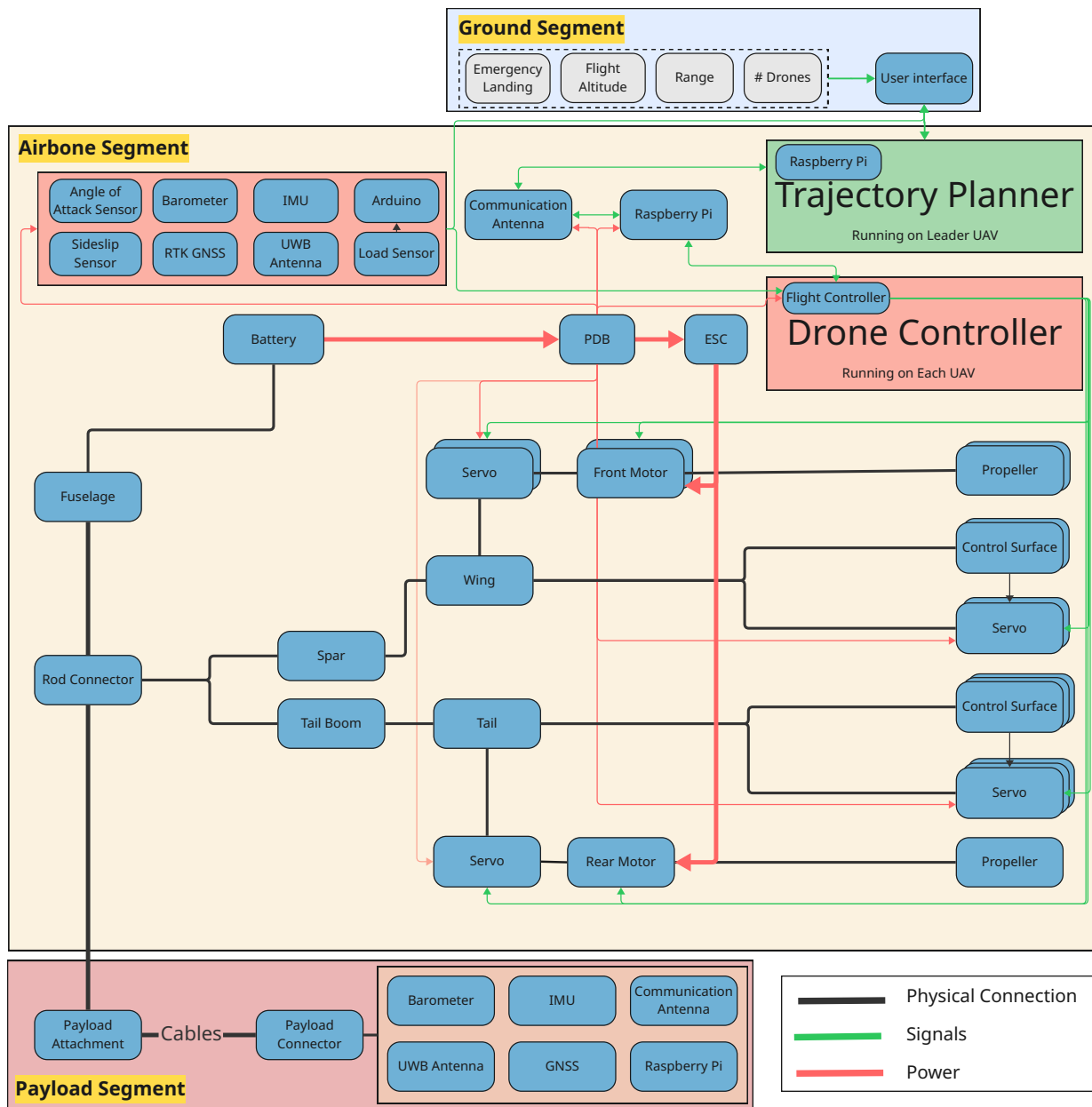


Figure 20.2: Connections between hardware and software components.

20.2. Physical System Configuration

The drone configuration is a three propeller, conventional tail design, which achieves VTOL capabilities through rotatable propellers. Each UAV uses two wing-mounted front propellers and one rear propeller mounted at the top of the vertical tail, the horizontal tail is placed in front of the vertical one to minimise the wake effects from the rear propeller. The drone is designed to maximise cruise efficiency (SUS-1 ) while still allowing vertical take-off. The most important characteristics of the drone design are summarised in Table 20.2.

The drones are connected to the payload through cables and a payload connector. The payload connector includes a brake, which allows for stopping the rotation of the payload after the take-off manoeuvre. In addition, a sensor box is included in the payload connection to enable the drones to establish a relative position with respect to the payload.

The physical system is modular, allowing assembly of the wings, tail boom, payload connector, cables, and net at the operating site before the mission. This allows to have a low storage volume of 1.47 m³. This value makes the system comply with the requirement of van transport volume. Modularity also contributes to maintainability and reparability (SUS-5  and SUS-6 ) because inspection and repair are simpler with each component being individually accessible.

Table 20.2: Drone design parameters summary.

Category	Parameter	Symbol / Unit	Value
General	Number of drones	[-]	3
	Vehicle mass	m_{veh} [kg]	7.737
	Payload carried per drone	m_{pl} [kg]	19.138
	Loaded drone mass	m_{loaded} [kg]	26.875
	Propeller type	[-]	12"8
Wing Geometry	Wing area	S_w [m ²]	1.5168
	Wing span	b [m]	3.00
	Aspect ratio	AR [-]	5.934
Aerodynamics	Cruise lift coefficient	C_L [-]	0.782
	Lift-to-drag ratio	L/D [-]	6.27
Tail Geometry	Horizontal tail area	S_h [m ²]	0.3997
	Vertical tail area	S_v [m ²]	0.0598

20.3. Software and Control Architecture

The software architecture of the Dronado system is divided into three main layers: the ground-station user interface, the leader-follower UAV trajectory planner, and the individual drone controllers. The user interface provides the operators an easy way to input the mission characteristics and provides access to the emergency landing command. Then, the trajectory planner takes these inputs and calculates the optimal phase-specific trajectories for each one of the UAVs. Finally, the drone controllers track the assigned trajectories using onboard sensor feedback and actuator commands.

Figure 20.3 shows a visualisation of the user interface for the Dronado system. The operators need to define the payload route, target cruise altitude, number of drones, and the payload mass in order to run the trajectory planner. Figure 19.2 will be used to determine the number of UAVs required for a specific mission range and payload mass. The interface performs a feasibility check on the weather, checking if the current weather is below pre-defined bounds for example for the requirements for wind-gusts. An estimated mission time is given depending on the range the operators decide to put. Furthermore, the interface shows the allowed input ranges for the cruise altitude. The cruise altitude is limited to a maximum of 90 m to comply with the Netherlands

maximum limit of 120 m altitude for flying drones¹. During the mission the drones will be at a maximum vertical distance of 18 m above the payload, which leaves the system with a margin of 12 m to comply with regulations if the maximum altitude of 90 m is used. A minimum altitude of 60 m was chosen to ensure enough operational clearance from trees, houses, people and animals. Because the target market for Dronado is isolated and remote areas, high buildings do not need to be taken into account in this margin.

Mission Parameters

Cruise altitude

m

allowed 60-90 m

Payload route

Origin → Destination

Number of UAVs

-

Payload mass

kg

✓ Weather acceptable

19°C, 2.0 m/s wind, 0% precip

Estimated mission time:

min

Run Trajectory Planning

Figure 20.3: First window of the user interface where the main mission parameters need to be defined by the operators to calculate the trajectory for the mission phases.

The trajectory planner is the high-level coordination module. It receives the operator inputs, together with pre-defined payload trajectories, and system constraints, and calculates UAV trajectories for the entire mission. This trajectories are be visualised in the operators through the user interface, visualised in Figure 20.4. The operators will be able to visualise the current trajectories drones are performing on the map, status of the charging of the drones, the estimated tension of the cables, estimated position error for the payload, weather conditions, and most importantly they can easily effectuate an emergency landing by clicking the emergency landing button.

Drones

UAV 1

96 %

UAV 2

96 %

UAV 3

96 %

Live-Tracking

Weather conditions: 19°C, 2.0 m/s wind, 0% precip

1

2

3

EMERGENCY LANDING

Payload & Cables

Payload position error:

Cable tension:

Figure 20.4: Second window of the user interface where current mission phase is displayed in a map together with other relevant parameters. The map background was obtained from Google Maps and shows the area around the Italian alps.

