

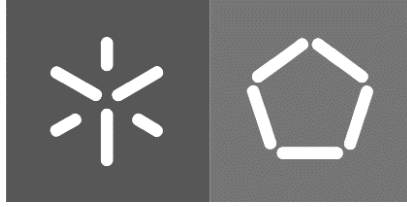


University of Minho
School of Engineering

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Long-range UAV configuration project

October 2024



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School of Engineering

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Long-range UAV configuration project

Specialization in Aerospace Engineering Design

Work carried out under the guidance of the
Professor Dr. Gustavo Rodrigues Dias

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ACKNOWLEDGMENTS

This master's dissertation marks an important stage in my life, both personal and professional, crowning a journey that began five years ago, when I started my degree. Along this path, I have sailed through tides of knowledge and experienced moments of joy and overcoming, difficulties and achievements. Although words are insufficient to express my deep gratitude, it is with gratitude that I register here my appreciation for all those who have contributed to my growth and helped me become the person I am today.

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To friends and fellow aspiring engineers, who throughout this journey have offered me not only friendship, but also welcome distractions and moments of companionship, I leave a special thanks. May you have the greatest success in your careers and in life.

INTEGRITY STATEMENT

I declare that I have acted with integrity in the preparation of this academic work and confirm that I have not resorted to the practice of plagiarism or any form of misuse or falsification of information or results in any of the stages leading to its preparation.

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Projeto de configuração de um UAV de longo alcance

RESUMO

Este trabalho aborda a operação de Veículos Aéreos Não Tripulados (VANTs) de longo alcance pela Força Aérea Portuguesa (FAP) na Zona Económica Portuguesa (ZEP). A análise foca-se nos sistemas não tripulados existentes, visando o projeto de um VANT inovador que preencha uma necessidade, explorando desafios operacionais específicos e propondo soluções inovadoras. A metodologia envolve uma revisão crítica da literatura, análise detalhada dos componentes e sistemas dos VANTs e a aplicação de conceitos fundamentais de projeto, aerodinâmica, performance e materiais, com o uso de ferramentas como o OpenVSP para o dimensionamento da aeronave. O projeto da aeronave abrange o dimensionamento da fuselagem e das superfícies de voo, a análise do sistema propulsivo e trem de aterragem. Por fim, é realizado o refinamento do peso máximo a decolagem, são realizadas análises aerodinâmicas, de estabilidade dinâmica e de distribuição de pressão e escoamento visando garantir a eficiência e viabilidade do design proposto. Esta dissertação contribui para a compreensão aprofundada dos VANTs de longo alcance, oferecendo recomendações valiosas para fortalecer as capacidades operacionais da FAP na ZEP. O trabalho funciona como um guia técnico para o desenvolvimento de VANTs, considerando desafios específicos da missão proposta.

PALAVRAS-CHAVE

Projeto, Força Aérea Portuguesa, VANTs, Zona Económica Portuguesa

Long-range UAV configuration project

ABSTRACT

This work addresses the operation of long-range Unmanned Aerial Vehicles (UAVs) by the Portuguese Air Force (FAP) in the Portuguese Economic Zone (ZEP). The analysis focuses on existing unmanned systems, aiming to design an innovative UAV that meets operational needs, exploring specific operational challenges and proposing innovative solutions. The methodology involves a critical literature review, a detailed analysis of UAV components and systems, and the application of fundamental concepts in design, aerodynamics, performance, and materials, using tools like OpenVSP for aircraft sizing. The aircraft design encompasses the sizing of the fuselage and flight surfaces, analysis of the propulsion system, and landing gear. Finally, a refined estimate of the maximum take-off weight is performed, along with aerodynamic, dynamic stability, and pressure distribution and flow analyses, aiming to ensure the efficiency and viability of the proposed design.

This dissertation contributes to a deeper understanding of long-range UAVs, offering valuable recommendations to strengthen the FAP's operational capabilities in the ZEP. The work serves as a technical guide for UAV development, considering specific challenges of the proposed mission.

KEYWORDS

Design, Portuguese Air Force, Portuguese Economic Zone, UAVs.

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LIST OF ABBREVIATIONS

2D	- Two-Dimensional
3D	- Three-Dimensional
AAV	- Autonomous Aerial Vehicle
ACP	- Aerodynamic Loads Computing Point
AES	- Advanced Encryption Standard
AIS	- Automatic Identification System
AGL	- Above Ground Level
AMSL	- Above Mean Sea Level
BLOS	- Beyond Line of Sight
BRLOS	- Beyond the Radio Line
C2	- Command and Control
CAD	- Computer Assisted Project
CBRN	- Chemical, Biological, Radiological and Nuclear
CIAFA	- Air Force Academy Research Center
CFD	- Computational Fluid Dynamics
CG	– Center of gravity
DES	- Unreleased Turbulent Effect Simulation
DGAIED	- Directorate-General for Armaments and Defense Equipment
DOF	- Degrees of Freedom
DSTO	- Defense Science and Technology Organization
EASA	- European Aviation Safety Agency
EDA	- European Defense Agency
EEZ	– Exclusive Economic Zone
EMSA	- European Maritime Safety Agency
EO	- Electro-optical
EPIRB	– Emergency Position Indicating Radio Beacon
EU	- European Union
FAP	- Portuguese Air Force
FEA	- Finite Element Analysis

FI - Fuel Injection
FINAS - Flight Information Navigation Services
FRONTEX - European Border and Coast Guard Agency
GMTI - Ground Moving Target Indicator
GPS - Global Positioning System
IR - Thermal Infrared Sensor
LOS - Line of Sight
LPM - Military Programming Law
MMTI - Maritime Moving Target Indicator
MoC - Means of Compliance
MTOW - Maximum Takeoff Weight
NRC - National Research Council
NATO - North Atlantic Treaty Organization
OpenVSP - Open Vehicle Sketch Pad
PITVANT - Technological Research Project in Unmanned Aerial Vehicles
PSD - Power Spectral Density
RC - Remote Control
SAR - Search and Rescue
SAS - Stability Augmentation System
SFN - National Forces System
SHOL - Ship-to-Helicopter Operational Limits
STANAG - Standardization Agreement
TDLAS – Tunable Diode Laser Absorption Spectroscopy
UAS - Unmanned Aerial System
UAV - Unmanned aerial vehicle
UCAV - Unmanned Combat Aerial Vehicles
VIMAR - Maritime Surveillance
WBS - Work Breakdown Structure
ZEP – Portuguese Economic Zone

LIST OF GREEK, ROMAN, AND SUBSCRIPTS SYMBOLS

<i>Symbol</i>	<i>Description</i>	<i>Units</i>
α	Angle of attack	°
α_C	Clearance angle	°
α_{TO}	Take-off angle	°
a	Speed of sound	m/s
a	Acceleration (for landing calculations)	m/s ²
A_R	Aspect ratio	-
B	Distance between main and nose gear	m
B_m	Distance from main gear to CG	m
B_n	Distance from nose gear to CG	m
b	Wingspan	m
β	Sweep angle	°
C_D	Drag coefficient	-
CD_0	Parasitic drag	-
CD_i	Induced drag	-
C_f	Skin friction coefficient	-
C_L	Lift coefficient	-
c_m	Mean chord	m
C_{M_x}	Roll moment coefficient	-
C_{M_y}	Pitch moment coefficient	-
C_{M_z}	Yaw moment coefficient	-
c_p	Specific Fuel consumption	lb/hp/hr
c_r	Root chord	m

c_t	Tip chord	m
$\bar{c}$	Aerodynamic chord	m
D	Drag	N
d	Diameter	m
D_{max}	Maximum fuselage diameter	m
E	Flight endurance	m
E_t	Total energy equation	-
e	Oswald efficiency factor	-
F	Form factor	-
F_f	Friction of movement on the ground	N
F_n	Static load on nose gear	N
F_m	Static load on main gear	N
g	Gravitational acceleration	m/s ²
H_f	Fuselage tail clearance height	m
H_c	Clearance height	m
H_{TR}	Transition height	m
I_{xx}	Longitudinal inertia moment (Roll)	kg·m ²
I_{yy}	Lateral inertia moment (Pitch)	kg·m ²
I_{zz}	Vertical inertia moment (Yaw)	kg·m ²
L	Lift	N
L_G	Ground lift	N
l	Length	m
M	Mach number	-
MF_{Struct}	Structural weight fraction	-

MF_{Subs}	Subsystems weight fraction	-
MF_{Energy}	Energy weight fraction	-
η_p	Propeller efficiency	-
p	Pressure	Pa
P_r	Prandtl number	-
π	Pi number	-
q	Dynamic pressure	Pa
q	Heat flux	W/m ²
Q	Interference factor	-
R	Range (UAV calculations)	km
R	Ideal gas constant	J/(kg·K)
Re	Reynolds number	-
R_{TR}	Transition slope	m
ρ	Air density	kg/m ³
S	Wing reference area	m ²
s_A	Approach distance	m
s_B	Braking distance	m
s_{BFL}	Total take-off distance	m
s_{CL}	Climb distance	m
s_{FR}	Free roll distance	m
s_G	Ground roll distance	m
s_L	Total landing distance	m
s_R	Rotation distance	m
s_{TR}	Transition distance	m

S_{wett}	Wetted area	m ²
T	Temperature (in fluid dynamics)	K
T	Thrust (take-off/landing calculations)	N
t	Time	s
u	Velocity in x-direction	m/s
v	Velocity in y-direction	m/s
V	Speed	m/s
V_c	Cruise speed	m/s
V_{max}	Maximum speed	m/s
V_{TO}	Take-off speed	m/s
V_{TD}	Landing transition speed	m/s
w	Velocity in z-direction	m/s
W	Weight	N or kg
W_{avion}	Avionics weight	kg
W_{begin}	Initial cruise weight	N or kg
W_{end}	Final cruise weight	N or kg
W_{fuel}	Fuel weight	kg
W_{other}	Other weights	kg
$W_{payload}$	Payload weight	kg
$W_{propulsion}$	Propulsion weight	kg
W_{struct}	Structural weight	kg
x, y, z	Specific coordinates	m
γ_{CL}	Take-off angle	°
γ	Specific heat ratio	-

λ	Taper ratio	-
λ_{LE}	Leading edge sweep angle	°
μ	Dynamic viscosity	Pa·s
μ	Friction coefficient (take-off/landing)	-
τ	Stress tensor	N/m ²

1. INTRODUCTION

Portugal has an extensive area of maritime jurisdiction for Search and Rescue (SAR), covering more than 5 million km^2 (see Figure 1), making it one of the largest in the world and the most important in Europe. The vast operational landscape underlines the need for advanced technological solutions capable of efficient monitoring and surveillance. The integration of Unmanned Aerial Systems (UAS) with manned aircraft emerges as a strategic approach to meet these demands (Oliveira, 2016).

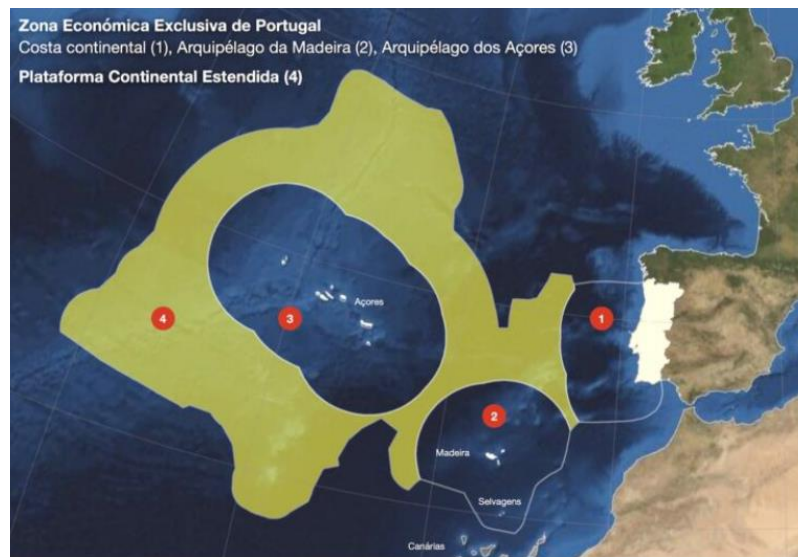


Figure 1 – Portugal's Exclusive Economic Zone

(Batista, 2023)

The evolution of these platforms in the context of the Portuguese Air Force (FAP) began in 2009, involving manufacturing, testing and deployment of continuous missions. Currently, the existing UAS at the Air Force Academy Research Center (CIAFA) reveals certain operational limitations observed over the years. There is a recognized need for more capable aircraft, equipped with state-of-the-art systems, suitable for both domestic and international applications (Morgado, 2017).

In addition, FAP has secured a key role as a class I ($\leq 150kg$) UAS service provider to monitor maritime pollution on behalf of the European Maritime Safety Agency (EMSA). In this context, it is imperative to strengthen the capabilities of the CIAFA fleet to meet the demands of maritime surveillance and monitoring of air pollution, particularly induced by cargo ships, in line with European and national interests.

The motivation behind this research is guided by the need to understand and enhance FAP's operational capabilities in the domain of long-range UAVs. The choice of this theme stems from the strategic relevance of these systems in the surveillance and protection of the ZEP, highlighting the importance of developing innovative solutions to optimize the effectiveness and efficiency of unmanned aerial operations.

Therefore, this project involves the development of a class I aircraft, responding to a main distance requirement covering broader surveillance needs of the Portuguese Economic Zone, aligning the project with regional properties. The choice of the theme " Long range UAV configuration design" is driven by the strategic military relevance and the emerging civilian applications of UAVs. The growing need for operations without exposing pilots to risks, combined with the potential for innovation in CIAFA, justifies the exploration of composite materials. This context offers challenging technical opportunities, in line with global trends in efficiency and sustainability in the aerospace sector. The approach to the topic at CIAFA represents a unique opportunity to contribute to scientific and practical advances in this area.

Throughout this report, the overview of long-range UAVs will be addressed, delving into the analysis of the unmanned systems already in use by the FAP. In addition, the unique nature of the ZEP and the specific challenges the Air Force faces when operating in these conditions will be explored.

The present work will follow a structured methodology, starting with the critical review of the literature related to long-range UAVs, until the review of fundamental concepts such as design, flow conditions, OpenVSP and relationship with CFD and materials used. Additionally, methods to improve the range of action and for the effective implementation of the concepts discussed will be summarized. The UAV design will follow a structure widely accepted by the literature, from market survey study, definition of the mission profile, payload analysis and avionics. A study will also be conducted on the propulsion system, definition of the characteristics of the fuselage and layout, characteristics of the wing surfaces and union of the results using OpenVSP, ensuring the coherence and efficiency of the project.

2. OVERVIEW OF LONG-RANGE UAVs IN PORTUGAL

History repeatedly demonstrates that immediate needs originating in times of war are a catalyst for the creation or improvement of technologies. The Armed Forces combine need, capacity, resources, and motivation to discover technical solutions that provide advantages over enemies (Ribeiro, 2022).

The historical feats of unmanned aircraft often replace a consistent operating pattern, known as the three D's: dangerous, dirty, and dull. Dangerous refers to situations where someone tries to bring down the aircraft or the pilot's life may be at undue risk operationally (Morgado, 2017). Dirty is when the environment can be contaminated by chemical, biological, radiological and nuclear (CBRN) hazards, preventing human exposure. Finally, dull is when the task requires long hours of manned, stressful and exhausting flight, being undesirable. Since the initial developments of unmanned aerial vehicles in wars, the dynamic Unmanned Aerial Systems (UAS) industry continues to improve at a much faster rate than ever before, a result of the constant advancement of science and technological enablement (Dave, 2023).

Currently, UAS have a wide range of possible missions (Morgado, 2017). The military interest in a system capable of simultaneously performing Intelligence, Surveillance, Target Acquisition, Reconnaissance and Neutralization, removing human risk from the equation is well known. An example of such systems with comprehensive capabilities is the Unmanned Combat Aerial Vehicles (UCAV), already in front-line operations in war zones (Ribeiro, 2022). With the greater predominance of UAS in aerospace defense, the main advantages of the absence of a pilot are low cost (cheaper aircraft and reduced operating costs per mission), reduced risk, and practicality.

The worldwide expansion of UAS has led to the need for proper regulations. The laws applied to Portugal's unmanned fleet are mainly derived from the North Atlantic Treaty Organization (NATO), the defense alliance of which Portugal is a historical member (Teixeira, 1999). The evolution of the law on the concept of UAS in NATO is recent, starting only in 2002. "NATO's UAS airworthiness standards represent 15 years of work by military experts, drawing on the experience of academic and national UAS platforms, to meet the requirements of UAS airworthiness standards" (Mayer, 2017). NATO's first Standardization Agreement (STANAG), intended to establish the technical requirements for the airworthiness certification of military fixed-wing UAV systems to operate regularly in a non-segregated airspace (FRONTEX, 2024).

This document is an airworthiness code derived from the European Aviation Safety Agency, made up of countries such as Italy, Australia, the United Kingdom, the United States of America, among others.

In the current European context, one of the active military operations that uses UAS is FRONTEX, the European Border and Coast Guard Agency. This entity provides support for the countries of the European Union (EU) and the countries associated with the Schengen Agreement in the management of their external borders, contributing to the harmonization of EU border controls (FRONTEX, 2024).

Due to the increasing capabilities, UAS have some advantages compared to other methods of continuous surveillance available to FRONTEX, such as tracking a target for a longer amount of time than a satellite that tracks the movements of the Earth, as the latter may not be able to focus on a certain point for the necessary time. In addition, each UAS deployed by EMSA, acting as a service provider for FRONTEX, is equipped to detect the slightest movement at sea, regardless of visibility conditions, through state-of-the-art technologies such as cameras, gimbals and radars (FRONTEX, 2024).

These advantages spark the desire for a broad application of UAS for border control, maritime surveillance (Mediterranean migratory routes) and security of some EU maritime borders.

FAP's activities and work in UAS date back to 2009, at the beginning of the Research and Technology Project on Unmanned Autonomous Aerial Vehicles (PITVANT). This project highlighted the development of several technological areas, such as design, manufacturing and testing, cooperative control, system interoperability, advanced vision systems, data fusion and navigation systems, through the development of three platforms: micro-RPA (Remotely Piloted Aircraft) (1 kilogram and 1 meter wingspan), ANTEX-X02 (15/25 kilograms and 3 meters wingspan) and ANTEX-X03 (110 kilograms and 6 meters wingspan) (Gonçalves, 2016). Since then, CIAFA has participated in several other projects involving UAS, namely: PERSEUS, SEAGULL, TROANTE and SUNNY. The main focus of these projects has been the development of operational procedures, capabilities and technologies for Maritime Surveillance missions. Within the last 8 years, FAP has accumulated more than 750 flying hours by UAS flights.

2.1 Portuguese Economic Zone (ZEP)

With a rich maritime tradition, Portugal possesses an ample Exclusive Economic Zone (EEZ) playing a determinant role in the national economy. The Portuguese EEZ is an area of more than one million square kilometers into the Atlantic, a real treasure trove of natural resources that range from fisheries to renewable energy and marine minerals. To guarantee the safety and security of such strategic assets, the employment of maritime Unmanned Aerial Vehicles stands out as a necessary tool (Kowalski & Antunes, 2023).

The unique geography of the Portuguese EEZ, with deep waters and extensive areas to explore, makes maritime surveillance a complex challenge. Maritime UAVs prove to be an efficient technological solution to these challenges. They provide advanced sensors, high-resolution cameras, and state-of-the-art technology to create a constant and accurate monitoring capability. Their importance to the protection of the Portuguese EEZ is manifold; constant surveillance allows for early detection against illegal activities such as unregulated fishing, hence contributing to the preservation of fisheries resources and environmental sustainability. Moreover, these vehicles play an essential role in deterring threats to infrastructure. The rapid response to critical events, such as environmental disasters or threats to public integrity, is another significant advantage provided by UAVs. The ability to cover vast areas in a short time and to transmit data in real time allows for effective action in emergency situations, minimizing environmental and economic damage (Laghari et al., 2023).

In addition, the security of commercial maritime routes that cross the Portuguese EEZ is enhanced by the constant presence of these UAVs. The detection of suspicious activities, such as illegal vessel traffic, contributes to the security of international trade and the prevention of illicit activities, such as smuggling (Viana & Carriço, 2016).

2.2 Portuguese Air Force (FAP)

Over the last years, geopolitical and geoeconomic tensions have sharply increased, matched by military assertiveness on behalf of international actors, reflected in utter disrespect for treaties and attempts at redefining borders. Events like the 2022 invasion of Ukraine by Russia contributed to changing this global scenario-a real strategic shock that has profoundly altered the international security landscape.

In this context, the Armed Forces face complex challenges, especially in the vast Atlantic area, where Russia and China intensify naval activities. Instability in regions such as Africa and the Middle East contributes to violent conflicts, threatening European security. These conflicts, many driven by territorial disputes and demands for resources, often generate spillover effects: organized crime, terror, and disorderly flows of migration.

Digital transformation, favored by the COVID-19 pandemic, has boosted challenges associated with the dissemination of disinformation, cyber-attacks, and counter-information. The Armed Forces are essential to strengthen public communication, share information nationally, with NATO and the EU, and protect military networks, including possible offensive operations in cyberspace.

The hybrid threat, characterized by coordinated actions by state actors, involves both military and non-military coercion, highlighting the importance of increasing national resilience. Responses to these threats require critical civilian capabilities, challenging the distinction between peace and conflict situations.

Finally, climate change and environmental degradation increase the risks of natural disasters, affecting safety and well-being. The archipelagos of the Azores and Madeira, historically vulnerable, require special attention. The Armed Forces play a crucial role in military support missions for civil emergencies, standing out in the areas of planning, logistics, and strategic transportation. This complex scenario requires continuous adaptation by the Armed Forces to address multidimensional challenges and contribute to global security (Ribeiro, 2022).

2.2.1 FAP Unmanned Systems Analysis

The aircraft produced allows the development of several platforms with different characteristics and performance, depending on the purpose for which it is being produced. These performance and cost characteristics are tabulated according to the classes and can be consulted in the Table 1.

Table 1- FAP platforms

	Mini				Small
	Flying Wing	Tactical Mini-UAV	ALFA	ALFA Extended	Antex
Maximum Takeoff Weight (MTOW)	3 kg	4,35 kg	13 kg	25 kg	100 kg
Payload	1,250 kg	1,8 kg	6,5 kg	10 kg	33 kg
Endurance (Thermal Motorization/Electric Motorization)	0h40m	0h45m	2h30m / 0h40m	8h00 / 2h00m	5 h
Speed	15 m/s (55km/h)	15 m/s (55km/h)	18 m/s (65km/h)	25 m/s (90 km/h)	25 m/s (90 km/h)
Altitude	1000 m	1000 m	2000 m	2000 m	3000 m
Range / Radios of action	20 km	25 km	80 km / 22,5 km	360 km / 90 km	225 km
Launch Method	Manual	Manual / Catapult	Pista / Catapult	Runway	Runway
Recovery Method	Landing	Forced Landing	Runway	Runway	Runway
Control (RC or Autonomous)	Both	Both	Both	Both	Both
Average Construction Cost (Materials, Personnel and Mission equipment)	13 000 €	17 000 €	32 000 €	55 000 €	100 000 €
Operating Cost (Fuel/Energy cost)	0,1 €/h	0,1 €/h	0,8 €/h	1 €/h	15 €/h

(Oliveira, 2016)

The Navy has shared its ambitions and needs for the use of UAS in conferences and interviews, demonstrating an ongoing desire to acquire this capability. Despite the current restrictions on the acquisition of new equipment, the Navy has been working discreetly in this direction, excelling in activities such as maintaining capacity during the reviews of the National Forces System (SFN) and the EDA.

The Navy is also attentive to the activities carried out in the context of the European Union (EU) and the European Defense Agency (EDA), actively participating in the work related to the DGAIED initiative on the national UAS capability. In meetings at the DGAIED, the Navy

confirmed the formation of a working group to define operational requirements in a more consistent manner.

Table 2 - Compilation of UAS requirements for the Navy

Compiling potential UAS requirements
Flexibility of posting and recall;
Ability to exchange data with other information systems;
Ease of dissemination of information to selected users, in appropriate formats;
Ability to detect, locate, identify, reconnoiter and verify surface targets;
Compatibility with the Navy's ISTAR system and friendly systems;
Operating capacity H24;
Comply with the requirements defined by the authorities responsible for airspace management;
Disseminate, in real time, the electro-optical image and recording capacity on board;
Communications relay capability;
Possibility of transferring control between ground stations, each having the ability to control two UAVs and define a pre-planned route with the ability to change at any time;
Requirements related to operation, logistics and maintenance.

(Oliveira, 2016)

To verify whether the platforms previously tested by the Portuguese Air Force meet the requirements and needs of the Navy, let us analyze the Table 3, which results from comparing the listed requirements with the characteristics of existing platforms Table 1.

Table 3 – Satisfaction of existing platforms according to the requirements of the Navy

Requirements	FAP Tested Platforms	
	Flying Wing	Mini-UAV Tactical
Low cost	✓	✓
Autonomous flight	✓	✓
Radius of Action > 12 MN	✓	✓
Geotagged images	✓	✓
Launch and recovery flexibility	✓	✓
Interoperability	✓	✓
Detect, locate, identify, recognize and verify	✓	✓
H24 Availability	✓	✓
Requirements of aeronautical authority	✓	✓
Real-time dissemination and recording capability	✓	✓

Communications relay	✓	✓
Transfer of control, pre-defined flight plan and control of two UAVs per ground station	✓	✓

(Oliveira, 2016)

The Portuguese Military Army also has, like the Navy, a relationship between the existing platforms studied by the FAP and its own operational needs, having a closer relationship with platforms of the Antex caliber, which has appropriate characteristics in relation to the NATO classification, as we can see in the Table 4.

Table 4 - Satisfaction of existing platforms according to Army requirements

Requirements	FAP Tested Platforms	
	Mini Platforms	Antex
Operate with GCS on the move	✓	✓
Night, day and low-visibility operation	✓	✓
Reception of video and photo in various formats	✓	✓
Laser target design	✓	✓
Interoperability with Army Command and Control (C2) systems	?	?
Multiple payload configurations	✓	✓
Real-time data transmission and in-flight storage capacity	✓	✓
Recording weather information	✓	✓
Multi-Frequency Operation	?	?
Plan mission to be executed, ability to change in flight and contingency operation due to control link failure	✓	✓
Technical Manuals	✓	✓

(Oliveira, 2016)

The release of MFA 500-12 established FAP's ambition regarding unmanned systems, outlining guidelines for both research at CIAFA and future operations. Academic research, until then focused on exclusively academic objectives, now needs to allocate resources to develop a platform capable of improving FAP's operational capacity.

The system is broadly divided into 3 classes defined by MTOW. Additional class subdivisions are defined by MTOW for smaller UAS in Class I and the role of the aircraft in Class III Table 5.

Table 5 - UAV or UAS classification

Class	Category	Altitude	Radius of action	Example
Class I <150 kg	Micro < 2 kg	60,96 m	5 km	Black widow
	Mini 2-20 kg	914,4 m	25 km	Scan Eagle
	Small > 20 kg	1524 m	50 km	Moon
Class II 150-600 kg	Tactical	3048 m	200 km	Watchkeeper, Shadow, Hermes
Class III >600 kg	MALE	13716 m	Limitless	Heron, Predator
	HALE	19812 m	Limitless	Global Hawk
	Strike	19812 m	Limitless	Reaper

(Fell et al., 2015)

It is essential to implement a classification system to stratify the necessary levels of airworthiness as in the Table 5, equipment and crew training standards. This aims to ease the burden of entry into the National Airspace System for lower-level systems, while imposing substantially higher entry requirements for UAS seeking to perform Flight Information Navigation Services (FINAS).

In the field of UAS, there are several classification systems in use (Table 5), typical designs encompass Micro, Mini (along with Small - SUAS), Tactical (TUAV), Medium Altitude - Long Duration (MALE), and High Altitude - Long Duration (HALE). In addition, there are additional groupings such as Combat (UCAV), Lighter-Than-Air (LTA), and Vertical Takeoff (VTUAV).

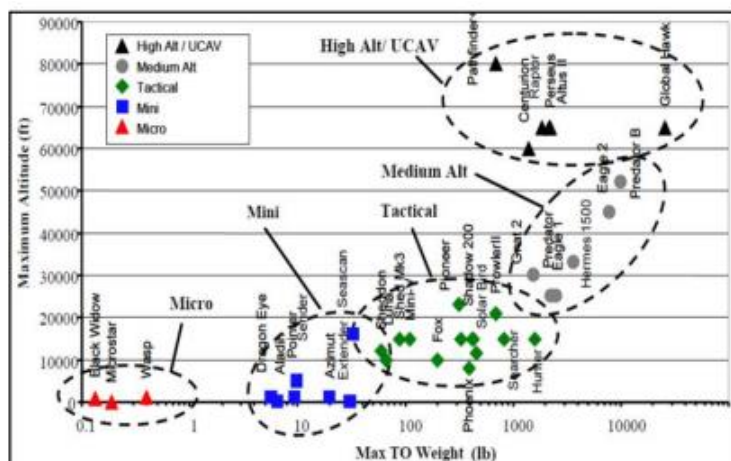


Figure 2 - Mapping of the different UAV classifications by MTOW

(Gambold, 2011)

2.2.2 Challenges faced by FAP in the operation of systems

The Portuguese Air Force faces several challenges in the operation of UAV systems. These challenges cover several areas, reflecting the complexity and specific characteristics of these systems. Following this chapter, examples of the main challenges imposed will be presented:

- **International Regulations and Standards:** Ensure compliance with national regulations and international standards, especially those established by NATO. The rapid evolution of UAV/UAS technology requires constant adaptation to ever-changing regulations (Teixeira, 1999).
- **Integration into Civil Airspace:** Effectively integrate UAVs into civil airspace, ensuring safety and coordination with conventional air traffic. Involving the development of air traffic management systems specific to UAVs.
- **Qualification and Training:** Ensure that FAP teams are adequately trained to operate and maintain UAVs. This includes training in advanced technology, remote control systems, data analysis, and mission-specific procedures.
- **Cybersecurity:** This is a major concern today because it involves safeguarding the UAV or UAS against all forms of cyber threats. Making sure data transmitted and received will not be lost, and unauthorized access into the system will not be tolerated.
- **Maintenance and Logistics:** Management in operative UAVs, together with logistic management, is a very complex activity, mainly because of the wide variety of platforms currently in service (Ribeiro, 2022).
- **Continuous Technological Development:** The rapid advancement of UAV/UAS technology requires constant commitment to technological development. Keeping platforms up to date, embracing innovations, and incorporating emerging technologies (Morgado, 2017).

Acting appropriately to these challenges requires a comprehensive approach to skills beyond investigation, research or development strategies, as well as effective human and technical resource management (Kosters, 2021).

3. OBJECTIVES AND REQUIREMENTS ANALYSIS ACCORDING TO CIAFA

The dissertation to be carried out will focus on the detailed design of an Unmanned Aerial Vehicle (UAV) belonging to class I, based on the requirements specified in the Table 6 of CIAFA.

Table 6 - Requirements of a Class I UAS according to CIAFA

Requirement	Value	Requirement	Value
Wingspan	≤ 5 m	Ceiling	4500 m
MTOW	≤ 150 kg	Take off	Optional
Endurance	8 p.m.	Maximum T/O altitude	3000 m
Range	1000 km	Recovery	Optional
Range (comms)	100 km	Operational temperature	-25° C + 50° C
Cruise speed	83.34 km/h	Anti-icing measures	Heated pilot - static tube
Max level speed	129.64 km/h	Environmental protection	≤ 5 mm/h rain
Propulsion:			
Fuel Type	Automatic	Engine Type	Internal Combustion, FI
Generator	≥ 100 W	Temperature control	Automatic
Payload:			
Transponder	Mode C	Sniffer	by Deimos Engineering
Vision Payload	≤ 5 kg	SatCom	C2, HD broadcast
Radar SAR	≤ 20 kg		
Datalink:			
Link Rate	~ 12 Mps	Encryption	128/256-bit AES
Frequency	$\sim 2,4$ Ghz	Frequency	VHF, capable of C2
Flight System:	Autopilot type	Piccolo or UAVision	

(Angelo, 2019)

Although it is known that the developed UAV will be classified as Class I due to its design style, it is important to understand some of the class differences between the respective UAVs. Therefore, Table 7 and Table 8 present the characteristics of Class II and Class III UAVs, respectively.

Table 7 - Requirements of a Class II UAS according to CIAFA

Requirement	Value
Cruise speed	111.12 kph
Operating altitude	5000 - 15000 m
Endurance	9 a.m.
Range (comms)	90 nm ELOS (radio)
Payload:	
Performance	Communications RT, EO visible/IR mid resolution
Desirable	Laser designator, Marine Band Relay
Configurable	Receptor AIS

(Emanuel & Pereira, 2016)

Table 8 - Requirements of a class III UAS according to CIAFA

Requirement	Value
Cruise speed	166.68 km/h
Operating altitude	10000 - 35000 m
Endurance	30 hrs
Range (comms)	Limited BLOS (stylite)
Payload:	
Performance	Communications RT, EO visible/IR high resolution
Desirable	Equipment SIGINT and ELINT
Configurable	AIS Receiver, Laser Redesigned
Future provisions	Stealth technology, armament

(Emanuel & Pereira, 2016)

Following the project, more requirements will be detailed and studied not to contradict those already imposed by CIAFA, but to complement the project, chapter 7.1. To meet structural, mass, and operational requirements, structure design requires a proactive

approach to optimize the design of each individual component. This process involves a balance between four fundamental criteria, accompanied by specific conditions and constraints, weight minimizing the load on the structure, design simplifying the structural geometry to facilitate fabrication, the materials used must be available or possibly to be acquired by CIAFA and the developed aircraft must be able to maximize the distance traveled considering the airspace of the ZEP.

In addition, extra contributions to the project will be highlighted, including systems integration, which includes the determination of the Payload, Avionics and Propulsion System required to execute the desired mission.

4. REVIEW OF FUNDAMENTAL CONCEPTS

Aircraft design encompasses four fundamental areas of aerospace engineering: aerodynamics, structures, control and propulsion, as represented in the Figure 3. These areas will be the central emphasis of the thesis on aircraft design, each of these areas involves parameters that govern the size, shape, weight and performance of an aircraft. When designing a new aircraft, the crucial starting point is the clear identification of its purpose. Given that it is not feasible to optimize all performance disciplines in an aircraft, the definition of the underlying reason guides to establishing the design factors (Corke, 2003).

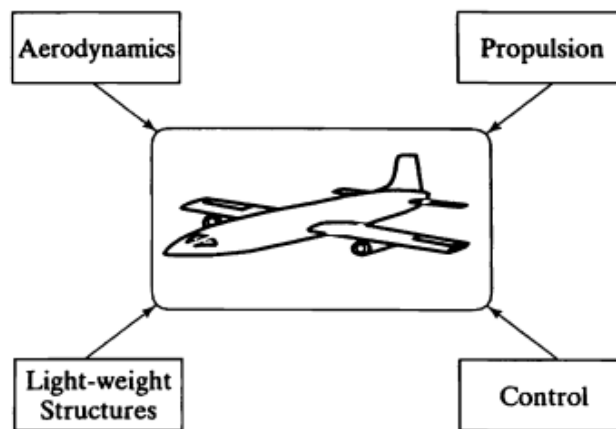


Figure 3 – Fundamental areas of aerospace engineering
(Corke, 2003)

To balance the various aspects of overall performance, we seek to optimize some (or one) requirements based on the well-defined mission profile. Mission requirements can specify many aspects of performance, including the purpose of the aircraft or mission profile, the type and amount of payload, the cruise and maximum speeds, the normal cruising altitude, the range or radius at normal payload, the range, the takeoff distance at maximum weight, and the landing distance at 50 percent of the maximum fuel weight. This process aims to find the ideal balance between these parameters, considering the constraints and trade-offs inherent in aircraft design. In this case this information will not be created because there are already basic characteristics as presented in the Table 6, Table 7 and Table 8.

A class I UAV designed for maritime surveillance can be subdivided into two subcategories, based on specific requirements to meet the mission, namely autonomy and payload.

The aircraft's primary function is to carry the mission payload along a route designed for surveillance. In addition, it must carry the subsystems necessary for complete operation, including communications, control equipment, and power supply. The requirement for high operational autonomy (one of the main drivers of the project) will determine the amount of fuel to be transported, or the number of batteries that the system must carry by adapting an electrical system. From an aerodynamic point of view, to achieve the desired range, it is crucial to optimize performance through an efficient propulsion system and optimized aircraft aerodynamics (Morgado, 2017).

The Israel Aircraft Industries RQ-2 Pioneer stands out as a prominent figure in surveillance, accumulating more than 50,000 flight hours. With a two-blade side configuration and a central motor at the rear, driven by a single AR-741 rotary motor (in the latest update), this system has an autonomy of five hours, considering its maximum take-off weight (MTOW) of 205 kg (Parsch, 2007).