¹<https://english.ilent.nl/topics/aviation/drones-and-model-aircraft/drones-eu-residents> [accessed on 19/06/2026]

For the current configuration of the system, the trajectory planner always converges to a spinning manoeuvre around the vertical line followed by the payload for the climb and vertical descent mission phases. This results from the optimiser finding an efficient way to generate lift with the fixed wings while maintaining the cable and vehicle constraints.

The assigned reference trajectory is to be hosted by the leader drone, which sends the corresponding reference trajectories to the other two drones. Each UAV has its own cascaded PID controller to follow the assigned reference trajectory. The controller compares the assigned reference with the estimated drone state to compute the required actuator commands to follow better the reference.

20.4. Final System Characteristics

The current physical configuration and its implementation demonstrates its feasibility through the computation of phase-specific trajectories and trajectory tracking. Table 20.3 summarises the main characteristics of the system.

Table 20.3: System-level parameters of Dronado.

Category	Parameter	Symbol / Unit	Value
Mission	Nominal mission range	R [km]	20
	Nominal cruise speed	V_{cruise} [m s^{-1}]	20
Operation	Number of operators	[–]	2
	Maximum set-up time	t_{setup} [min]	40
	Total mission time	t_{mission} [min]	19.4
Operational Area	Required take-off area	A_{TO} [m^2]	855.3
	Storage volume	V_{storage} [m^3]	1.47
Cost	Estimated system parts cost	C_{sys} [EUR]	15 900
Sustainability	Recyclable mass fraction	[%]	60.2
	Material-production emissions	[kg CO ₂ e]	182.4
Safety	One-drone-failure cruise range	R_{fail} [km]	1.35–6.38

20.5. Compliance

Table 20.4: Final design compliance matrix.

ID	Means of compliance	Status
STK04	The system can effectively transport the payload using three drones together with the trajectory planner, as visualised in Figure 20.1.	✓
STK19	The user interface checks for safe atmospheric conditions before running the mission, as Figure 20.3 shows.	✓
STK20	This section summarises the completed design within the DSE timeline.	✓
STK21	This report documents the design according to DSE standards.	✓
STK34	The system is designed so it needs to take off from a field, as exemplified in Figure 20.1.	✓

21. Production Plan

This chapter will outline a production plan, by giving an overview of all parts needing to be produced in Section 21.1. All manufacturing techniques required for the manufacturing of these parts and their flow diagrams are presented in Section 21.2 and Section 21.3. The assembly steps for the system are presented in Section 21.4.

21.1. Custom Parts

The designed system consists mostly of off-the-shelf components, however, some elements still require custom manufacturing. In Table 21.1, the parts requiring custom manufacturing are summarised.

Table 21.1: Bill of materials for custom parts.

Part Name	Number of Parts	Manufacturing Technique
Wing Rib	4	CFRP sheet laser cutting
Fuselage Structure	1	Foam CNC machining
Wing Segment	4	Foam hot wire cutting
Horizontal Tail Segment	2	Foam hot wire cutting
Vertical Tail	1	Foam hot wire cutting
Motor Mount	3	Additive manufacturing
GFRP Cloth	4.1 m ²	Additive manufacturing
Polymer Resin	0.41 kg	Hand lay-up
Mounting Plate Brake Caliper	1	Metal sheet laser cutting

21.2. Manufacturing Techniques

The various manufacturing techniques required to produce the custom parts are detailed in this section. The motivation behind the choice of manufacturing methods is presented and the specific considerations relevant to the manufacturing of specific parts are explained.

21.2.1. Foam Manufacturing

The manufacturing of the foam parts can be performed using either a CNC machine or hot wire cutting, depending on geometric complexity and facility availability. As the aerodynamic surfaces of this design are of a rectangular planform and untwisted, they can all be manufactured with hot wire cutting, which is suitable for simpler geometries. The more complex shaped fuselage will be manufactured using a CNC machine.

An important limiting factor to the foam manufacturing is the size of the manufactured part. In particular, the wing, measuring three metres in span, cannot be manufactured in one piece, due to limited worktable size. As such, the part needs to be manufactured in smaller pieces and subsequently glued.

An example CNC machine to use for the foam cutting is the 3-axis Hermle machine available at TU Delft's DEMO facility.

21.2.2. Composite Skin Manufacturing

After the fuselage and aerodynamic surfaces are made out of the EPP foam, they need to be covered with a composite skin to ensure surface toughness, strengthen the structure and provide a smoother surface enhancing aerodynamic properties. Hand lay-up of the composite is chosen, since automated methods are not feasible within the given budget and under the limitation that the system should be manufacturable in a university setting.

The hand lay-up can be performed under standard atmospheric conditions and does not require specialised equipment.

21.2.3. Composite Ribs Manufacturing

The ribs are manufactured by cutting the desired shape from off-the-shelf CFRP sheets. Such parts could also be manufactured by hand lay-up with a mould, but such manufacturing is much more complex and time consuming. As the ribs are mainly used to transfer propeller loads into wing spars, rather than being crucial load bearing components of the wing, they are simply designed as flat plates with cutouts for the spars, which means they can be manufactured with simpler methods.

21.2.4. Plastic Parts Manufacturing

The plastic parts required for the drones are mainly the structures that allow integration of the propellers into the wing and tail. As they are not load bearing parts, since the loads are carried by the ribs and spars, they can be made out of low strength plastics like PLA. To have large geometric freedom and to limit the costs, the parts are made with additive manufacturing techniques.

21.2.5. Payload Connector Manufacturing

The payload connector is made entirely out of metal and some custom parts need to be made. A metal mounting plate for the brake disc and caliper can be laser cut from a metal plate. Additionally the aluminium parts need to be welded together with a TIG weld to ensure a clean weld. These manufacturing facilities are available at DEMO in TU Delft.

21.3. Manufacturing Methods Flow Diagrams

The manufacturing methods described in the preceding sections are described in more detail in the form of flow diagrams presented in Figure 21.1.

21.4. Assembly

The assembly process is strongly driven by the operational requirements (STK-18, STK-33), which dictate that the assembly needs to be simplified to minimise the assembly time and allow full assembly by only two operators. The assembly strategy makes use of the structural features of the design to facilitate easier assembly. In particular, the structural rods are used as easy attachment points for detachable aerodynamic surfaces. Additionally, these rods serve as routing paths for wiring. In Figure 21.2 the assembly steps are laid out as a flow diagram. The red colour indicates the steps that need to be taken when first assembling the system, while blue signifies the recurring assembly steps that need to be performed when setting up the system after transport.

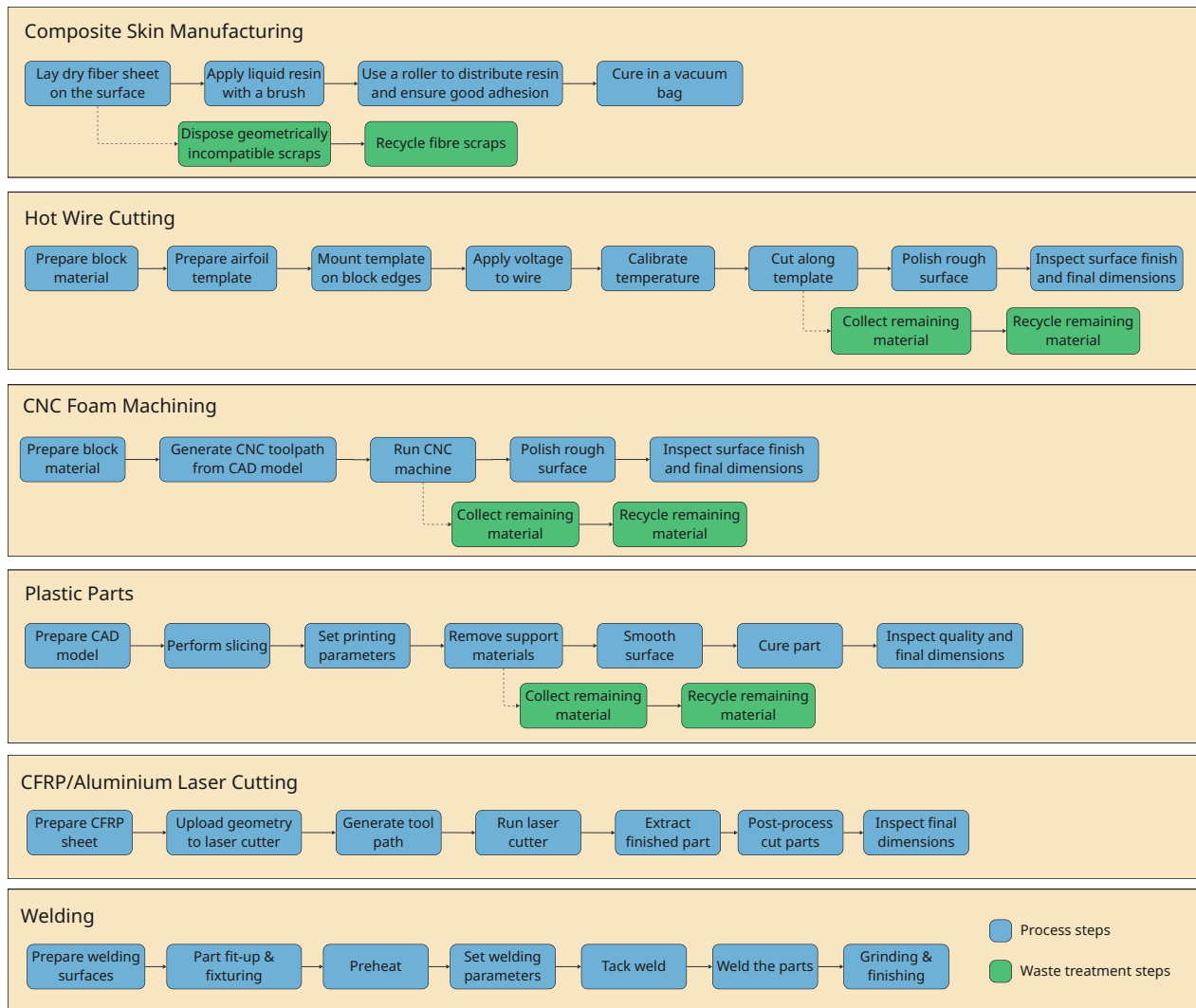


Figure 21.1: Flow diagram of manufacturing processes.

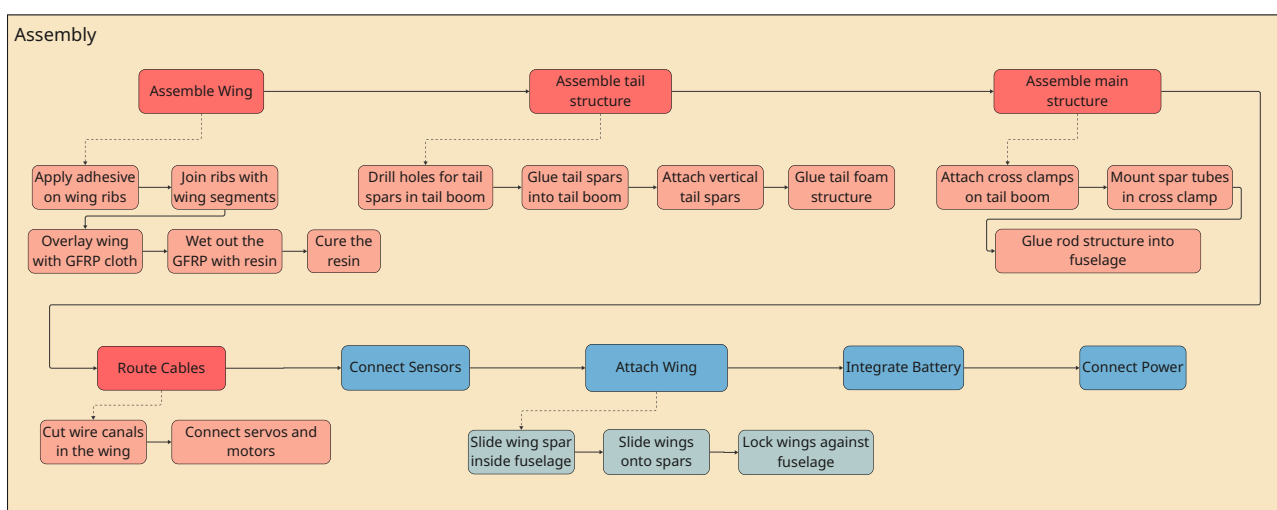


Figure 21.2: Flow diagram of assembly process.

22. Operations and Logistics

This chapter describes the system operations across the full mission life cycle, including the operational and logistical flow in Section 22.1 and the mission profile in Section 22.2. Compliance with the operational requirements, shown in Table 22.1, is discussed in Section 22.3.

Table 22.1: Requirements relevant to system operations and maintenance.

ID	Requirement
STK26	The system shall provide the operator with information on system status.
STK27	The system shall provide a safe mission abort.
STK28	The system shall provide access to all mission-critical components required for inspection, maintenance, or replacement between missions.
STK33	The system shall be safe to set up.
STK18	The system shall have a set-up time of less than 40 min.

22.1. Operations and Logistics

The operational flow of the system is summarised in Figure 22.1, covering four major phases from storage and deployment to end-of-life handling. The colours of the functions correspond to the colours of the phases

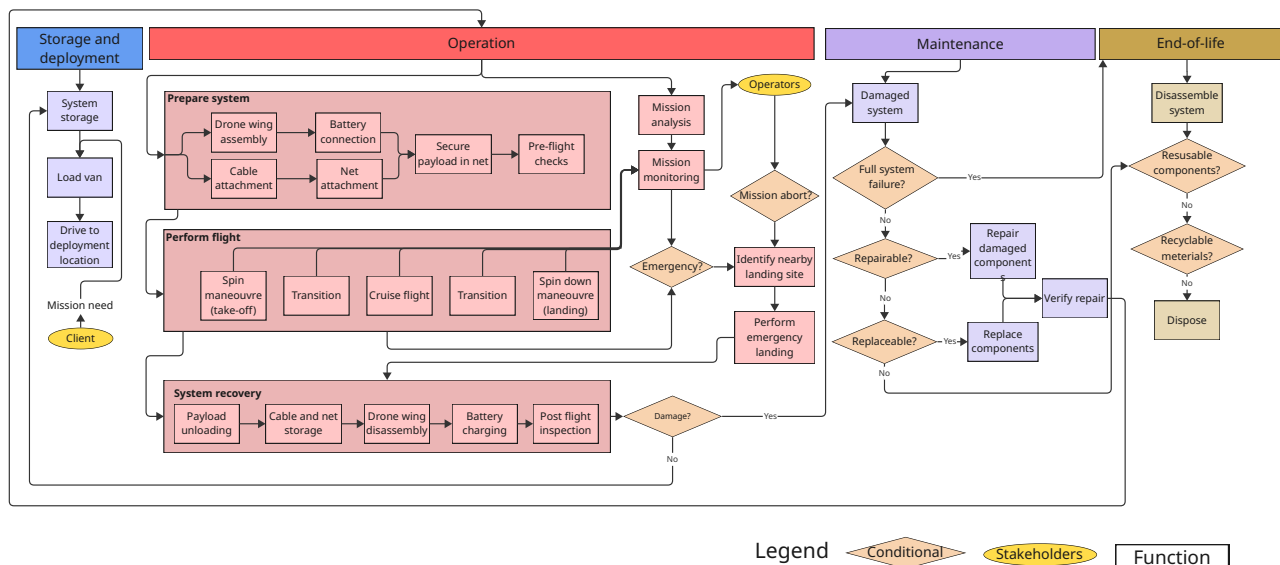


Figure 22.1: Operations and Logistics Flow Diagram.

The life cycle is divided into five phases: production, storage and deployment, operation, maintenance, and end-of-life, each defining the required logistical and operational activities.

Production phase: The system is manufactured, assembled, and tested prior to deployment, including airframe assembly, software validation, calibration, and electrical and communication system validation as defined in the verification and validation plan. These aspects of the life cycle are addressed in Chapter 16 and Chapter 21.

Storage and deployment phase: This phase covers transport and preparation for mission use. The system is stored in a disassembled state, facilitated by the modular wing design. The system is transported in a standard sized Mercedes Sprinter van. The choice of take-off site is motivated by the client's mission need.