Figure 4 – Israel Aircraft RQ-2
(Parsch, 2007)

In the 2000s, Israel introduced the Aerostar, a UAV that has achieved several world records in its class, serving as a standard pivot of reference, feasibility, life cycle, operations, distance, payload, efficiency and cost (Israeli weapons, 2006).

The quality standard imposed by this UAV and other examples such as Penguin C, the Shadow family, RQ-5 Hunter, BAE SkyEye and the Bayraktar defined the common configurations for two side blades and a central engine at the rear.

The UAVs developed by the Portuguese Air Force share the external characteristics in the mentioned weight range. The configuration with two side blades in the tail has been the predominant choice for the Antex configuration ($\approx 150\text{ kg}$) over the last decades, demonstrating effectiveness.

Exploring options for smaller UAS, we found alternatives with high range and the traditional rear engine configuration at the end of the fuselage, such as the TEKEVER AR3 and Boeing ScanEagle, both with MTOW equal to 22 kg and light rear engine. On the other hand, for an MTOW close to 450 kg , there are other options with the same conventional configuration (rear motor placement), exemplified by the Hermes 450 and the WatchKeeper WK450. In this scenario, the payload of these aircraft is approximately equal to the desired weight for the UAV, which mitigates the impact of having a heavier rear engine.

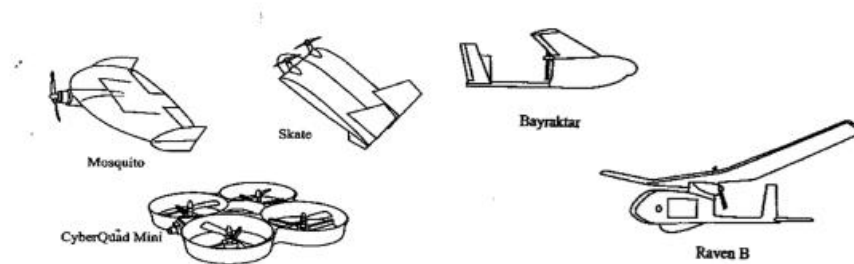


Figure 5 - Small UAV configurations
(Giffin et al., 2021)

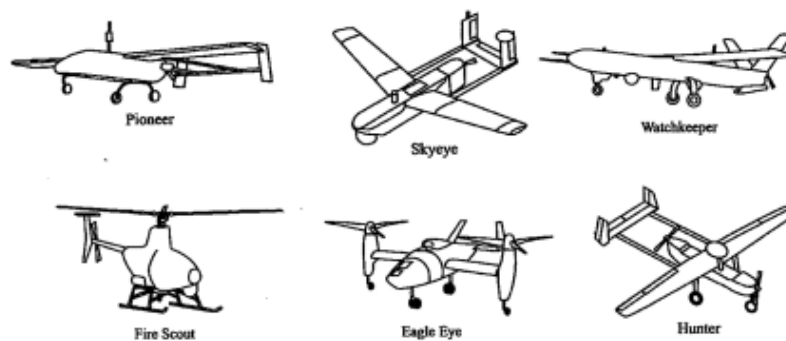


Figure 6 - Midsize UAV configurations
(Giffin et al., 2021)

4.1 Project

The process of designing and developing an aircraft, from the initial phase to the creation of a flight test prototype, involves a sequence of fundamental steps, as illustrated in the Figure 4. It begins by identifying a need or opportunity for a new aircraft, driven by both perceived market perspectives and technological advances from research and development.

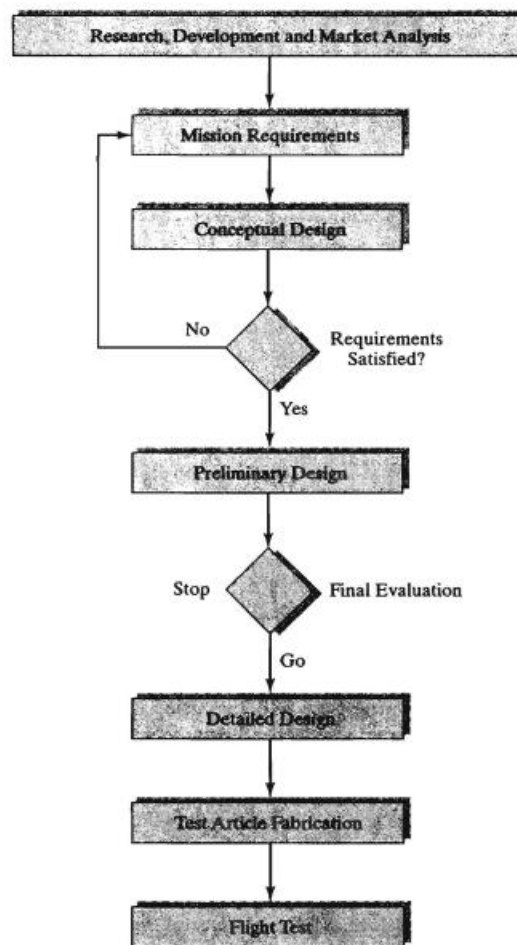


Figure 7 – Flowchart of the design process

(Corke, 2003)

The market analysis includes a market share forecast, evaluating factors such as the demand for a new design of specific size and performance, the existing competition, and the similarity to existing aircraft. A new design, competitive in performance and cost, is designed to garner an equitable share of sales relative to existing competitors. Market analysis is also an important parameter to study to understand where the developed project is, and a study

is made of aircraft characteristics that resemble the one being proposed, but to emphasize a specific requirement.

The needs and capabilities identified in the market research define the mission requirements for a concept aircraft, compiled into a design proposal that lays out the motivation for the new design and the "technological readiness" of the innovations to be incorporated. The clear definition of mission requirements precedes the start of the project and allows for the identification and optimization of key performance aspects, known as "design protocols".

After the design proposal, the sequence progresses to the conceptual design stage, which develops the first overall configuration and dimensions for the aircraft. This stage includes weight estimates, choice of aerodynamic characteristics and sizing of the systems. The conceptual design seeks to meet the mission requirements set out in the design proposal by identifying and optimizing the essential elements such as payload, wing, and engine layout.

The next stage is preliminary design, a step of fine-tuning the conceptual design through parametric testing on scale models. This stage deals with more challenging aspects of forecasting, such as engine interaction with the fuselage and wing, and wing interaction with control surfaces. It also involves a more detailed analysis of aerodynamic loads and component weights, further refining the structural design.

Subsequently, the process progresses to detailed design, where every aspect of the structural design is meticulously worked out for the construction of the aircraft. At this stage, detailed considerations are made about the manufacture of the aircraft, with further refinement of cost estimates. The decision to proceed with the construction of the aircraft is made, marking the "freeze" of the project.

4.2 Performance & Aerodynamics

The dissertation explores the process of aircraft design, accentuating aerodynamics and flight performance. Flight performance involves different stages, including straight-line stabilization, stabilized ascent and descent flight, level turns, gliding flight, take-off and landing. However, when analyzing the design proposal, it is evident that stabilized flight in a straight line constitutes the core of the mission, and autonomy emerges as one of the main design decision factors. While a detailed theoretical analysis of all phases is exhaustive,

unnecessary, and impractical, as for the purpose of the project, it is crucial to understand the concept of autonomy and how to optimize it in level flight.

Autonomy is the representation of the maximum period in which the aircraft can remain in the air without the need for refueling (Gunston, 2012). (Roskam & Lan, 1997) apply Breguet's equation to propeller-driven airplanes, and define autonomy as follows:

$$E = \int_{W_{begin}}^{W_{end}} \frac{\eta_p}{c_p g} \frac{dW}{DV} = \frac{\eta_p}{c_p g} \frac{C_L^{\frac{3}{2}}}{C_D} \sqrt{2\rho S} \left(\frac{1}{\sqrt{W_{end}}} - \frac{1}{\sqrt{W_{begin}}} \right) \quad (1)$$

In the equation presented, E it symbolizes the flight autonomy, W_{begin} and W_{end} the weights of the aircraft at the beginning and end of the cruise flight, η_p it is the efficiency of the propeller, c_p indicates the specific fuel consumption, g corresponds to gravitational acceleration, V is the speed during level flight, C_L and C_D is the total lift and drag coefficients of the aircraft, ρ it is the density of the air and S the reference area of the main wing.

The Breguet equation resulting from the formulation of the previous integral is an approximate solution, not an exact one, this is due to the fact that the integration is carried out assuming constant conditions, such as altitude, propeller efficiency, fuel consumption and lift and drag coefficients. On long-haul flights, longer than 3 hours, these assumptions are not true, and the parameters mentioned tend to vary. For better accuracy, (Roskam & Lan, 1997) numerically integrate the equation, dividing the autonomy into segments and recalculating the variable parameters in each segment. Even so, the approximate solution is widely used for aircraft design and in the case of UAVs, highlighting the importance of various factors that influence autonomy (Anderson Jr, 1999; Corke, 2003; Gundlach, 2012; Raymer, 1992).

When the parameter $\frac{\eta_p}{c_p g} \frac{C_L^{\frac{3}{2}}}{C_D}$ is maximum, the maximum range is reached in flight at a given altitude. The first term is mostly influenced by the characteristics of the propulsion system, while the second depends on the aerodynamic coefficients of lift and drag. Therefore, by keeping all other factors constant, increasing the lift and reducing the drag promotes an increase in the aircraft's autonomy.

Considering a stabilized horizontal flight, cruising conditions, the lift required to balance the weight of the aircraft has to be equal (Corke, 2003).

$$L = W = \frac{1}{2} \rho V^2 S C_L \quad (2)$$

In this equation, lift is represented by L and weight by W , the increase in the lift coefficient C_L is also not indicated, as it causes vertical acceleration that directs the aircraft upwards, constantly bringing it closer to the Stall. Stall occurs when the angle of attack becomes too high, leading to loss of lift and potentially to the control of the UAV. The constant correction of lowering the nose of the aircraft is not natural, which can lead to critical errors for automatic flight control systems (Corke, 2003).

On the other hand, the reduction in drag does not cause negative effects during flight in stable conditions, directly decreasing air resistance. This results in an immediate drop in the power required from the propulsion system, which contributes to an increase in energy efficiency, extending flight time and enhancing the aircraft's range. Additionally, this reduction can lead to an improvement in range, allowing the aircraft to travel longer distances without increasing fuel consumption.

4.2.1 Viscous Flow

Two dimensionless parameters characterize the flight regime of any aircraft, Mach and Reynolds (Gundlach, 2012). The Mach number is defined as the ratio between the velocity of free flow V and the velocity of sound $V_a = \sqrt{\gamma RT}$, which is the ratio of the thermodynamic properties of the medium, in the case of perfect gases such as air, depends exclusively on that of temperature T , because γ the ratio of specific heats to air is 1,4, R it is the constant of perfect gases $287 \text{ J}/(\text{kg} * \text{K})$ resulting thus:

$$M = \frac{V}{a} = \frac{V}{\sqrt{\gamma RT}} \quad (3)$$

When $M \leq 0,3$, the flow is considered incompressible, because the density of the air is considered constant (Anderson Jr, 1991). The Mach number is the metric to describe the different types of flow, being $M < 1$ subsonic, $M = 1$ sonic, and $M > 1$ supersonic. The speeds studied for the UAVs in question are all under the subsonic regime and are characterized by smooth current lines and no discontinuity in the inclination. Flow disturbances propagate both upstream and downstream. However, an aerodynamic shape does not guarantee a fully subsonic flow over the body. If the Mach number is close to 1, local areas may have supersonic flow. Therefore, a Mach number less than 0,8 is subsonic for rounded bodies (Anderson Jr, 1991).

The Reynolds number (R_e), in turn, defines the flow regime, which can be laminar, transition or turbulent, depending on tests and data already documented. The Reynolds number depends on the density of the air ρ , the dynamic viscosity μ , the flow velocity V , and a length l that usually refers to the average aerodynamic chord of the aircraft's main wing, and is described in the following equation:

$$R_e = \frac{\rho V l}{\mu} \quad (4)$$

High numbers of R_e represents that the inertial forces outweigh the viscous ones and R_e low the viscous forces outweigh the inertial ones (Anderson Jr, 1991). For UAVs, Reynolds numbers vary between $3 * 10^4$ and $2 * 10^7$, mostly characterized by what is considered a low Reynolds number, which occurs when $R_e \leq 5 * 10^5$ (Mueller, 1999).

Except for micro aerial vehicles, most UAVs operate at numbers of $R_e < 2 * 10^5$ (Gundlach, 2012). Viscosity plays a key role in determining flow behavior. In fact, the distinguishing feature of the flow of a viscous fluid like air around a body like a wing is the fact that, at the fluid-solid interface, there is no relative motion between the two. Because of viscosity, a non-slip condition occurs on the solid surface. This boundary condition states that, on the wall, the total speed is reduced to zero.

The non-slip condition decreases as the distance from the surface increases, until it disappears, the region adjacent to the body where the effects of viscosity are concentrated is called the boundary layer. On a wing, the thickness of the boundary layer varies from practically zero to near the leading edge and increases along the chord to the trailing edge. The consequence of viscosity is the appearance of shear stresses exerted by the fluid on the surface, in the tangential direction, giving rise to frictional drag (Anderson Jr, 1991; Corke, 2003; Kundu, 2010; Roskam & Lan, 1997).

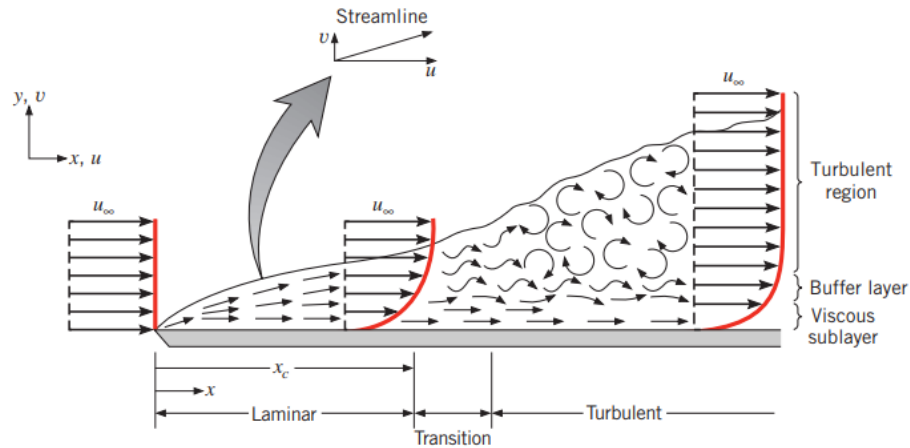


Figure 8 - Development of the speed limit layer on a flat plate

(Bergman et al., 2011)

On Figure 8 is represented the development of the boundary layer on a flat plate, where the behavior of the three regimes can be observed according to the length x . The laminar layer is characterized by an orderly motion and is more susceptible to flow separation in the presence of adverse pressure gradients. The transition from laminar to transient flow occurs in x_c , and can occur due to the separation of current lines in relation to the surface, in aeronautics the transition is natural and occurs due to surface roughness or pressure impulses that tend to grow, giving rise to high frequency fluctuations called Tollmien-Schlichting waves (Dryden, 1947). Two other reasons for the appearance of turbulence are turbulence in free flow, and the transition induced by separation in the laminar boundary layer, which occurs when the Reynolds number is greater than $5 * 10^4$, to adverse pressure gradients that are not too intense, allowing the flow to reacquire sufficient kinetic energy through the incorporation of fluid from the surrounding environment, facilitating its reconnection to the surface of the object. This process results, under average conditions, in the formation of a fluid recirculation zone, technically called a laminar separation bubble. This structure is characterized by a rotational movement of the fluid, creating a region of low pressure that can significantly influence the aerodynamic or hydrodynamic characteristics of the body in question (Dryden, 1947; Mueller, 1999). On the other hand, it is known that there are laminar separation bubbles in $Re > 5 * 10^5$ that severely disturb the aerodynamic performance of the airfoils and cause a dramatic impact on the loss of lift, raising the possibility of stall. The formation of these bubbles drastically results in a significant increase in drag on the wings or other aerodynamic profiles.

The turbulent regime as represented in the Figure 8, is characterized by the random and irregular nature of the flow, comprising sets of vortices of different dimensions in a circular and twisted direction. The turbulent regime occurs $3 * 10^6 < R_{ecr} < 4 * 10^6$ with minimal disturbance. The critical Reynolds or R_{ecr} occurs in the transition zone, in $x_c \geq$, the first value of the transition point x_{cr} is determined considering $R_{ecr} = 5 * 10^5$. With high Reynolds numbers, there is an increase in frictional drag, deteriorating the aircraft's performance.

4.2.2 Drag

Drag is the resistive force that acts on a body in motion through a fluid, always being parallel to the direction of movement (Gunston, 2012). The terminology adopted in this context follows the definitions of authors such as (Anderson Jr, 1999; Corke, 2003; Kundu, 2010; Roskam & Lan, 1997), consolidating the necessary key concepts

The total drag of the aircraft is commonly divided into induced drag and parasitic drag. Induced drag is directly related to the generation of lift. The downwash angle, which tilts the lift force backwards, is caused by the vortices generated by the main bearing surface, the wing, and the stabilizers are responsible for a smaller portion of this drag. This kind of drag can be responsible for up to 50 % the total drag of the aircraft. The induced drag coefficient is equal to:

$$C_{Di} = \frac{C_L^2}{\pi A_R e} \quad (5)$$

Where C_L is the lift coefficient, A_R the aspect ratio and e the efficiency factor (Oswald efficiency factor). A_R is the square of the wingspan (b^2) divided by the wing area (S) $\frac{b^2}{S}$. For a rectangular wing, A_R reduces to the relationship between span and chord. Long, slender, high-aspect ratio wings have less induced drag than short, thick, low-aspect ratio wings. The sustaining line theory shows that the optimal (lowest) induced drag occurs for an elliptical end-to-end lift distribution. The efficiency factor is equal to 1 for an elliptical distribution and has some value less than 1 for any other lift distribution.

Parasitic drag is generated by aircraft components that do not produce lift and cause energy waste, reflected in increased fuel consumption. Parasitic drag is composed of two main components: profile drag, and interference drag. In detail, profile drag can be subdivided into lift-related profile drag, form drag, and skin-friction drag. The lift-related profile drag is

connected to vortices and turbulences that increase resistance to movement, form drag is a consequence of the distribution of pressure around a body immersed in viscous flow, a larger cross-section or less aerodynamic shapes face greater resistance to movement through the air. Skin-frictional drag is the result of the object and the fluid passing over it. The surface of the object "pulls" a layer of air along with it, creating resistance (SKYbray, 2024). The rougher the surface, the greater the frictional drag, as we can conclude with chapter 5.2.1.

In the case of this project, the aircraft will only operate at low subsonic speeds, which disregards wave drag, however, for Mach numbers above the critical Mach number, shock waves and compressibility condition wave drag, which affects both induced drag and parasitic drag.

The most common way to express drag is in relation to the dimensionless drag coefficient C_D , air density ρ , flow velocity V , and S a reference area that is usually wing area.

$$D = \frac{C_D \rho V^2 S}{2} \quad (6)$$

The total drag coefficient is equal to the drag coefficient at zero lift (C_{D0}), plus the induced drag coefficient.

$$C_D = C_{D0} + \frac{C_L^2}{\pi A_{Re}} \quad (7)$$

Understanding the different forms of drag and their influences on aircraft performance is key to optimizing aerodynamic efficiency, allowing for a more effective design that is suited to the intended operating conditions.

4.2.3 Drag Reduction Techniques

Reducing the drag plays a key role in aircraft design for long-range missions. This is especially true for UAVs, where energy efficiency and flight time are vital, making this factor even more crucial. In unmanned aircraft, there are weight limits. As a result, the use of fuel to cover large distances makes the optimization of induced and parasitic drag a central focus of the design. Modern designs implement solutions such as laminar flow control, the use of winglets, and the reduction of surface roughness.

Parasitic drag is strongly influenced by surface friction, to reduce this type of drag, it is possible to minimize turbulent surface friction and delay the transition from laminar to turbulent flow. The laminar layer causes less drag, consequently, it increases the laminar

portion of the flow resulting in a decrease in drag. One way to reduce fuel consumption and increase aerodynamic efficiency is to apply riblets, small cracks that align with the airflow on aircraft surfaces, reducing turbulence in the boundary layer (Cacciatori et al., 2022). Large Eddy Break-Up devices also help reduce parasitic drag. They work by disintegrating large vortices of air in the turbulent boundary layer into smaller, less energetic eddies, which decreases total drag. Choosing smoother aerodynamic profiles and smoothing surfaces are simple but effective ways to control laminar flow.

Based on equation 5, which relates the induced drag coefficient to the efficiency factor and aspect ratio, increasing both the Oswald efficiency factor and aspect ratio is an effective way to reduce induced drag. However, increasing A_R comprises structural problems and makes the aircraft structurally heavier, so it is necessary to balance aerodynamic efficiency with structural strength. The Oswald efficiency factor calculates the proximity between the actual lift distribution and the elliptical ideal distribution. Achieving this correct distribution is key to keeping drag to a minimum. This can be done by changing the shape or twist of the wing, adjusting aerodynamic performance along the wingspan.

In addition, to promote the reduction of induced drag, winglets are used, vertical or inclined extenders located at the tips of the wings, which reduce the intensity of the vortices generated at the ends, favoring fuel consumption (Memon, 2024).

However, new technologies have been investigated, such as split winglets and raked wingtips, as they provide additional improvements in the reduction of vortices at the wingtips, promoting a better overall performance of the aircraft.

The constant review of these points during design, as well as the constant innovations and studies dedicated to these problems, not only optimize the operational efficiency of aircraft, but also set new standards for the future of increasingly sustainable flight.

4.3 OpenVSP and Computational Fluid Dynamics

What is known today as the Open Vehicle Sketch Pad (OpenVSP) began in 1990 at NASA Ames as the Rapid Aircraft Modeler developed by J.R. Gloudemans and Paul Davis while working collaboratively with colleagues such as Paul Gelhausen, Andy Hahn, Mark Moore, and Dave Kinney who worked in aircraft design and related fields (McDonald & Gloudemans, 2022). Rapid Aircraft Modeler used dedicated libraries such as Iris GL and FORMS for its 3D graphics and graphical interface, and it emerged that it could only run on Silicon Graphics

computers. The need for a tool like Rapid Aircraft Modeler, Vehicle Sketch Pad or OpenVSP and their use cases have not changed in more than thirty years (McDonald & Gloudemans, 2022). In 2004, Rapid Aircraft Modeler evolved into the Vehicle Sketch Pad by adopting new technologies such as Extensible Markup Language and Fast Light Toolkit.

Several projects and collaborations, including proposals Subject to Tax Rule and Non-Resident Aliens, drove the continued development of VSP. Enabling its release in 2012 as an open-source software under the NASA Open-Source Agreement (McDonald's & Gloudemans, 2022).

OpenVSP was created to provide an accessible tool for engineers and designers to explore different aircraft configurations during the early stages of development, especially in conceptual design, the main phase of this dissertation (Litherland, 2024). It is the free alternative to using proprietary CAD programs, which are often overly complex and expensive. In addition, it allows for rapid iteration of designs before moving on to advanced features such as computational fluid dynamics and finite element analysis. In fact, this tool allows designers to test parameters such as weight distribution, aerodynamic efficiency, and flight stability in an intuitive and easy-to-use environment. It also makes it possible to export geometric models in the format of aerodynamic and structural analysis programs, such as ANSYS and OpenFOAM, in STL or OBJ formats, for more complex analyses (Litherland, 2024).

Among its varieties of functionality, some of the most distinctive are:

- VSPAero - An aerodynamic solver based on the Vortex Lattice Method or Panel Method, which calculates aerodynamic forces, such as lift and induced drag, using simplified meshes. Used in Mach flight regimes and moderate angles of attack.
- Wave Drag - Calculation of wave drag in subsonic and supersonic regimes, based on the Whitcomb Rule Area. This rule helps minimize drag by smoothing out variations in the profile of the cross-sectional area along the fuselage.
- Parasite Drag - Parasitic drag estimate, which includes shape drag and skin friction drag, calculated based on empirical approximations.

As the design evolves and becomes more detailed, the limitations of OpenVSP's simplified analysis tools begin to appear. For example, the Panel Method does not perform nonlinear flows or flow separation, which is critical for the study of high velocities or angles of

attack. This implies the use of more complete techniques, such as CFD, which directly solves the Navier-Stokes Equations.

$$\text{Continuity} \quad \frac{\partial p}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (8)$$

$$\begin{aligned} \text{X-} \\ \text{Momentum} \end{aligned} \quad \begin{aligned} & \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} \\ & = -\frac{\partial p}{\partial x} + \frac{1}{R_e} \left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \right] \end{aligned} \quad (9)$$

$$\begin{aligned} \text{Y-} \\ \text{Momentum} \end{aligned} \quad \begin{aligned} & \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} \\ & = -\frac{\partial p}{\partial y} + \frac{1}{R_e} \left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \right] \end{aligned} \quad (10)$$

$$\begin{aligned} \text{Z-} \\ \text{Momentum} \end{aligned} \quad \begin{aligned} & \frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} \\ & = -\frac{\partial p}{\partial z} + \frac{1}{R_e} \left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right] \end{aligned} \quad (11)$$

$$\begin{aligned} \text{Energy} \end{aligned} \quad \begin{aligned} & \frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} \\ & = -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} - \frac{1}{R_e P_r} \left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] \\ & + \frac{1}{R_e} \left[\frac{\partial}{\partial x} (u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y} (u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) \right. \\ & \quad \left. + \frac{\partial}{\partial z} (u\tau_{xz} + v\tau_{yz} + w\tau_{zz}) \right] \end{aligned} \quad (12)$$

The previous equations include a time-dependent continuity equation for the conservation of mass, three equations for conservation of momentum, and one equation for conservation of energy, both of which are time-dependent. All equations have four independent variables, the spatial coordinates x , y and z , of a given domain, and time t . It further comprises six dependent variables, pressure p , density ρ and temperature T , included in the total energy equation E_T , and three components of the velocity vector, u the component in direction x , v the component in direction y , and w the component in direction z . In addition, the Reynolds number R_e emerges as a parameter of similarity that characterizes the relationship between inertial forces and viscous forces in the flow. The variable q , represents the heat fluxes and P_r is the Prandtl number, another parameter of similarity,

which relates the thermal diffusion to the viscous moment diffusion in the fluid. The behavior of the flow is described through the stress tensor, whose components, designated by τ , are generated from the multiplication of velocity vectors, this tensor describes the internal tensions of the fluid, fundamental for the analysis of the viscous forces acting on the flow and as there are three velocity components the tensor results in nine components (NASA, 2021).

Solving the Navier-Stokes equations is computationally intensive, requiring high processing power (CPU/GPU) and simulation time, especially for three-dimensional models and complex flows. The significant time and processing power required can lead to increases in project costs.

OpenVSP is a valuable tool for conceptual aircraft design, providing a fast and affordable approach to geometric modeling and preliminary aerodynamic analysis. Although its capabilities are limited for complex analyses, it excels in the conceptual phase. CFD, on the other hand, is indispensable for design refinement and detailed analysis, but it has greater demands on time and resources. Both methods complement each other in an efficient aeronautical design workflow. The following SWOT analysis provides a more straightforward visual understanding of the key advantages and limitations of OpenVSP and CFD, making it easier to strategically compare the two methods.

Table 9 – SWOT analysis of OpenVSP

	Positive Factors	Negative Factors
<u>Internal Factors</u>	Simplicity and speed in the conceptual modeling of UAVs	Limitations in complex simulations (flow separation, turbulence)
	It offers parameterizable geometric solutions for various UAV configurations, allowing quick design changes and facilitating the iterative conceptual	Unable to resolve nonlinear phenomena such as compressibility effects
	Ease of export to other analysis platforms (CAD, CFD)	Dependent on simplified methods
	Ideal for exploring multiple aircraft configurations during the conceptual stage	Does not support detailed structural analysis or advanced optimization
	Provides immediate feedback on mass distribution and center of gravity	Does not perform high-precision aerodynamic calculations at high angles of attack
<u>External Factors</u>	Free and open-source, ideal for projects with a limited budget	Not very efficient for analysis in advanced project phases
	Allows export to software such as ANSYS, OpenFOAM, and XFLR5 for detailed analysis	Requires external tools for high-fidelity calculations
	Can be used on mid-range computers, without the need for significant resources	Increasing complexity when integrating with more precise analysis methods
	Support from an active community that contributes to updates and development	Does not predict real performance under extreme flight conditions (e.g., supersonic flight)
	Perfect for the concept phase, reducing preliminary design time	The development of more advanced features may be slower

Table 10 - SWOT analysis of CFD

	Positive Factors	Negative Factors
Internal Factors	High accuracy in resolving complex flows, flow separation, and turbulence	High computational cost and the need for long processing times
	Solves the Navier-Stokes equations for realistic and transient flight conditions	Requires advanced technical knowledge, and more time consuming
	Able to simulate nonlinear aerodynamic effects and fluid-structure interactions	Modeling and simulation can be excessively complex for conceptual projects
	Generation of fine meshes for resolving boundary layers and turbulence	High dependence on robust hardware (computing clusters or dedicated servers)
	Applicable to various industries	Setup and execution time for simulations can be extremely long
External Factors	Integrates well with CAD and FEA for advanced multidisciplinary analysis	The process of integration and data transfer between tools can be time-consuming
	Allows simultaneous aerodynamic and structural optimization	The use in conceptual design phases can be unnecessarily complex and burdensome
	Simulates phenomena that vary across different time and space scales	The validation and verification process of simulations can be time-consuming
	Ensures reliable analyses for extreme flight conditions and transonic regimes	Requires significant investments in IT infrastructure and licensing to support processing

OpenVSP was then selected as being the tool that best suits the conceptual design and in turn this work, on the other hand, CFD offers a much deeper level of detail and is suitable for more advanced design phases that would be employed if this work had time to achieve it.

4.4 Materials

In the design of Unmanned Aerial Vehicles, the selection of materials plays an essential phase for the development of the project. There are several options, focusing on the resources available at the Air Force Academy Research Center.

Carbon Fiber, widely available at CIAFA, stands out for its lightness, strength and rigidity, with a matrix usually composed of epoxy resin. Affordable and corrosion-resistant Fiberglass uses polyester as the matrix (Ashby & Jones, 2014). Kevlar, available from CIAFA, is known for its exceptional strength, and is often combined with phenolic resin (KREVELEN & K. TE NIJENHUIS, 2008). In addition, we consider Sandwich Materials, structures composed of lightweight cores between outer layers. This approach offers high strength with efficient vibration absorption.

At CIAFA, there are a variety of composite materials available, providing flexibility in design. Dies play a vital role in structural integrity. Epoxy and polyester resins, common in CIAFA, offer distinct characteristics, their high strength maintains integrity under stress, while their lightness contributes to energy efficiency. In addition, these materials demonstrate durability by resisting corrosion (Gay et al., 2002).

The judicious choice of these materials, aligned with the availability at CIAFA, not only enhances the UAV's performance but also highlights the effectiveness in applying these advanced materials. In Table 11 the main characteristics of the main materials used in UAVs are presented.

Table 11 - Material characteristics

Material	Density [g/cm ³]	Tensile strength [MPa]	Modulus of Elasticity [GPa]	Stretching (%)	Typical Thickness (mm)	Corrosion Resistance	Vibration Absorption	Impact Resistance	Operating Temperature [°C]
Carbon Fiber	1,6	3500+	230	1,5	0,5 - 3	High	Average	Average	- 50 to +80
Fiberglass	2,5	2000	70	2,5	1 - 5	Very high	High	High	- 50 to +70
Kevlar	1,44	3000	125	3,6	0,5 - 3	High	Very high	Very high	- 60 to +160
Sandwich Materials	Varies	Depends on the materials	Depends on the materials	Depends on the materials	2 - 20+	High	Very high	High	Depends on the materials

After analyzing the characteristics of the different materials present in CIAFA, carbon fiber stands out in terms of lightness, high tensile strength and rigidity (Campbell, 2010). Kevlar also expresses an excellent ratio of tensile strength and vibration absorption (Cunniff, 1992), however, carbon fiber has a more favorable balance between strength and weight.

Therefore, the material selected for this project will be Carbon Fiber, which, due to its high tensile strength 3500 MPa and stiffness of 230 GPa , will withstand stress levels close to yield stress, allowing to optimize the weight of the UAV without compromising its structural integrity (Anderson Jr, 1999).

4.5 Summarization of methods to improve the range of action

The effective range of Unmanned Aerial Vehicles is a critical consideration in the design, especially during the conceptual and preliminary stage. Implementing strategic design measures can significantly improve the range of action of aircraft.

As we saw earlier during chapter 5.2, one of the key factors is aerodynamic efficiency and minimization of drag contributions, where wing design and fuselage play crucial roles. Optimized aerodynamic profile and wing elongation, fuselage fineness ratio contributes to reduced drag, allowing for greater efficiency during flight. In addition, the careful choice of lightweight and aerodynamically efficient composite materials can result in significant gains.

Another important factor is the efficiency of the propulsion system, as previously seen playing a key role in autonomy. High-power engines, along with propellers or advanced propulsion systems, can improve energy efficiency, thereby increasing operational range. However, finding the sweet spot between the power to weight ratio of systems is critical.

Finally, intelligent payload management is another crucial measure. The design must carefully consider the carrying capacity and weight distribution to accommodate sensor systems, batteries, and other necessary components. Reducing non-essential weight on the structure, without compromising integrity, will contribute to increasing flight time.

The conceptual and preliminary stage of the UAV project are the ideal phases to implement measures aimed at improving the range of action. By focusing on aerodynamics, propulsion system efficiency, and intelligent payload management, engineers can create more effective UAVs with greater autonomy, thus meeting specific operational demands. These are the points that will have the most prominence in the development of the UAV in question, as it is possible to see throughout this dissertation.

5. MARKET SURVEY

As with any development project, the market survey is an essential part of aligning current and future market needs and demands. The more complex the systems such as UAVs, the more pertinent this analysis becomes, so this chapter aims to analyze the market for analysis and understanding of trends, emerging technologies, innovation opportunities and provide critical comparisons that guide design and development decisions, favoring not only technical feasibility, but also commercial.

This collection involves the detailed analysis of existing products, and their technical specifications such as maximum take-off weight (MTOW) [kg], empty weight [kg], wingspan [m], payload capacity [kg], range [km], cruise altitude [m], cruising speed [km/h], maximum speed [km/h], propulsion information, wing profile, piloting, number and location of propeller, power source and endurance [h] of the three classes of UAVs.

The main objectives are to identify UAV technologies of different characteristics and classes in the market understanding their technical and operational properties to establish a benchmark and project orientation, recognize the trends, challenges and gaps enabling the project in relation to current and future demand, the market survey can be consulted in the Annex 1 – Market Survey.

The market survey was developed through a combination of research and analysis of market data, compiling the information obtained in a table with the specifications mentioned. The data analysis will be focused on comparing the characteristics of the different UAVs in relation to other parameters studied in graph format, facilitating understanding and their relationships. This will be a valuable tool for market analysis, providing a solid basis for strategic decisions in the project, being able to identify trends.

The first graph shows the relationship between the Endurance and the MTOW of the different UAVs, with this type of visualization it is possible to understand how the flight autonomy behaves as a function of the maximum take-off weight, highlighting how the weight of the UAV affects its ability to stay in the air for a long period of time, the higher the MTOW, the lower the endurance due to the need to consume more energy to sustain the additional weight, however, this behavior is not applicable to all cases as can be analyzed in the Figure 9, because it also depends on other factors.

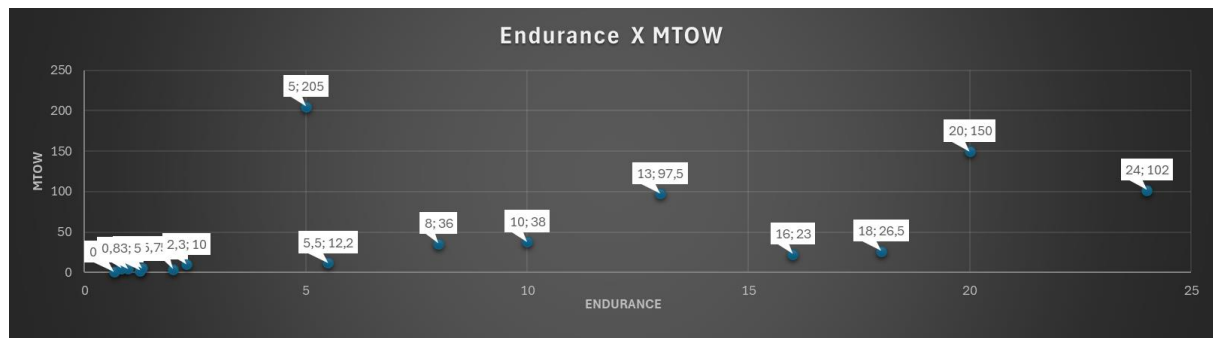


Figure 9 - Ratio between Endurance and Maximum Takeoff Weight (MTOW) of UAVs

From the analysis of Figure 9 the draw attention to UAV is AeroVironment T-20 which with less than 150 kg of MTOW (102 kg) is the one with the most Endurance (24 h), in addition to it the Tekever AR5 which has 150 kg of MTOW and 20 h of Endurance.