Operation phase: This includes mission execution, from pre-flight preparation through flight and recovery. Additionally, the flow of handling emergency conditions is considered. The system preparation stage includes the assembly of single drones, as well as the attachment of drones to the payload and secure payload storage. Mission conditions such as weather and wind are assessed during preparation. During flight, operators monitor the system during the five flight phases and have the option of aborting the mission if required. The same mission abort flow is triggered if one of the drones fail. The recovery of the system includes disassembly of wings and detachment of the battery for charging. The electronics are also easily accessible through a hatch in the fuselage. Post-flight inspection ensures readiness for subsequent use.

Maintenance: Maintenance actions are initiated when faults are detected during pre- or post-flight checks, including repair or replacement decisions followed by system re-verification.

End-of-life phase: This phase covers retirement and disposal of non-repairable components. Parts are evaluated for reuse or recycling and, where possible, reintegrated into production. Otherwise, they are disposed of in accordance with sustainability guidelines defined in Chapter 24.

22.2. Mission Profile

The mission profile consists of nine phases. First, the drone swarm takes off vertically until the cables are in tension. Then, the drones transition to VTOL lift-off, where drones go in circles before lifting the payload. When the payload is lifted drones enter the climb phase, where they keep spinning until the payload reaches an altitude of 90 m is reached. Then drones transition to cruise, where they go up extra 10 m, and enter the cruise phase, which in real operations is designed for the full range of 20 km. Once drones get near the target destination they enter the transition back phase, where drones decelerate and start vertical descent, where drones spin-down. Once the payload touches the ground the drones enter the landing manoeuvre where they tilt up their propellers and finally perform drone descent. An illustration of this profile can be found in Figure 13.1.

In the case one drone fails, the system has the capability to reach an emergency landing zone at most 1 km away from any point in the system's trajectory in compliance with requirement SYS-83. Once above this zone, it will perform a spin-down manoeuvre until the transition altitude and then land vertically. A more detailed description of the trajectory that the two drones would perform for emergency landing can be observed in Figure 13.29.

22.3. Compliance

Compliance with the requirements listed in Table 22.1 is demonstrated in Table 22.2, confirming that all operational and logistical requirements are satisfied by the current design.

Table 22.2: Operations and maintenance requirements compliance.

ID	Means of compliance	Status
STK26	The system status is reported in the mission planner software.	✓
STK27	The safe-abort method is part of the communication flow with operators and its feasibility is demonstrated in RAMS section.	✓
STK28	A hatch in the fuselage allows access to both the battery and electronics. The structural components are easily replaceable thanks to a modular design.	✓
STK33	The system setup does not include manipulation of heavy parts or any procedures requiring extra safety procedures.	✓
STK18	The assembly consists entirely of tool-free operations: snapping in the wings into the fuselage, inserting the battery, and attaching carabiner clips between the payload and drones.	✓

23. RAMS

This chapter details Dronado’s Reliability, Availability, Maintainability, and Safety (RAMS) characteristics, an important part of any engineering project, detailing its ability to perform its intended function throughout its life. Reliability, safety, availability, and maintainability are explained in Section 23.1, Section 23.2, Section 23.3, and Section 23.4 respectively.

23.1. Reliability

The system reliability quantifies the probability of mission success, where individual component failure rates compound to determine the overall likelihood of system failure. Limited data on the reliability for fixed-wing, hybrid drones exists in literature. As such, the general UAV failure rate estimate of 10^{-3} per flight hour [91] is assumed. The Dronado system is characterised by a high complexity due to the need for drones to collaborate. The failure of a single drone does not lead to catastrophic failure, but causes a mission abort scenario, which means the likelihood of mission completion decreases with the number of drones. As such, the total system reliability, understood as the likelihood of completing the mission, scales as

$$R_{\text{sys}} = R_{\text{UAV}}^{n_{\text{drone}}}.$$

Based on this relation and the total mission time reported in Chapter 13, the system reliability can be estimated at 0.9990. Additional failure causes like cable entanglement or payload connector failure will likely bring this reliability figure considerably lower. Although cable entanglement is prevented in the trajectories found by the trajectory planner, predicting whether entanglement happens under realistic disturbances is a much harder problem. The total impact of these effects on reliability cannot be quantified without thorough testing.

Although the system’s inherent complexity decreases the expected reliability, many steps can be taken to ensure the final reliability is kept at an acceptable level. The system is designed with redundancy in mind, and thorough testing can ensure that the failures inherent to drone collaboration can be minimised.

23.2. Safety

As stated in Section 23.1, the system complexity introduces various failure scenarios characteristic for a collaborative payload carrying scenario. In particular, to ensure safe operations over inhabited areas, a single drone failure cannot lead to a fatal failure of the whole system. In addition, it is ensured that the failure of a single drone engine does not lead to loss of controllability, which could lead to drones crashing.

23.2.1. One Drone Failure

A key requirement in the design of the system is to prevent complete system failure in case one of the drones malfunctions. This condition follows from risks ELEC01, ELEC02, and STRC01 from Chapter 5. To ensure that there is sufficient energy to perform a landing manoeuvre with 2 drones, an 80% depth of discharge of the battery is chosen. This leaves at least 20% of the total drone battery capacity available at each point in the cruise phase. The remaining cruise capability of the system in case a drone fails along any point of the nominal cruise range is plotted in Figure 23.1. This is a line with a negative slope, starting at the cruise range of two drones and ending at the remaining cruise range of the two drones with 20% of the total battery capacity.

The drones are designed such that two remaining drones can carry the payload and the inactive drone following a single drone failure. Post-failure cruise speeds between stall and 25 m s^{-1} are evaluated, with the required lift coefficient, total drag, thrust per propeller, and electrical power draw verified against their respective limits, and the lift coefficient checked against $C_{L_{\text{max}}}$ to prevent stall. The speed minimising energy consumption per kilometre is selected as the failure cruise speed, yielding 19.92 m s^{-1} , near-identical to the nominal 20 m s^{-1} . The maximum failure cruise range, computed from the energy remaining at the start of nominal cruise, is 6.38 km; the minimum, using only the 20% reserve at the end of nominal cruise, is 1.35 km.

Furthermore, Figure 13.6 showcases the robustness of the trajectory planner in the case that one drone fails.

This proves that the system is capable of performing an emergency landing with only two operational drones.

23.2.2. One-Engine-Inoperative

The one-engine-inoperative condition follows from risks PROP01, STRC02 and ELEC04 in Chapter 5. This condition poses an important sizing constraint on the rudder. As mentioned in Chapter 9, the front propellers have a lateral offset from the fuselage and therefore an offset from the centreline of the drone. In case one fails, the cruise yaw equilibrium is disturbed and the rudder needs to be deflected to counter the resulting yaw moment. This constraint is taken into account in the sizing of the rudder described in Section 7.4.

The rear propeller is placed on the centreline of the drone and will therefore not create a yaw disturbance when it fails. Instead, due to its large vertical offset from the centre of gravity of the drone, its nose-down pitching moment will disappear. Since the incidence angle of the horizontal tail is chosen such that no elevator deflection is required to satisfy the pitch moment equilibrium during nominal cruise, the elevator will have to be deflected in the case of rear engine failure. This poses a constraint on the elevator sizing described in Section 7.4. In both cases, the remaining two propellers can provide enough thrust to maintain cruise speed and altitude.

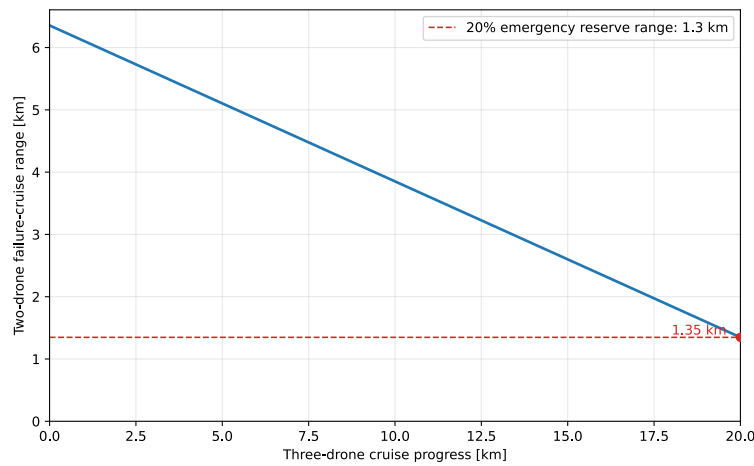


Figure 23.1: One-drone failure range diagram.

23.3. Availability

The system availability captures the various constraints which limit the system's readiness to perform its mission. The Dronado system's major strength in the context of availability is the VTOL capability. No dedicated take-off site is required for the system, which implies no turnover time connected with take-off site availability. The availability of the system is also increased by the possibility of transporting the system with a standard-sized van. The system availability is further facilitated by the short setup time and operability by only two people. In practice, the most limiting factor for the system availability is atmospheric conditions, since the system can only operate in winds of 10 m s^{-1} mean speed and 5 m s^{-1} gusts.

23.4. Maintainability

Over the operational lifetime of the system, component performance will gradually degrade, and this must be accounted for in both the design margins and the maintenance programme. Electric motors lose efficiency over time due to thermal degradation and mechanical wear, because motor temperatures affect material properties linked to efficiency and reliability [92], and heat transfer and mechanical design are both critical for motor performance. Battery capacity also degrades with each charge cycle, leading to less usable energy and increased resistance, causing higher heat losses with decreased efficiency [93].

Over its operating lifetime, the structure of the drone may also suffer degradation, as well as suffer damages from hard landings or collisions. Regular pre-flight inspections, combined with more thorough inspections at defined flight-hour intervals, can help mitigate these risks; however, more detailed inspection plans should be developed to detect cracks and short circuits and assess their severity. Avionics may also be susceptible to these effects, so their influence on sensor accuracy should be evaluated and anticipated using suitable detection, monitoring, and mitigation methods.

24. Sustainability Assessment

The sustainability assessment explains the key ways sustainability has been considered in the Dronado system. It follows a Life Cycle Analysis timeline, starting from the design phase in Section 24.1, the manufacturing phase in Section 24.2, the operations phase in Section 24.3, and the end-of-life phase in Section 24.4. Compliance with the sustainability requirements, listed in Table 24.1, is shown in Section 24.5.

Table 24.1: Requirements relevant to sustainability.

ID	Requirement
STK13	At least 60% of the system mass shall consist of recyclable materials.

24.1. Design Phase

The design focused on system efficiency (SUS-1 🌱): a more efficient system requires less energy, limiting the resources required for operation. The fixed-wing UAVs are an aerodynamically-efficient solution to transporting payloads (see Section 2.5). The trajectory planner reduces overall energy consumption with its cost function (see Section 13.3) producing energy-efficient trajectories. Easy repairability (SUS-5 🌱) and maintainability (SUS-6 🌱) through modular design also limits the need for replacement parts, reducing the amount of materials required and extending the system's usable lifetime.

An important stakeholder requirement is that at least 60% of the system mass is recyclable. The recyclability of materials (SUS-3 🌱) is quantified in Table 24.2. The design also satisfies the stakeholder's wish of the system being entirely electric, using batteries for its power requirements. The equivalent CO₂ of material procurement and production was also evaluated (SUS-10 🌱), the numerical results of which are shown in Table 24.2. This limits negative environmental effects of initial manufacturing, as well as possible repair processes.

For the mass recyclability fraction in Table 24.2, only the mass of the components used for the drone is accounted for, not the mass of all the bought components. Further notes about material recyclability are given below:

- Annex XII part B of the Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries¹ specifies that recycling of lithium-based batteries should recover 65% by average weight no later than 31 December 2025. This percentage will increase to 70% no later than 31 December 2030, further increasing the mass recyclability fraction of the system.
- Approximately 600 kg of carbon fibre can be recovered from one ton of CFRP waste [94], meaning that approximately 60% of the CFRP is recyclable.
- The chosen net is made from polyester webbing with a knot-less, stitched construction. Polyester webbing is a woven fabric and has a mechanical recycling yield of 85%-90%². The midpoint of this range is used for the recyclability for both the cargo net and polyester cables.
- Thermoset polymers like EL2 crosslink during curing and cannot be melted. Instead, when processed by thermal pyrolysis, recovery of the composite constituents is possible with volatilisation of the resin matrix into gas and oil, while the fibres are isolated [95]. Because the EL2 resin matrix completely volatilises during the process, its material recovery fraction is 0%. However, the resulting gas and oil can be used as fuel for pyrolysis [95]. 100% of the recovered structural mass consists of the glass fibre fraction, matching the weight percentage of the glass cloth embedded in the initial laminate. Because the ratio of the resin to the glass sheet is one-to-one, the overall mass recyclability fraction of the GFRP laminate is 50%.
- The rod connectors are made of 6061-T6 aluminium, which is 100% recyclable with no downgrade in quality³. The brake is also made out of aluminium and therefore also recyclable.

¹URL <https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng> [accessed 12.06.2026]

²URL <https://szoneierfabrics.com/what-is-polyester-made-of/> [accessed 16.06.2026]

³URL <https://copperloy.com/what-6061-t6-aluminum-is-and-how-it-is-manufactured/> [accessed 16.06.2026]

- The carabiner clips are made of stainless steel, a fully recyclable material⁴.

All carbon dioxide equivalent values are taken from a Life Cycle Analysis Excel tool developed by Stichting Sustainability Impact Metrics⁵. Because the location of the extraction and production of all materials is not known, worst-case values of each material were considered. Two components had no data available, both in the Excel tool and online. Their impact requires more in-depth research that can be conducted outside of the DSE.

Polyester in the net structure and suspension ropes are assumed to have the same CO₂e of material procurement and production at this stage of the DSE. Research into the differences of production processes and their corresponding CO₂e measurements should be conducted in the future. The LiPo batteries must also be considered separately, with the metric CO₂/kWh of the battery's production (see Section 6.3). While not readily available, information about the MG UAV Solid-State LiPo (see Chapter 9) should be investigated in future project steps.

Table 24.2: Material mass breakdown, estimated recyclability, and CO₂ of material procurement and production.

Material Group	Mass [kg]	Recyclability [%]	Carbon Dioxide Equivalent [kg CO ₂ e]
EPP Foam Structures	2.814	100	5.40
CFRP Components	5.583	60	129.08
2x2 Twill Woven Glass Cloth	1.230	100	6.61
EL2 Epoxy Laminating Resin	1.230	0	8.97
Aluminium 6061-T6 Rod Connectors	1.260	100	14.81
LiPo Batteries	5.251	65	No data available (0)
VCI 4218 350KV FPV Motors	2.880	No data available (0)	No data available (0)
Electronic Systems, Sensors, Wiring and Connectors	3.152	No data available (0)	No data available (0)
Polyester Cables	3.747	87.5	7.19
Polyester Webbing Cargo Net	2.980	87.5	6.11
Steel Carabiners	0.160	100 ¹	0.26
Aluminium Brake Caliper and Disc	0.338	100	3.97
Total	30.625	60.2	182.40

Table 24.2 calculates the recyclability of the system to be 60.2%, meeting the stakeholder requirement of 60%. It also determines the total CO₂e of material procurement and production (excluding batteries, electronic systems, and motors) to be 182.40 kg CO₂e. Table 24.2 does not account for the emission-intensive battery procurement, nor system manufacturing, operations, and end-of-life. Carbon emission data for material procurement and production of comparable drones is scarce, and a meaningful comparison cannot be made. However, this metric provides a starting point for future carbon emission analyses, to ensure the design is sustainably competitive.

24.2. Manufacturing Phase

The manufacturing phase was planned sustainably by choosing low-energy production methods when possible. For instance, hot-wire cutting is utilised for manufacturing the foam aerodynamic surfaces. This process is energy-efficient, because the wire is only heated using electrical resistance⁶. Similarly, hand lay-up composite processes consume little energy, because no high-temperature ovens or large-scale machinery is required⁷.

⁴URL <https://www.okonrecycling.com/industrial-scrap-metal-recycling/stainless-steel/stainless-steel-recyclable/> [accessed 12.06.2026]

⁵URL <https://www.ecocostsvalue.com/data-tools-books/tool-in-excel/> [accessed 16.06.2026.]

⁶URL <https://www.knight-group.co.uk/products/hot-cutting-wire/> [accessed 16.06.2026.]

⁷URL <https://www.muifatt.com.my/blog/detail/frp-hand-layup-guide> [accessed 16.06.2026.]

Furthermore, Dronado was designed for simple manufacturing: simpler geometries requiring fewer machining operations, reducing production energy and material waste. Unavoidable waste material can often be recycled (SUS-3 🌱): EPP is fully recyclable⁸ and CFRP scraps have been commercially recycled for over a decade⁹.