The next comparison was made using the Range and Cruise Altitude, revealing how the flight altitude affects the operating range of a UAV. UAVs that fly at higher altitudes generally have a higher range due to favorable atmospheric conditions and lower air resistance.

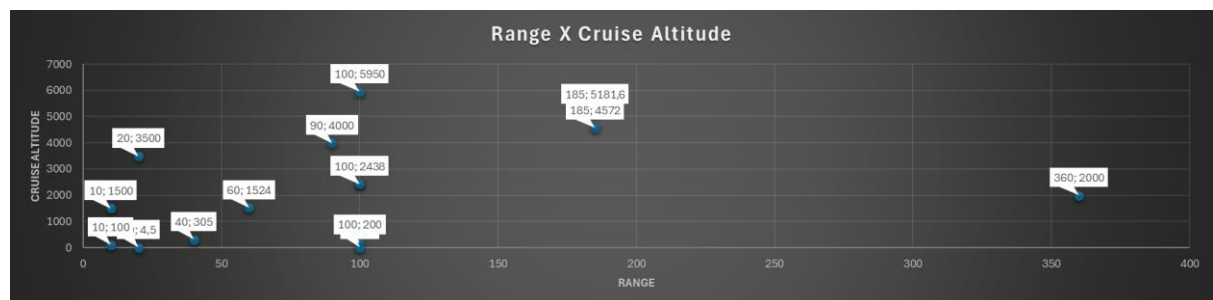


Figure 10 - Ratio between Range and Cruise Altitude of UAVs

According to the Figure 10 we can prove this behavior apart from the ANTEX-X02 which has a 2000 m of flight altitude has a range of 360 km, although this UAV stands out, it is unrealistic because it is a very light aircraft.

The third study was conducted comparing Cruise speed with Max speed is a relationship between flight efficiency and energy conservation (Cruise speed) and the responsiveness and maximum performance of the UAV (Max speed).

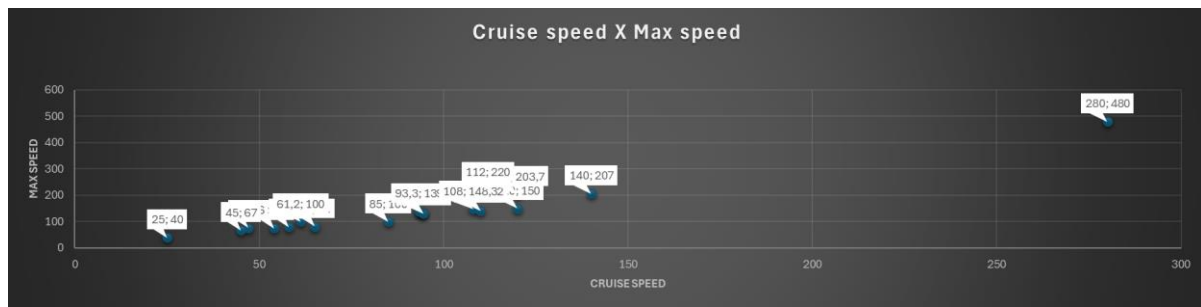


Figure 11 - Relationship between Cruise and Max speed of UAVs

Analyzing the results of the Figure 11 The General Atomics MQ-9 Reaper is the most prominent UAV with 280 km/h cruise speed and 480 km/h max speed, however it is a very heavy aircraft being higher classes compared to what is intended with the project, however, the RQ-2 Pioneer despite having a weight above expectations is closer and with great results 120 km/h cruise speed and 203 km/h max speed.

The sequence analyzed the relationship between the Payload and the MTOW to complement this analysis was calculated the empty weight fraction this metric indicates that the amount of the maximum takeoff weight of the aircraft is composed of the weight of the structure and systems of the aircraft, leaving the rest for payload.

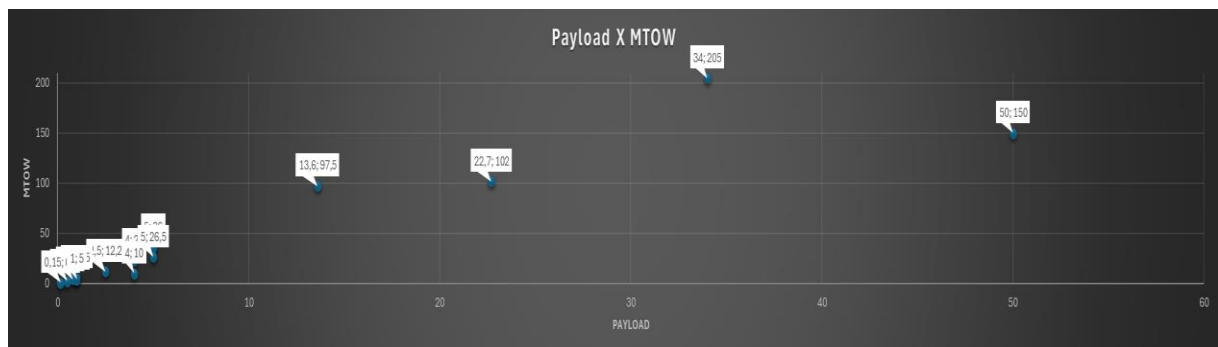


Figure 12 – Relationship between Payload and MTOW of UAVs

On Figure 12 there is a roundup of UAVs with a low payload weight value independent of the MTOW value, however, the Tekever AR5 has a good ratio, although it is not the best empty weight fraction.

Already in the Table 12 it is possible to have another perspective on the structural efficiency and payload capacity of UAVs. The values vary between 0,4 and 0,9 respectively, the lowest values such as General Atomics MQ-9 Reaper with 0,4 and ANTE-X02 with 0,6 contain a structure that allows a greater payload capacity in relation to the total weight,

however, these UAVs are very extreme regarding the MTOW and Payload they carry, not identifying with the reality of the project developed.

Table 12 - Empty weight fraction

<u>Manufacture</u>	<u>Empty weight fraction</u>
Tekever AR5	0,7
Tekever AR4	0,9
Tekever AR3	0,8
Wingtra	0,8
UAVISION OGASSA OGS42	0,9
UAVUSION OGASSA OGS42V	0,9
AeroVironment RAVEN® B RQ-11	0,8
AeroVironment PUMA LE	0,9
AeroVironment JUMP® 20	0,9
AeroVironment T-20	0,8
Quantum Systems Trinity Tactical	0,8
BlueBear	0,8
Cavok UAS	0,8
ANTEX-X02	0,6
ScanEagle	0,8
RQ-2 Pioneer	0,8
IAI Heron Machatz-1	0,8
General Atomics MQ-9 Reaper	0,4
Elbit Systems Hermes 900	0,6

On the other hand, more median values such as Tekever AR3, Wingtra, AeroVironment RAVEN® B RQ-11 with 0,8, suggest a good combination between structural robustness and load capacity, which may indicate a balanced design for multiple types of mission, more in line with what is expected with this project. Higher values such as UAVISION OGASSA OGS42 and AeroVironment PUMA LE with 0,9 represent less payload capacity, which can limit operational flexibility, especially for missions that require varied or heavy loads.

Finally, the relationship between the WingSpan and the MTOW was studied, showing how the size of the wings is related to the total weight of the UAV and a larger wing allows for a higher load capacity and aerodynamic efficiency, but also requires a more robust and complex structure.



Figure 13 - Relationship between WingSpan and MTOW of UAVs

A Figure 13 allows the understanding of the wing lengths used for their weights and how they influence it, UAVs with wingspans of 5 m or more have significantly larger MTOWs, ranging from 102 kg to 205 kg.

The UAV with the longest wingspan (7,3 m) has an MTOW of 150 kg, which indicates that the wingspan is not the only determining factor for the MTOW increment.

6. DEFINED MISSION PROFILE

A crucial component in the development of a long-range UAV is the definition and understanding of the mission profile, as it defines the operational requirements and characteristics necessary for the fulfillment of the specific mission objectives. Based on the detailed study of the market and current technological capabilities, a mission profile has been outlined that will guide the development of the UAV, ensuring that it meets the established requirements.

As already commented in previous chapters, there is a need to fill a gap in the surveillance of the Exclusive Economic Zone, so the mission profile outlined will guide the main objective of surveillance and will be extremely important for the understanding of the UAV requirements as well as the equipment necessary for its realization. The mission profile will be developed considering five stages, preparation and launch, ascent and navigation to the area of operation, patrol and surveillance, return to base and descent, landing and demobilization.

- **Preparation and release:**

The mission begins at the Lajes Base, where it is considered a preparation phase that includes critical system checks and fuel supply. This process is estimated to take 10 minutes. It is essential that at this stage all the necessary inspections are carried out to ensure that the UAV is in optimal operating condition before launch.

- **Ascent and navigation to the area of operation:**

After launch, the UAV will ascend to a cruising altitude of 4000 meters. At this altitude, it will navigate to the area of operation at a cruising speed of 180 km/h. The distance considered to the area of operation is 150 km, resulting in an estimated time for this phase of 50 minutes. This phase ensures that the UAV reaches the operating position with maximum efficiency and within the time limits.

- **Patrol and surveillance:**

The main function of the UAV will be to patrol an area of 800 km². During this phase, the UAV will maintain a cruising altitude of 4000 meters and a patrol speed of 100 km/h. The operation time in this area is estimated at 8 hours, during which the UAV will carry

out monitoring and data collection tasks, depending on the specificity of the launch. The extended operating time reflects the ability to carry out long-duration missions, a crucial point for surveillance and reconnaissance operations.

- **Return to base and descension:**

Concluding the patrol operation, the UAV will return to base, maintaining a cruising speed of 180 km/h. To facilitate the understanding of the mission, devaluing the final position of the UAV at the end of the patrol, the return distance will be considered 150 km with an estimated time of 50 minutes. This part of the mission is important to request the equipment safely and with the data collected from the mission that cannot be sent.

- **Landing and demobilization:**

Finally, the UAV will carry out the landing phase, which is expected to last between 10 and 20 minutes. After landing, post-flight checks and maintenance procedures will be carried out to ensure the success of future missions. Demobilization is essential to ensure the longevity of the system.

The mission profile as shown is only considered the cruising speed, however it was calculated in the Table 13 for all the different stages the execution time of the same using the maximum speed of the UAV of 200 km/h and how this varies the execution time of the mission, as it is only used during the round trip of the UAV to the mission location the difference is not very significant, but it can be relevant depending on the needs of the mission.

Table 13 - Summarization of the maximum distance traveled, time of the different phases considering V_c and V_{max}

Phase	Distance [km]	Time at V_c	Time at V_{max}	Total time at V_c [h]	Total time at V_{max} [h]
Preparation and launch	-	10 min	-	0,167	0,167
Ascension and flight to the operating area	150	50 min	45 min	0,833	0,75
Patrol and surveillance	800	8 a.m.	8 a.m.	8	8
Return to base and descension	150	50 min	45 min	0,833	0,75
Landing and Demobilization	-	20 min	10 min	0,333	0,167
Total	1100			10,17	9,83

This profile not only guides the design and construction of the UAV, but also ensures that the system will be able to carry out complex and prolonged operations, contributing

significantly to the operational capabilities of the Portuguese air force or user entity. In Annex 2 – Mission Profile it is possible to observe the tabulated profile as well as the mission graph.

6.1 Developments of requirements, composition, characteristics and justifications

The development of the requirements for the UAV was carried out based on two fundamental pillars, the CIAFA requirements and the previously defined mission profile, serving as a reference to ensure that the project meets the required operational and performance needs. The requirements have been classified and organized into five main categories, each enhanced key aspects of the UAV.

For a better understanding of the structure and content of the columns of the requirements table, it is essential to understand the function of each of them within the context of UAV development. The table is designed to organize and control requirements in a clear and traceable way, ensuring that every aspect of the project is considered and validated.

- **Work Package:** Through a specific division of labor, it groups related activities of a certain feature of the UAV's development. This organization allows tasks to be assigned efficiently and to be easily tracked throughout the project cycle.
- **WBS (Work Breakdown Structure):** WBS divides the project into smaller components, organizing it in a hierarchical way. It allows for accurate management of activities, ensuring that all aspects of the project are identified and connected to a specific objective.
- **Requirements:** The specific requirements that must be met by the UAV are described, separated by Performance Requirements, Airframe Requirements, Operational Requirements, PowerPlant Requirements, and Instrumentation Requirements.
- **Project/Product:** The column identifies whether the requirement applies to a specific aspect of a product, the UAV, or a specific part of the UAV.
- **References:** Displays where the requirement is originally taken from, such as the Market Survey.

- **Responsible:** Specifies the team responsible for ensuring that the requirement is met. This ensures that there is a clear assignment of responsibilities within the project.
- **MoC (Means of Compliance):** Identifies which MoC or MoCs are identified for that requirement.
- **MoC Text:** Indicates which tests are necessary for the study and validation of the requirement.
- **MoC Details:** Details the type of analysis required during testing and provides additional information on how the MoC is implemented
- **MoC Reference Documents:** Lists examples of reference documents that support the MoC, such as standards, technical procedures, or operational guidelines that define the compliance criteria for the requirement.
- **Equipment:** Specifies what equipment, sensors, or systems are needed to meet the requirement. It is particularly important when it comes to instrumentation systems, sensors, or any other component that needs to be installed on the UAV.

The Work Package, the WBS and the Responsible were developed based on the (NASA, 2010), which is a widely used guide for structuring complex engineering projects. NASA's approach makes it easy to break down large projects into smaller, more manageable pieces.

Means of Compliance are an essential part of requirements management in the development of any aeronautical system, including UAVs. Providing a clear and verifiable path to ensure that each defined requirement is met (Xiaofeng, 2011). These include simulations, flight tests, documentary reviews, among others, ensuring that each requirement is validated with technical rigor and precision. Additionally, they ensure complete traceability of the development process, allowing for efficient audits and reviews throughout the project lifecycle.

The UAV requirements have been classified and divided into five classes, each covering specific characteristics that the UAV must comply with:

- **Performance Requirements:** Focuses on the operational capability of the UAV like operating speed, top speed, stall speed and other characteristics.

- **Airframe Requirements:** Includes aspects such as materials, geometry and durability of the fuselage, as well as requirements related to aerodynamics and structural strength.
- **Operational Requirements:** Addresses the ease and characteristics of operation and handling of the UAV, such as the environmental conditions in which the system can be used.
- **PowerPlant Requirements:** Represents the electrical characteristics of the UAV such as power supply, electrical power safety of power supply systems.
- **Instrumentation Requirements:** Deals with the control and navigation systems, sensors, communication and other tools necessary to monitor and command the UAV during the mission and equipment necessary for its realization.

Within the Performance Requirements, some parameters of the UAV are calculated, these first values are considered based on the Market Survey and are of great importance in the attribution of performance goals that must be achieved or even improved during the development of the UAV.

In the Annex 3 – UAV Requirements is possible to consult the developed requirements taking into account the explanation given during the chapter of their formulation, give prominence to the context of this specific project, the use of a systematic and documented approach to the requirements offers numerous advantages, such as the traceability of decisions, the mitigation of technical and operational risks and compliance with applicable regulations. Thus, the requirements not only guide the development of the UAV, but also ensure that the final product meets the quality and safety standards established from the beginning.

6.2 Presentation and analysis of the payload required for the mission

Before entering the analysis of the payload in demand for the mission, it is important to remember the main objectives of this operation: maritime surveillance and protection, encompassing the concepts of Maritime Surveillance (VIMAR) and Search and Rescue (SAR) mission, and that although these equipment's are required to carry out the mission, the aircraft is capable of flying without them.

According to (Moutinho, 2011) the VIMAR mission, its primary objective is the monitoring of large maritime areas, with the purpose of ensuring the safety of navigation, recognizing possible threats, and assisting in the inspection of illegal activities, such as smuggling, illegal fishing or in the case of Portugal, illegal immigration. In the case of the SAR mission, search and rescue operations are interspersed in circumstances where vessels or crews are in danger, being vital in emergency scenarios to locate and rescue people in adverse conditions (Ferreira, 2014).

Both missions can be interpreted by the developed mission profile, for these missions to be carried out successfully, the detailed study of the payload becomes indispensable, in addition the correct distribution of the payload by the aircraft directly affects the layout, its stability and dimensions, detailing the study of the equipment obtains a greater proximity to reality. All equipment on board the aircraft can be consulted in the CIAFA requirements at Table 6 or in more detail in the Annex 3 – UAV Requirements.

In addition, it is important to consider the operational conditions that the UAV must act in, since all equipment on board must be able to act under the same conditions, as such they must be able to withstand winds with intensities of 10 to 15 m/s, including crosswinds, operating at temperatures ranging from -25º C to +50º C. They must be able to withstand an intensity of light rain, less than or equal to 0,5 mm per hour, maintaining their operational capabilities at an altitude of 4000 meters.

6.2.1 Gimbal

The gimbal is a fundamental equipment for surveillance and monitoring operations in UAVs, allowing the stabilization and precise orientation of the onboard sensors, facilitating the capture of high-definition images and videos, regardless of flight conditions. This system allows the UAV to maintain a stable and clear view of the surrounding environment, even under conditions of movement, vibration, or adverse winds (EDGE ATONOMY, 2024). For the development of the project, several gimbals options were studied, as presented in the Table 14, to meet the technical and operational requirements of the mission.

Table 14 - Tabulation of the technical characteristics of the various gimbals

Gimbal	Weight [g]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Electro-Optical Sensor	Infrared Sensor	IR Laser Illuminator
Octopus ISR Systems Epsilon E140Z G2	1270	40	195	140	140	3822000	1920x1080, Field of view 40 degrees, optical zoom up to 30x	640x512, Field of view 30 degrees, optical zoom up to 5x	Integrated for night operations
AVT CM62 Micro Gimbal	260	20	102	70	70	499800	1920x1080, optical zoom up to 50x	LWIR Sensor	Not specifically mentioned, but should include
Ventus HD6-0.6 MWIR Thermal Camera	14500	16	590	329	329	63862190	1280x960, up to 14x optical zoom	MWIR thermal image	Not specifically mentioned
CF01 30X/10X Quad-Sensor Pod	1540	30 - 50	187	168	198	6220368	1920x1080 or 3840x2160, 30x - 10x optical zoom	Integrated IR imager, 640x480	Integrated for night operations 640x512

Among the options considered are the AVT CM62 Micro Gimbal, the Ventus HD6-0.6 MWIR Thermal Camera, and the CFO1 30X/10X Quad-Sensor Pod, each with its unique characteristics in terms of weight, power consumption, dimensions, and integrated sensor types, both optical and infrared. However, the Octopus ISR Systems Epsilon E140Z G2 was the gimbal selected for the project, as it comprehensively meets the defined requirements. This gimbal is fully stabilized, offering forward vision and the ability to steer in all directions, making it compatible with missions that require high precision in surveillance. In addition, it includes an electro-optical (EO) sensor, an infrared thermal (IR) sensor and a laser illuminator, making it ideal for night operations. Its optical zoom capability is greater than 10x and its wide field of view ensures high definition (1920x1080) and significant visual coverage. Although the Octopus ISR Systems Epsilon E140Z G2 is not the lightest of the gimbals evaluated, it stands out as the most complete in terms of weight-quality ratio, offering an ideal combination of advanced features and relatively compact dimensions. For example, compared to the AVT CM62 Micro Gimbal, which is significantly lighter, the Epsilon 140Z G2 offers a much wider range of capabilities, including IR sensors, laser illuminator, and a superior stabilization system. In addition, its IP64 protection ensures resistance to dust and water, another important factor is its ability to operate at a wide range of temperatures, from 0 to 2000 °C, making it suitable for the harsh and operational conditions described in the mission profile.

6.2.2 Radar SAR

The Synthetic Aperture Radar (SAR Radar) is an advanced system that takes advantage of the movement of the aircraft to create high-resolution images of the surface it is flying over, regardless of weather conditions or time of day, regardless of the lighting problem. Radars of this style are profusely used in missions such as the one developed (Ball, 2021).

The versatility of use of a SAR radar is one of the advantages that determines its implementation in surveillance UAVs, in addition, more modern radars integrate technologies such as Ground Moving Target Indicator (GMTI), Maritime Moving Target Indicator (MMTI) and multi-mode capability, which allows different modes of operation to meet a wide range of needs adapting to the needs of the moment of the mission. Most of these radars are installed externally on the aircraft, which allows them to take up less internal space, being developed to operate in harsh environmental conditions.

Table 15- Tabulation of the technical characteristics of the various SAR Radar

Radar SAR	Weight [kg]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm3]	Range [km]	Capacity	Operation	Location
RASAR	11,34	150	450				30	SAR, GMTI and MMTI	All-weather, day and night	Posted outside does not occupy inner volume
Northrop Grumman AN/ZPY-1 STARLite	29,5	200-250	432	188	188	15268608	8	SAR, GMTI and MMTI	All-weather, day and night	UAV-mounted
IAI ELM-2054	15	200-250	300				20	Multi-mode SAR/GMTI	Real-time tactical data, all-weather	
IMSAR NSP-7 Long-Range	10,9	300	1476	137	173	34982676	55	Multi-mode SAR, GMTI and MMTI	Real-time data, rugged, all-weather, day and night	Posted outside does not occupy inner volume
IMSAR NSP-3 Synthetic Aperture	20	200-250	300	150	150	6750000	20	Multi-mode SAR	All-weather, high resolution imagery, with third-party integration software	

For the development of the project, different models of SAR radar present in the Table 15, several SAR radar models with different capacities, sizes and power consumption were considered. The IMSAR NSP-7 Long-Range was selected as the most suitable SAR radar for the project, due to its compatibility with the established mission requirements. It operates day and night, with a range of up to 55 km, and integrates GMTI and MMTI capabilities. Compared to other radars, such as RASAR or Northrop Grumman AN/ZPY-1 STARLite, the IMSAR NSP-7 Long-Range offers a significantly longer range, lower weight and can withstand operations in adverse weather conditions, making it the best choice to meet project requirements.

6.2.3 AIS

AIS is an automatic tracking system that provides an exchange of information such as position, speed, identification, and course between entities such as coastal installations or vessels. It is commonly used to increase safety during mission operation, as well as to improve control and tracking, avoiding collisions. AIS is essential, identifying and locating ships in real-

time, complementing UAV surveillance systems like the SAR radar seen earlier (Falkman, 2024).

In Table 16 all the AIS studied for the development of the project are present, each system has unique characteristics, however, SA161-UA was the AIS selected for this project. When compared to the other systems, the power consumption of 2 W and the weight of 70 g and small dimensions are the main distinguishing features. In addition, it meets the requirement imposed for the project by having a high sensitivity, ensuring efficient operation in adverse maritime environments.

Other systems such as SR161 have a high sensitivity and compatibility with real-time tracking software, but it is relatively heavy and bulky, as well as AIS700 Class B, while the Vesper Marine Cortex M1 has a slightly higher power consumption than other systems and its use is not justified. In order to minimize the total weight of the payload, the lighter, low-power AIS was integrated into the design to also mitigate the weight required to power the systems integrated into the main generator or the backup batteries dedicated to the payload.

Table 16 - Tabulation of the technical characteristics of the various AIS

AIS	Weight [g]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Relevant aspects
SR161 (AIS)	400	1,5	115	75	28	241500	High sensitivity with dual stage RF input protection; Includes vessel name, size, position, course, and cargo details; Compatible with AIS-enabled software for real-time ship tracking
SA161-UA	70	2	62	70	13	56420	High sensitivity; Low power consumption; Superior RF input protection; Exclusive Shine Micro Enhanced Signal Processing (ESP) software; GPS input for slot numbering, VDL loading, and packet time of arrival information; Ideal for UAVs due to its small size and lightweight design (Shine Micro)
AIS700 Class B	1080	4	128	160	60	1228800	Full transmit and receive AIS; Built-in antenna splitter; NMEA2000, NMEA0183, PC, and SeaTalkNG compatibility; Software or hardware switchable Silent Mode; Enhanced situational awareness with SO-TDMA technology for longer range and faster performance (Raymarine)
Vesper Marine Cortex M1 Class B	400	5	127	50	65	412750	Full Class B SOTDMA AIS transponder; Built-in VHF splitter; NMEA 2000 and NMEA 0183 compatible; Mobile app integration for remote monitoring and configuration; Suitable for UAV applications with moderate payload capacity;

6.2.4 Air Pollution Monitoring Payload

It is the system used to detect and monitor levels of air pollution, measuring levels of gases such as CO₂, NO₂, SO₂ and other compounds that can alter the environment. In Portugal, maritime surveillance missions include monitoring pollution within the exclusive economic zone, collecting data on air quality and the presence of harmful gases, ensuring environmental safety and complying with international standards of ecological preservation, being a requirement imposed by CIAFA (Kumar, 2023).

The equipment's considered are present in the Table 17, the Deimos SkyEye, has a slightly larger total volume than the other systems, the DJI D-RTK 2 Mobile Station supports multiple GANSS systems, but does not specialize in gas measurements as much as the other devices, which makes it less suitable for the project. The Prophet 5th Gen Gas Detector offers an advanced range of gas detection and is designed to minimize the impact of UAV airflow, which is beneficial in terms of accuracy, but has a relatively higher weight and volume than the selected AIR.

Table 17 - Tabulation of the technical characteristics of the various AIR Pollution Monitoring Payloads

Air Pollution Monitoring Payload	Weight [kg]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Relevant aspects
Deimos SkyEye	1,2	30	250	150	150	5625000	Capable of measuring multiple pollutants such as CO ₂ , NO ₂ , and SO ₂ ; Provides real-time data transmission; High sensitivity and precision sensors
DJI D-RTK 2 Mobile Station	1,5	40	300	200	150	9000000	Supports multiple GNSS systems for accurate positioning; Integrated atmospheric sensors for pollution monitoring; Designed for use with DJI Matrice series drones
Prophet 5th Gen Gas Detector	1,3	35	280	180	140	7056000	Detects a wide range of gases including SO ₂ , CO, NO ₂ , VOCs; Equipped with advanced electrochemical and laser scattering detection methods; Designed to minimize the impact of UAV airflow on sensor accuracy
Purway UAV TDLAS Detector Model II	1,1	25	240	160	120	4608000	TDLAS for precise measurements; Can detect trace gases with high sensitivity; Suitable for harsh environments and varying altitudes (Purway Innovation)

The Purway UAV TDLAS Detector Model II was the system selected for the project, it uses tunable diode laser absorption spectroscopy, a technology that provides accurate measurements of trace gases such as CO₂, NO₂ and SO₂ with high sensitivity. In addition, it is lightweight and compact, with low power consumption and ideal for applications in harsh environments and at various altitudes.

6.2.5 Conclusion

In order to conclude the study of the project's payload, we analyzed the Table 18, where the systems considered for the development of this project are present and it is possible to observe more succinctly information from each equipment considering the total weight of the payload, as well as the energy consumption of all systems.

Table 18 -Summarization of the systems selected for the UAV payload

Payload	Weight [kg]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]
Gimbal: Octopus ISR Systems Epsilon E140Z G2	1,27	40	195	140	140	3822000
Radar SAR: IMSAR NSP-7 Long-Range	10,9	300	1476	137	173	3.50E+07
AIS: SA161-UA	0,07	2	62	70	13	56420
Air Pollution Monitoring Payload: Purway UAV TDLAS Detector Model II	1,1	25	240	160	120	4608000
Total	13,34	367				

The total weight of the payload is 13,34 kg, and the total power consumption reaches 367 W, ensuring that the payload is compliant with the aircraft's design constraints, optimizing aerial monitoring and surveillance operations.

To ensure mission efficiency and success in data collection systems are integrated to provide cohesive and synchronized information with the operator, for example the IMSAR NSP-7 Long-Range SAR radar, responsible for the detection of moving targets and maritime surveillance, will act in conjunction with the AIS SA161-UA system to identify vessels, facilitating the confirmation and identification of targets in real time. The AIS system allows

the transmission and reception of data about the vessels, ensuring that any target detected by the SAR radar can be cross-referenced with automatic identification information, such as name, position, and type of vessel. At the same time, the Purway UAV TDLAS Detector Model II provides data on possible sources of pollution or anomalies in the environment, all these systems will be processed in real time, allowing a more efficient surveillance operation, with the collection of maritime and environmental data working in a coordinated manner.

6.3 Presentation and analysis of Avionics and Subsystems

In this chapter, all the systems and avionics, subsystems and electrical components necessary for the UAV to fly and complement the success of the mission will be presented. In this chapter, we will present and analyze the avionics systems and subsystems required for the mission, divided into the following categories: Transponder, Distress Sensor, SatCom, Autopilot, Servo-actuators, Power Supply, Data Link, Onboard Computation, and other important avionics. An integration of all systems in an effective and essential way to ensure the operability, safety and efficiency of the aircraft, focusing on the requirements of the aircraft present in the Annex 3 – UAV Requirements and in the Table 6 where the CIAFA requirements are presented.

6.3.1 Transponder

It is the equipment responsible for air traffic control, providing greater safety in the operation of any aircraft. Its main function is to send electronic signals that help radars and control systems to identify the aircraft's position, altitude, pressure and other parameters (Santos, 2011). Mode C which is mandatory according to CIAFA requirements in the Table 6 and also considered for the UAV requirements in the Annex 3 – UAV Requirements it is responsible for providing information about the pressure altitude of the aircraft. Combined with A-mode, ATC and other aircraft can receive an aircraft's unique alert code, position, and altitude.

In Table 19 the three transponders considered for the project and their main characteristics are present.

Table 19 - Tabulation of the technical characteristics of the various Transponders

Transponder	Weight [g]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Mode
Microair Avionics T2000SFL	600	8	134	61	61	498614	Mode 3A/C operation, altitude response, selectable VSI/Vario display
Sandia Aerospace STX 165R	526	6	175	46	81	652050	Remote Mode C transponder, ADS-B compatibility when combined with a UAT 978 system
Trig Avionics TT21	500	130	160	68	48	522240	Mode S and Mode C transponder, suitable for small aircraft and UAVs

The Microair model is compatible with C mode, includes an altitude response and additional displays making it a very robust option, but it is the heaviest option. On the other hand, the Trig Avionics TT21 although it is compatible with mode C has significantly higher power consumption, which makes it less efficient.

After analyzing the transponders, the Sandia Aerospace STX 165R was chosen for the project. Sandia Aerospace directly meets the UAV requirements by offering compatibility with Mode C as required by CIAFA and additionally contains ADS-B, which is terminating for real-time tracking and communication. In addition, lighter weight and lower energy consumption make it an ideal choice for maximizing aircraft efficiency.

6.3.2 Distress Sensor

Distress Sensor or EPIRB is a piece of equipment that facilitates the rescue of the aircraft in emergency situations, transmitting emergency signals or protocols via satellite, sending high-precision signals allowing the aircraft to be located in the event of an accident or critical failure. In the case of the project, it offers an extra layer of safety by UAV flying over large bodies of water.

It is a piece of equipment that contains its own power, which means that energy consumption is not considered in the total consumption of avionics and systems. It can be activated automatically or manually in case of emergency, and its transmission autonomy must remain active until the rescue is completed (Cospas Sarsat, 2021).

Of three distress sensor options presented in the Table 20, the Ocean Signal EPIRB1 will be the system considered for this project, fully meets the established requirements, in addition, it is highly efficient, with a compact design, offering better integration into the UAV without compromising space and weight. It contains a built-in GPS and the ability to interpret and send accurate location data in real-time.

As all the systems studied had an autonomy of 48 h, this factor was not decisive in the selection of the system, so only efficiency and weight were considered.

Table 20 - Tabulation of the technical characteristics of the various Distress Sensors

<u>Distress Sensor</u>	<u>Weight</u> [g]	<u>Energy</u> <u>consumption</u> [W]	<u>Length</u> [mm]	<u>Width</u> [mm]	<u>Height</u> [mm]	<u>Approximation</u> <u>to volume</u> [mm3]	<u>Relevant aspects</u>
GME MT603FG GPS EPIRB	770	Minimal - unknown	260	102	83	2201160	Float-free activation, integrated GPS for precise location, 48-hour operational battery life once activated (SARSAT NOAA)
ACR GlobalFix™ V4 EPIRB	680	Minimal - unknown	247	116	119	3409588	Manual and automatic activation, built-in GPS, strobe light for visibility, 48-hour operational battery life once activated (SARSAT NOAA)
Ocean Signal EPIRB1	580	Minimal - unknown	178	89	100	1584200	Compact size, manual activation, integrated GPS, strobe light, 48-hour operational battery life once activated

6.3.3 SatCom

Satellite Communication is a satellite communication system used to ensure the transmission and reception of data, especially remote areas such as the high seas. As far as this project is concerned, SatCom is a fundamental component for real-time communication between the aircraft and the base, allowing the data collected during the mission to be obtained.

The use of this system is of great importance to provide global coverage and allowing connection in any area of the EEZ where communication may be limited or non-existent (Sencinet, 2023).

Different SatCom models were considered for the implementation of this project as presented in the Table 21.

Table 21 - Tabulation of the technical characteristics of the various SatCom

SatCom	Weight [g]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Range	Relevant aspects
NAL Research Corporation A3LA-RS	122	1,75	92	48	23	101568	Global coverage	Supports SBD, SMS, Data Switch, and RUDICS connectivity. This model is known for its small form factor and lightweight design, making it highly suitable for UAV applications (NAL Research) (ApolloSat). Operating temperature between 30C and +70C
Iridium 9602	30	1,5	41	45	13	23985	Global coverage	This modem is designed for short burst data (SBD) applications, making it ideal for tracking and telemetry purposes in UAVs
Skytrac ISAT-200A	2504	55	131	99	338	4383522	Global coverage	Provides global communication capabilities through the Iridium network and supports both voice and data services. It is slightly heavier but offers robust features for comprehensive communication needs
Honeywell Aspire 200	4000	60	376	60	190	4286400	Global coverage	This SatCom unit supports both Inmarsat and Iridium networks, providing versatile communication options. It's suitable for larger UAVs due to its weight and power requirements

After analyzing the different models, the NAL Research Corporation A3LA-RS was selected for the project, featuring compatibility with different means of communication, low power consumption, global mission reach, guaranteed by the Iridium satellite constellation. In addition, it is lightweight with a compact size, not compromising integration, performance and energy efficiency.

6.3.4 Autopilot

The autopilot is one of the most complete components of any UAV, being responsible for the automatic management of flights and control of the aircraft in various operating conditions. The Table 22 presents some of the autopilot options that were considered for this project: Piccolo Elite, Piccolo SL, Piccolo Nano, MicroPilot MP2128HELI, and VectorNav VN-300.

Table 22 - Tabulation of the technical characteristics of the various Autopilots

Autopilot	Weight [g]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm3]	Additional I/O support
Piccolo Elite	200	4	142	46	63	411516	16 configurable GPIO lines; Support for various peripherals, including CAN and serial buses; Multiple PWM outputs for controlling servos and ESCs, edge register and digital sensor interfaces for optional expansion
Piccolo SL	110	4	131	57	19	141873	14 configurable GPIO lines; Interfaces for various peripherals including transponders, servo-based pan-tilt cameras, and Iridium SATCOM systems
Piccolo Nano	29	2	76	46	11	38456	Configurable GPIO lines for custom applications; Supports integration with GPS, air data sensors, and other peripherals; Interfaces for external devices and sensors
MicroPilot MP2128HELI	28	5	100	60	15	90000	Multiple PWM outputs for control of servos and ESCs Analog and digital inputs for sensor integration; Serial ports for telemetry and data logging; I2C and SPI interfaces for additional sensor and device connections (AeroExpo)
VectorNav VN-300	24	2,5	46	46	11	23276	Dual serial ports (UART) for data communication and configuration; GPIO for custom applications; CAN bus interface for advanced communication; Support for multiple external sensors including magnetometers, barometers, and differential GPS

It is important to highlight that CIAFA already has experience with Piccolo and UAVISION autopilot systems. For this project, UAVISION autopilots were not considered, as they are not accepted by the regulatory body EMSA, so we will also disregard the MicroPilot MP2128HELI and VectorNav VN-300 models, which are less used for missions in compliance with DGAIED European guidelines. In the case of this project, this limitation is not a problem, however, it is

an impediment to the development of UAVs in general, as circumventing the use of a certain system can compromise both operational and airframe requirements.

Therefore, the first viable option for the project is the Piccolo Elite, being a long-standing standard in the UAS industry (Collins Aerospace, 2024). However, it only offers two additional GPIO lines to Piccolo SL, which, in terms of project needs, may not justify the choice, given that Piccolo SL already meets the requirements.

The Piccolo Nano is the lightest option among the autopilots of the Piccolo series, including low energy consumption and an extremely compact volume, however, for its proper use it is important to consider its three parts: Avionics Placo (76 x 46 x 11mm), Radio (61 x 46 x 14mm) and GPS (28 x 26mm). Despite the advantages presented for more complex missions that require the integration of advanced control and multiple sensors, the Piccolo Nano is not a good option.

Bearing in mind the previous considerations, Piccolo SL is the most balanced option being more compact than the Piccolo Elite and lighter, however, it does not feature as many configurable General-Purpose Input/Output. In addition, it measures a pressure differential of up to 6 KPa, translated into a maximum indicated air speed of 355 km/h, on the other hand, the Piccolo elite is limited to a pressure differential of 4 KPa, resulting in a maximum indicated air speed of 287 km/h. Although the difference is considerable, for the current project the maximum speed is set at 200 km/h, so both options are valid.

During the project, the Piccolo SL will be the autopilot chosen for its weight and compact size and the advantage of improving maximum speed if necessary, however, if greater expansion capacity is required, General-Purpose Input/Output configurable, the Piccolo Elite can be considered.

6.3.5 Servo-actuators

The control of the flight surfaces of a UAV is carried out by servo actuators, adjusting angles of the control surfaces, such as ailerons, rudders and elevators, during flight to ensure stability and control. It is empirical that the actuator system is reliable and prepared to operate under mission conditions. Servo actuators are placed on the outside of the aircraft, directly on the wing and tail surfaces, and are exposed to more severe conditions of temperature variation than other equipment. For safety and redundancy issues, the system is duplicated to ensure that the UAV maintains control in the event of a failure of one of the

actuators (AERO Engenharia, 2023). Thus, for the project four main actuators will be considered (two in the ailerons and one in the elevator and one in the rudder), due to the duplication required by safety, it will be necessary to install 8 actuators, if it is required to implement six servo-actuators the installation is 12 actuators.

Table 23 - Tabulation of the technical characteristics of the various Servo-actuators

Servo-actuators	Weight of 1 [g]	Weight of 4 [g]	Energy consumption of 1 servo [W]	Energy consumption of 4 servos [W]	Operating temperature	Observations
CBS-20 CAN Brushless Servo	84	336	10	40	T: -20°C a +85°C	They must operate at temperatures of -25 C +50 °C, each system must be duplicated for safety reasons: 4 to 6 servos which implies 8 or 12 actuators
CBS-15 CAN Brushless	45	180	10	40	T: -20°C a +60°C	
Hitec HS-5087MH	22	88	3	12	T: -20°C a +60°C	
Savox SH-0257MG	14	56	5	20	T: -10°C a +50°C	
Futaba S3150	23	92	4,5	18	T: -10°C a +60°C	

CIAFA already has experience in the use of the CBS-15 CAN Brushless, having been implemented in other developed UAVs. According to the information collected in the Table 23, none of the servo-actuators studied fully comply with the operating temperature of the UAV, however, no servo was found that would fit the project that did. Therefore, the CBS-20 CAN Brushless was chosen for this project being an evolution of the CBS-15, as it can withstand a wide range of temperatures, being robust and highly reliable, connecting directly to the autopilot of the Piccolo range, allowing precise control of the flight surfaces (Currawong Engineering, 2024).

Considering 8 servo actuators of the CBS-20, we have a dedicated weight of 672 g and an energy consumption of approximately 80 W.

6.3.6 Power Supply

The power supply system on board the UAV ensures the continuous operation of all subsystems and equipment. The power supply will be mainly by an integrated generator, which operates from the moment the UAV's engine is running and will have to be able to power all the instrumentation on board (Bruzza et al., 2022). Adding up approximately all the on-board instrumentation, an estimated power of 650 W is obtained.

Power consumption varies during the mission and not all components are operating at the same time, let's consider, in excess, that the generator will have to provide 650 W of

continuous power to meet the most demanding needs, to ensure that the generator will be sized to have a weight of 3.25 kg.

In addition to the main generator, it is essential to consider an energy backup system based on the use of batteries, ensuring the continuity of the systems in the event of a generator failure. In Table 24 the safety time and the power dedicated to both the payload and the avionics are presented, as well as the estimated weight, once again considering the expenditure of excess energy.

Table 24 - Power Supply considerations

<u>Power Supply</u>	<u>Weight</u> [kg]	<u>Energy</u> output [Wh]	<u>Time</u>
Main generator	3,25	650	The whole flight
Backup batteries for main systems	3,75	750	Average consumption of 250 W during 2 to 3 h
Payload backup batteries	1	200	Average consumption of 400 W during 20 a 30 min

It is interesting to note that the weight of avionics batteries is higher than the weight of the generator, this is because the batteries have to store all the energy needed for the emergency period, while the generator converts energy continuously, this factor reflects the energy density of the batteries, which despite providing a good autonomy in case of emergency, They have considerable weight in weight and volume ratio.

With this configuration, the operation of all systems is guaranteed, as well as an effective security and redundancy solution.

6.3.7 Data Link

The data link is responsible for ensuring real-time communication between the aircraft and the ground station, allowing the transmission of data, such as telemetry, video and control commands, resulting in the operator having full control of the UAV (Pedro & Azevedo, 2022). In Table 25 the two data links considered for this project are presented, as well as specific characteristics of each one.

Table 25 - Tabulation of the technical characteristics of the two Data Links

Data Link	Weight [g]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Operating temperature	Relevant aspects
Octopus ISR Systems Air Link	350	8	162	82	28	371952	T: -40°C a +85°C	It supports multiple communication protocols, making it versatile for different types of missions; Already integrated into UAVs due to energy efficiency and compact size
MIMO Wireless Data Link	500	10	200	150	40	1200000	T: -40°C a +85°C	Uses multiple inputs and outputs to improve the quality and speed of data transmission; Ideal for applications that require high bandwidth, such as real-time video transmission

There is no limitation that prevents the use of either of the two data links, on the other hand, there are advantages in the use of Octopus ISR Systems, because in addition to being lighter and more compact, the Octopus ISR Systems Epsilon E140Z G2 gimbal has already been implemented in this project, offering direct compatibility and simplified integration, proven high quality capacity with very low latency and reliability and efficiency over long distances ensuring communication steady and reliable.

6.3.8 Onboard Computation

The Onboard Computation system processes data from cameras, sensors and other equipment in real time. It ensures that these operations are automated and without delays. The processed data is transmitted via Data Link, allowing continuous communication between the UAV and the ground station, enabling effective control, requiring a good iteration between the two components (Klenke, 2005).

In addition, Rosie and Rudi in the systems already used by CIAFA in the Table 26 the systems considered for this project are presented.

Table 26 - Tabulation of the technical characteristics of the various Onboard Computation systems

Onboard Computation	Weight [g]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Operating temperature
Rosie Embedded System	1430	15	164	108	96	1700352	T: -20°C a +80°C
Rudi Embedded System	703	30	135	50	105	708750	T: -20°C a +80°C
NVIDIA Jetson Xavier NX	79	15	70	45	2	6300	T: -25°C a +80°C
Hexagon 820 (Qualcomm)	35	4	40	40	7	11200	T: -40°C a +85°C

Rosie's system can process a large amount of data. However, due to its high weight, it was disregarded in this project since Rudi is an efficient system in processing, but has a high energy

consumption compared to other options, both of these systems, however, should be taken into account in future reviews due to the existence of quality assurance by CIAFA because they have already been used in missions, with a proven track record.

Hexagon, although an option initially considered, may reveal limitations in terms of processing power for real-time operations involving large volumes of data, particularly in complex mission scenarios. This restriction made it unsuitable for the computational demands of the project.

In contrast, the NVIDIA Jetson Xavier NX has emerged as the ideal solution, combining portability and high performance. Its architecture optimized for artificial intelligence and real-time image processing, combined with its low weight, makes it exceptionally suitable for embedded applications that require high-performance computing on mobile platforms.

6.3.9 Other Avionics

At this stage of the project, the complete specification of the components required by CIAFA was carried out, except for the propulsion system. However, to ensure the full operability of the aircraft, the need to incorporate additional equipment was identified, in addition to those initially stipulated (Franco, 2018). In Table 27 additional equipment is presented, as well as its weights and assigned energy consumption.

Table 27 - Tabulation of a set of equipment that complements the operation of the UAV

Other Avionics	Weight [g]	Energy consumption [W]
Pilot Cam	300	5
Energy Converter Box	1000	15
Air Data System	500	10
GPS antenna	200	1
Inertial Navigation System	1200	20
Strobe lights	200	10
Environmental Control System	2000	50
Wiring system	1500	0

The considered camera is crucial for capturing clear images in a variety of conditions. The inertial navigation system, consisting of precision accelerometers and gyroscopes, allows navigation in areas with limited GPS signals. The high-precision GPS antenna, with differential correction capability, ensures accurate navigation. The DC-DC converter optimizes power distribution, while the HVAC (Heating, Ventilating and Air Conditioning) system regulates the optimal temperature for electronic equipment. High-intensity LED lights ensure visibility in

nighttime operations, and cabling interconnects all electronics and avionics, reducing electromagnetic interference and ensuring signal integrity.

6.3.10 Conclusion

To conclude the study of avionics, the various systems selected are present in the Table 28, the total weight of the avionics was estimated at 17,3 kg with a maximum power consumption of approximately 226 W, considering all systems in operation.

Table 28 - Summarization of the systems selected for the UAV avionics

All Avionics	Weight [kg]	Energy consumption [W]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm3]
Transponder: Sandia Aerospace STX 165R	0,53	6	175	46	81	652050
Distress Sensor: Ocean Signal EPIRB1	0,58	Minimal - unknown	178	89	100	1584200
SatCom: NAL Research Corporation A3LA-RS	0,12	1,75	92	48	23	101568
Autopilot: Piccolo SL	0,11	4	131	57	19	141873
Servo-actuators: CBS-20 CAN Brushless Servo - 8 of them	0,67	80				
Power Supply	8					
Data Link: Octopus ISR Systems Air Link	0,35	8	162	82	28	371952
Onboard Computation: NVIDIA Jetson Xavier NX	0,08	15	70	45	2	6300
Other Avionics	6,9	111				
Total	17,3	226				

The systems have been integrated with the purpose of ensuring efficient and safe operation of the UAV. The Piccolo SL, together with SatCom and Data Link enables control and continuous communication during the mission. The NVIDIA Jetson Xavier NX system processes the data from the sensors and actuators, which in turn ensures the correct manipulation of the aircraft's control surfaces. Redundancy has been implemented in the servo actuators and safety measures in the event of generator failure through the use of dedicated batteries. The entire avionics suite has been carefully selected to meet operational needs, keeping energy consumption under control and optimizing weight.

6.4 Propulsion System

The design of the propulsion system is limited due to CIAFA requirements that require the integration of an internal combustion engine. They could be considered jet or turboprop engines but are nevertheless discarded as their typical application and operating conditions are outside the scope of the project. Restricting the study to reciprocating-propeller engines that can be implemented in two possible arrangements: pusher or tractor (Gundlach, 2012).

Pusher-style configurations benefit from payload integration, freeing up the front of the aircraft for payload installation, offering an unimpeded view to the front, protecting the payload from engine exhaust and sources of contamination such as potential leaked fluids. The tractor configurations are exactly the opposite, increasing aerodynamic performance due to the flow drag at the front of the aircraft where the propeller is reduced, in turn, it is easier to control the yaw and pitch angles. Having the disadvantage of reducing the efficiency of the propeller and increasing the noise, both things originated by the wake generated by the body in front of the propeller (Gundlach, 2012).

On the other hand, the impact that the configuration of the propulsion system has on the weight distribution of the aircraft is also worth considering. Deliberating the longitudinal stability, the center of gravity of the UAV should be located in front of the neutral point, which is consistent with the tractor configuration, as this way, the aircraft has more easily greater weight in the front part than in the rear, in turn the pusher engine is located in the rear or in the central sections of the aircraft, its integration is more challenging from the point of view of stability (Gundlach, 2012).

6.4.1 Engine review and analysis

CIAFA already has consolidated experience in the use of the Wankel AR-741 engine, having been implemented in the ANTEX-M x03. The AR-741 is a widely used engine since its implementation in the RQ-2 Pioneer and RQ-7 Shadow, confirming itself in the market as a viable and reliable and efficient option for long-duration missions. Its viability can be confirmed by its use and integration in projects to this day, even though there are already engines with superior performance.

Even so, several options were considered in the market study carried out in the Table 29.

Table 29 - Market study and comparison of engines

Engine	Weight [kg]	Length [mm]	Width [mm]	Height [mm]	Approximation to volume [mm ³]	Maximum Power [hp]	SFC at Max.Power [lb/hp/hr]	Fuel Consumption [l/hr]	Price	Power/Weight	Needed fuel for the mission [l]	Fuel weight in [kg]	Total weight [kg]
AR-741	10,7	280	203	215	12220600	38	0,57	4,97		3,55	49,7	36,8	47,5
Zanzottera 498H	16,3	776	474	450	165520800	44	0,572	4,3		2,70	43	31,8	48,1
3W-342i B2 TS CS	8,82	240	371	170	15136800	35,8	0,489	10	5325	4,06	100	74,0	82,8
Rotax 912 ULS	56,6	590	576	375	127440000	100	0,42	15	20000	1,77	150	111,0	167,6
Hirth F33	12,7	299,5	380	300	34143000	30	0,35	6	2350	2,36	60	44,4	57,1
Simonini Victor 2 Plus	52	400	440	510	89760000	102	0,39	14	11730	1,96	140	103,6	155,6

Initially, as comparison criteria, only power, the ratio between power and weight were considered, and this method quickly proved to be insufficient because it disregarded the consumption of the engine. In this first phase of the consumption study, we will only consider the information in the datasheet of the respective engines and their expenses in liters per hour. For the conversion from liter to kg, the same density of 0,74 kg/l was considered.

Therefore, both the Rotax 912 ULS and the Simonini Victor 2 Plus are no longer options for this project because they exceed 150 kg. The 3W-342i B2 TS CS is a viable option, as far as total weight is concerned, however, its fuel consumption is very high, making it unsuitable for the mission period. The Hirth F33 boasts a good weight-to-efficiency ratio and balanced fuel consumption, making it one of the three main engines reviewed. The AR-741 and Zanzottera 498H are both light, fuel-efficient engines and have more than enough power for mission operation.

The final choice between the AR-741, Zanzottera 498H and Hirth F33 may depend on very detailed and specific considerations, but the AR-741 offers the best overall performance and will be the engine considered in the development of this project.

In addition to the engine, the fuel tanks were measured, which could be classified between three options: lightweight and corrosion-resistant polyethylene tanks, aluminum tanks heavier than polyethylene tanks, but also durable, and lightweight flexible tanks (Bladders), adaptable to the available space and safe in the event of an impact. Considering a safety margin of 15% the aircraft must carry 57,16 l of fuel, distributing the fuel over more than one tank to facilitate the balance and safety of the UAV, two tanks of 28,58 liters each, considering that polyethylene tanks are very light will be estimated a weight 1 kg of per tank, totaling 2 kg for both.

The tanks should be positioned in such a way as to contribute to the stabilization of the UAV's center of gravity, so ideally one tank on each side or other configuration that benefits balance of the main structure. In order to further detail the propulsion system, the use of

connections, monitoring sensors, fire protection and shock absorbers was considered, all these materials can be consulted in the Table 30.

Table 30 - Complementary instrumentation to the propulsive system and approximation of weights

Valves and couplings: Approx. 0,5 kg
Fuel Pipes: Approx. 0,5kg
Fuel level sensors: Approximately 0,3 kg
Wiring and connectors: Approximately 0,2 kg
Small fire extinguisher or suppression system: Approx. 1 kg
Flame retardant material: Approximately 0,5 kg
Cushions: Approximately 0,5 kg

The total weight of engine, fuel, tanks, fittings, monitoring, protection and shock absorbers is approximately 58,5 *kg*.

6.4.2 Conclusion

The approximation made previously for fuel consumption serves as a first analysis of the problem, however, as the project progresses, these parameters can be updated. It is not correct to consider that the consumption of the UAV is constant in the different stages of flight, (Corke, 2003) already addresses this problem by relating a fraction of the weight of a mission segment, this ratio being the weight at the end and at the beginning of each segment, these results can be consulted in the Table 31.

Table 31 - Fuel weight fractions

Segment	Take-off	Climb	Cruise (Range)	Cruise (Endurance)	Descent	Landing
Fraction	0,97	0,994	0,971	0,846	1	0,97

(Corke, 2003)

The cruise segment is the only one that can contain variations depending on the objective of the mission and as such the fractions studied are the only ones not determined by historical trends. The cruise segment is calculated using Brequet's equations of resistance and range:

$$R = \frac{V}{c_p} \frac{L}{D} \ln\left[\frac{W_i}{W_f}\right] \quad (13)$$

Where R is the range, V is the cruising speed, L is the lift, D is the drag and c_p is the specific fuel consumption of the thrust, these parameters at this stage of design are not yet known, the speed range are stipulated by the mission profile, the specific fuel consumption can be

found in the datasheet of the engines the remaining parameters have to be estimated which makes it impossible to obtain accurate calculations, these values are assigned according to operational experience or estimated according to equations as the ratio of $\frac{L}{D}$ to the following equation (Corke, 2003).

$$\frac{L}{D} = 0,94 \left[\frac{L}{D} \right]_{max} \quad (14)$$

For project continuity, the previously estimated values will be taken into account, but by advancing in the project it is possible to return to this point and detail the propulsion system. According to (Gundlach, 2012), the fuel weight varies from 30 % to 40 %, considering the estimated weight of fuel with 15 % safety the aircraft operates with 42,3 kg of fuel and taking into account the maximum weight of 150 kg, a margin of 28,2 % of maximum weight is obtained at the take-off of the aircraft of fuel which is close to what is expected.

6.5 Preliminary Estimate of MTOW

At this point in the project, it is already possible to determine the first weight estimate of the UAV due to the detail in the definition of the payload, avionics and propulsion system. Regarding UAVs, the weight of the structures varies from 10 % to 20 % of the maximum take-off weight, as a subsystem only the landing gear will be considered, which can vary from 3% to 6 % (Gundlach, 2012).

With all fixed weights and fractions determined, it is possible to obtain a first estimate of the MTOW using the following equation (Gundlach, 2012).

$$W_{TO} = \frac{W_{PL} + W_{Avion} + W_{Propulsion} + W_{Other}}{1 - (MF_{Struct} + MF_{Subs} + MF_{Energy})} \quad (15)$$

According to the equation W_{PL} is the weight of the payload 13,34 kg, W_{Avion} the weight of the avionics 17,3 kg, $W_{Propulsion}$ the weight of the propulsion system is 58,5 kg, the W_{Other} , will not be considered in this project because no detail is assigned. The MF_{Struct} , MF_{Subs} and MF_{Energy} are the structure, subsystems and energy fractions respectively, however, the energy fraction will not be considered as the powerplant has been studied and detailed within the avionics as seen previously.

Considering the values of the excess fractions, i.e. 0,2 and 0,06 for the fraction of the structure and subsystems respectively, the first MTOW of 120,5 kg is obtained, remembering that the maximum W_{TO} allowed is 150 kg.

Recalling the Empty weight fraction (Table 12) studied during the Market Survey the value of 0,8 indicated a good relationship between design, payload and structure weight with the first weight estimate of 120,5 kg, the no-load weight ratio is 0,89 which can be considered high, however for the UAVs studied with 0,9 the limitation are heavy or varied payloads, which is not a problem in this project because they have already been detailed. It is important to take into account that the estimated values were overestimated, which influences this result, but even so, it serves as a metric to indicate coherent progress in the project.

6.6 Fuselage

At an early stage, it is essential to start with an overview of the different types of structures present in the aeronautical industry. The core of the aircraft is shaped by a fuselage, to which the wings, tail, engine, landing gear and flight devices are connected.

Within the framework of the basic structure for wing or tail: pressure and shear loads are applied to the skin, transmitted to the ribs and supported by the spar (Niu, 1988). The wing skins are usually of fine features, and the spars are the main structural component of wing loading. With a beam shape, they extend along the wingspan or tail, carrying most of the forces and moments (MEGSON, 2003). When we talk about the structure of the fuselage, several options arise, such as Frame, Monocoque and Semi-Monocoque structures. In the Frame structure, the frame absorbs virtually all loads and consists of a series of vertical, horizontal, diagonal and longitudinal supports. Prevalent in modern light aircraft, it frequently exhibits a composite skin covering. In the Monocoque structure, the skin is the central component, supporting all flight and ground loads and providing rigidity to the shape of the structure. This design is inherently more robust, but also heavier and more delicate, since any damage to the skin affects the carrying capacity. The Semi-Monocoque structure distributes the loads between stringers, skin and the frame. It has more redundancy than the previous one and a solid relationship between weight and resistance (Niu, 1988).

The configuration of the fuselage is intrinsically linked to the configuration of the tail and the location of the propulsion system. The tail to be effective needs to be positioned at a specific distance from the wing to provide a suitable moment arm. By placing the engine at

the rear of the aircraft, creating a continuous fuselage that acts as a support on the tail, on the other hand, this approach has the disadvantage of placing significant weight behind the center of gravity, requiring minimal weight in the nose to compensate for the engine momentum, thus avoiding stability problems. If you choose to place the engine closer to the center section of the aircraft, brackets must be used to provide the necessary moment arm to the tail, and double or single brackets can be selected. Tractor configurations result in simpler airframes since the engine at the front does not generate stability problems (Gundlach, 2012).

6.6.1 Fuselage Sizing

When dimensioning the fuselage, the main objective is to ensure the accommodation of the equipment and systems studied, ensuring adequate dimensions of length, width and height, which provide the appropriate internal volume, keeping the parasitic drag as minimal as possible (Gundlach, 2012).

Therefore, the fuselage configuration must prioritize the best possible use of volume, minimizing voids and maintaining a simple configuration both in access and maintenance. According to the systems studied, it is possible to observe that both the width and height vary between 0,045 (Onboard Computation) and 0,215 (AR-741), these dimensions are not unreasonable, as the sections vary from 0,3 to 0,4 millimeters.

Thus concluding, the analysis of the width and height is followed by the determination of the length of the fuselage. From the analysis of the systems, we already know that it must be greater than 1,476 meters because the IMSAR NSP-7 Long-Range requires it, although this equipment does not occupy an internal volume it still has to be added to the outside of the fuselage. In order to complement the determination, the ratio of fineness $\frac{d}{l}$ will be used, ratio between the maximum diameter and the length (Corke, 2003). According to the definition of the fineness ratio, considering a circular cross-section with the same area as the rectangular one, an equivalent diameter is calculated in each cross-section. The maximum value D_{max} in this case is 0,40 meters, which is more than enough to accommodate the systems studied, with regard to the length close to the ideal would be approximately 2 meters, which would result in a fineness ratio of 0,2. Considering the recommended value to minimize the total drag coefficient for airframe for subsonic conditions the fineness ratio is approximately 0,3, however, for most subsonic aircraft, this fineness ratio of 0,3 is not practical, as payload needs tend to be a more important factor in the design. Instead, smaller fineness ratio values,

ranging from 0,08 to 0,125. Which reflects that the amount obtained does not present problems (Corke, 2003).

After defining the geometry of the fuselage, it is possible to move on to the next design phase of estimating the parasitic drag generated by it. Only parasitic drag is studied because the fuselage does not produce lift (Corke, 2003).

$$D_0 = q * S_{wet} * C_f * F * Q \quad (16)$$

In the equation q represents the dynamic pressure [N/m^2], S_{wet} the wetted area [m^2], C_f it is the coefficient of surface friction coming from the study of the flat plates and depends on whether laminar or turbulent flow, F the form factor depends solely on the fineness ratio and Q the interference factor which in most cases is negligible and is assumed to be $Q = 1$ (Corke, 2003).

Considering the cruising speed and altitude of the UAV, $q = \frac{1}{2} * 0,82 * 50^2 = 1025 N/m^2$, $0,82 kg/m^3$ being the air density 4000 m and 50 m/s the cruising speed, the wet area can be determined by OpenVSp obtaining $1,67 m^2$, C_f it can be estimated by dividing the fuselage into N segments of constant length and for each of them, the wet area and the surface friction coefficient are calculated, the Reynolds used in determining its determination is the local Reynolds segment, the total of the sum is the drag (Corke, 2003). Considering the end of the fuselage and that it is in a turbulent regime $C_f = \frac{0,455}{(\log_{10} Re)^{2,58}(1+0,144M^2)^{0,65}} = \frac{0,455}{6,26^{2,58}} = 0,004$, on the other hand, considering the initial area of the fuselage and that it is in a laminar regime $C_f = \frac{1,328}{\sqrt{Re}} = \frac{1,328}{951,9} = 0,001$, as the fuselage is not very long, only the calculation for these two sections will be considered, resulting in $C_f = 0,005$ approximately.

The form factor $F = 1 + \frac{60}{(l/D_{max})^3} + \frac{l}{400} = 1 + \frac{60}{5^3} + \frac{5}{400} = 1,49$ according to (Corke, 2003).

The corresponding drag of the fuselage is approximately $D_0 = 12,75 N$ ($C_{D0} = 0,00749$).

6.6.2 Design and Layout

The chosen UAV design features an elliptical structure, a widely used shape due to its efficiency and its ability to minimize resistance to movement progress (Corke, 2003). The elliptical shape offers a distinct ratio between volume and aerodynamic resistance, ensuring

greater stability and performance during flight, especially for long flight times. In addition, it facilitates the internal accommodation of the UAV systems, optimizing the available space.

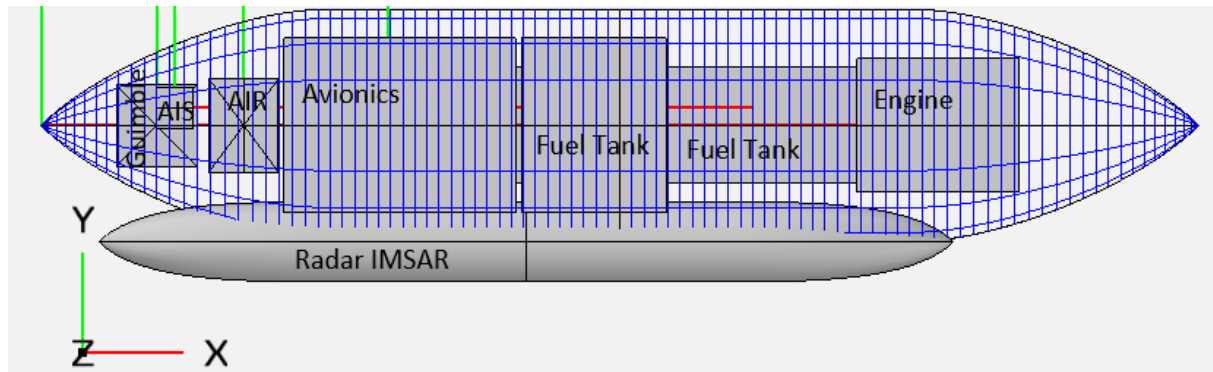


Figure 14 – UAV Layout

On Figure 14, view from above of the aircraft is represented, demonstrating a good distribution of the components, ensuring proper weight balance. The IMSAR radar was positioned on the side of the fuselage, being one of the few externally installed components with significant dimensions, however, its shape is already designed for external placement, which minimizes the aerodynamic impact of this decision.

The gimble was placed at a distance of $x = 0,2 \text{ m}$, from the nose of the aircraft, being the first component in the fuselage favoring its panoramic view. Above this equipment is placed the AIS system at $z = 0,07 \text{ m}$. The air pollution monitoring system is positioned further back, in $x = 0,35 \text{ m}$ and $z = 0,12 \text{ m}$, ensuring an organized, accessible layout with no critical overlaps.

To facilitate representation, the avionics were condensed into a single representation in the model, occupying a position of $x = 0,42 \text{ m}$. To minimize increased loads on the tail of the aircraft, the arrangement of the fuel tanks is asymmetrical, with one tank located at the bottom of the UAV at $x = 0,42 \text{ m}$ and $z = -0,123 \text{ m}$, and the other tank positioned more centrally, at $x = 0,83 \text{ m}$. Finally, the engine was placed next to the tail of the aircraft in $x = 1,6 \text{ m}$, compensating for the concentration of systems in the front and center of the aircraft and not favoring weight concentrations behind the UAV.

In order to obtain a first relationship between the components and the center of gravity (CG), during modeling each component received a "Blank" approximately in the center of mass of each of them to represent their respective weight. The exception was the IMSAR radar, where, due to its external installation, a more specific calculation involving a

relationship between weight, theoretical volume and density was used. This same density approach was applied to the fuselage to ensure a realistic mass distribution: the density of the fuselage was considered $60,98 \text{ [kg/m}^3\text{]}$ approximately and the radar density of $495,45 \text{ [kg/m}^3\text{]}$.

Once the assignment of weights and all the characteristics is completed, the "Mass Properties" function is used, which allows us to obtain a representation of the center of gravity. This tool operates through cross-sections "slices" in which the model is divided along the length, the higher the number, the more accurate the mass distribution will be (Litherland, 2024). In Figure 15 The result for 100 "slices" is represented, allowing us to know that the center of gravity is $x = 0,91 \text{ m}$, $y = 0,017 \text{ m}$ and $z = 0,007 \text{ m}$. Whereas the fuselage length is 2 m and $D_{max} = 0,4 \text{ m}$, the CG obtained can almost be considered ideal, reflecting a balanced distribution of the systems and favoring stability during flight.

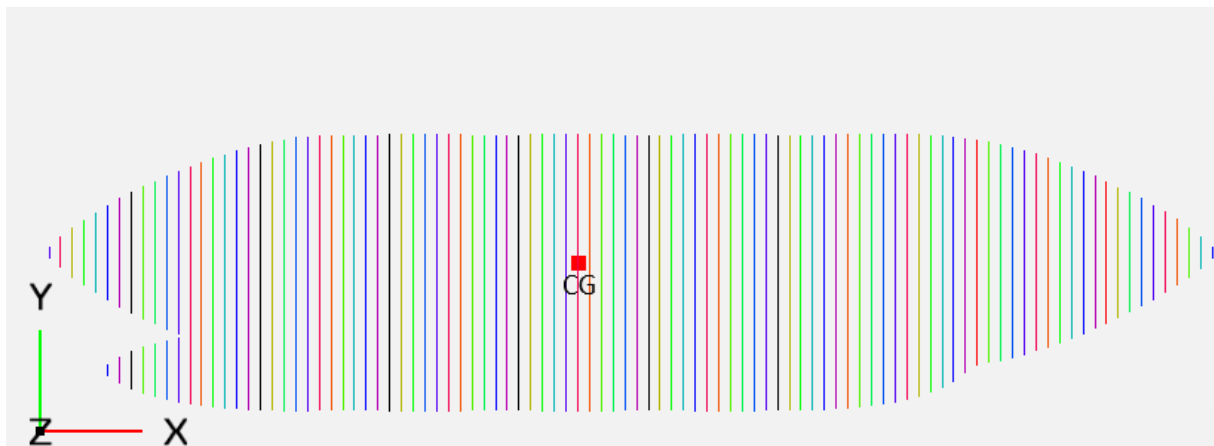


Figure 15 - Top view of 100 slices and CG position

The "Mass Properties" tool also offers a representation of the weight of the components considered, with the exception $3,5 \text{ kg}$ of the engine instrumentation that were not considered for this analysis, a weight was obtained $89,5 \text{ kg}$, disregarding the weight of the instrumentation and adding the weights previously studied a total is obtained $85,64 \text{ kg}$, which ensures that the approximation is in accordance with the expected and the first CG is a valid value for analysis.

Subsequently, the study of the center of gravity for a complete aircraft configuration will be resumed, studying its static stability.

6.7 Flight surfaces

According to (Gundlach, 2012) the configuration of the wing system is the combination of the lift surfaces, and the pitch compensation surfaces, the configurations of the primary wing system are represented in the Figure 16. These functions are performed by separate surfaces in most configurations but are combined in the case of a Flying wing. Most unmanned aerial vehicles adopt conventional configurations with the tail positioned behind the wing, although flying wing designs rank second in prevalence.

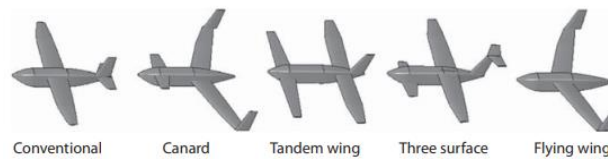


Figure 16 - Primary wing system configurations

(Gundlach, 2012)

The conventional configuration provides high aerodynamic efficiency in terms of lift-drag and range parameters. This wing system is favored by its conceptual simplicity and the fact that it is well understood by design experience, which makes it a low-risk, high-performance option (Gundlach, 2012). The rear stabilizer is responsible for the trim of the aircraft, the main wing is suitable to generate high lift coefficients, negative effects such as downwash or turbulence in the main wing do not occur because there are no surfaces in front of it.

The canard configuration uses a single horizontal surface in front of the main wing, this configuration can be aerodynamically superior or inferior to the conventional configuration, depending on the source consulted, (Gundlach, 2012) is in favor of the conventional wing, emphasizing that to avoid an unstable break of the pitching moment, the canard's stall margin requirement, limits the wing from reaching its lift potential, thus reducing the range parameter. This same requirement implies a decrease in the maximum lift coefficient, which corresponds to a higher maximum stall speed. In addition, the canard increases the total drag, so it generates an effect and downward drag on the main wing. On the other hand, (Raymer, 1992) argue that the use of canard is aerodynamically more efficient, as both surfaces generate positive lift, reducing induced drag. The integration of payload or the need for a short fuselage justify its approach, as it is agreed that this arrangement reduces the effectiveness

of trim and control due to the proximity of the canard to the center of gravity of the aircraft (Gundlach, 2012).

The third configuration presented, the tandem wing configuration, is characterized by the existence of two wings of similar dimensions, one positioned at the rear of the aircraft near the tail and the other at the front of the aircraft near the nose of the aircraft. In particular tandem, has lower aerodynamic efficiency and a less favorable stall behavior, when compared to the conventional configuration, due to the drag coming from the front wing in relation to the rear wing (Gundlach, 2012). The tandem configuration is commonly used for payload-specific integration or to accommodate large-span folding wings within the fuselage (Raymer, 1992).

The penultimate configuration of the Figure 16, the three-surface configuration seizes a main wing, a horizontal stabilizer in the tail of the aircraft behind the main wing, and a canard in the nose of the aircraft in front of the main wing. This configuration model has the potential to surpass the conventional configuration in terms of efficiency and aerodynamic performance, however, analyzing this configuration for its optimization requires much higher complexity and time. Other pejorative factors are the increase in weight, manufacturing and maintenance costs and a greater difficulty in analyzing stability and control.

The last configuration, the Flying wing configuration is the most complex configuration to stabilize, even with the use of computational tools, due to the reduced effective tail arm (Raymer, 1992). It has a single wing that acts simultaneously as a lift and trim surface. On the other hand, manufacturing, maintenance, simplicity and transport are favored factors over other configurations, due to the use of fewer components. In addition, it offers a lighter aircraft favoring stealth missions, due to the reduction of components there is a decrease in drag which leads to a greater lift-drag ratio, improving performance in long-range missions, however, at the same time it disfavors long-duration missions, where the lift capacity is reduced due to the deflection of the elevon control surfaces (control relationship between the elevator and the aileron control function) and the trim conditions that provide a lower range parameter than the conventional configuration (Gundlach, 2012).

In addition to the primary wing system configurations, the vertical positioning of the wing in relation to the fuselage as represented in the Figure 17.

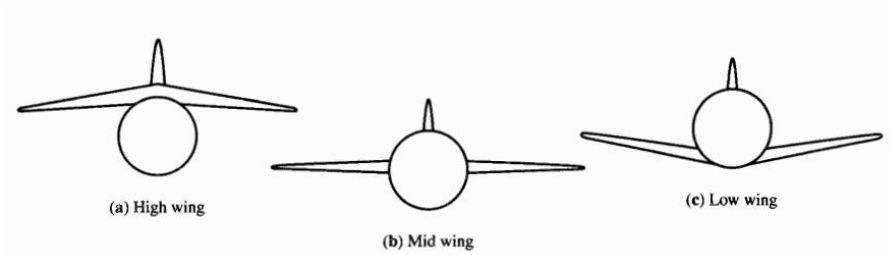


Figure 17 - Comparison of the vertical position of the main wing in relation to the fuselage

(Anderson Jr, 1999)

In UAVs, the high-wing configuration allows for significant advantages, such as the fuselage closer to the ground, which facilitates the loading and unloading of cargo and favors a greater distribution of the payload in the fuselage in relation to the CG and the aircraft's own weight. In addition, this configuration provides greater lateral and rolling stability, an essential feature for maintaining balance during flight. Even without dihedral, the increased pressure in the area between the fuselage and the lowered wing helps to restore the wings to the equilibrium position. However, this stability can be pronounced so that some high-wing aircraft use anhedral to correct for overly stable behavior in rolling (Anderson Jr, 1991). The mid-wing configuration on UAVs is advantageous because it offers the lowest drag among the three wing locations, minimizing interference between the wing and fuselage. However, it has significant structural drawbacks. To transmit the bending moment of the wings through the fuselage without obstructing the internal space, structural reinforcements such as support rings would be required, which can considerably increase the weight of the aircraft. Unlike high or low wing configurations, the mid-wing typically does not require dihedral, simplifying the design (Anderson Jr, 1991). The low-wing configuration in UAVs has the advantage of facilitating the design of the landing gear, which can be retracted directly into the wing box, one of the strongest parts of the aircraft structure. On multi-engine aircraft, the landing gear can also be retracted into the engine nacelles. However, this setup requires sufficient height to ensure the distance between the ground and the engine or propeller, which can add extra weight. In addition, it is necessary to include a dihedral to improve lateral stability (Anderson Jr, 1991).