Some parts of the system can be produced from recycled rather than virgin materials, contributing to a circular economy (SUS-2 🌱). Sensors can be found on second-hand websites and/or from TU Delft student teams. These will first be tested to ensure their working condition. APRO¹⁰ offers 15% recycled marine waste content and 90% recycled post-consumer content EPP, demonstrating that recycled EPP can be purchased. Old cargo nets can also easily be sourced, for instance from second-hand military sources (e.g. eBay Item 175053151195). Alternatively, rope can be repurposed from other applications to make an appropriate net. Standard steel carabiners can be bought second-hand online. Recycled CFRP rods are also available¹¹, although future research is required into the different sizes that can be purchased.

24.3. Operations Phase

To operate sustainably, system lifetime will be maximised. Careful use of the system will limit damage, with trajectories that minimise potential obstacles. Battery lifetime (SUS-4 🌱) will be increased through proper storage between missions: a cool and dry place removed from direct sunlight and sources of heat.² The batteries will also be kept at 50-60% if they will be stored for extended periods of time.² Renewable energy sources can also be used for charging Dronado's batteries. The Netherlands has a large focus on using renewable energies, with significant energy demands being met by solar, wind, and biofuel sources.¹² As such, renewable energy is accessible in the Netherlands, and can be used by contracting a Dutch green energy supplier, at no extra cost.¹³

Operations should also limit damage to natural areas (SUS-9 🌱). This can be done by choosing take-off and landing areas with limited flora and fauna, so as to not damage the system's surroundings.

Section 9.4 demonstrates that sound levels (SUS-7 🌱) are comparable to road traffic. Arregi et al. [96] explain that prolonged noise pollution at these sound levels lead to chronic inflammation and oxidative stress in animals and humans. However, local fauna and human populations will only be exposed to temporary noise pollution as the drone passes by overhead, therefore not causing health damage. System take-off and landing takes less than a minute (see Section 13.6), hence also do not yield negative health effects.

24.4. End-of-Life Phase

The system at its end of life will be recycled (SUS-3 🌱), in line with stakeholder requirement STK13 (at least 60% of the system mass shall be recyclable). This will involve disassembly and potentially some additional processes to fully reduce the system into recyclable materials (see Table 24.2). Working parts (e.g. working sensors) that are not recyclable can be sold second-hand to other design groups or given to TU Delft student teams. Non-recyclable components will be disposed safely at the appropriate sites.

24.5. Compliance

Table 24.3: Sustainability compliance matrix.

ID	Means of compliance	Status
STK13	As seen in Table 24.2, the recyclability of the drone is 60.2%.	✓

⁸URL <https://bewi.com/material/epp/> [accessed 16.06.2026.]

⁹URL <https://compositesuk.co.uk/composite-materials/faq/end-of-life-options/> [accessed 16.06.2026.]

¹⁰URL <https://www.arpro.com/sustainability/circularity/arpro-recycled> [accessed 16.06.2026.]

¹¹URL <https://zdcomposite.com/products/carbon-fiber-rod-suppliers-for-eco-recycled-material/?> [accessed 16.06.2026.]

¹²URL <https://www.energie-nederland.nl/en/topics/renewable-energy/> [accessed 19.05.2026.]

¹³URL <https://selectra.nl/energie/vergelijken/energieprijzen-index?.com> [accessed 19.05.2026.]

²URL <https://www.herewinpower.com/drone-battery/drone-battery-replacement-and-its-importance-for-optimal-performance-2/> [accessed 19.05.2026.]

25. Future Developments

This chapter details the future developments of Dronado. Section 25.1 details the design and development logic, Section 25.2 gives the post-DSE Gantt chart, and Section 25.3 provides the cost breakdown structure of the next steps of the Dronado project. Compliance with the system’s manufacturing requirement from Table 25.1 is shown in Section 25.4.

Table 25.1: Requirements relevant to manufacturing time.

ID	Requirement
STK29	The system shall be manufacturable in less than 6 months.

25.1. Design and Development Logic

Technology Readiness Levels (TRLs) are a nine-stage framework used to evaluate the maturity of a technology, ranging from a basic concept (TRL 1) to a fully operational and proven system (TRL 9) [97]. Originally developed by NASA for the assessment of space technologies, the TRL framework is now widely adopted throughout the aerospace industry [98]. Figure 25.1 shows all TRLs and their meaning.

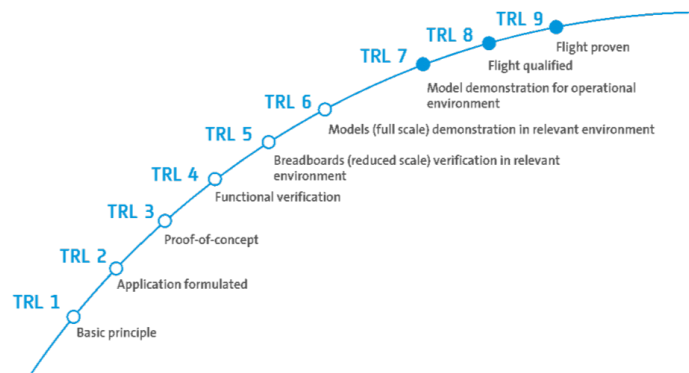


Figure 25.1: Technology Readiness Levels (TRLs) used within ESA technology programmes.¹

Figure 25.2 presents the main steps that the project is expected to follow after the completion of the DSE, in chronological order. This roadmap is divided into five main development phases: Design Maturation, Prototype Development, Integrated Demonstrator, Prototype Demonstration and Certification, and Service. Each phase is associated with a target TRL, indicated below the phase title as “Target Maturity”. Coloured arrows connecting the activity blocks represent logical dependencies between tasks. By the end of the DSE project, the Dronado Design Maturation is expected to reach a maturity of TRL 3.

The roadmap is organised into four parallel workstreams that evolve concurrently throughout the development process. First, the Technical Design & Analysis workstream focuses on the evolution of the system architecture, aerodynamic modelling, flight dynamics, mission simulation environment, and control system development. In parallel, the Hardware & Manufacturing workstream addresses subsystem integration, prototype manufacturing, assembly procedures, and the preparation of operational hardware. The Testing, Verification, and Validation workstream spans the entire development life cycle and continuously validates the outputs of the other workstreams through simulations, subsystem testing, integrated prototype demonstrations, and operational evaluations. Finally, the Business & Regulatory workstream covers certification activities, industrial partnerships, funding strategies, operational deployment planning, and commercialisation efforts.

¹URL https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Technology_Readiness_Levels_TRL [accessed 20.05.2026.]