For the design of the tail there are numerous possibilities, some of which can be observed in the Figure 18.

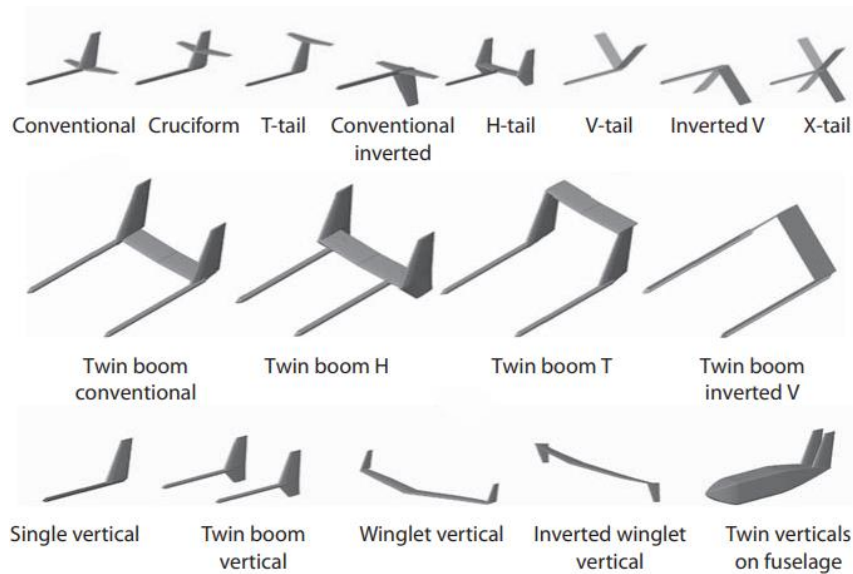


Figure 18 - Examples of tail and vertical stabilizer configurations

(Gundlach, 2012)

On Figure 18, the two main tail configurations, single attachment point, and dual boom tails and vertical tail configurations independent of the other horizontal tail surfaces respectively are represented. Tail design in UAVs offers some creative freedom to the designer, as drag is little affected by tail style, especially when it comes to the vertical tail, if the sizing is adequate. Some tail configurations follow popular trends in the industry in certain periods, such as the dual-tail UAVs of the 1970s to 1990s, whose vertical tails resemble those of the Cessna 337 (Gundlach, 2012).

Conventional tails provide sufficient stability and control with the lowest tail weight, serving as a reference to comparing other configurations. T-tails allow for smaller vertical stabilizers due to the endplate effect, and smaller horizontal stabilizers because they are outside the main wing track. The downside is the increase in weight required to reinforce the vertical tail to support the horizontal. The cruciform tail is a middle ground between the two, but without the benefit of the endplate effect (Raymer, 1992).

The H-tails offer advantages in positioning the vertical stabilizers in undisturbed air and allow to reduce the size of the horizontal stabilizer due to the endplate effect. However, this configuration requires additional structural reinforcement, which increases weight compared to the conventional tail. V-tails, on the other hand, reduce the total surface area, reducing drag, especially interference drag. However, the control is more complex, as rudder and elevator are combined on the same surface, which can result in adverse effects such as

yaw-rolling. Inverted V-tails avoid this control problem, but they have difficulties in ensuring adequate ground clearance. The considerations for twin-booms are similar, although this configuration tends to be heavier than the conventional fuselage. In inverted V-tails, ground clearance is no longer an issue and the endplate effects of vertical stabilizers on the horizontal can be considered (Corke, 2003; Raymer, 1992).

Twin-boom systems can adopt connected or disconnected tails. Disconnected tails can have the same configurations as a single fuselage, but also allow for asymmetrical arrangements. The use of swept tails, i.e. sloping backwards, increases the moment arm between the center of gravity and the aerodynamic center of the tail, allowing a reduction in the size of the tail necessary to maintain a fixed volume coefficient. However, swept tails can generate more drag at high angles of attack, which has a stabilizing effect. It is important to note that the rear tail should not stall before the wing, to avoid an unstable pitch break, which usually requires less elongation compared to the wing, allowing for a greater range of angle of attack before stalling. Tails designed to carry zero-lift have the characteristic of not generating lift coefficient in design flight conditions, which minimizes induced drag and maximizes the use of the internal fuselage volume for payload. However, this configuration is rarely used in modern operating systems, despite its pioneering in UAV designs by the U.S. Naval Research Laboratory (Gundlach, 2012).

6.7.1 Wing Sizing

The flight and flow regime characterized by the Mach number and the Reynolds number are fundamental to determining the flow behavior in the wing. To size the wing of the UAV, an approach based on principles of aeronautical projects established by authors such as (Corke, 2003; Gundlach, 2012; Raymer, 1992), will be followed.

First, the wing area will be studied, one of the key parameters to define the aircraft's lift capacity. To determine the wing area the lift coefficient equation is used which can be rearranged to determine S using the estimated weight of the aircraft in chapter 7.5 and a lift coefficient typical for the cruise phase.

$$S = \frac{2W}{\rho V^2 C_L} \quad (17)$$

In the previous equation W is the weight of the aircraft in Newtons $= 120,5 \text{ kg} * 9,81 \frac{\text{m}}{\text{s}^2} = 1182,11 \text{ N}$, ρ it is the density of the air at 4000 meters altitude $0,82 \text{ kg/m}^3$, V it is

the cruising speed $180 \text{ km/h} = 50 \text{ m/s}$ and C_L it is the lift coefficient in cruise, a typical value in cruise flight is about 0,6 to 0,7 according to (Raymer, 1992).

Substituting the respective values into the equation, the area of the base wing for the wing sizing is $1,77 \text{ m}^2$.

Next, another crucial factor to study is the aspect ratio, defined as the ratio of the wingspan to its middle chord (Raymer, 1992). Optimizations of the aspect ratios of UAVs occur for reduced speed values, ranging between 7,5 and 16,5. Only heavier UAVs have ratios higher than 16, such as General Atomics MQ-9 Reaper with an aspect ratio of 23, while most UAVs have aspect ratios between 7,5 and 10. This range reflects a balance between maximizing lift efficiency and minimizing drag, with higher aspect ratios favoring range at lower speeds, making them ideal for UAVs that need to stay in flight for long periods with minimal power consumption (Götten et al., 2021). Taking into account the conditions of the performance requirements and the type of mission, this project will be considering $A_R = 10$.

In view of the aspect ratio equation and the wing area already obtained, it is possible to determine the wingspan of the wing.

$$A_R = \frac{b^2}{S} \rightarrow b = \sqrt{A_R S} \quad (18)$$

From the previous equation we get a wingspan of $4,2 \text{ m}$.

With the wingspan and wing area defined, we can now calculate the chord using the taper ratio λ , which determines how the wing chord changes from the root c_r and c_t to the tip. Generally, the tapering ratio for small UAVs can vary between 0,3 e 0,6. This means that the width of the wing tip is between 30 % and 60 % the width of the wing root (Morais et al., 2018). In addition, the leading-edge sweep angle λ_{LE} is studied, which for subsonic flows (cruise regime $M = 0,15$) can be considered as zero, however, the addition of a sweep angle can be considered depending on the specific characteristics desired in the performance of the wing. In UAVs the sweep angle can vary widely, common values are between 0° and 15° . A smaller angle may be preferred to improve stability and maneuverability at low speeds (Morais et al., 2018).

$$\text{Root Chord} \quad c_r = \frac{2b}{A_R(1 + \lambda)} \quad (19)$$

$$\text{Tip Chord} \quad c_t = \lambda c_r \quad (20)$$

$$\text{Medium Aerodynamic Chord} \quad \bar{c} = \frac{c_r(1 + \lambda + \lambda^2)}{3(1 + \lambda)} \quad (21)$$

Based on these parameters it is possible to design the string according to the previous equations. For the realization of the equations a tapering ratio will be considered $\lambda = 0,5$, because for long-range UAVs it provides a good balance between aerodynamic efficiency and simplicity of construction. According to (Gundlach, 2012; Raymer, 1992), wings with a moderate tapering ratio, such as 0,5, allow a reasonable load distribution along the wingspan, which helps to improve efficiency and reduce induced drag, without harming the structure too much. Applying the formula of the chord at the root $c_r = \frac{2*4,2}{10(1+0,5)} = 0,56 \text{ m}$, the chord at the end $c_t = 0,5 * 0,56 = 0,28 \text{ m}$, a medium aerodynamic chord $\bar{c} = \frac{0,56(1+0,5+0,25)}{3(1+0,5)} = 0,22 \text{ m}$ and a medium rope $c_m = \frac{1,8}{4,2} = 0,42 \text{ m}$.

With the geometric characteristics of the wing determined, the Reynolds number is calculated, which defines the cruise flight as being approximately $R_e = \frac{0,82*50*0,42}{1,7*10^{-5}} = 1,02 * 10^6$, which lies outside the low Reynolds numbers.

6.7.2 Airfoil Selection

The airfoil is the base of the wing, the main source of its aerodynamic characteristics and its shape is selected based on the C_L , in level flight and the range of C_L values from the beginning to the end of the cruise, to generate the lowest possible drag (Corke, 2003). There are two possibilities: either you create a new airfoil style or use an existing one, the first option requires a lot of time and investment that this dissertation does not have, the second option requires less investment in time and money and favors the use of a vast and rich database (Gundlach, 2012).

Using or (Airfoil Tools, 2024), and the airfoils identified in the Market survey, taking into account the aerodynamic characteristics ($R_e = 1,02 * 10^6$ and $M = 0,15$) and relating the parameters: maximum lift coefficient C_{lmax} at maximum value of the lift coefficient that an airfoil can generate before stalling, lift coefficient as a function of angle of attack $C_{l\alpha}$ indicating how much lift increases for each degree of increase in angle of attack, C_{d0} the profile drag coefficient associated with the shape of the airfoil, regardless of the lift generated, C_{dmin} the minimum drag coefficient that the airfoil can have in any flight condition, C_{lminD} minimum lift

coefficient for drag, $(t/c)_{max}$ the maximum relative thickness of the airfoil, $\alpha_{stall}(\circ)$ the stall attack angle and C_{l0} the lift coefficient at zero angle of attack, it was established the Table 32 as a basis for comparison.

Table 32 – Two-dimensional characteristics of the main wing profiles

Airfoils	C_{lmax}	$C_{l\alpha}$	C_{d0}	C_{dmin}	C_{lminD}	$(t/c)_{max}$	$\alpha_{stall}(\circ)$	C_{l0}
NACA 64008	1,5	0,098	0,0082	0,0055	0,56	0,08	10	0,3
NACA 6512	1,6	0,095	0,0053	0,0079	0,62	0,12	15	0,32
Eppler 230	1,5	0,1	0,0048	0,0075	0,6	0,09	14	0,33
NACA 0012	1,3	0,105	0,0058	0,0085	0,5	0,12	16	0
NACA 0015	1,4	0,11	0,0062	0,0087	0,55	0,15	17	0
NACA 4415	1,5	0,11	0,0055	0,0077	0,65	0,15	14	0,35
DAE-21	1,6	0,1	0,0048	0,0073	0,65	0,13	15	0,38

(Airfoil Tools, 2024)

Based on the parameters presented, to maximize the range of airfoils with low C_{dmin} and good C_{lminD} are ideal, the Eppler 230 and the DAE-21 have low drag values and C_{lminD} competitive are the main profiles highlighted, in addition, the DAE-21 has higher C_{lmax} , which gives greater flexibility in steep climbs if the mission requires it. Given the stability at low-speed airfoils with higher $\alpha_{stall}(\circ)$ and $C_{l\alpha}$ are desirable, the NACA 4415 can generate lift at low angles of attack and is the best option for stability. Regarding the overall efficiency, the DAE-21 is the profile that appears to be more competitive, with better balance of maximum lift, minimum drag and balance, however, to complement the study, a relationship of the performance values of the aircraft in the two-dimensional and three-dimensional regime was carried out.

Therefore, it is necessary to rescue from chapter 5.2 the efficiency of Oswald, which is a necessary parameter for this analysis (Sadraey, 2024).

$$e = 1,78(1 - 0,045 * A_R^{0,68}) - 0,64 \quad (22)$$

The previous formula was developed by W. Bailey Oswald in 1936 and relates the aspect ratio that has already been defined previously with Oswald's efficiency and permits to obtain that $e = 0,76$ (Anderson Jr, 1991). This parameter is essential to convert the ratio of the Table 32 of profiles for a full-wing performance as shown in the following equation (Corke, 2003):

$$C_L = \frac{C_l}{1 + \frac{C_l}{\pi A_R e}} \quad (23)$$

This reasoning is also applied to the C_D one presented as (Corke, 2003):

$$C_D = C_d + \frac{C_L^2}{\pi A_R e} \quad (24)$$

Consolidating the results in the Table 33, it is possible to analyze an approximation of the real behavior of the wing with its profiles, considering three-dimensional effects. The formulation of the table allows the evaluation of the overall performance of the aircraft wing and establishes a relationship between the aerodynamic efficiency ratio $\frac{C_L}{C_D}$ which directly indicates the fuel efficiency of the flight per distance travelled and the specific energy efficiency $\frac{C_L^{3/2}}{C_D}$ which is a fundamental parameter in surveillance missions that demand slow and sustained flights where the time of stay is more important than the distance traveled, taking into account the mission defined for this project a balance between the two is ideal.

Table 33 – Approach to the three-dimensional characteristics of the wing

Airfoils	$\alpha_{trim}(^\circ)$	$\alpha_{stall}(^\circ)$	C_D	C_{Lmax}	$\frac{C_L}{C_D}$	$\frac{C_L^{3/2}}{C_D}$
NACA 64008	2,95	10,7	0,09	1,41	15,34	18,23
NACA 6512	3,1	12,3	0,10	1,50	15,01	18,38
Eppler 230	3,32	13,5	0,09	1,41	15,93	18,93
NACA 0012	0	14,3	0,07	1,23	17,68	19,63
NACA 0015	0	15,3	0,08	1,32	16,58	19,06
NACA 4415	3,64	12,6	0,09	1,41	15,81	18,78
DAE-21	3,87	13,8	0,10	1,50	15,09	18,48

Analyzing the results obtained, the profile remains a solid option for the project, however, the Eppler 230 is a competitive alternative, standing out for being slightly more efficient in terms of $\frac{C_L}{C_D}$ and $\frac{C_L^{3/2}}{C_D}$, which can be an asset for the mission in question and in addition, its stall angle is comparable to that of the DAE-21. Therefore, the profile used to shape the main wing is the Eppler 230 as represented in the Figure 19.

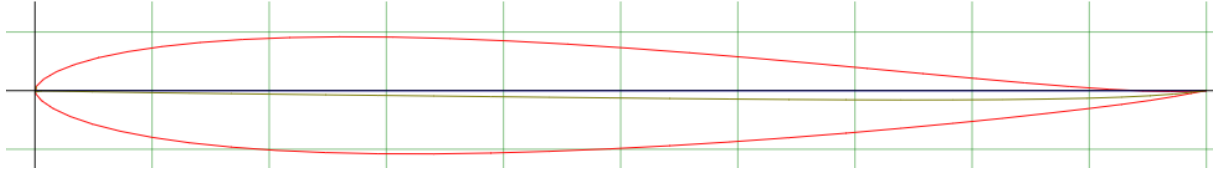


Figure 19 – Airfoil Eppler 230

(Airfoil Tools, 2024)

To finish the study of the wing, the lift coefficient is calculated as a function of the angle of attack $C_{L\alpha}$ to understand how the wing responds to variations in the angle of attack during flight, directly affecting cruise efficiency and performance in different phases of flight (Corke, 2003).

$$C_{L\alpha} = \frac{2\pi A_R}{2 + \sqrt{4 + \left(A_R \frac{1 + \tan^2(\Lambda_{t/c})}{1 - M \cos(\Lambda_{LE})} \right)^2}} \quad (25)$$

The value is $C_{L\alpha} = 5,85 \text{ rad}^{-1} \approx 0,102/^\circ$ a relatively high value for a long-range UAV wing. Indicating that the wing is efficient in generating lift for small increases in angle of attack. In terms of flight performance, this is desirable, especially in cruising flight situations or in maneuvers where moderate changes in the angle of attack must produce a significant amount of lift. About stability and control, the aircraft should respond quickly to changes in the angle of attack and in terms of cruise performance this value suggests saving in fuel, as the UAV does not need to increase its angle of attack much to generate the lift.

6.7.3 Designed wing and Drag Estimation

The wing presented in the Figure 20 It highlights the decision of a high-wing configuration, positioned at $x = 0,75 \text{ m}$ and $z = 0,18 \text{ m}$ in the fuselage. Its position changed the arrangement of the center of gravity to $x = 0,925 \text{ m}$, $y = -0,014 \text{ m}$ and $z = 0,34 \text{ m}$, the change was already expected, but the proper distribution and stability remained, small adjustments may still be made, but, for now, the configuration is within the expected for the project. By re-evaluating the CG, a new iteration of the weight accounting for the wing was now obtained closer to the value calculated in chapter 7.5 of 107 kg , which allows establishing a first iteration of the weight of the wing alone of approximately $17,5 \text{ kg}$.

The modelling of the wing in OpenVSP integrated some values calculated during the sizing step, adjusting them to values closer to reality, the first value was the area of the wing that

had been estimated for $S = 1,77 \text{ m}^2$ and the value was reset to $S = 1,66 \text{ m}^2$, which in turn led to an increase in the aspect ratio that had been set to $A_R = 10$ and its value was iterated to a slightly higher ratio $A_R = 10,7$ which is advantageous for the project.

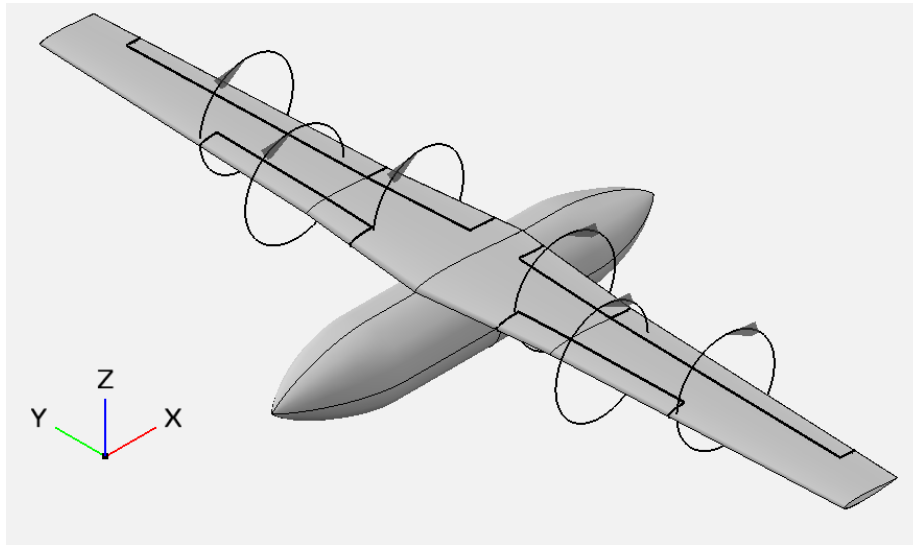


Figure 20 – Main wing added to the fuselage

The modeled wing is divided into two sections, the first section near the wing root, with a projected span of $0,64 \text{ m}$, and the second section with a projected span of approximately $1,47 \text{ m}$. The rope transition value was considered based on the aerodynamic average rope, equal to $0,42 \text{ m}$. The sweep location for both sections was set at $0,5$, meaning that the sweep was measured from the midpoint of the rope. This value is used to ensure proper aerodynamic behaviour in terms of drag and lift.

The wing was subdivided into three sub surfaces, corresponding to different types of flight control devices. The flaps occupy the inner part of the trailing edge, close to the root of the wing occupying 30 % the wing extension from the root to 50 % the extension still close to the root, they increase the curvature of the wing, allowing more lift at lower speeds. The ailerons control the roll of the aircraft, being placed on the outer side of the wing, in this configuration they occupy 50 % the extension near the middle of the wing to the 71 % wing extension near the tip, also positioned on the trailing edge. The slats are positioned on the leading edge, have the function of improving the flow of air over the wing at high angles of attack, preventing flow separation for low speeds and increasing the efficiency of the wing, in this case, they were positioned at 40 %, from the wing extension just in front of the flaps to 60 % the wing extension, occupying a central section.

With the design characteristics of the wing defined, as well as in the fuselage it is possible to move on to the next design phase and calculate the total wing drag according to (Corke, 2003) the wing drag can be described.

$$C_{D0} = C_f F Q \frac{S_{wet}}{S} \quad (26)$$

Just like for the fuselage, C_f it's the viscous drag coefficient, F it's the form factor, Q it's the interference factor, and S_{wet} it's the wet area of the wing and S the wing area. (Corke, 2003) defines that the interference factor provides for the increase in parasitic drag caused by the interference effects on the fuselage and wing accessories and that for high-configuration wings $Q = 1$. The C_f is the same reasoning presented for the fuselage is the sum of the laminar and turbulent regime, taking into account approximately $Re_x = 1,24 * 10^6$ the transition, the turbulent section $C_f = \frac{0,455}{(\log_{10} Re_x)^{2,58} (1 + 0,144 M^2)^{0,65}} = 0,00429$ and the laminar section $C_f = \frac{1,328}{\sqrt{Re_x}} = 0,00119$, giving a total frictional drag of $C_f = 0,0055$. Just as in the fuselage the wetted area was determined with the use of OpenVSP $S_{wet} = 3,28 m^2$, as the shape factor of the wing is different from that of the fuselage the value of the thickness-chord ratio is required for the application of the equation and the value can also be taken from OpenVSP $\frac{t}{c} = 0,09971$ and F is defined according to the following equation (Corke, 2003).

$$F = \left[1 + \frac{0,6}{(x/c)_m} \left[\frac{t}{c} \right] + 100 \left[\frac{t}{c} \right]^4 \right] \left[1,34 M^{0,18} \left(\cos(\Lambda_{t/cmax}) \right)^{0,28} \right] \quad (27)$$

Applying the previous equation $F = 1,097$, which translates a $C_{D0} = 0,01188$, which results in a force of approximately $D_0 = 20,21 N$.

6.7.4 Tail Sizing

In the conceptual designs of aircraft, the sizing of the vertical and horizontal tail surfaces are based on historical trends, through coefficients that relate characteristics of different aircraft that are relevant to the tail design, these aircraft are grouped according to the mission requirements (Corke, 2003).

The coefficients used to design the vertical stabilizer, and the vertical stabilizer are named C_{VT} and C_{HT} respectively. The area of the stabilizers can be determined by the following equations (Corke, 2003).

$$S_{VT} = C_{VT} \frac{b_W S_W}{l_{VT}} \quad (28)$$

$$S_{HT} = C_{HT} \frac{\bar{c}_W S_W}{l_{HT}} \quad (29)$$

In the previous equations, b_W and S_W represent the wingspan and area of the main wing, l_{VT} it is the distance between the chord locations of the average aerodynamic chords of the main wing and the vertical stabilizer, in turn, l_{HT} it is the same thing only for the horizontal stabilizer and $\bar{c}_W$ represents the average aerodynamic chord of the main wing. One difference between the two equations is that the vertical stabilizer area S_{VT} includes only the part that is exposed above the fuselage, while the horizontal stabilizer area S_{HT} includes the portion that runs through the fuselage. The distance l_{VT} acts as the moment arm on which the aerodynamic force generated by the vertical stabilizer acts on the fuselage, so it is possible to conclude that a greater distance requires a smaller area of vertical stabilizer (Corke, 2003). As no documentation or historical trends were found on (Corke, 2003; Raymer, 1992) the tail coefficients for UAVs, approximation values will be used according to the class of home-built aircraft, therefore, $C_{VT} = 0,04$ and $C_{HT} = 0,5$.

For simplicity it will be considered that the horizontal and vertical stabilizers are located near the tail of the aircraft, in $x_{tail} = 1,78 \text{ m}$ and to determine the distances will be used the approximation of the following equation.

$$l_{VT} = l_{HT} = x_{tail} - \left(x_{wing} + \frac{\bar{c}}{2} \right) \quad (30)$$

In the previous equation, it is possible to obtain an approximation of l_{VT} and l_{HT} , defining its positioning in the fuselage x_{tail} in relation to the positioning of the wing in the fuselage $x_{wing} = 0,75 \text{ m}$ both distances are equivalent to the center of the respective components, obtaining an arm distance of approximately $l_{VT} = l_{HT} = 0,82 \text{ m}$.

Resuming the previous equations, $S_{VT} = 0,04 \frac{4,2 * 1,66}{0,77} = 0,34 \text{ m}^2$ and $S_{HT} = 0,5 \frac{0,22 * 1,66}{0,77} = 0,22 \text{ m}^2$. However, as an H-shaped configuration will be adopted, the vertical stabilizer is divided into two panels coupled to the horizontal stabilizer, thus the $S_{panel} = S_{VT}/2 = 0,17 \text{ m}^2$.

Once the areas of both platforms are defined, we implement the same logic of the kite, it is necessary to determine the typical values of aspect ratio and the thinning ratio to be able

to use the equations previously studied for each of them. Corke and Raymer (Corke, 2003; Raymer, 1992) set values for both stabilizers, typically for vertical tails the aspect ratio values vary between 1,3 – 2 and the tapering ratio varies between 0,3 – 0,6, for horizontal stabilizers A_R varies between 3 – 5 and λ varies between 0,3 – 0,6. For this design to starting point the vertical tail will comprise $A_R = 2$ and $\lambda = 0,5$ compromising values of stability and performance, avoiding excessive drag and maintaining effective control, the horizontal tail is assigned a value of $A_R = 4$ and $\lambda = 0,45$, values that provide good maneuverability and stability while maintaining aerodynamic efficiency and lightweight structure.

Using the formulas previously applied to the main wing we can now define all the geometric considerations of the tail, the results obtained for each of the equations are represented in the Table 34.

Table 34 - Geometric features and Reynolds number of the tail

	Vertical Tail	Horizontal Tail	
$b =$	0,58	0,94	[m]
$c_r =$	0,39	0,33	[m]
$c_t =$	0,19	0,15	[m]
$c_m =$	0,29	0,24	[m]
$\bar{c} =$	0,15	0,13	[m]
$R_e =$	7.04E+05	5.69E+05	

Once the geometric calculations are completed, we move on to the next stage of tail sizing, the study of the dedicated profile, the selection of the type of airfoil used for the horizontal and vertical stabilizers must be based on a low base coefficient and being a symmetrical airfoil (Corke, 2003). One factor to pay attention to is the provision of pitch-up, as such, the selected airfoil must ensure that the horizontal stabilizer enters stall after the main wing $\alpha_{SHT} > \alpha_{SW}$.

Returning to the use of (Airfoil Tools, 2024), the most common profiles are the NACA for their simplicity and good aerodynamic performance in the Table 35 and Table 36 the characteristic values studied for the respective airfoils are represented considering a change in the Oswald efficiency $e = 0,93$ that represents the horizontal stabilizer according to the equation studied above.

Table 35 - Two-dimensional characteristics of tail profiles

Airfoils	C_{lmax}	C_{d0}	C_{lminD}	$(t/c)_{max}$	$\alpha_{stall}(^{\circ})$
NACA 0009	1,2	0,0045	0-0,2	0,09	12
NACA 0012	1,35	0,0055	0-0,2	0,12	15
NACA 0015	1,4	0,0035	0-0,2	0,15	16
NACA 0018	1,8	0,001	0-0,2	0,18	18
NACA 0021	2,1	0,002	0-0,2	0,21	19

(Airfoil Tools, 2024)

Table 36 - Approximation to the three-dimensional characteristics of the horizontal stabilizer

Airfoils	$\alpha_{stall}(^{\circ})$	C_D	C_{Lmax}
NACA 0009	15	0,05	1,15
NACA 0012	18	0,06	1,29
NACA 0015	16	0,06	1,34
NACA 0018	17	0,10	1,70
NACA 0021	18	0,13	1,96

For non-zero angles of attack and taking into account aerodynamic efficiency in cruise flights, the NACA 0015 profile offers the highest lift coefficient, which is beneficial for maintaining flight at lower speeds and improving fuel efficiency. Increased stall margin and good maneuverability is gained by utilizing the NACA 0012 and for further drag reduction the NACA 0009 is ideal. The profile selected for the course of the project is the NACA 0015, however, the NACA 009 is still an excellent option and if it is necessary to reduce drag, this would be the selected profile, however we will maintain the NACA 0015 in this study that is represented in the Figure 21.

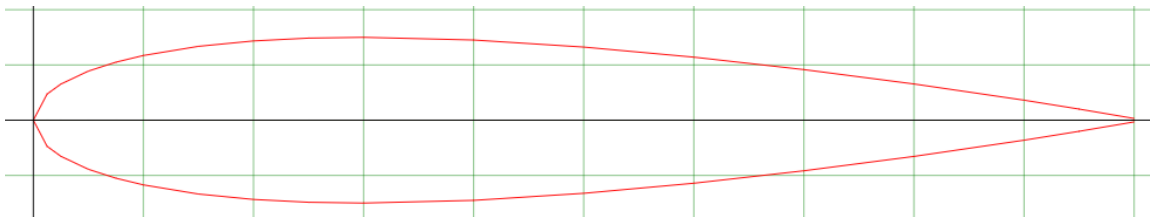


Figure 21 - NACA 0015 airfoil

(Airfoil Tools, 2024)

Again, as well as in the fuselage and as for the main wing after defining all the characteristics of the tail it is possible to calculate the shape drag coefficient of the vertical component and the horizontal component of the tail. The formulas used for this process are the same as those already used for the wing, however, they have some small differences, such

as the value of the interference factor Q , which for the H-shaped tails is considered $Q = 1,08$, according to (Corke, 2003). In addition, the form factor, F , is the same as that of the main wing, however, this equation slightly underestimates the effect of hinge clearances that occur by the elevator and the rudder. As a result, the format should be increased by approximately 10 % (Corke, 2003), so $F = 1,097 * 1,1 = 1,21$. The ratio S_{wett}/S is the ratio of the horizontal wet area of the tail to the flat area of the wing.

The vertical stabilizer presents $Re_x = 8,58 * 10^5$, thus, the C_f for the turbulent regime $C_f = \frac{0,455}{(\log_{10} Re_x)^{2,58} (1+0,144M^2)^{0,65}} = 0,00459$ and C_f for the laminar regime $C_f = \frac{1,328}{\sqrt{Re_x}} = 0,00143$, obtaining a total C_f of $C_f = 0,006$, considering through the OpenVSP the wet area of the panel, $S_{wett} = 0,325$, which is obtained $C_{D0} = 0,0017$ equivalent to a drag force, $D_0 = 2,84 \text{ N}$. The horizontal stabilizer maintains the values of the interference factor and in the same way as previously stated, however, the rest undergo changes the Reynolds transition is $Re_x = 6,94 * 10^5$, which translates into a turbulent regime of $C_f = 0,00478$ and in a laminar regime $C_f = 0,00159$, obtaining a total C_f of $C_f = 0,0064$, considering the value of $S_{wett} = 0,42$ originated by OpenVSP, is obtained a $C_{D0} = 0,0021$, which is equivalent to a drag force $D_0 = 3,61 \text{ N}$.

On Figure 22 the design obtained from the tail and its integration into the UAV according to the calculated geometric characteristics is represented.

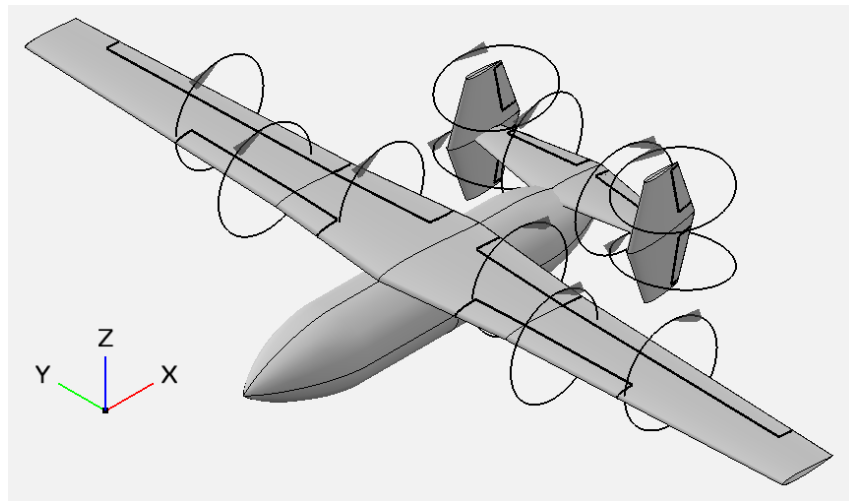


Figure 22 - Integration into the tail in the UAV

The tail surfaces were not separated into sections as in the case of the main wing, however, the sweep location for both surfaces was fixed at 0,5, meaning that the sweep was

measured from the midpoint of the chord. This value is used to ensure adequate aerodynamic behavior in terms of drag and lift, as well as on the main wing.

The horizontal stabilizer integrates the elevator responsible for controlling the pitch movement, it adjusts the angle of attack of the tail, allowing the altitude to control the altitude, in the case of the configuration presented, the elevator is positioned between 37 % and 62 % of the horizontal stabilizer extension, being a significant part of the trailing edge of the horizontal surface of the tail. This centralized location offers a balance between pitch control and structural efficiency of the stabilizer. The vertical stabilizer houses the rudder, which controls the yaw movement, which is critical for maintaining directional stability and performing coordinated turns. In the H-tail configuration, the vertical stabilizers are positioned at the tips of the horizontal stabilizer, forming the "H" part of the tail. The rudder in the design presented occupies the extension of 40 % to 65 % the vertical stabilizers, allowing effective yaw control.

The position of the tail has changed the arrangement of the center of gravity to $x = 0,977\text{ m}$, $y = -0,013\text{ m}$ and $z = 0,39\text{ m}$, the change is within expectations, as the proper distribution and stability have been maintained, small adjustments may still be made, but, for now, the configuration is within the expected for the project. Once again, a new iteration of the weight accounting for the tail was obtained even closer to the value calculated in chapter 7.5 of 113 kg , which allows us to establish a first iteration of the tail weight of approximately $6,7\text{ kg}$.

6.8 Landing Gear

The landing gear allows the UAV to perform conventional takeoffs and landings, as well as sustain it on the ground. The integration of the landing gear significantly affects the design of the aircraft, especially in terms of positioning in relation to the center of gravity and payload. In the design process, the landing gear is the final major component of the aircraft to be boarded. In other words, the design of all major components, including the wing, tail, fuselage, and propulsion system, must be completed before the landing gear is studied. And in certain cases, the landing gear design may require the aircraft designer to change the aircraft configuration to meet the requirements of the landing gear design. There are several landing gear configurations as depicted in the Figure 23, the most common being tricycle,

taildragger, bicycle, and monowheel in fixed, retractable, and partially retractable format (Gundlach, 2012).

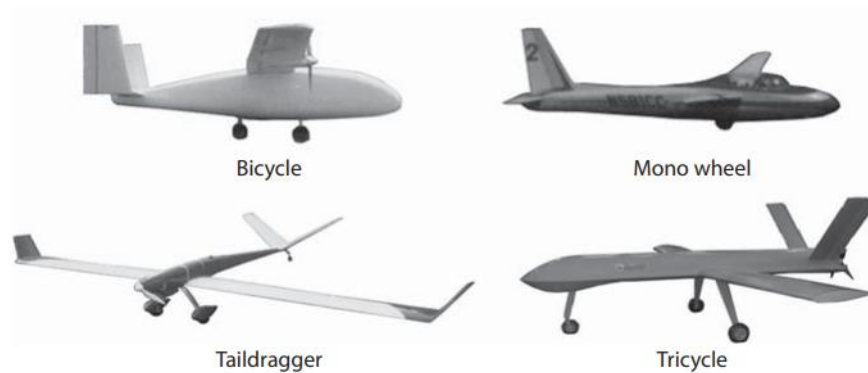


Figure 23 - Common landing gear configurations

(Gundlach, 2012)

The tricycle configuration is the most common due to its simplicity for takeoff, landing, and maneuverability on the ground. This configuration, which consists of two main wheels positioned behind the CG and a nose wheel, which is usually steerable, makes it easier to control the aircraft on the ground. Other configurations, such as the taildragger, have greater complexity during takeoff and a higher risk of ground-loops, which require more sophisticated control logic. The bicycle configuration, which positions the main wheels along the aircraft's axis of symmetry, can be useful in certain contexts, but it is less stable on the ground, requiring additional stabilizers. The monowheel offers simplicity and lower drag, but limits parking capacity and requires external support to keep the wings level before takeoff (Gundlach, 2012).

Fixed landing gear configurations offer simplicity during the design phase and lower weight compared to retractable, but at a higher cost of dragging. Retractable landing gear benefit from reduced drag and improved stealth, however, their increased weight, complexity, and costs are often drawbacks, especially for small UAVs (Gundlach, 2012).

For the design of the landing gear, this project will focus on aspects such as the height of the landing gear, the angle of rotation during takeoff, the load distribution between the main gear and the nose gear, and the static and dynamic loads that the landing gear needs to support.

The first aspects to depict are the distances from the main train and the nose train B , known as the wheelbase. This distance affects load distribution and controllability on the

ground. For aircraft to adopt the tricycle configuration, the nose gear must support between 5 % and 20 % of the total load of the aircraft, while the main gear loads from 80 % to 95 %. And the static load distribution in trains is given by (Chai & Mason, 1996; Currey, 1988):

$$\text{Nose Gear static load} \quad F_n = \frac{B_m}{B} W \quad (31)$$

$$\text{Main Gear static load} \quad F_m = \frac{B_n}{B} W \quad (32)$$

In the previous equations B_m represents the distance from the main train to the center of gravity and B_n , is the equivalent for the train in the nose at the Figure 24.

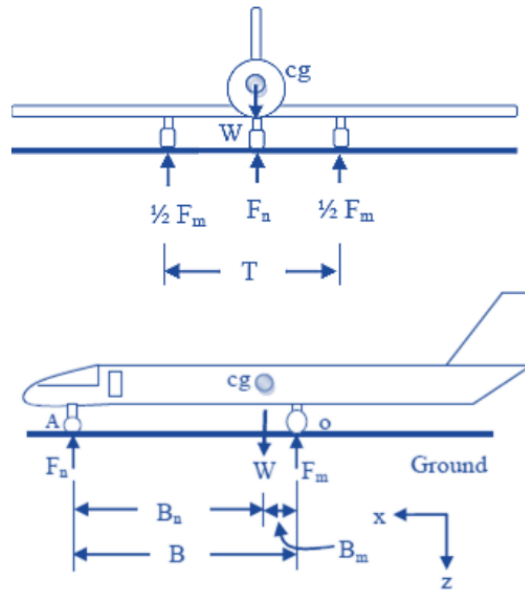


Figure 24 - Tricycle configuration geometric features

To ensure the balance of forces, the sum of all forces in the direction z must be equal to zero:

$$\sum F_x = 0 \Rightarrow F_n + F_m = W \quad (33)$$

In turn, the sum of the moments around point zero must also be equal to zero:

$$\sum M_o = 0 \Rightarrow F_n B - W B_m = 0 \quad (34)$$

Taking into account the last positioning of the CG obtained for $x = 0,977 \text{ m}$, $y = -0,013 \text{ m}$ and $z = 0,39 \text{ m}$, the determination of the positioning of the gear in the nose and the main gear began, in order to comply with the load percentages, these values were adjusted until the conditions were fulfilled. The front wheel was positioned on $x_n = 0,2 \text{ m}$ and the rear wheels on $x_m = 1,1 \text{ m}$, thus obtaining a distance from the front wheel to the CG

of $B_n = 0,577 \text{ m}$ and from the rear wheels of $B_m = 0,123 \text{ m}$, which results in a distance between them of $B = 0,7 \text{ m}$. By calculating the static loads for each of the supports is obtained $F_n = 207,713 \text{ N}$ and $F_m = 974,392 \text{ N}$ that in percentage is equivalent to 17,57 % of the weight on the front wheel and 82,43 % on the rear wheels, as each rear wheel supports $\frac{1}{2} F_m$, then each wheel of the main gear is equivalent to $487,196 \text{ N}$, which results to 41,214 % of the force on each wheel respectively. This configuration is within the recommended values for the design, however, the CG has a tendency to oscillate and as such is study the variation of the B_n and of the B_m for a maximum and minimum position according to the Figure 25.

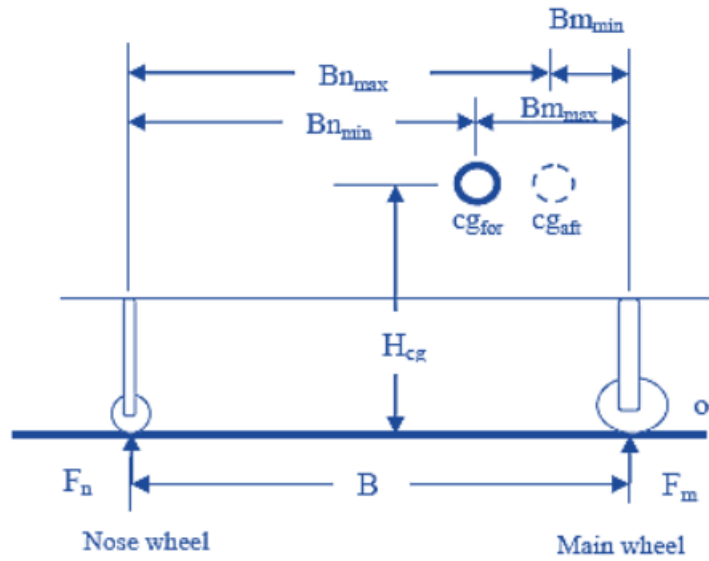


Figure 25 - Geometry of the wheel loads

As represented in the Figure 25 when a maximum distance from the front wheel to the CG is considered $B_{n_{max}}$, a minimum distance from the rear wheel to the CG of $B_{m_{min}}$ is considered and respectively the reverse also applies. With this condition in mind, an approximation of the maximum and minimum values was carried out. When is considered $B_{n_{min}} = 0,627 \text{ m}$, in turn $B_{m_{max}} = 0,153 \text{ m}$, the percentage of forces distributed is $F_n = 90,62 \%$ and $F_m = 80,38 \%$, studying the inverse case $B_{n_{max}} = 0,477 \text{ m}$ and $B_{m_{min}} = 0,118 \text{ m}$ the forces on the respective front and rear wheels are $F_n = 19,83 \%$ and $F_m = 80,17 \%$. These are values very close to the beginning of failure of the recommended percentages for weight distribution and serve as an analysis metric if changes need to be made to the UAV design, through the positioning of the nose gear or main gear, if these values are

exceeded, the distribution of equipment and systems must be reevaluated to maintain the recommended percentages.

Now that a landing gear positioning interval has been defined according to the static balance, let's continue the design by looking at the clearance angle α_c that evaluates the probability of an impact on the tail of the fuselage during takeoff is the corresponding angle between the ground and the line from the point of contact of the main gear to the beginning of the upsweep angle on the fuselage, as represented in the Figure 26 (Chai & Mason, 1996; Currey, 1988).

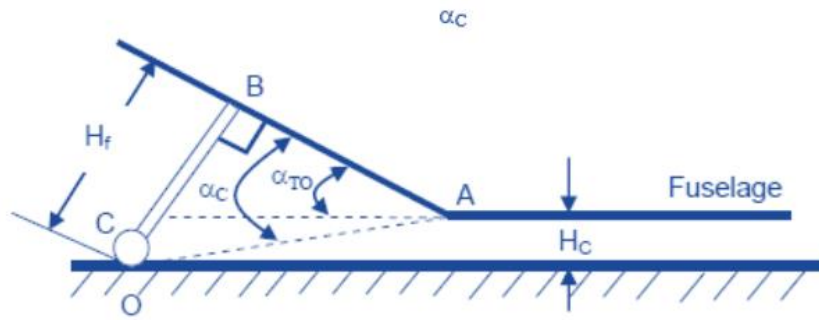


Figure 26 - Schematic representation of the take-off of an aircraft

To avoid this accident, one approach is to increase the height of the landing gear. Another common solution is to introduce an upward tilt angle cutting through the rear fuselage. However, increasing the size of the landing gear results in an increase in drag, so it should be found in balance. The angle of rotation during take-off α_{TO} can be estimated in documented data from other aircraft, ranging from 8° to 15° depending on its configuration and geometry, for the design we will consider one $\alpha_{TO} = 12^\circ$ (Anderson Jr, 1999). Considering the positioning of the main gear the distance between the point of contact of the main gear and the start of the fuselage can be approximated to $AB = 0,9 \text{ m}$, the height of the rear fuselage H_f will be considered equal to the height of the landing gear supports $H_{LG} = H_f = 0,3 \text{ m}$, the clearance angle α_c can then be calculated using.

$$\alpha_c = \tan^{-1}\left(\frac{H_f}{AB}\right) \quad (35)$$

Applying the previous equation, we obtain that $\alpha_c = 0,322 \text{ rad}^{-1} \approx 18^\circ$, which is higher than the estimated value of the angle of rotation during take-off from $\alpha_{TO} = 12^\circ$, which ensures that the fuselage does not hit the ground during take-off. The reverse process can be applied to determine the minimum height required to obtain $\alpha_c = \alpha_{TO}$, which would

result in approximately $H_f = 0,2 \text{ m}$, however this value is very close and does not provide any security.

As well as, for the previous components to finish the landing gear study the second drag component is estimated (Sadraey, 2024). The components that generate drag on the landing gear are the tires and the structure and their contribution to the parasitic drag can be calculated using the following equations:

$$C_{D0_{tires}} = \sum_{i=1}^n C_{D0_{tires}i} \left(\frac{S_{tiresi}}{S} \right) \quad (36)$$

$$C_{D0_{strut}} = \sum_{i=1}^n C_{D0_{struti}} \left(\frac{S_{struti}}{S} \right) \quad (37)$$

In the previous equations n it is the number of tires/structures, $C_{D0_{tires}i}$ and $C_{D0_{struti}}$, represent the drag coefficient of each tire/structure and S_{tiresi} and S_{struti} the frontal area of each tire/structure. For the tires, an elliptical shape was considered where the larger axle shaft $a = 0,05 \text{ m}$ and the minor axle shaft $b = 0,03 \text{ m}$, resulting in a tire area of $A_{tire} = \pi * 0,05 * 0,03 = 0,00471 \text{ m}^2$ the brackets area was calculated using $A_{strut} = 0,3 * 0,05 = 0,015 \text{ m}^2$. To perform the calculations will be considered for the drag coefficient of the tires $C_{d0_{tires}} = 0,02$ and the drag coefficient of the brackets $C_{d0_{strut}} = 0,05$. Thus, applying the previous equations we obtain $C_{D0_{tires}} = 0,02 * 3 \frac{0,00471}{1,66} = 0,00017$ and $C_{D0_{strut}} = 0,05 * 3 \frac{0,015}{1,66} = 0,00135$, resulting in a total drag of the landing gear of $D_0 = 3,88 \text{ N}$, on the ground and $D_0 = 2,59 \text{ N}$, the cruising altitude.

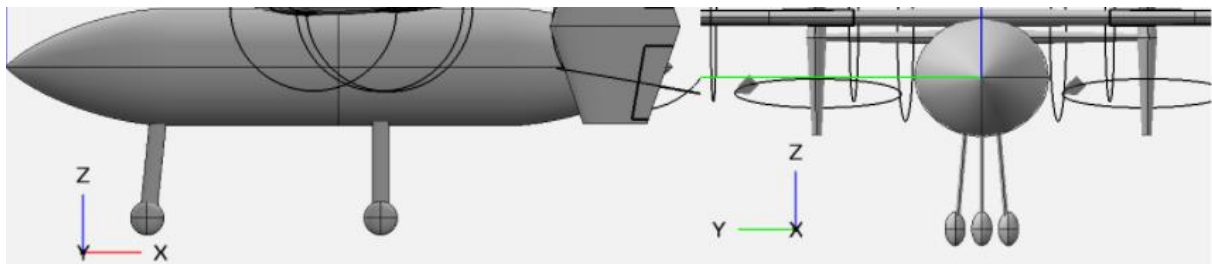


Figure 27 - Left and front view of the UAV with the integration of landing gear

On Figure 27 the configuration of the UAV with the landing gear is represented and as in the previous cases a new iteration of $MTOW = 117,08 \text{ kg}$ is obtained which is very close to the weight calculated during the preliminary study, remembering that for these simulations the weight of the propulsive equipment of $3,5 \text{ kg}$, which if we add to the previous value

$MTOW = 120,58 \text{ kg}$ which allows us to conclude that the landing gear weighs approximately $W_{LG} = 4 \text{ kg}$. At this stage you don't hear significant variations in the center of gravity because it has been adjusted for the positioning of the train in the nose and for the main gear.

Moments of inertia represent stability and are another important parameter of UAV design and illustrate the distribution of mass relative to a specific axis. They indicate how much force is required to generate a rotation around a given axis. I_{xx} moment of inertia around the axis x , measures the resistance to rotation along the longitudinal axis (roll), I_{yy} moment of inertia around the axis y , refers to the resistance to rotation about the lateral axis (pitch) and finally, I_{zz} the moment and inertia about the axis z , refers to the resistance to rotation along the vertical axis (yaw).

Through the analysis of the "Mass Properties" it is possible to obtain an initial idea of these values in which $I_{xx} = 19,96$, $I_{yy} = 18,03$ and $I_{zz} = 35,1$. The values obtained indicate a good balance between stability and manoeuvrability. The elevated I_{zz} suggests that the aircraft will have good resistance to unwanted yaw, which is important for directional stability. Lower moments of inertia on the rolling and pitching shafts indicate that the UAV will be maneuverable without sacrificing too much stability. However, it is possible to deepen the study of the behavior of moments empirically in terms of their derivatives such as (Corke, 2003).

$$C_{M_{y\alpha}} = \frac{dC_{M_y}}{d\alpha} < 0 ; C_{M_{x\beta}} = \frac{dC_{M_x}}{d\beta} ; C_{M_{z\beta}} = \frac{dC_{M_z}}{d\beta} \quad (38)$$

In the previous equations, C_{M_y} , C_{M_x} and C_{M_z} represent, respectively, the coefficients of the pitch moment, roll moment and yaw moment of the aircraft and the angle of attack α and β sweep angle of the aircraft. The appropriate value range for derivatives is $-1,5 < C_{M_{y\alpha}} < -0,16$ and $0,08 < C_{M_{z\beta}} < 0,28$ (Corke, 2003). According to (Raymer, 1992) $C_{M_{x\beta}}$, should have a magnitude about half that $C_{M_{z\beta}}$ at subsonic speeds. Knowing that, $C_{M_{y\alpha}}$ it is determined directly from the product symmetry between the static margin and the lift coefficient of the main wing, considering the contributions of the main wing, fuselage, horizontal tail and engine, $C_{M_{y\alpha}} = -0,537$. $C_{M_{x\beta}}$ depends on the main wing and vertical stabilizers $C_{M_{x\beta}} = -0,00603$ and $C_{M_{z\beta}} = 0,0887$, are dependent on the main wing, the fuselage and the vertical tail.

The approximations of the coefficients obtained are within the expected ranges, indicating good static stability characteristics for this UAV design, as well as the values obtained for the moments of inertia in OpenVSP.

7. COMPLETE AIRCRAFT

At this point, within the scope of the dissertation, the conceptual design is complete, resulting in a UAV capable of adequately meeting the mission requirements. The exterior layout of the aircraft is represented below in Figure 28 to Figure 31, and in the Table 38 presents the main characteristics after refined weight calculation.

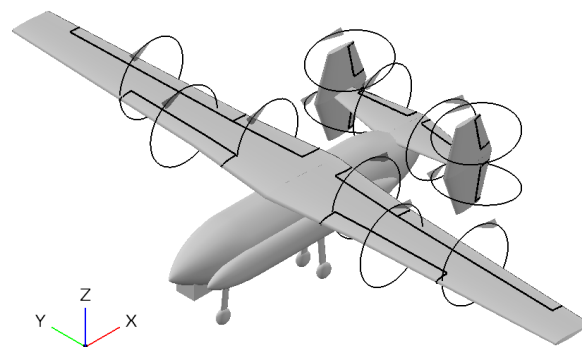


Figure 28 - Full view of the UAV

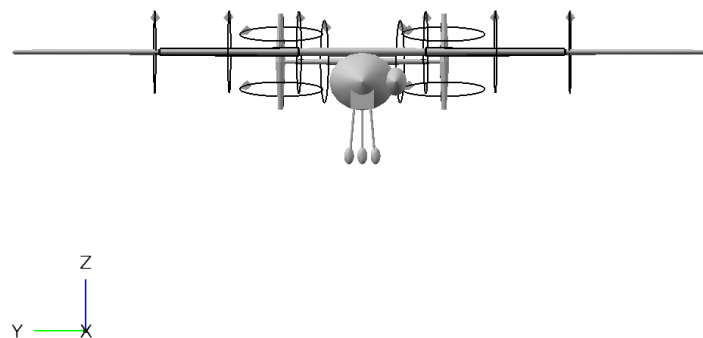


Figure 29 - UAV front view

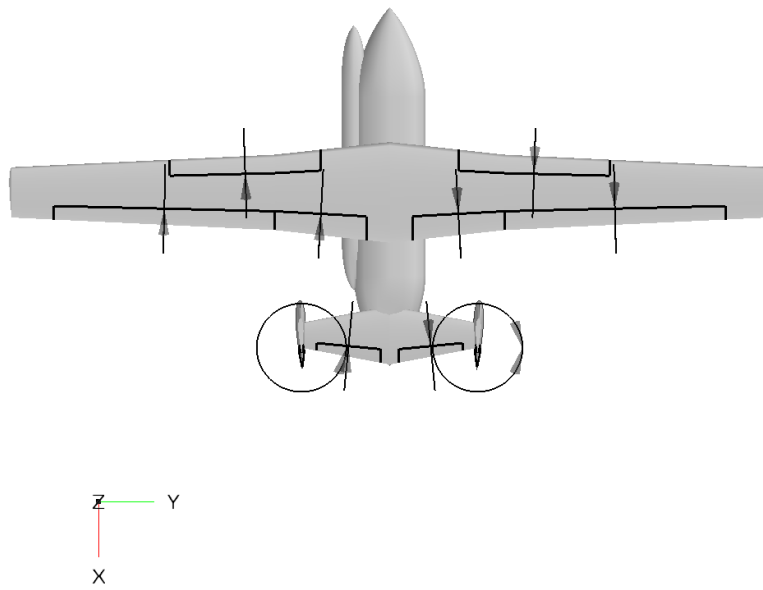


Figure 30 - View from above the UAV

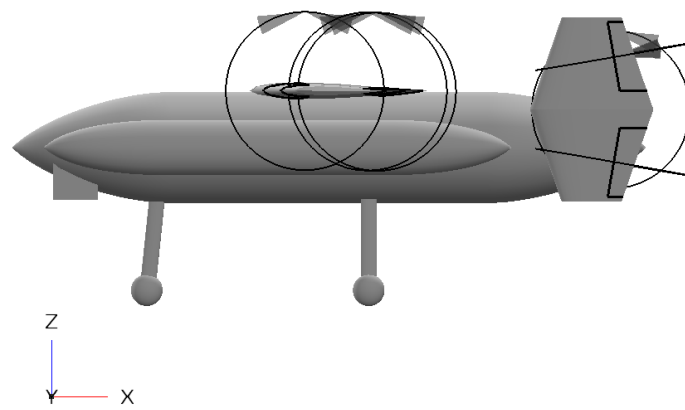


Figure 31 - UAV side view

As the design matures and more information about the aircraft is known, more complex weight ratios can be utilized, as we have confirmed in the course of the previous chapter. The main objective is to define the MTOW and distribute the weights among the main groups with greater precision, during the course of the project a preliminary calculation of the MTOW was used in the first instance using a second methodology (Gundlach, 2012) and during the course of the project as each component was integrated into the UAV it was possible to observe a constant approximation to the calculation of the preliminary study of the MTOW. At this point in the project, it is important to have a refined notion of the weight of the aircraft, again adopting a methodology that is based on statistical data and what was obtained from iterations of the OpenVSP weight. The methodology adopted for this is based on statistical data from previous projects, where the total weight of the aircraft is divided into five main groups: structural weight (W_{struct}), weight of the propulsion system ($W_{propulsion}$), weight of avionics (W_{avion}), weight of the payload ($W_{payload}$) and weight of fuel (W_{fuel}) (Gundlach, 2012).

Structural weight includes the masses of the fuselage, wing, tail, and landing gear. Although there is no ideal statistical approach, the empirical relationships used in manned aircraft design (Corke, 2003; Raymer, 1992), although abundant, may not be fully suitable for UAV design, due to the significant differences in performance characteristics and total gross weight. When considering empirical relations of general aviation, results on weights of the structure higher than reality, always considering the worst scenario.

Table 37 - Determined structural weight for manned aircraft (Corke, 2003), UAVs by (Gundlach, 2012) and OpenVSP

Structural component	(Corke, 2003) [kg]	(Gundlach, 2012)[kg]	OpenVSP [kg]
Fuselage	7,8	5,8	5,24
Wing	11,2	7,2	17,5
Tail	4,9	1,4	6,7
Landing Gear	6,9	1,9	4
Total Weight	30,8	16,3	33,44

As you can see in the Table 37, the weights between Corke's considerations and OpenVSP do not differ in totality, however, when compared to Gundlach the difference between them is notorious. Considering the worst scenario for each component among the

comparisons presented, is obtained $W_{struct} = 38,9 \text{ kg}$, which results in a $MTOW = 126,04 \text{ kg}$.

The propulsion weight we will consider the maximum value previously obtained of $W_{propulsion} = 14,2 \text{ kg}$, the fuel weight of $W_{fuel} = 42,3 \text{ kg}$, an $W_{payload} = 13,34$ according to the equipment defined for the mission and which may change if necessary and the weight of the avionics of $W_{avion} = 17,3 \text{ kg}$.

Considering the refinement of the final weight of $MTOW = 126,04 \text{ kg}$, the value is below the weight requirement of class 1 UAVs up to $MTOW = 150 \text{ kg}$ and taking into account that many characteristics have been assumed by excess this value tends to decrease, in the Figure 32 it is possible to observe a graphical representation of each mass component influence on the total weight of the aircraft.

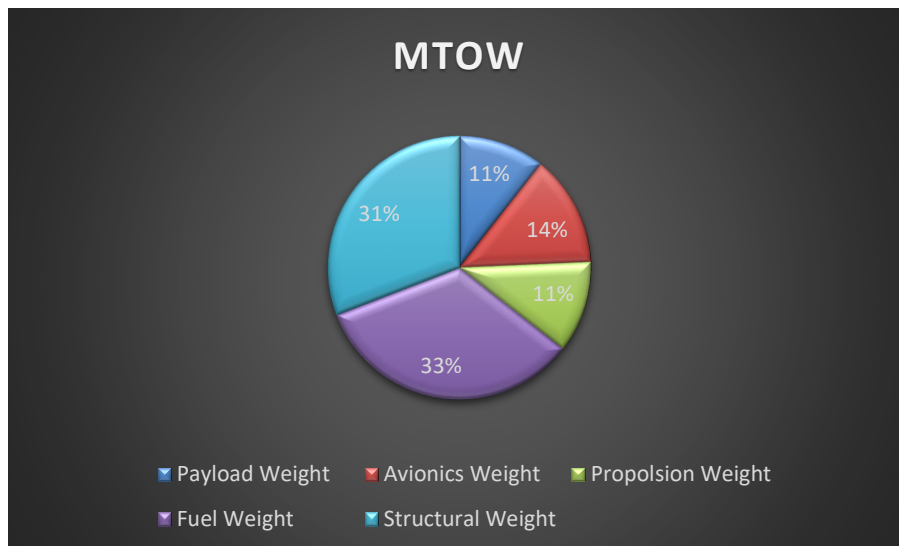


Figure 32 - Percentage result of refined weight analysis

The weight percentages obtained, considering general comparisons for UAVs of the same size are in no way very differentiable, however, it is important to take into account the purpose of each UAV and for which mission it was developed. The only values obtained above the common are the weight of the fuel, but even that is close to the expected (between 20 % to 30 %), and the structural weight that is expected according to (Gundlach, 2012) to be between 10 % to 20 %, but this percentages don't count the percentage from the landing that is between 3 % to 6 %, if we consider the summary of the two the max percentage is 26 %, which is not so different from 31 %. As UAV was developed for long-range missions, the resulting percentage of fuel is understandably higher.

To conclude, the conceptual study of the UAV will be summarized in the Table 38 all the geometric features of the UAV and other relevant information about the aircraft.

Table 38 - Summary of the main features of the UAV

Weights									
$MTOW$	W_{struct}	$W_{propolsion}$	W_{fuel}		$W_{payload}$		W_{avion}		
126,04	38,9	14,2	42,3		13,34		17,3		
Fuselage									
Length [m]			Maximum width [m]			Maximum height [m]			
2			0,4			0,35			
Wing									
b [m]	c_m [m]	c_r [m]	c_t [m]	S_w m ²	A_R	t/c	$\alpha_{stall}(^{\circ})$	C_{lmax}	Airfoil
4,212	0,421	0,56	0,28	1,66	10,7	0,099	13,5	1,41	Eppler 230
Vertical tail (panel)									
b [m]	c_m [m]	c_r [m]	c_t [m]	S_{VT} m ²	l_{VT} [m]	A_R	t/c	$\alpha_{stall}(^{\circ})$	Airfoil
0,58	0,29	0,39	0,19	0,17	0,82	2	0,15	16	NACA 0015
Horizontal tail									
b [m]	c_m [m]	c_r [m]	c_t [m]	S_{HT} m ²	l_{HT} [m]	A_R	t/c	$\alpha_{stall}(^{\circ})$	Airfoil
0,944	0,236	0,33	0,15	0,22	0,82	3,99	0,15	16	NACA 0015
Landing Gear									
Struct length [m]	Struct Height [m]	S_{strut} [m ²]	Wheel a [m]	Wheel b [m]	S_{tire} [m ²]	F_n	F_m	B	H_f
0,3	0,05	0,015	0,05	0,03	0,0047 1	207,7 1	974,3 9	0,7	0,3
Static Stability									
x_{CG}		y_{CG}	z_{CG}	I_{xx} (roll)		I_{yy} (pitch)		I_{zz} (yaw)	
0,975		-0,013	0,024	19,96		18,03		35,1	

7.1.1.1 OpenVSP Parasite Drag Analysis

Throughout the project, the respective parasitic drag coefficients of the components were evaluated empirically, however, not all components were taken into account due to the lack of contribution of payload components such as gimbal and IMSAR radar. With the refinement of the geometry and total weight of the aircraft, it is possible to obtain more accurate results

of parasitic drag with the help of OpenVSP, allowing a more detailed analysis of aerodynamic behavior, offering a comparison to previously calculated data.

Despite this, manual calculations are more conservative and play an important role as a preliminary check and aid in understanding the individual contributions of each component to the total drag of the aircraft, most often in situations of excess. Both approaches combined ensure greater precision in aerodynamic design, allowing for efficient optimization of the overall UAV performance.

The study of the UAV's parasitic drag was refined using OpenVSP, where the conditions imposed on the software were essential to obtain more accurate results. The conditions involving the cruising, flight speed 50 m/s , 4000 m at altitude conditions, with the 1976 US Standard Atmosphere option, define the conditions of the study.

The detailed results for C_{D0} and D_0 of the different components of the aircraft are summarized in the Table 39 Presented.

Table 39 - Summarization of the UAV parasitic drag study

Structural component	C_{D0}		$D_0 [N]$	
	Calculated	OpenVSP	Calculated	OpenVSP
Fuselage	0,00749	0,00386	12,75	6,57
Wing	0,0119	0,01083	20,21	18,43
Vertical Tail	0,0017	0,00272	2,84	4,63
Horizontal Tail	0,0021	0,0017	3,61	2,89
Landing Gear	0,00152	0,00197	2,59	3,35
Payload	-	0,00198	-	3,37
Total Parasite Drag	0,025	0,023	42,00	39,24

A Table 39 compares the manually calculated values with those obtained through VSPAERO and reflects the distribution of parasitic drag between the fuselage, wings, tail, landing gear and payload. The values indicate that the empirical results are higher for all components in relation to those obtained by OpenVSP (exception from vertical tail and landing gear, probably because flow and area considerations), which was to be expected from what is assumed for the respective contributions to be mostly excess values, however, the contributions are not very discrepant between both results, which proves the veracity of both methods.

A Figure 33 reinforces the analysis by demonstrating the percentage contribution of each component to the total parasitic drag. Comparing these values with what is typical in UAVs of similar configuration, it is observed that the contribution of the wings to parasitic drag is relatively high. Typically, in aircraft with straight wings, this value can vary between 40 – 50 % the total drag, which is in line with the present study. The fuselage, on the other hand, tends to contribute 15 – 20 %, also compatible with the result found (Götten et al., 2021; Gundlach, 2012).

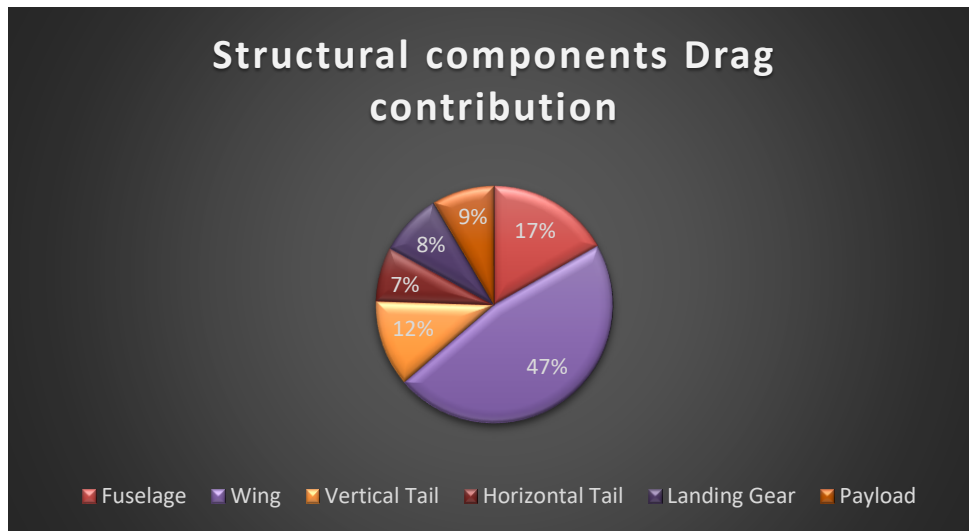


Figure 33 – Drag contribution in % of each structural component of the UAV

Recalling the engine study, the UAV was to be sized as an AR-741, which provides a maximum power of 38 BHP at 7800 RPM (Maguire, 2012). Fuel consumption, at full power, is 4,97 l/h, with an estimated propeller efficiency of 0,4 during cruising (Corke, 2003). By relating the total parasitic drag obtained with the capacity of the engine, it is possible to infer the UAV's ability to generate sufficient force both in cruising flight and on the ground (static thrust of 695 N at mean sea level and 562 N at cruising altitude).

In conclusion, the study of the parasitic drag of the UAV demonstrated that, with the refinement of the geometries in OpenVSP, the UAV presents a well-balanced drag distribution among its components.

7.1.2 Dynamic Stability

In previous chapters, the static stability of the UAV has already been studied, and stability in all three directions has been ensured. However, static stability does not mean dynamic stability, and the next step is to ensure dynamic stability. Dynamic stability refers to the way

the aircraft returns to a state of equilibrium after being disturbed, considering restoration and damping forces, as well as mass distribution. If the dynamic movements of the aircraft allow a return to the original state of flight, the aircraft is considered dynamically stable (Anderson Jr, 1999).

In the chapter dedicated to the dynamic stability of the UAV, the methodology adopted should be the Panel Method for the study, however, due to computational limitations, the Vortex Lattice Method was used. The choice of the Panel Method was more advantageous for its greater ability to handle complex surfaces and detailed geometry of the aircraft, as is the case with the project in question, providing more accurate results for stability analysis, however, the Vortex Lattice method uses less computational power and is able to deliver acceptable preliminary results (Litherland, 2024; McDonald & Gloudemans, 2022). Even using the Vortex Lattice method, the simulation took 14 hours to run, using better computation this study can be redone and compared. The simulation performed for this chapter is the same for chapter 8.1.4 and 8.1.5. The analysis considers the main wing as the main lift area, with the CG previously studied. The study covers a range of angles from -15° to 20° , considering the cruising conditions, with $M = 0,15$ and $R_e = 1,02 * 10^6$ the Reynolds number, characteristics already previously defined.

To study dynamic stability, it is necessary to use the Run Mode-Stability Type, which will conduct the stability study. This mode is particularly useful for evaluating the dynamic behavior of the aircraft in flight, as it allows a detailed analysis of the aircraft's responses to disturbances, essential to ensure a stable and controlled flight (Litherland, 2024; McDonald & Gloudemans, 2022). When using this mode, you need to cogitate the free air speed $V_{inf} = 50 \text{ m/s}$ and air density $\rho = 0,82$, which are adjusted according to the UAV's cruising conditions. These parameters are key to ensuring that the UAV's behavior is analyzed within a realistic context of operation.

The separation of the control surfaces will be organized in the Control Grouping system, allowing an isolated and specific study of each surface. Separate groups will be created for the Ailerons, Rudder and Elevator, facilitating the individual evaluation of each system and its contribution to the stability and control of the aircraft.

The study of dynamic stability is then aided with the graphical representation generated during the simulation. From the Figure 34, it is possible to observe the behavior of C_{M_x} roll

moment related to lateral stability as a function of two angles, the angle of attack α and the sideslip angle β .

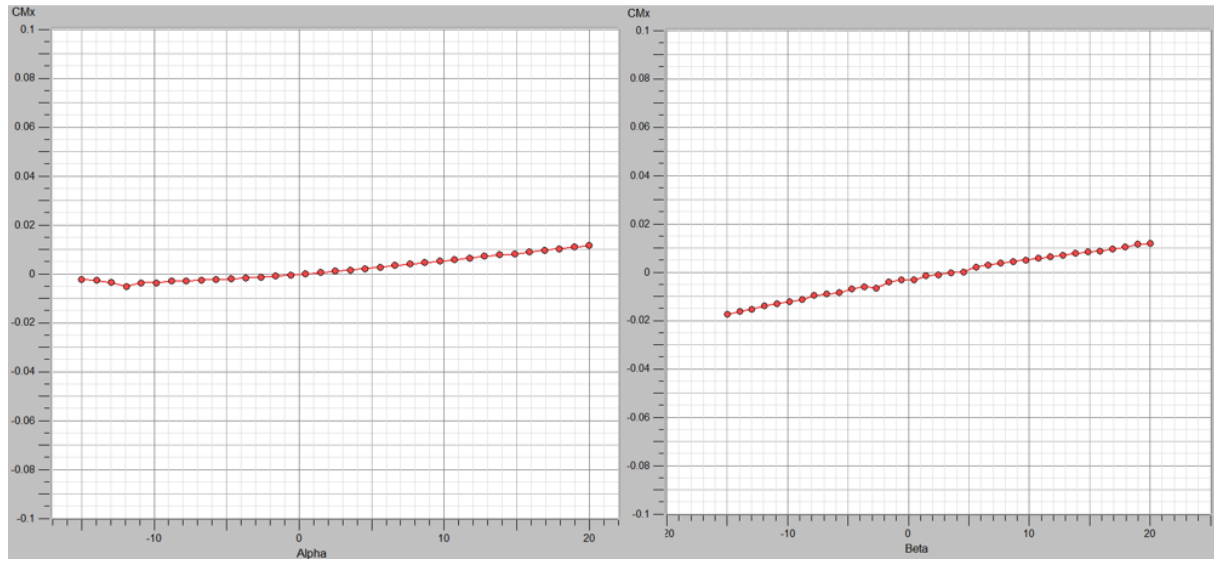


Figure 34 - Graphical representation of the UAV roll moment as a function of α and β

In the graph on the left, the variation of C_{M_x} as a function of α , reveals a slight positive inclination along with the variation of the angle of attack, for reduced values of the angle of attack the aircraft presents little response to rolling, as the angle increases C_{M_x} begins to increase, indicating a greater tendency to roll. This behavior is expected since, for high angles of attack, there may be an asymmetry of lift in the wings, generating rolling moments. The behavior of C_{M_x} in relation to α indicates stability in straight and level flight. The graph on the right shows the relationship between the C_{M_x} and β , where it can be seen that C_{M_x} gradually increases as β moves away from zero, both for negative and positive values. This behavior suggests that the UAV tends to roll when subjected to lateral disturbances. Positive pitch indicates that the UAV responds to lateral deviations of flow by generating rolling moments to correct deviation and keep flight stable, which is beneficial in terms of lateral control. As the rate of climb is a linear variation, it suggests that the aircraft's response in terms of roll is predictable and smooth, without significant abrupt oscillations or instabilities.

With the complete analysis of C_{M_x} , C_{M_y} will be studied what is related to longitudinal stability and its response in relation to pitch. The graphics of the Figure 35 illustrate the behavior of pitch moment in relation to α and β .