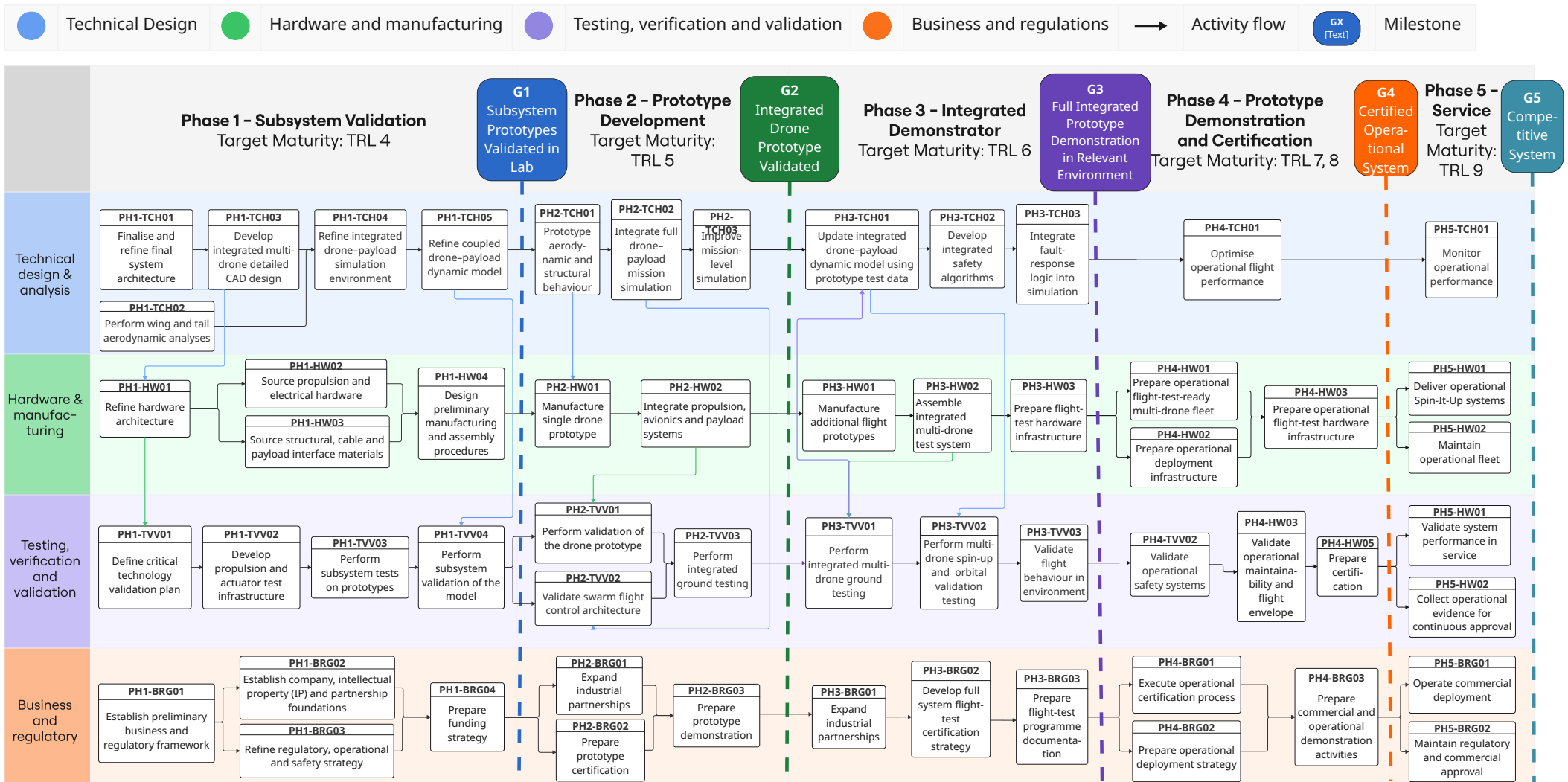


Figure 25.2: Product Design and Development Logic for the future development of Dronado.

25.2. Project Gantt Chart

The Gantt chart gives an overview of the timeline of all the tasks that will have to be performed after the completion of DSE in late June 2026 to realise the Dronado system. The timeline for the remainder of 2026 is specified at weekly resolution, while the 2026–2030 period is less detailed due to higher uncertainty in task duration. The first step in this process is completing the detailed design, which will be performed in July and August 2026. Prototyping of the system will be performed throughout September and October 2026. Testing of the system will then be performed continuously throughout the rest of the year and until the end of 2028. In parallel to the system being tested at Valkenburg, the production of the system will be expanded to industrial scale in preparation of introducing the system to the market. The system is estimated to enter operation beginning in 2029. The major tasks are broken up into two sublevels of tasks that have to be performed for the higher level task to be considered complete.

25.3. Cost Breakdown Structure

In addition to the parts cost, already covered in Chapter 18, the Cost Breakdown Structure (CBS) for the prototyping phase investigates the additional expenses after the Research & Development of the DSE, as shown in Figure 25.3. The non-recurring cost of manufacturing and testing is taken into consideration, as well as the recurring operational and maintenance cost of the Dronado system (R).

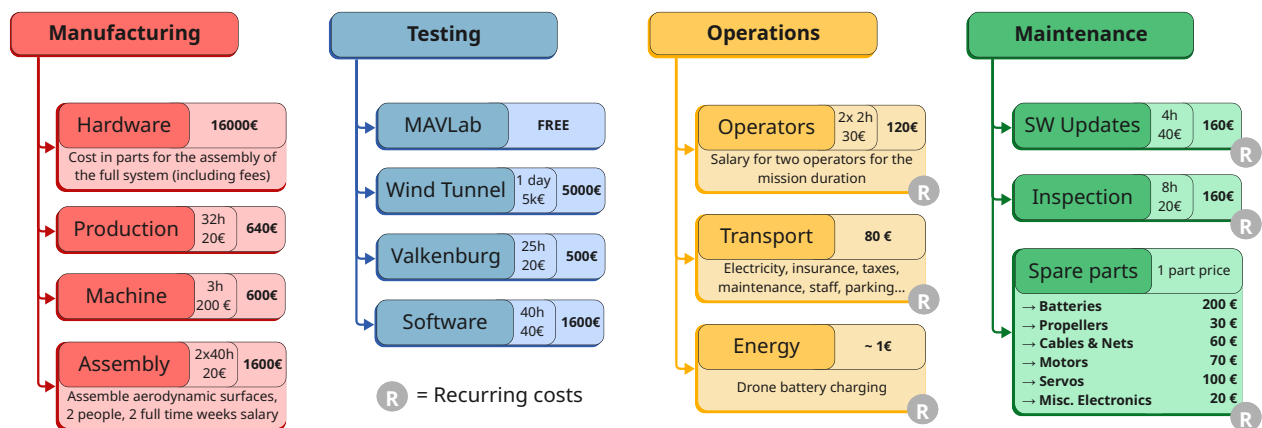


Figure 25.3: Cost Breakdown Structure

Non-recurring manufacturing costs are led by parts procurement at 16,000 EUR. As Dronado is designed for university-scale manufacturing, TU Delft student salaries of ~20 EUR/hour apply throughout. Hot-wire cutting of the aerodynamic surfaces across three drones requires a 32-hour student contract, costing ~640 EUR. CNC machining of the foam fuselages totals three hours across the three drones at ~200 EUR per drone, amounting to ~600 EUR. Assembly requires two full-time student weeks per drone, totalling ~1,600 EUR. Testing costs, reported from Chapter 16, include one senior software engineer week at ~1,600 EUR.

Recurring costs cover operations and maintenance. Transportation to a safe take-off area via electric Mercedes-Benz Sprinter van is estimated at 80 EUR per mission, including staff, insurance, charging, and parking. Battery charging costs ~1 EUR per mission per drone (capacity ~600 Wh, electricity at 0.25 EUR/kWh as of April 2026²). Two operators at ~30 EUR/hour cover each two-hour mission (40 min setup, 20 min flight). Maintenance includes software updates for the flight controller and trajectory planner (~40 EUR, four hours, per patch release) and monthly inspections — or every 10 mission cycles — requiring an eight-hour expert overhaul at ~20 EUR/hour, totalling ~160 EUR. Spare part replacements are detailed in Figure 25.3.

25.4. Compliance

Table 25.2: Manufacturing time compliance matrix.

ID	Means of compliance	Status
STK29	The manufacturing is done in 1 month.	✓

²URL <https://www.anwb.nl/energie/wat-kost-1-kwh> [accessed 16.06.2026]