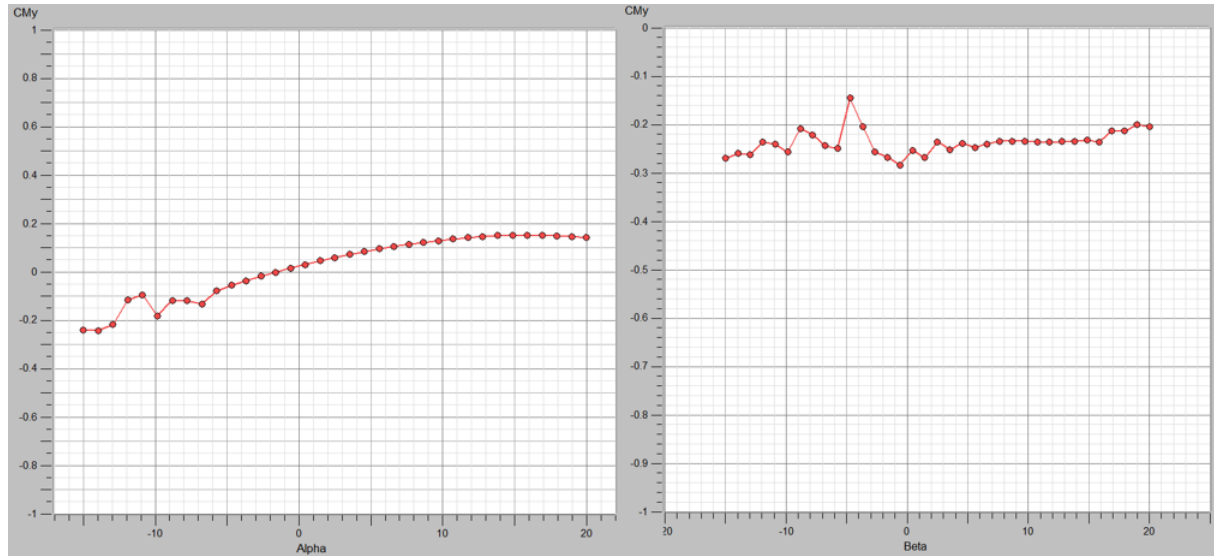


Figure 35 - Graphical representation of the UAV pitch moment as a function of α and β

C_{M_y} in function of the angle of attack, the behavior of C_{M_y} shows that as the angle of attack increases, the coefficient of pitch moment also increases gradually, going from negative to positive values, suggesting that in low incidences the aircraft tends to generate a pitch moment to compensate and maintain longitudinal stability. The increase of C_{M_y} indicates that the UAV is well designed to maintain balance in flight with different angles of attack. The smooth shape of the graph lets you know that the aircraft has predictable responses and no abrupt changes in behavior, essential to maintain stability. The graph on the right C_{M_y} by β has a higher oscillation, which represents more erratic behavior during sideways changes compared to α . However, it remains relatively stable on the basis of negative values, which indicates that the UAV has adequate and predictable lateral stability characteristics to keep the flight stable, even under sideslip effects.

To conclude the study of the moments, the yaw moment C_{M_z} will be analyzed, related to the UAV's ability to react to lateral forces that affect rotation around the vertical axis. The graphs presented in the Figure 36 demonstrate the behavior of the UAV as a function of α and β as in the two previous cases.

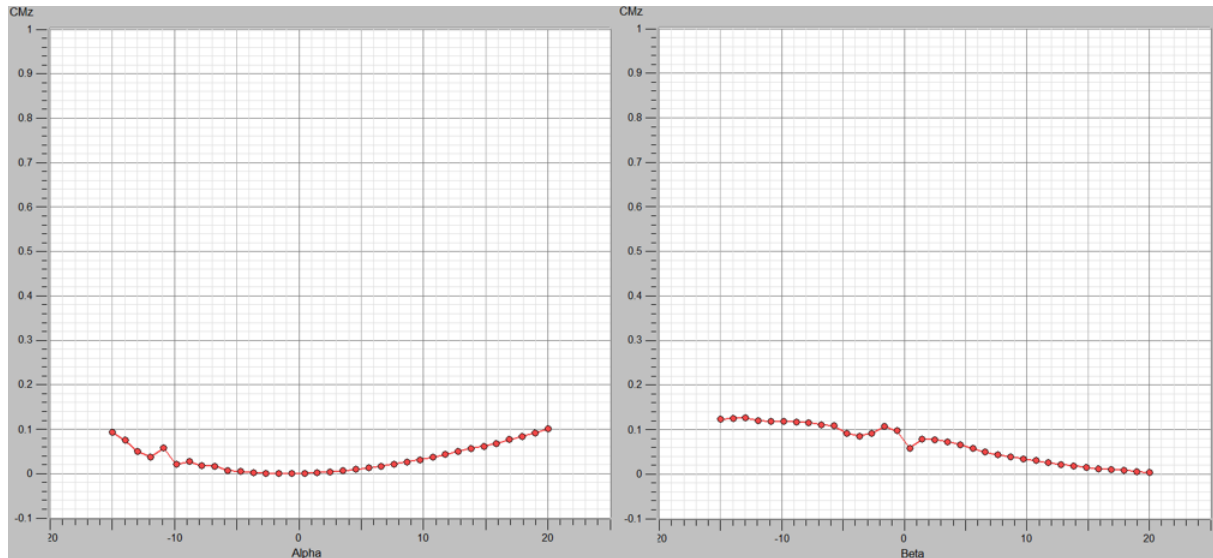


Figure 36 - Graphical representation of UAV yaw moment as a function of α and β

The graph on the left the variation of C_{M_Z} by α we observe a nonlinear behavior, for values of approximately -10° , the C_{M_Z} value decreases until it reaches a minimum value, followed by a gradual recovery as the angle of attack increases. This behavior suggests that the stable yaw of the aircraft is maintained over a wide range of angles of attack, the lowest point in the curve indicates that the UAV may experience a negative yaw moment at negative angles of attack, however, at positive angles, directional stability improves. It is an expected response, because as the UAV reaches greater angles of attack, the flow of air over the control surfaces, specifically the vertical tail, contributes to the restoration of directional stability. The graph on the right C_{M_Z} shows constant behavior, with small variations for different sideslip angles, but without drastic variations. For negative values of β , the yaw moment coefficient decreases slightly, while for positive values, the yaw coefficient tends to stabilize near zero, indicating that the UAV has a stable response to lateral skidding, with little tendency to yaw unwantedly. The flat shape curve of the C_{M_Z} relative to the sideslip suggests that the UAV is well balanced directionally to avoid unwanted yaw variations.

The graphs of the analyzed moments indicate that the aircraft has favorable characteristics of dynamic stability in all control directions. The balance between the coefficients and the moments of inertia studied at the end of chapter 7.8 reveal that the UAV will be able to maintain the necessary stability during long-range operations without compromising maneuverability, ensuring safe performance in the operations proposed by the FAP in the EEZ.

7.1.3 Take-off and Landing

An important point of the design is the study of the aircraft take-off and landing behavior. In this chapter we will study the different stages for each of the two stages of flight, according to the process of (Corke, 2003). In Figure 37 the take-off process is represented divided into different stages Ground Roll, Rotation, Transition and Climb. The study of the five steps features the UAV take-off study.

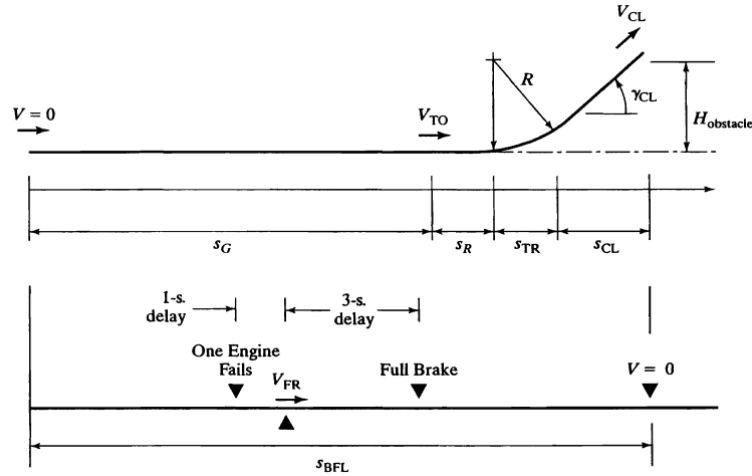


Figure 37 - Schematic illustration of aircraft take-off

(Corke, 2003)

In order to calculate the take-off performance, it is necessary to calculate the take-off speed:

$$V_{TO} = 1,2V_s = 1,2\left[\left(\frac{W}{S}\right)_{TO} \frac{2}{\rho C_L}\right]^{0,5} \quad (39)$$

In the previous equation $V_{TO} = 14,7 \text{ m/s}$, considering $\rho = 1,225$ and with this it is possible to start the study of the distance of Ground Roll s_G , which can be calculated with the following equation second (Corke, 2003).

$$s_G = \int_0^{V_{TO}} \left(\frac{V}{a}\right) dV = \frac{1}{2} \int_0^{V_{TO}} \frac{dV^2}{da} \quad (40)$$

Acceleration a , which can be determined $a = \frac{g}{W} \sum F_x = \frac{g}{W} (T - D - F_f)$, g is the gravitational force, T the thrust of the motor (considering 45 % of the total thrust of the motor), D the drag, and F_f is the friction of movement on the ground. At this point in the project, all this information is already known, except for the friction of the movement, which can be calculated using it.

$$F_f = \mu[W - L_G] \quad (41)$$

The coefficient of friction μ , which varies with the runway conditions and the lift generated during ground rotation L_G , is based on an improved lift configuration for the wing and the angle of attack produced when the aircraft is on the ground. According to (Corke, 2003), for wet or dry concrete floor $\mu = 0,03 - 0,05$.

$$L_G = qSC_{LG} \quad (42)$$

The lift generated by the rotation can be calculated using the previous equation where C_{LG} is the contribution of the drag of the aircraft's landing gear and the reference area S , i.e. the main wing, is needed to keep in mind that when the aircraft is close to the ground the aspect ratio is greater $\frac{A_R}{A_{Reffective}} = \sqrt{\frac{2H}{b}}$, where H is the altitude and b the wingspan.

Applying the previous equations $L_G = 0,43 \text{ N}$, $F_f = 29,8 \text{ N}$, $a = 18,97 \text{ m/s}^2$ and $s_G = 5,7 \text{ m}$, thus concluding the study of the Ground Roll.

In the rotation portion of takeoff, the aircraft angle is increased until $C_L = 0,8C_{Lmax}$, by convention, this maneuver takes three seconds, and the speed of the aircraft is the takeoff speed (Corke, 2003).

$$s_R = 3V_{TO} \quad (43)$$

Therefore, $s_R = 44,05 \text{ m}$.

In the transition portion the aircraft lifts off the ground and begins flight at a constant speed and ends when the radial vector becomes equal to y_{CL} .

$$s_{TR} = R_{TR} \sin y_{CL} \quad (44)$$

The distance $R_{TR} = \frac{V_{TO}^2}{0,15g} = 146,5 \text{ m}$, while the angle $\sin y_{CL} = \frac{T-D}{W} = 0,22 \text{ rad}^{-1}$, which is approximately equivalent to $12,8^\circ$, which is a value close to the α_{TO} previously defined value of 12° (also considered a fraction of the thrust of the engine of 45 %). Being so, $s_{TR} = 32,1 \text{ m}$, the transition altitude ends when $H_{TR} = R_{TR}(1 - \cos y_{CL}) = 3,6 \text{ m}$.

To finish the take-off study, the portion of Climb at the end of the transition and ends when the UAV reaches the altitude $H_{obstacle}$ is studied, for military aircraft $H_{obstacle} = 15 \text{ m}$ (Corke, 2003). From this portion the angle of ascent is equal to the angle y_{CL} , so as shown in the diagram, the distance s_{CL} is:

$$s_{CL} = \frac{H_{obstacle} - H_{TR}}{\tan y_{CL}} \quad (45)$$

Applying the previous equation to the conditions described $s_{CL} = 50,82 \text{ m}$. Considering the sum of all contributions, the runway must have a length of $s_{BFL} = 132,71 \text{ m}$. This length regarding take-off is not at all a nuisance for the operation of the UAV if it departs from the Lajes Base as in the mission profile, as this runway is more than 600 meters long.

The beginning of the landing phase of flight occurs at $15,24 \text{ m}$ altitude, with a distance traveled on the ground at speed V_{TO} , a free roll at constant speed and a braking deceleration until the UAV stops. The required landing distance s_L is shown in the graphical representation of the Figure 38 (Corke, 2003).

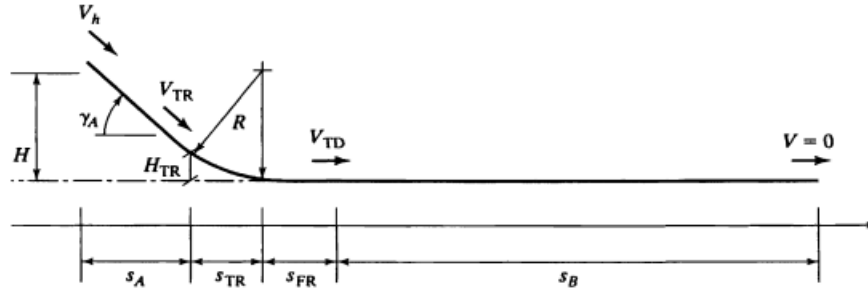


Figure 38 - Schematic illustration of aircraft landing

(Corke, 2003)

In the first phase of landing (Approach s_A), the aircraft then begins the altitude $15,24 \text{ m}$ and speed of $V_{15} = 1,2V_s = 32,15 \text{ m/s}$, which is the value used for military aircraft, in the second phase of the landing the aircraft travels a constant circular arc and at the end of the arc touches the ground the speed $V_{TD} = 1,15V_s = 30,81 \text{ m/s}$ (Transition s_{TR}). In the third phase the aircraft travels the runway at constant speed V_{TD} (Free-Roll s_{FR}) and in the end the UAV brakes until it stops movement (Braking s_B). Considering the worst landing scenario the weight of the UAV W_L is assumed to be $W_L = W_{TO} - 0,5W_{fuel}$, W_L is approximately $W_L = 104,89 \text{ kg}$. In addition, the aircraft even before touching the ground will produce an angle of attack so that $C_{L_{touchdown}} = 0,8C_{L_{max}}$ (Corke, 2003).

During the Approach the velocity is constant from the $15,24 \text{ m}$, until the height H_{TR} and the angle of descent can be determined using the following equation.

$$y_{approach} = \frac{-D}{W} \quad (46)$$

In the previous equation, the thrust of the motor is not considered because at this point $T = 0$. The angle should not be greater than 3° and the distance can be calculated by the following equation.

$$s_A = \frac{H_{TR} - 15,24}{\tan y_{approach}} \quad (47)$$

To calculate H_{TR} it is necessary to analyze the Transition stage where the velocity decelerates from V_{15} , to V_{TD} , so the relationship between the distances R_{TR} and H_{TR} , can be calculated according (Corke, 2003) to using the following expressions.

$$R_{TR} = \frac{(1,23V_s)^2}{0,19g} \quad (48)$$

$$H_{TR} = R_{TR}(1 - \cos y_{approach}) \quad (49)$$

Using the previous equations $y_{approach} = -2,19^\circ$, $R_{TR} = 582,58 \text{ m}$, $H_{TR} = 0,42 \text{ m}$, and $s_A = 388,27 \text{ m}$.

Therefore, it is already possible to calculate the transition distance if agreed using the following equation.

$$s_{TR} = -R_{TR} - \sin y_{approach} \quad (50)$$

The result obtained for s_{TR} was $s_{TR} = 22,21 \text{ m}$.

During the free-roll portion the aircraft maintains constant velocity equal to V_{TD} and by convention, it is assumed that this period lasts three seconds (Corke, 2003).

$$s_{FR} = 3V_{TD} \quad (51)$$

Applying the previous equation $s_{FR} = 92,43 \text{ m}$. For the calculation of Braking, the same strategy applied to the Ground Roll will be used with the difference that $T = 0$. Recalculating the previous parameters for the new weight condition $L_G = 1,90 \text{ N}$, $F_f = 24,72 \text{ N}$, $a = -5,98 \text{ m/s}^2$ and $s_B = 79,35 \text{ m}$, which concludes the study of all landing stages.

The sums of all the contributions allow us to calculate $s_L = 582,26 \text{ m}$, a value much higher than the take-off value that was expected, but it still does not present any limitation, it must be considered that $T = 0$ it is a very conservative consideration and studies the worst case of landing, which leads to a significant increase in s_L , which leads to believe that this distance tends to decrease.

7.1.4 Aerodynamic Coefficient Analysis

In this chapter, the analysis of the main aerodynamic coefficients of the UAV, essential for the evaluation of its performance in flight, will be presented. Design efficiency and aerodynamic stability are key to optimizing UAV performance, especially for long-range missions. Thus, the lift coefficients C_L , total drag $C_{D_{tott}}$, parasitic drag C_{D0} , induced drag C_{Di} , and the glide ratio L/D , as a function of the angle of attack, will be analyzed.

The evaluation of these coefficients allows us to understand the aerodynamic behavior of the UAV in addition, it is fundamental for the optimization of the aircraft's design, allowing adjustments in the geometry of the aerodynamic surfaces, ensuring greater efficiency and range.

The first chart to be studied in the Figure 39 shows the relationship between the lift coefficient and the angle of attack for the full UAV, according to the parameters defined during chapter 8.1.2.

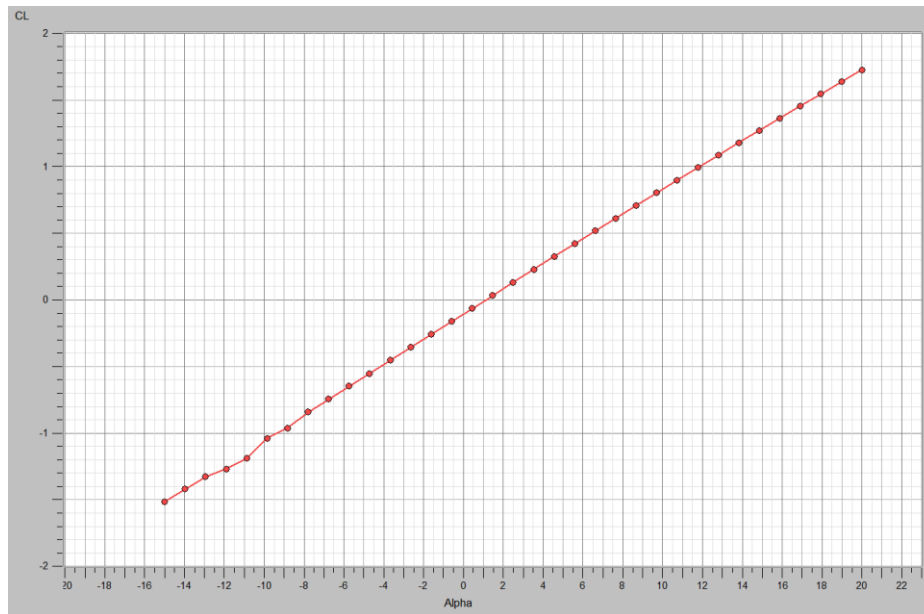


Figure 39 – Graph of the lift coefficient in function of the angle of attack

Observing the C_L behavior from within the simulation interval, it is evident that the lift coefficient increases linearly with the increase of the angle of attack. However, based on the aerodynamic profiles used for the main wing and tail, the E230 and NACA 0015 stall around $\alpha = 14^\circ$ and $\alpha = 16^\circ$ respectively. Despite this, the overall UAV graph does not show a sharp drop until $\alpha = 20^\circ$, which indicates that the collective behavior of the control surfaces and the wing extend the efficient lift interval for UAV. On the other hand, in the following chapter

we will study the flow and variation of the pressure coefficients in the aircraft that indicate that for the UAV $\alpha = 20^\circ$ it suggests a stall behavior and that this behavior appears only less accentuated to approximately $\alpha = 12^\circ$.

The next graph to be studied was the lift coefficient by the total drag coefficient represented in the Figure 40.

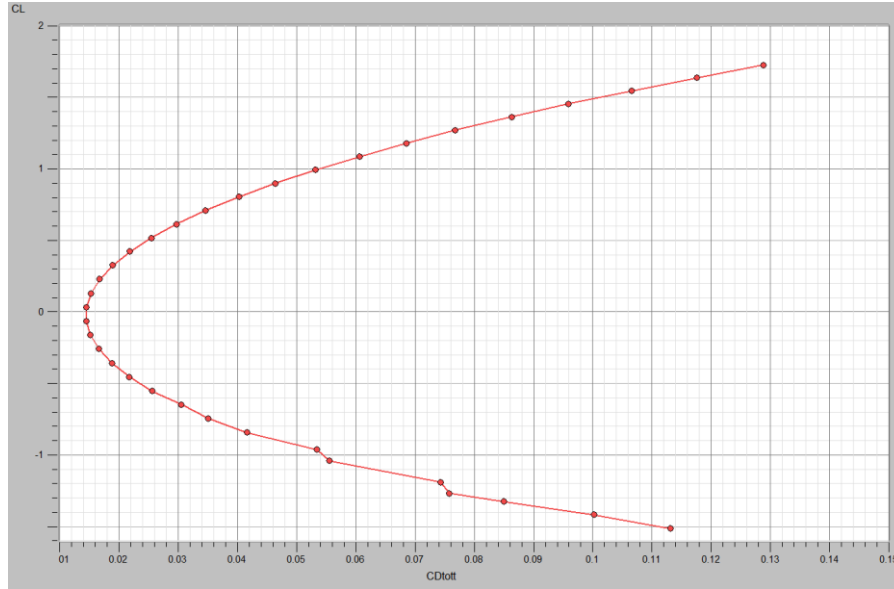


Figure 40 – Graph of lift coefficient in function of total drag

The result was a typical polar drag curve, where C_L increases to low values of $C_{D_{tott}}$, to a point where the growth in drag becomes more pronounced. In a low angle of attack regime, the variation is linear, indicating the increase in lift that is proportional to the increase in drag. In this phase, the predominant drag contribution is parasitic drag, since the flow over the surfaces is smoother and the regime is laminar. The result obtained indicates that the UAV is aerodynamically efficient in cruising conditions, with a good compromise of lift and drag between $0^\circ < \alpha < 12^\circ$ approximately. Around $\alpha = 12^\circ$, the curve begins to indicate a steeper slope, which is accompanied by a deterioration of lift, corresponding to the start of stall, initiating a disproportionate increase in drag. This behavior is more expected than the non-appearance of the stall as in the case of Figure 39.

Concluding the understanding between the lift coefficient and the total drag, it is pertinent to divide the drag into its fundamental components, parasitic drag C_{D0} and induced drag C_{Di} , both by α , as represented in the Figure 41. The C_{D0} is generated independently of lift, showing the impact of the aircraft's shape and its interaction with the air, and C_{Di} in turn it will be

essential for studying how lift induces additional drag, particularly at high angles of attack (Anderson Jr, 1999).

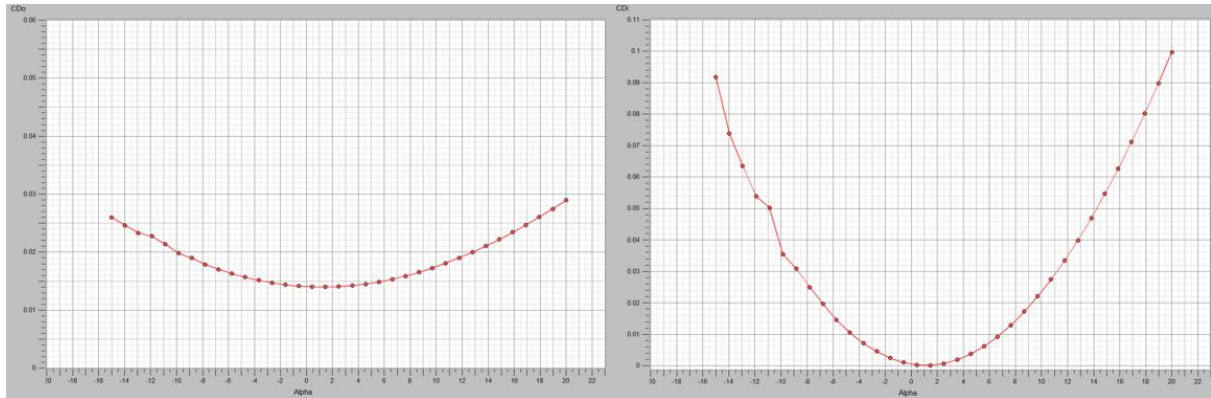


Figure 41 – Graph of the parasitic drag and induced drag coefficients in function of the angle of attack

The C_{D0} graph on the left reveals that for small values of α , C_{D0} remains relatively constant, which is expected, as the wing profile and the body of the UAV generate a smoother flow. Near $\alpha = 0^\circ$ is where there is the least resistance to parasitic drag, reaching maximum aerodynamic efficiency in terms of shape and friction. Values close to $\alpha = 10^\circ$, the C_{D0} begins to increase, suggesting an increase in runoff separation. The graph on the right C_{Di} , is minimal near $\alpha = 0^\circ$, which coincides with the least need to induce additional airflow over the wing. With the increase of α , there is an increase in C_{Di} , especially above $\alpha = 5^\circ$, reflecting the increase in the number and intensity of the end vortices.

The next step in this chapter is to combine both components, C_{D0} and C_{Di} , by analyzing the graph of $C_{D_{tott}}$, which is the representation of total drag, allowing an understanding of how the UAV responds along the variation of the angle of attack, represented in the Figure 42, making it easier to highlight a range of optimal operating regimes both in cruise and during maneuvers.

In the region of low angles, the $C_{D_{tott}}$ is relatively high, which occurs by the generation of negative lift, which causes an increase in drag due to the need to compensate for the direction of the lift. The point of lowest total drag occurs close to $\alpha = 1^\circ$, indicating the maximum drag efficiency of the aircraft, being the ideal angle for cruising flight.

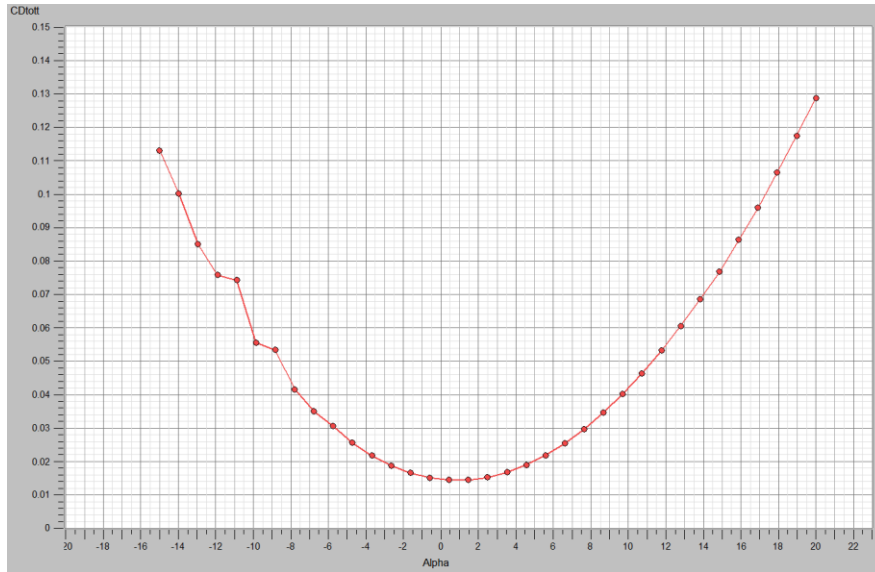


Figure 42 – Graph of the total drag coefficient in function of the angle of attack

As the angle of attack increases, the $C_{D_{tott}}$ increases rapidly, this increase occurs mainly due to the increase in drag induced due to the greater lift generated and the formation of end vortices in the wing, again this behavior is intensified to values close to $\alpha = 10^\circ$.

In order to finalize the study of lift and drag, and now that each of its coefficients has been graphically detailed, the glide ratio L/D as a function of α , represented in the Figure 43, which allows the efficiency of the flight to be assessed.

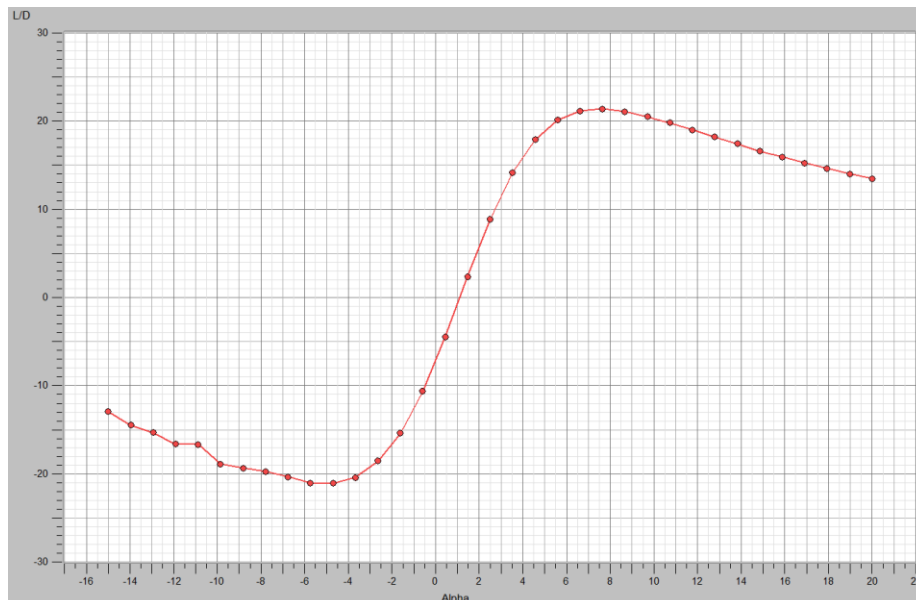


Figure 43 – Graph of the glide ratio in function of the angle of attack

The point of greatest efficiency occurs near $\alpha = 7^\circ$, around $L/D = 24$, and this is the most efficient point regarding the generation of lift and drag, a value that can be important for

autonomy and fuel consumption issues. After the peak, L/D begins to gradually decrease, indicating the increase in drag in relation to the lift generated.

This chapter helps to understand the aerodynamic behavior of the designed UAV, highlighting that the UAV has better aerodynamic efficiency between $\alpha = 2^\circ$ and $\alpha = 6^\circ$, where drag is minimized and lift is maximized, allowing for efficient cruise flight with low energy consumption. The UAV should avoid operating in $\alpha = 13^\circ$, to avoid stall and loss of aerodynamic control.

7.1.5 Pressure distribution and flow analysis

As part of an even deeper analysis of aerodynamics, a study will be carried out focused on the distribution of pressure along the aerodynamic profile of the wing, which directly influences the generation of lift and the flow behavior around the surface of the aircraft. For the simulation, the model with the respective characteristics previously presented was used, highlighting the behavior of the Eppler 230 profile, known for its efficiency in low-speed applications, such as the long-range UAV dimensioned.

The analysis of the pressure coefficient along the chord allows a better understanding of the interaction between the flow and the wing, revealing critical points in the pressure distribution and providing information on aerodynamic performance in cruise flight.

The Figure 44 represents the distribution graph of the inverted pressure coefficient along the chord along the surface of the E230 profile. This inversion is common in aerodynamic analyses to facilitate the understanding of flow behavior. In this graph, it can be seen that at the leading edge (position $x = 0$), there is a strong suction, with a negative peak of $-C_p$. This behavior is expected, since the acceleration of the air in the upper part of the profile generates a significant reduction in pressure, which results in the creation of the lifting force. As one progresses along the chord, the pressure on the upper surface stabilizes, approaching more neutral values near the trailing edge (position $x = 1$). On the lower surface, the behavior of the C_p is different, remaining at values closer to zero or slightly positive, reflecting a lower pressure variation. This pattern is typical of efficient profiles, in which the pressure difference between the upper surface (where there is suction) and the lower surface (where the pressure is higher) is the main mechanism to generate lift.

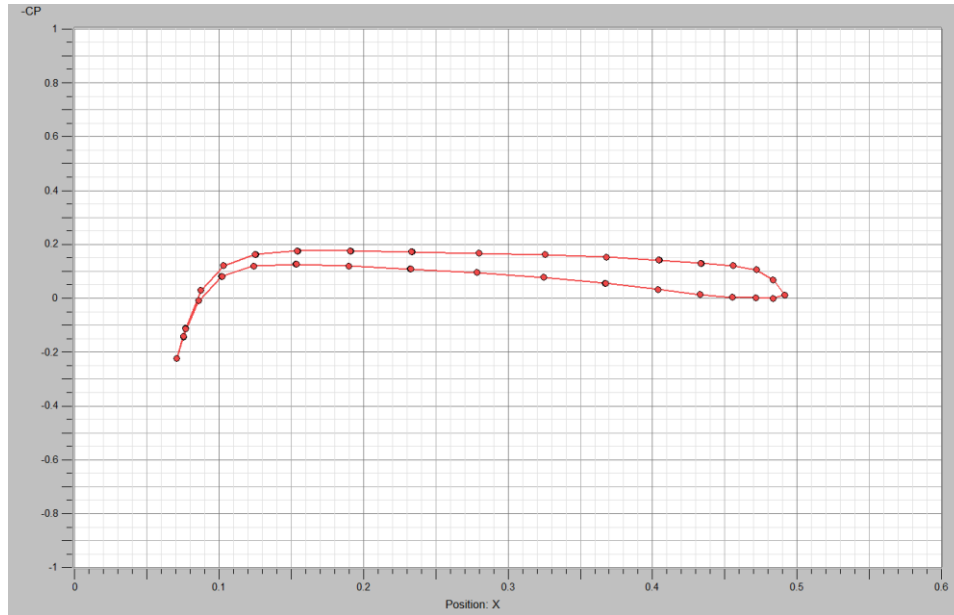


Figure 44 – Pressure distribution along the main wing chord to $\alpha = 0$

It is important to consider that the E230 profile is an optimized profile to mitigate parasitic drag and maximize lift in low-speed flight regimes, which is consistent with the operation of a UAV and from the result of the analysis the flow remains favorable along most of the profile, with no signs of premature separation, which contributes to flight efficiency. The smooth behavior of the curves C_p along the chord confirms that the flow remains predominantly laminar, which is desirable to reduce drag, as will be observed in the simulation of the flow lines. The pressure distribution obtained reinforces the choice of the E230 profile as an efficient solution for the developed project and as a viable option for low-drag and high-lift UAVs, essential characteristics for the range and autonomy in general.

In the second part of this analysis, the behavior of the pressure distribution ΔC_p around the UAV and the flow to different angles of attack is examined, increasing it progressively to angles equal to $\alpha = -10,88^\circ$, $\alpha = -4,7^\circ$, $\alpha = 0,44^\circ$, $\alpha = 5,59^\circ$, $\alpha = 12,79^\circ$ and $\alpha = 20^\circ$, represented in the Figure 45 to Figure 50. This variation allows a broad understanding of the UAV's behavior at different operating regimes.

- Angle of Attack $\alpha = -10,88^\circ$, Figure 45:

For this extreme negative angle, a predominant area of positive ΔC_p is observed in the extrados, suggesting a strong compression of air on the surface. Simultaneously in the intrados, there is a negative concentration of ΔC_p , indicating that the airflow is behaving in an inverse way to that necessary for the generation of lift. In this case the flow is slightly

disturbed, with scattered lines which indicates an operation in inverted stall conditions, where lift is almost absent, and drag is higher. It is possible to observe a difference ΔC_p in the wing on the left surface of the right, this difference is probably due to the disturbance caused by the ISMAR radar.

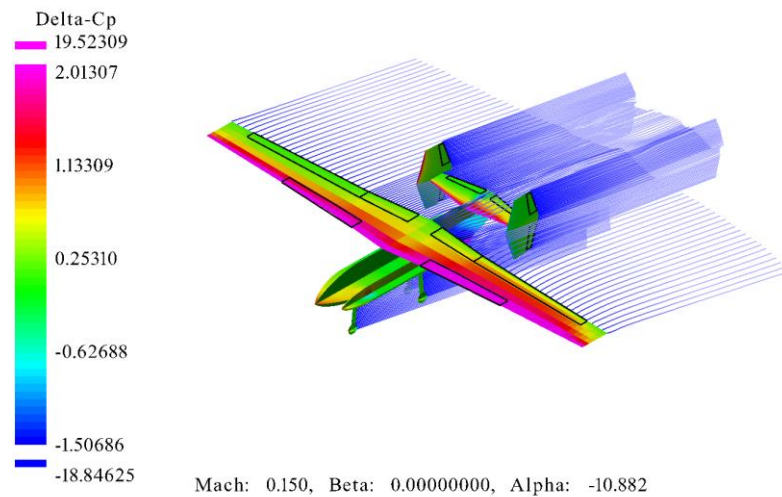


Figure 45 – Pressure distribution and flow behavior for $\alpha = -10,88^\circ$

- Angle of Attack $\alpha = -4,7^\circ$, Figure 46:

As the angle of attack decreases, there is a significant transition, initiating a ΔC_p decrease in the extrados, but still not sufficient, suggesting that the wing is in an inefficient lift condition. The flow in this condition is more controlled, especially near the tail, but far from ideal. The discrepancy of ΔC_p on the left and right wing is still permanent, but less pronounced.

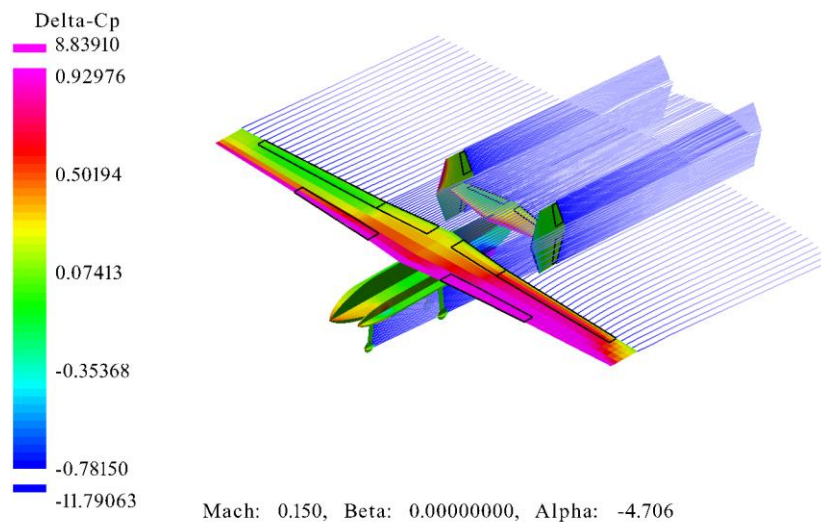


Figure 46 – Pressure distribution and flow behavior for $\alpha = -4,7^\circ$

- Angle of Attack $\alpha = 0,44^\circ$, Figure 47:

When the angle of attack approaches zero, there is a noticeable change in the behavior of the distribution of the variation of the pressure coefficients. On the extrados, negative areas of ΔC_p begin to appear, especially near the leading edge, which represents a possible increase in lift generation. On the intrados, it has a positive onset ΔC_p , which is expected. IMAR radar interference remains, however, in smaller variations, with little change in flow around the fuselage. The flow is more aligned with the aircraft and reveals better adhesion to the wing surface and favorable aerodynamic behavior.

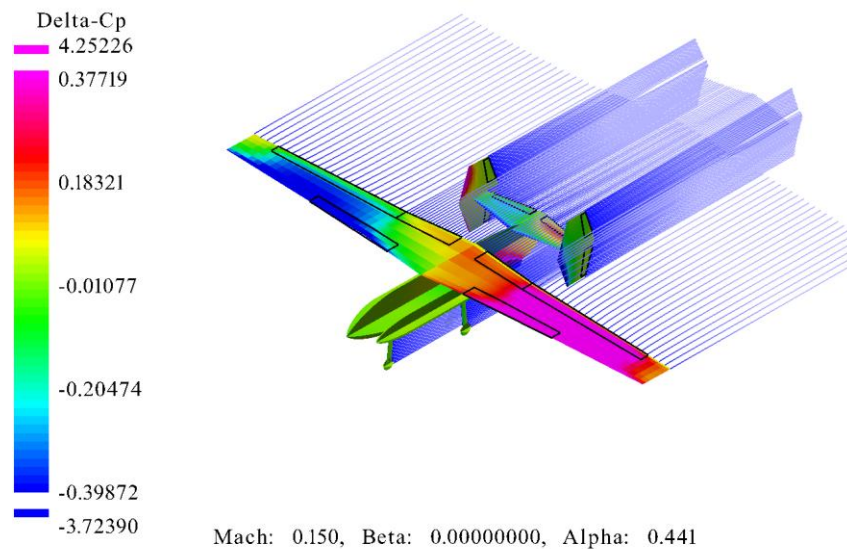


Figure 47 – Pressure distribution and flow behavior for $\alpha = 0,44^\circ$

- Angle of Attack $\alpha = 5,59^\circ$, Figure 48:

With the increase in the angle of attack, the lift generation becomes more evident. The ΔC_p negative on the extrados increases even more, covering an area of the wing, implying that the air on the upper surface is accelerated, creating ΔC_p effective. On the intrados, the positive areas of ΔC_p increase and consolidate the lift profile. The flow lines remain very smooth, without major separations, which suggests an adherent flow and an efficient flight regime for the generation of lift.

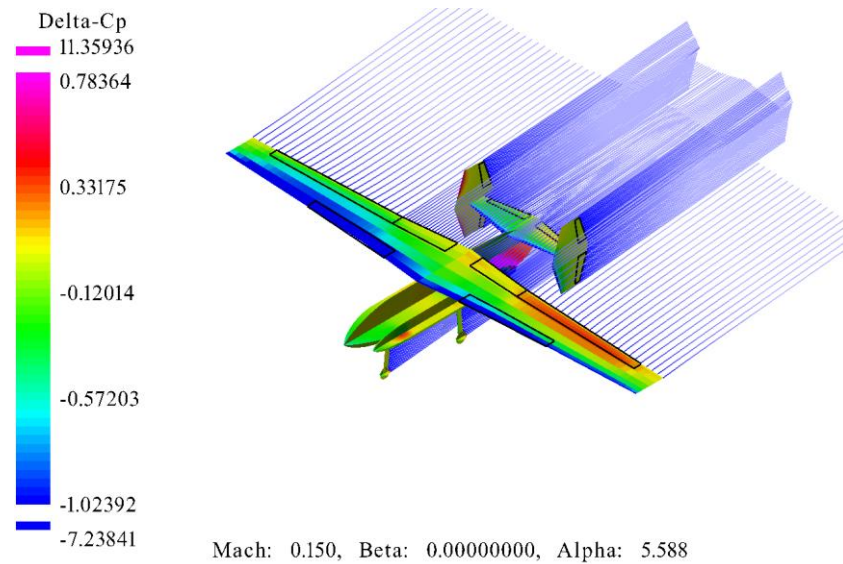


Figure 48 – Pressure distribution and flow behavior for $\alpha = 5,59^\circ$

- Angle of Attack $\alpha = 12,79^\circ$, Figure 49:

For this angle of attack, the negative ΔC_p , is close to the maximum on the extrados, which implies an increase in lift. In the intrados the positive ΔC_p is also more intense, suggesting a considerable increase in compression and possibly drag. On the other hand, the drain lines are still well organized, but signs of separation are beginning to appear suggesting an approach to the stall. The flow near the vertical stabilizer presents more disturbances due to the incidence of flow.

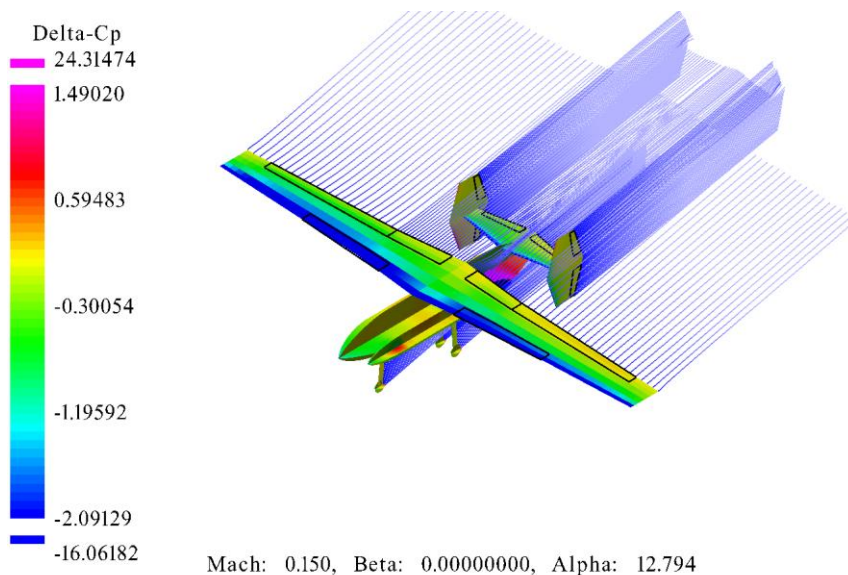


Figure 49 – Pressure distribution and flow behavior for $\alpha = 12,79^\circ$

- Angle of Attack $\alpha = 20^\circ$, Figure 50:

Upon hitting $\alpha = 20^\circ$, the wing enters a condition of destabilized flow, because despite maintaining negative ΔC_p in the extrados, the flow begins to separate, moving away from the wing surface. On the intrados the elevated positive ΔC_p suggests strong compression, which increases the resistance to advancement. With this flow distribution, the aircraft would find itself in a stall or very close to it, where the lift decreases drastically and drag increases, impairing aerodynamic efficiency.

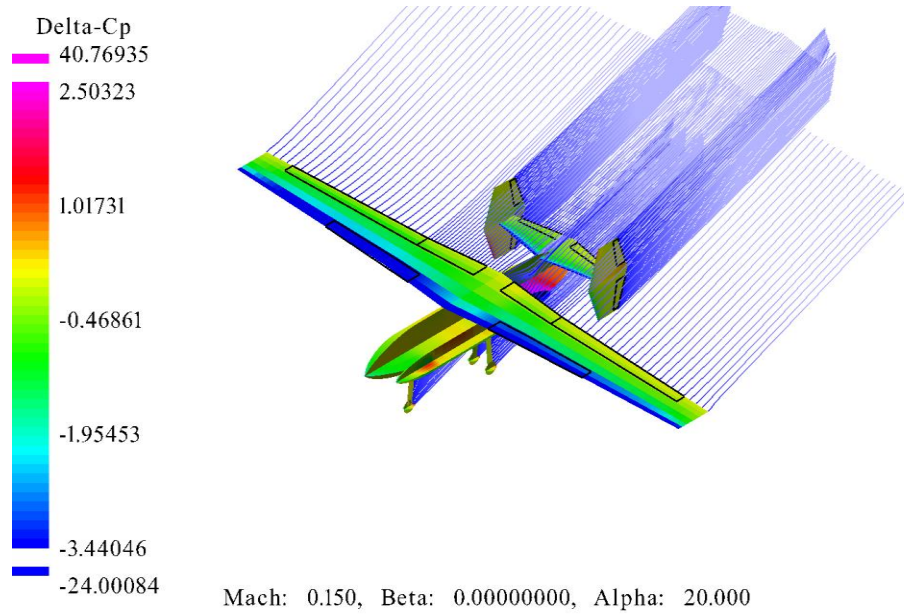


Figure 50 – Pressure distribution and flow behavior for $\alpha = 20^\circ$

With the analysis of the variation of ΔC_p in the different angles of attack conditions, it is possible to predict the aerodynamic behavior of the UAV in cruise flight. For negative angles, lift is almost non-existent, while for moderate angles of attack, the distribution of ΔC_p lift reveals an adherent flow and good lift generation. However, as the angle of attack increases to high values, the flow begins to destabilize, with the separation close to the stall condition, which comprises the aircraft's performance in flight. The aerodynamic profile responds well at moderate angles, but has limitations at extreme angles, which should not be a problem in the UAV's operating envelope range. However, ISMAR radar interference becomes pronounced as the airflow around the fuselage and control surfaces is disturbed, which can lead to layout changes for performance improvements if necessary.

8. CONCLUSION

The present work offered an in-depth and critical view of the challenges and opportunities associated with the operation of long-range UAVs by the Portuguese Air Force (FAP) in the Portuguese Economic Zone (ZEP). By addressing the evolution of these platforms, from their inception in 2009 to the current operational limitations, we recognize the pressing need for more advanced aircraft to meet the requirements of surveillance and monitoring in the vast maritime jurisdiction of Portugal, the challenge that the author proposed was met by presenting the entire process of sizing the class 1 UAV.

The initial motivation for this work was anchored in the understanding of the strategic importance of the ZEP, which covers one of the largest areas of Search and Rescue in the world. The integration of Unmanned Aerial Systems (UAS) with manned aircraft emerges as a strategic approach to address operational challenges, especially in the face of the need for efficient surveillance in a complex geographical context.

The critical review of the literature provided a solid theoretical framework, highlighting the evolution of UAVs in the context of FAP and their contribution to the monitoring of maritime pollution on behalf of the European Maritime Safety Agency (EMSA). In addition, the extensive review of characteristics and theoretical conditions that emphasize the design process of the UAV presented.

The choice of the theme "Design for the configuration of a long-range UAV" was driven by the strategic military relevance and the emerging civilian applications of UAVs. The growing need for operations without exposing pilots to risk, coupled with the potential for innovation at the Air Force Academy Research Center (CIAFA), justifies the exploration of composite materials and highlights the challenging technical opportunities aligned with global trends in efficiency and sustainability in the aerospace sector.

The work was divided with a first review of the general design of UAVs in Portugal, continuing a review of fundamental concepts about the UAV development process and design characteristics, performance and aerodynamics. The current computational methods dedicated to aeronautical study were evaluated, justifying the use of OpenVSP in this project as the main design and analysis tool. Then a mission was studied according to FAP standards that fit into maritime surveillance, starting the definition of characteristics that would be

deepened in the development of the UAV requirements, in addition, all the equipment necessary for the realization of the mission and for the operation of the UAV were studied.

Finally, the present dissertation started the conceptual development of the UAV, from fuselage, main wing, tail and landing gear based on several bibliographic references to follow its development in the most coherent way possible. Justifying the decisions made and comparing the results obtained with existing empirical data (Anderson Jr, 1991; Corke, 2003; Gundlach, 2012; Raymer, 1992; Sadraey, 2024).

In conclusion, this work completed its main objective not only identified operational challenges, but also realized the conceptual design of the UAV and studied all its equipment. The UAV designed meets the requirements developed in the initial stage of the project, however, some parameters required further analysis and testing for confirmation. In doing so, it has contributed to the expansion of knowledge in the field, underscoring the importance of continuous innovation and strategic adaptation to address the evolving challenges in the unmanned aerial operational landscape.

8.1 Future Work

Continuing the development started in this dissertation, the next steps in the study of the long-range UAV for the Portuguese Air Force should focus on experimental tests and validation of the computational models used. For example, wind tunnel tests and the construction of small-scale prototypes would be fundamental steps to refine the aerodynamic characteristics and validate the expected performance, especially in adverse operating conditions typical of maritime surveillance missions. In addition, more detailed studies on the behavior of the UAV in different flight regimes, such as low-altitude maneuvers or long-duration flights, can contribute to further optimizations in the design, improving fuel efficiency and durability of materials.

Another promising axis for future work is the integration of new propulsion systems, such as hybrid or electric engines, which have the potential to significantly increase the sustainability of operations. The analysis of the impact of these technologies on the overall performance of the UAV, as well as the exploration of more advanced autonomous control systems to allow missions of greater complexity and duration, are areas that deserve attention. An in-depth analysis of the load distribution of each component and what impact in the aircraft layout can also be important to complement the design.

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ANNEXES

Annex 1 – Market Survey

Table 40 - Tabulation of all UAVs considered in the Market Survey and their respective characteristics

Manufacture	MTOW [kg]	Empty Weight [kg]	Wingspan [m]	Cap. Payload [kg]	Range [km]	Cruise Altitude [m]	Cruise speed [km/h]	Max speed [km/h]	Propulsion:	Airfoil	Piloting	Propeller	Power source	Endurance [h]
Tekever AR5	150	100	7,3	50	40	305	110	140	4 turbine engines	NACA 64008	Autopilot		Jet-A1	20
Tekever AR4	4	3,5	2,1	1	20	4,5	54	75	4 turbine engines	NACA 6512	Autopilot		Jet-A1	2
Tekever AR3	23	19	3,5	4	100	3	85	100	2 turbine engines	Eppler 230	Autopilot		Jet-A1	16
Wingtra	4,5	3,7	1,25	0,8	100	200	58	80	2 electric engines	NACA 0012	Autopilot	2 at the Rear	Smart batteries	0,98
UAVISION OGASSA OGS42	38	33	4,2	5	100	2438	94,5	130	Combustion: 70cc - 11 l		Autopilot	Rear	Gasoline	10
UAVISION OGASSA OGS42V	36	31	4,2	5	100	2438	94,5	130	Combustion: 70cc - 11 l		Autopilot	1 rear, 4 on the flight surfaces	Gasoline	8
AeroVironment RAVEN® B RQ-11	2,4	1,9	1,37	0,5	10	1500	65	81	Combustion	NACA 0015	Autopilot/manual	1 at the Rear	Metanol	1,25
AeroVironment PUMA LE	12,2	10,7	4,6	2,5	60	1524	47	76	Electric engine		Autopilot/manual	1 on the nose	Dual Battery Bay 5,5 HR	5,5
AeroVironment JUMP® 20	97,5	83,9	5,7	13,6	185	5181,6	93,3	139	Combustion: MOGAS, 190 cc EFI		Autopilot/manual	1 on the nose, 4 on the flight surfaces	Gasoline	13
AeroVironment T-20	102	79,3	5,7	22,7	185	5181,6	93,3	139	Combustion: MOGAS, 190 cc EFI		Autopilot/manual	1 on the nose	Gasoline	24
Quantum Systems Trinity Tactical	5,75	4,8	2,4	1	90	4000	61,2	100	Electric engine			3 on the flight surfaces (2 on the wings, 1 on the tail)	Batteries	1,3
BlueBear	0,7	0,55	0,5	0,15	10	100	25	40	Electric engine	NACA 6512	Autopilot	Front	Batteries	0,67
Cavok UAS	5	4	1,2	1	20	3500	45	67	Electric engine	Eppler 230	Autopilot	4-quadrotor	Batteries	0,83
ANTEX-X02	10	6	2,4	4	360	2000	120	150	Combustion (But there is also a version with an electric motor)		Autopilot/manual	1 at the rear of the fuselage	Gasoline	2.3 with combustion, 30 minutes with electric engine
ScanEagle	26,5	21,5	3,11	5	100	5950	108	148,32	Combustion: JP-5 or JP-8		Autopilot/manual	1 at the Rear	Heavy fuel	18
RQ-2 Pioneer	205	160	5,15	34	185	4572	120	203,7	Combustion: Sachs SF-350, 26 hp	NACA 4415	Manual earth station	2 at the Rear		5
IAI Heron Machatz-1	1150	900	26	250	350	10000	140	207	Combustion: Rotax 914, 115 hp	DAE-21	Manual earth station	1 at the Rear	Gasoline	50
General Atomics MQ-9 Reaper	4763	1676	20	1361	1850	15000	280	480	Combustion: AlliedSignal Garrett TPE331-10T	Root: Drela GW-19/GW-25; Tip: Drela GW-27	Manual earth station	1 at the Rear	Gasoline	30
Elbit Systems Hermes 900	1180	670	15	350	1000	9100	112	220	Combustion: Rotax 914, 115 hp		Manual earth station	1 at the Rear	Gasoline	36

Annex 2 – Mission Profile

Table 41 - Mission profile tabulation

Mission Profile		
Preparation and launch	Launch Location:	Base das Lajes
	Time:	10 min
	Actions:	System checks, fuel supply
Ascension and flight to the operating area	Cruising altitude:	4000 m
	Cruising speed:	180 km/h
	Distance to the operating area:	150 km
	Estimated time:	50 min
Patrol and surveillance	Operation area:	800 km2
	Cruising altitude:	4000 m
	Patrol Speed:	100 km/h
	Operating time:	8 h
Return to base and descension	Return cruising speed:	180 km/h
	Distance to base:	150 km
	Estimated time:	50 min
Landing and Demobilization	Time:	10 - 20 min
	Actions:	Post flight check, maintenance

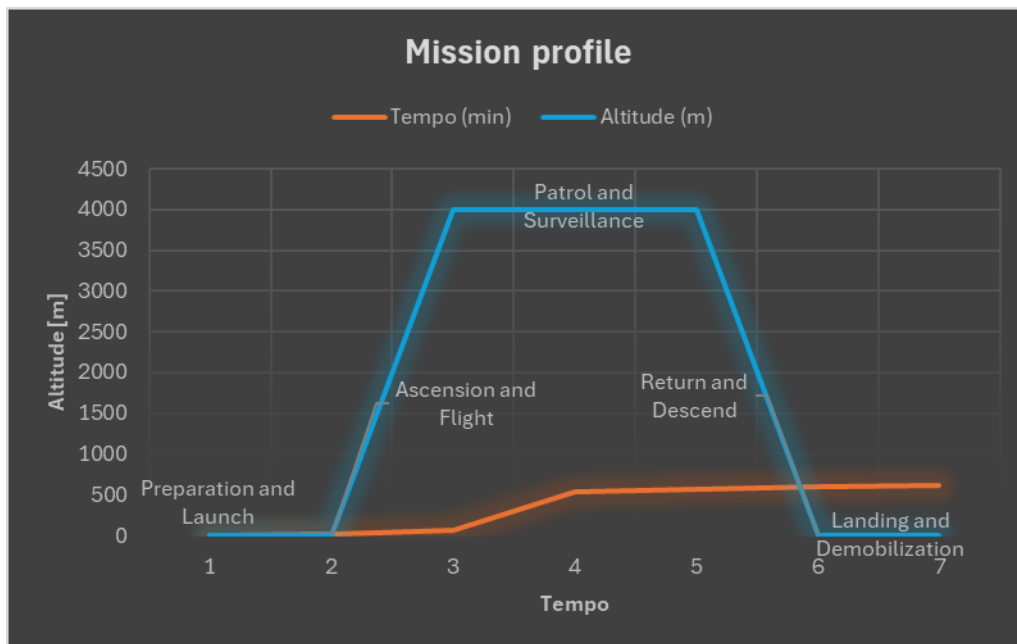


Figure 51 - Graphical representation of the mission profile

Annex 3 – UAV Requirements

Work Package	MBS	Requirements	Project/product	Ref.	Responsible	MOC	MOC Text	MOC is Identified?	MOC Details	MOC is Detailed?	MOC Reference Document	Documents are identified?	Requirements Status	Equipments
Propulsion/Engine and Structure configuration	Power Plant/Combustion power/Power control	Operating speed (V/c) of 180 km/h	Combustion engine capable of achieving desired speed	Market Survey Estimated	Performance team	MC2; MC6	Flying test	Yes	Analysis of the cruise speed of the flight test	Yes	Flight report	Yes	Wait for Completion	AR-741
Propulsion/Engine and Structure configuration	Power Plant/Combustion power/Power control	Patrol speed of 100 km/h	Combustion engine	Market Survey Estimated	Performance team	MC2; MC6	Flying test	Yes	Analysis of the patrol speed of the flight test	Yes	Flight report	Yes	Wait for Completion	
Propulsion/Engine and Structure configuration	Power Plant/Combustion power/Power control	Maximum speed (Vmax) of 200 km/h	Combustion engine	Market Survey Estimated	Performance team	MC2; MC6	Flying test	Yes	Analysis of the maximum speed of the flight test	Yes	Flight report	Yes	Wait for Completion	
Propulsion/Engine and Structure configuration	Combustion power/Structure	Stall speed (Vs) of 25 m/s	Surveillance UAV	Market Survey Estimated	Performance team	MC2; MC6	Performance analysis; Flying test	Yes	Analysis of the stall speed of the flight test	Yes	Performance test report in Flight test	Yes	Wait for Completion	
Propulsion/Engine and Structure configuration	Combustion power/Structure	Stall speed in landing configuration (Vso) of 20 m/s	Surveillance UAV	Market Survey Estimated	Performance team	MC2; MC6	Performance analysis; Flying test	Yes	Analysis of the stall speed in landing of the flight test	Yes	Performance test report in Flight test	Yes	Wait for Completion	
Wing/Load and Structure configuration	Wing Configuration	Glide Ratio 15:1 or better	UAV Wing	Market Survey Estimated	Performance team	MC2; MC6	Performance analysis; Flying test	Yes	Analysis of the wing profile and characteristic	Yes	Design documents; Drawings; Test reports	Yes	Wait for Completion	
Propulsion/Engine and Structure configuration	Combustion power/Load Distribution	Climb Rate at MTOW of 440 m/min	Combustion engine	Market Survey Estimated	Performance team	MC2; MC6	Performance analysis; Flying test	Yes	Analysis of the distribution of equipment in the structure and engine power	Yes	Design documents; Test reports	Yes	Wait for Completion	
Propulsion/Engine, Load and Structure configuration	Power Plant/Electrical Power/Power control	Carra maxima no envelope de vo entre -0.5 e 2.0 [Gs]	Surveillance UAV	Market Survey Estimated	Performance team	MC2; MC6	Performance analysis; Flying test	Yes	Analysis of the aircraft structure; Flight test for this loads	Yes	Analysis report; Flight report	Yes	Wait for Completion	

Figure 52- Performance Requirements

Airframe Requirements	Airframe Segment	Project management	MTOW ≤ 150 kg	Surveillance UAV	CIAFA Documents	Design Team	MC1; MC2	Design review; Calculation	Yes	Analysis of the maximum take-off weight so that it does not exceed 150 kg	Yes	Design documents; Drawings	Yes	Completed
	Airframe Segment	Project management	Wingspan ≤ 5 m	Surveillance UAV	CIAFA Documents	Design Team	MC1; MC2	Design review; Calculation	Yes	Analysis of the wingspan so that it does not exceed 5 m	Yes	Design documents; Drawings	Yes	Completed
	Airframe Segment	Structure	Simple fuselage configuration with straight lines and flat shapes	Surveillance UAV	Design Documents	Design Team	MC1; MC3	Design review; Safety assessment	Yes	Analysis and development of a practical and efficient structure	Yes	Design documents; Drawings; Safety analysis	Yes	In Progress
	Airframe Segment	Structure	Construction of the UAV using preferably composite materials	Surveillance UAV	Design Documents	Areas and structures team	MC1; MC3	Design review; Safety assessment	Yes	Efficient composite material analysis in accordance with the mission developed	Yes	Design documents; Drawings; Safety analysis	Yes	In Progress
	Airframe Segment	Structure	Facilitated structure maintenance and checks, preventive maintenance or repairs	Surveillance UAV	Design Documents	Design Team; Areas and structures team	MC1; MC3	Design review; Safety assessment	Yes	Analysis of a structure configuration for easy access and maintenance	Yes	Design documents; Drawings; Safety analysis	Yes	In Progress
	Airframe Segment	Wing structure	Easy wing maintenance and checking, access and repairs	Surveillance UAV	Design Documents	Design Team; Areas and structures team	MC1; MC3	Design review; Safety assessment	Yes	Analysis of a wing configuration for easy access and maintenance	Yes	Design documents; Drawings; Safety analysis	Yes	Completed
	Airframe Segment	Structure/Load distribution	Electronics separated from combustion elements (fuel tanks and engine) as much as possible	Surveillance UAV	Design Documents	Design Team; Areas and structures team	MC1; MC3	Design review; Safety assessment	Yes	Analysis of the distribution of electronic components in relation to the internal combustion engine for safety reasons	Yes	Design documents; Drawings; Safety analysis	Yes	Completed
	Airframe Segment	Structure	UAV avionics, including fasteners, must be protected against deterioration or loss of strength due to any unforeseen cause	Surveillance UAV	Design Documents	Design Team; Stability and control team	MC1; MC3	Design review; Safety assessment	Yes	Analysis of a structure for avionics safety reasons	Yes	Design documents; Drawings; Safety analysis	Yes	Wait for Completion
	Airframe Segment	Structure	The UAV must ensure that in the event of a collision, it is possible to make a controlled emergency landing or continue flying safely.	Surveillance UAV	Design Documents	Design Team; Stability and control team	MC1; MC3	Design review; Safety assessment	Yes	Structure resistivity analysis	Yes	Design documents; Drawings; Safety analysis	Yes	Wait for Completion
	Airframe Segment	Structure	Servo-actuators must be redundant	Surveillance UAV	Design Documents	Design Team; Stability and control team	MC1; MC3	Design review; Safety assessment	Yes	UAV security analysis and prevention	Yes	Design documents; Drawings; Safety analysis	Yes	Completed
	Airframe Segment	Structure	Distribution of the highest weights close to the CG	Surveillance UAV	Design Documents	Design Team; Areas and structures team	MC1; MC2; MC3	Design review; Calculation; Safety assessment	Yes	Analysis of weight distribution and related calculations	Yes	Design documents; Drawings; Safety analysis	Yes	In Progress

Figure 53 - Airframe Requirements

Operational Requirements	Mission overview	Project management	Patrol mission starting in BA4, monitoring anomalies in the Portuguese maritime region at different speeds and altitudes, adapting the UAV according to the development of the mission	Surveillance UAV	FAP, ZEP and CIAFA Documents plus objective of the dissertation	Process and planning team	MC0	Compliance statement	Yes	Study and development of the mission profile in order to fit the UAV into an area of need promoting research	Yes	Recorded statements	Yes	In Progress	NAL Research Corporation A3LA-RS
	Area of Operations	Project management	According to the defined mission, the UAV must reach 1100 km	Surveillance UAV	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC2; MC6	Design review; Calculation; Flying test	Yes	Analysis and study of the range to be covered by the defined mission	Yes	Recorded statements; Design documents; Test reports	Yes	Completed	
	Endurance	Project management	10 hours approximately taking into account the mission	Surveillance UAV	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC2; MC6	Design review; Calculation; Flying test	Yes	Analysis and study of the flight time to be taken for the defined mission	Yes	Recorded statements; Design documents; Test reports	Yes	Completed	
	Time of operations	Project management	Operation during the day and at night	Surveillance UAV	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC2; MC6	Design review; Calculation; Flying test	Yes	Analysis of flight conditions	Yes	Recorded statements; Design documents; Test reports	Yes	Completed	
	Operational weather (wind)	Project management	Withstand wind intensity including crosswind between 10 and 15 m/s	Surveillance UAV	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC2; MC6	Design review; Calculation; Flying test	Yes	Analysis of flight conditions	Yes	Recorded statements; Design documents; Test reports	Yes	Wait for Completion	
	Operational temperature	Project management	The UAV must withstand temperatures between -25° C + 50° C	Surveillance UAV	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC2; MC6	Design review; Calculation; Flying test	Yes	Analysis of flight conditions	Yes	Recorded statements; Design documents; Test reports	Yes	Wait for Completion	
	Operational weather (rainfall)	Project management	The UAV must withstand a slight rain intensity. Less or equal than 0.5 mm per hour	Surveillance UAV	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC2; MC6	Design review; Calculation; Flying test	Yes	Analysis of flight conditions	Yes	Recorded statements; Design documents; Test reports	Yes	Wait for Completion	
	Operating altitude	Project management	Operating altitude 4000 m according to the defined mission	Surveillance UAV	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC2; MC6	Design review; Calculation; Flying test	Yes	Analysis and study of flight height during most of the mission	Yes	Recorded statements; Design documents; Test reports	Yes	Wait for Completion	
	Communication Range	Project management	SatCom with mission-wide reach	SatCom	FAP, ZEP and CIAFA Documents	Process and planning team	MC0	Compliance statement	Yes	Analysis and study of equipment with functionalities according to the mission	Yes	Recorded statements	Yes	Completed	
	Communication Capabilities	Project management	Exchange and reading of information live with immediate response	SatCom	FAP, ZEP and CIAFA Documents	Process and planning team	MC0	Compliance statement	Yes	Analysis and study of equipment with functionalities according to the mission	Yes	Recorded statements	Yes	Completed	
	Take-off and landing	Project management	Landing gear optimized for BA4 operation	Landing gear	FAP, ZEP and CIAFA Documents	Process and planning team	MC0; MC1	Compliance statement; Design review	Yes	Analysis and study of the operating site for the take-off and landing stage	Yes	Recorded statements	Yes	Completed	

Figure 54 - Operational Requirements

PowerPlant Requirements	Electrical Segment	Electrical Power	On-board generator capable of powering subsystems (avionics) and sensors (payload + avionics)	Power generator	Market Survey and Design Documents	Power distribution team	MCO, MC1	Compliance statement, Design review	Yes	Analysis of energy distribution for different equipment	Yes	Recorded statements, Design documents	Yes	Completed
	Electrical Segment	Power Supply	Backup batteries for main systems capable of supporting 2 to 3 hours of power	Batteries set	Market Survey and Design Documents	Power distribution team	MCO, MC1, MC3	Compliance statement, Design review	Yes	Power supply analysis of main systems in case of emergency	Yes	Recorded statements, Design documents, Safety analysis	Yes	Completed
	Electrical Segment	Power Supply	Payload backup batteries capable of withstanding 20 to 30 min of power	Batteries set	Market Survey and Design Documents	Power distribution team	MCO, MC1, MC3	Compliance statement, Design review	Yes	Payload power analysis in case of emergency	Yes	Recorded statements, Design documents, Safety analysis	Yes	Completed
	Electrical Segment	Electrical Power	Optimization of electrical components to optimize MTOW	All payload and avionics	Market Survey and Design Documents	Power distribution team	MCO, MC1	Compliance statement, Design review	Yes	Analysis of the weights of power components in order to minimize MTOW	Yes	Recorded statements, Design documents	Yes	Completed

Figure 55 - PowerPlant Requirements

Instrumentation Requirements	Avionics Segment	Avionics instrumentation	The interaction between all components (sensors and devices) must be maintained in operating and storage conditions	Sensors and equipments	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis for each equipment to ensure operational and functional characteristics in accordance with the mission		Recorded statements; Design documents	Yes	Completed	Octopus ISR Systems Epsilon 140Z G2
	Avionics Segment	Payload instrumentation	Fully stabilized looking forward and steerable in all directions including an EO sensor and thermal IR sensor and laser illuminator	Specialized gimble	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes			Recorded statements; Design documents	Yes	Completed	
	Avionics Segment	Payload instrumentation	High definition, capable of greater than 10x optical zoom and a wide field of view	Electro optical (EO)	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis of the gimble to ensure operational and functional characteristics in accordance with the mission	Yes	Recorded statements; Design documents	Yes	Completed	
	Avionics Segment	Payload instrumentation	At least 600 x definition, high temperature range operation (0 to 2000 degrees C), optical zoom of at least 10x and a wide field of view	IR, either SWIR, MWIR or LWIR	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes			Recorded statements; Design documents	Yes	Completed	
	Avionics Segment	Payload instrumentation	High definition and wide field of view	Laser illuminator in the IR	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes			Recorded statements; Design documents	Yes	Completed	
	Avionics Segment	Payload instrumentation	Day and night operation with a minimum range of 20 km	Synthetic aperture radar (SAR)	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis of the SAR to ensure operational and functional characteristics in accordance with the mission	Yes	Recorded statements; Design documents	Yes	Completed	IMSR NSP-7 Long-Range
	Avionics Segment	Payload instrumentation	Incorporate Ground Moving Target Indicator (GMTI), and Maritime Moving Target Indicator (MMTI)	Synthetic aperture radar (SAR)	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes			Recorded statements; Design documents	Yes	Completed	
	Avionics Segment	Payload instrumentation	Able to transmit and receive, high sensitivity and low power consumption	Automatic Identification System (AIS)	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis of the AIS to ensure operational and functional characteristics in accordance with the mission	Yes	Recorded statements; Design documents	Yes	Completed	SA161-UA
	Avionics Segment	Payload instrumentation	Capable of measuring multiple pollutants such as CO2, NO2, and SO2 and provides real-time data transmission	Air Pollution Monitoring Sensors	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis of the sensor sets to acquire atmospheric characteristics during the mission	Yes	Recorded statements; Design documents	Yes	Completed	Purway UAV TDLAS Detector Model II
	Avionics Segment	Avionics instrumentation	Mode C transponder, ADS-B compatibility	Transponder	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis of the transponder to obtain detailed information on aircraft characteristics (position, altitude)	Yes	Recorded statements; Design documents	Yes	Completed	Sandia Aerospace STX 16SR
	Avionics Segment	Avionics instrumentation	Operational throughout the mission, ability to interpret and send data	Distress Sensor	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis of the Distress Sensor to detect emergency situations or critical failures and, in response, transmit distress signals or activate emergency protocols	Yes	Recorded statements; Design documents	Yes	Completed	Ocean Signal EPIRB1
	Avionics Segment	Avionics instrumentation	Compatibility with different media, low power consumption	SatCom	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Specialized analysis of the SatCom to be compatible with other equipment	Yes	Recorded statements; Design documents	Yes	Completed	NAL Research Corporation A3LA-RS
	Avionics Segment	Avionics instrumentation	Able to control the UAV during the mission with minimal interaction from the ground station (Autonomous)	Autopilot	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC0; MC1	Compliance statement; Design review	Yes	Analysis and definition of an automatic pilot taking into account CIAFA's history	Yes	Recorded statements; Design documents	Yes	Completed	Piccolo SL
	Avionics Segment	Avionics instrumentation	They must be duplicated for safety reasons, they must be able to interpret information from sensors and be controlled by the autopilot to adapt to different situations	Servo-actuators	Market Survey and FAP, ZEP and CIAFA Documents	Instrumentation team	MC1; MC3	Design review; Safety assessment	Yes	Analysis and definition of servo actuators capable of withstanding atmospheric conditions and mission execution	Yes	Design documents; Safety analysis	Yes	Completed	CBS-20 CAN Brushless Servo

Figure 56 - Instrumentation Requirements