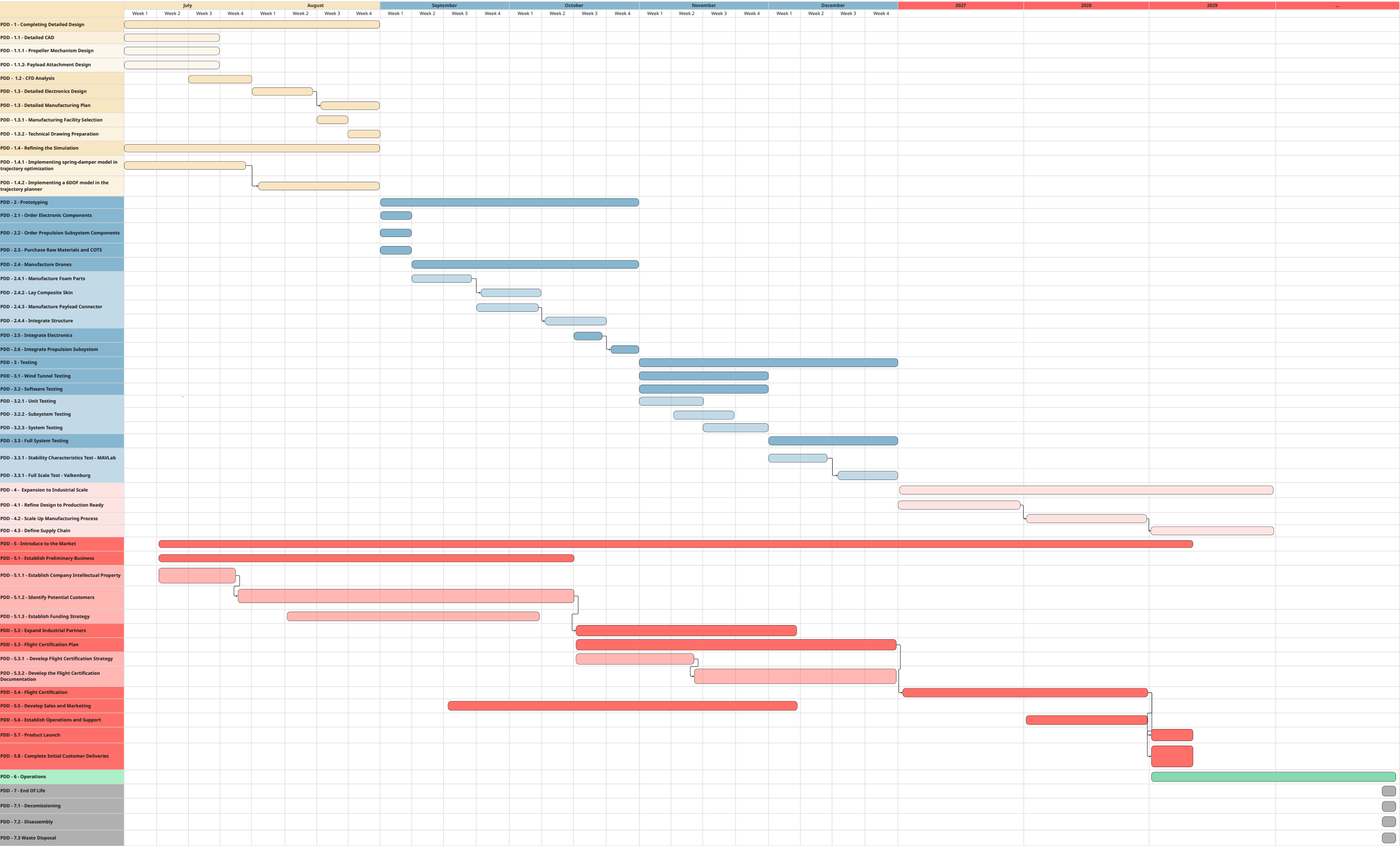


Figure 25.4: Post DSE Gantt Chart.

26. Recommendations

The following recommendations outline the steps required to further develop and validate the Dronado system design. The recommendations address both hardware and software aspects of the system and lay out a clear roadmap to bring the design closer to commercial viability.

The priority is to increase the fidelity of the trajectory generation. In particular, the current representation of the payload connection should be improved by explicitly including a spring–damper cable model. The limitations of the rigid cable assumption were clearly visible in the results, and while the system still functioned, the assumption is a poor representation of real cable behaviour at the lengths of the cables in the system, and the resulting trajectories were noticeably affected. Capturing cable dynamics more accurately would significantly improve the realism of predicted payload motion and drone interaction forces, and would likely lead to considerably smoother and more efficient trajectories.

A second key step is to enable online execution of the trajectory planner. This requires adapting the formulation to be compatible with onboard implementation constraints. For example, the initial state of each moving horizon iteration could be constrained to the current estimated position and velocity of each drone. In addition, the computational performance of the planner must be significantly improved to meet real-time requirements. Possible approaches include replacing the current CasADi-based optimisation backend with a more lightweight solver, tuning the moving horizon window size, and reducing the number of state variables or constraints where possible while maintaining acceptable accuracy.

The drone controller should be expanded to include Total Energy Control for pitch and thrust commands: pitch would control exchanges between kinetic and potential energies, and thrust would control total energy. This addresses the coupled nature of pitch and thrust, and the resulting undesirable phugoidal motion of the drone.

For validation purposes, the simulation environment should be extended to include higher system fidelity. This includes modelling control surface dynamics, actuator limits, and sensor effects such as noise and delay. The trajectories should then be re-evaluated under these conditions to assess robustness against realistic operational uncertainties.

Although the hardware capabilities are not the bottleneck of the system operations, several steps can be taken to further optimise the drone design. The sizing process has to further address the findings from the validation performed on the aerodynamic subsystem. Performed simulations uncovered simplifications in the sizing procedure, which led to an overestimation of the lift-to-drag ratio. With that, further work needs to be performed to ensure the range requirement of 20 km is fulfilled. In addition, the sizing procedure should be repeated with an updated mass estimate based on found COTS components.

Next to further polishing the design stage, further optimisations can be made by integrating more automated and accurate aircraft sizing methods like AeroSandbox¹ or OpenVSP² into the sizing loop, where detailed aerodynamic and structural analysis should be performed eventually using CFD and FEM to validate the design.

Finally, from a design-implementation perspective, the current system is sufficiently developed to justify physical prototyping. The recommended next step is to construct and test a single drone prototype under conditions representative of those it would experience in the final multi-drone configuration, to continue the verification and validation process of the structural design without requiring the full system to be built. This is a practical and cost-effective way to start testing and builds confidence that the design is physically viable before committing to complete system assembly.

¹URL <https://peterdsharpe.github.io/AeroSandbox/> [accessed on 17/06/2026]

²URL https://openvsp.org/pyapi_docs/latest/ [accessed on 17/06/2026]

27. Conclusion

This Design Synthesis Exercise project addressed the feasibility of a collaborative, scalable, swarm-based cargo transportation system capable of delivering a 50 kg payload over a distance of 20 km. The final concept consists of three hybrid VTOL fixed-wing drones with rotatable propellers, each weighing 7.8 kg, connected to a net-enclosed payload by cables. The system combines the flexibility of vertical take-off and landing with the efficiency of fixed-wing flight through cooperative “spinning” around the payload during climb and descent. Each drone is identical to the other units in the swarm, allowing for a scalable approach to adapt to a heavier payload. In the event one of the units breaks, replacement is also easily available.

The project’s central contribution was a trajectory optimisation framework formulating the load-sharing and coordination problem as an Optimal Control Problem, solved with CasADi. Related work has largely focused on cooperative transport with multirotors, which offer high agility and utilise simpler, less-coupled dynamic models. The fixed-wing case is considerably less explored, due to its strongly nonlinear and coupled dynamics. The framework was shown to generate trajectories for the entire fixed-wing swarm successfully for a complete mission, including vertical take-off, climb, cruise, descent, and vertical landing. A major finding was that the optimiser found the spinning motion as optimal for vertical ascent and descent, demonstrating this trajectory is dynamically feasible for fixed-wing swarms while maintaining payload tracking and coordinated load sharing. Furthermore, the descent and vertical landing mission phases are also shown to be performable in case one drone fails. The Optimal Control Problem follows a prescribed trajectory for the payload and accordingly orchestrates the swarm to achieve the smallest trajectory error to the payload reference.

Another major contribution was the development of the design of a drone with a ratio of payload-to-drone mass close to three, largely exceeding capabilities currently achieved by hybrid VTOL drones. This was addressed by ensuring the payload is lifted purely by the lift force generated by the wing and allowing the drone to be highly optimised in cruise, and only needing the VTOL capability at the initial and final swarm take-off, where the payload is not carried, and cables are relaxed. The fixed-wing UAV drone design also imposed a challenge on trajectory planning, with many constraints regarding the drone’s manoeuvrability. Rather than prescribing a take-off manoeuvre to resolve this, the optimiser was given freedom over the trajectory and tasked only with lifting the payload. The converged trajectory was a coordinated spin-up manoeuvre, with the three UAVs rotating about the suspended load.

The developed system needed to comply with a set of specific constraints posed by the client. The final design fulfilled the majority of these requirements. In particular, the drone mass of 7.8 kg and total system cost of EUR 15,900 were kept well below the client’s requirements of 10 kg and EUR 20,000. Operational constraints were met by making the structural design modular. Safe handling of failure criteria was ensured and demonstrated through a feasible trajectory generated for the system with one drone inoperative. The recyclability of the system was also kept at the prescribed level of 60 % of the drone mass. A certain degree of uncertainty was introduced by conflicting results in the estimates of aerodynamic efficiency. As such, further aerodynamic testing would need to be conducted to increase confidence in the system meeting the prescribed operational range. Another aspect in which user requirements have not yet been fulfilled is the system certification. However, this aspect was identified as exceeding the project’s scope and was not addressed further.

Overall, this project demonstrated that a safe, scalable, and sustainable swarm-based cargo transportation system is achievable. The combination of modularity, redundancy, and coordinated multi-drone operation provides a strong basis for further development and future implementation of large-scale aerial cargo transport.

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