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Study of a feasible solution for a specific mission with unmanned aerial vehicles(UAV/RPAS)

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Study of a feasible solution for a specific mission with unmanned aerial vehicles(UAV/RPAS)

Escola Superior d'Enginyeries Industrial, Aeroespacial i Audiovisual de Terrassa

ESEIAAT

Grau en Enginyeria en Tecnologies Aeroespacials

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Abstract

Due to the recent popularity of civil Unmanned Aerial Vehicles (UAV) and the expectation that are generating, the idea of developing a study related to the topic emerged.

The aim of the study is to propose a solution with UAV for surveillance applications and determine if is feasible for future implementation.

First of all, as an introduction, the legal framework and the state of the art of the UAV industry has been studied in order to define the background of the project. Then, the design requirements have been implemented in order to provide a solution that can accomplish the objectives of the mission.

The second part is based on the description of the solution proposed. From the information obtained in the background study and taking into account the design requirements, the most general aspects of an Unmanned Aerial System have been analysed and some decisions have been chosen.

Finally, by means of a technical and economical approach, the feasibility study has been made. Some conclusions concerning the implementation of the solution proposed in the actual market have been drawn.

Preface

Unmanned Aerial Vehicles (UAV) are aircrafts without a human pilot aboard and they have been used for military applications for decades. However, due to the effectiveness as an aircraft and sensor and also because of the automatic technology involved, its use is expanding in commercial, scientific and recreational applications. The UAV industry is expected to grow very fast in the next 10 years and therefore is an interesting sector to study.

One of the commercial applications in which the UAV will play an important role is surveillance. Thus, the general objective is to design a solution with Unmanned Aerial Systems for surveillance applications and determine if it is feasible.

At the present time, multi-copter drones with photography applications are beginning to success. However, UAV with commercial functions are not very usual and they are starting to be implemented. For this reasons, new solutions must be proposed in order to promote the use of these aerial vehicles for commercial purposes.

The expectation generated in the last years regarding UAVs, have created a potential market in which lot of stuff have not yet been developed. Thus, this industry can be considered as one of the most attractive for aeronautical engineers.

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List of Abbreviations

AoA: Angle of attack

AR: Aspect Ratio

BLDC: Brush-less DC motors

CFRP: Caron Fibre Reinforced Polymer

DC: Direct Current

GCS: Ground Control Station

GFRP: Glass Fibre Reinforced Polymer

GPS: Global Positioning System

ICE: Internal Combustion Engine

LOS: Line of Sight

MTOM: Maximum Take-Off Mass

MTOW: Maximum Take-Off Weight

PLW: Payload Weight

RF: Radio Frequency

ROC: Rate of Climb

RPAS: Remotely Piloted Aircraft Systems

SL: Sea Level

UAS: Unmanned Aerial System

UAV: Unmanned Aerial Vehicle

Nomenclature

P: Power

W: weight

η: Efficiency

C_{D_0}: Parasitic drag coefficient

S: Wing surface

n: load factor

ρ: density

V: speed

g: gravity acceleration

d_{TO}: Take-off distance

h: altitude

e: Oswald efficiency

A: Aspect Ratio

P_A: Available power

P_R: Required power

T: Thrust

D_p: Propeller diameter

P_{bl}: Power loading per blade

n_p: Number of propeller blades

R_e: Reynolds number

μ: air viscosity

V_{stall}: Stall speed

C_L: Lift coefficient

C_D: Drag coefficient

C_m: pitching moment coefficient

C_L/C_D: Lift-to-drag ratio

C_{m_α}: pitching moment slope

C_{tip}: chord at the tip

C_{root}: chord at the root

D: Drag Force

L: Lift Force

t: endurance

φ: Mass flow rate

$\dot{\psi}$: Turn rate

ϕ: Bank angle

L_v: Distance between leading edges of wing and elevator

V_v: Tail volume coefficient

S_V: Elevator surface

b: wingspan

1. Aim of the study

The aim of the study is to propose a solution with unmanned aerial vehicles (UAV/RPAS) for surveillance applications taking into account the basic requirements. Apart from that, a feasibility study has to be done in order to determine if the solution can be implemented.

2. Justification

The unmanned air vehicles (UAV) has been used for decades due to the effectiveness as an aircraft and sensor and also because of the automatic technology involved. Consequently, the potential benefits of this systems are being extended to civil applications – the first application was military- and in a near future the main utilizations will be settled. This is why the FAA (Federal Aviation Administration) estimates that in a five-year time, 7500 UAV would be operational in the U.S airspace.[1]

Nowadays the regulation is limiting the development of the UAS sector. However, it is expected that in less than 2 years the legislation will change enabling new applications. Hence, it has been predicted that the UAV sector will experience a considerable growth in the next decade. The UAV market evolution expected can be represented in Figure 1 with the amount of US dollars that will be spent.
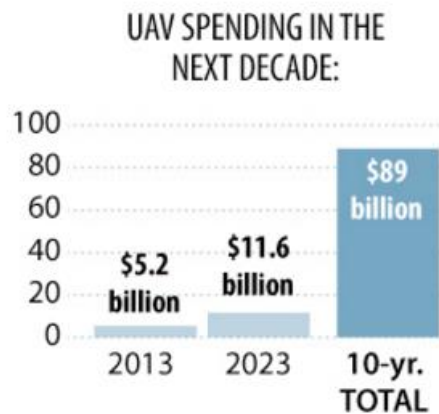
Figure 1: Expected growth of the UAV market [2]

Due to the expected growth of the sector, a UAV project ensures entering to a new market in which there are new issues to develop and consequently future feasibility can be easily guaranteed.

One of the main commercial applications of the UAVs is surveillance. The actual security systems are quite limited and in some scenarios, like large extensions or difficult access areas, there are practically useless. However, drones[1] have the potential to solve these problems and create a new concept of security.

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[1] Drone has been used as a synonym of UAV

3. Scope

The points that this study covers are:

- Study of the legal framework
- State of the art of the UAV industry
- Analysis of the design requirements
- UAV solution proposal
    - Definition of the type of system
    - Analysis of the different subsystems of the UAV (propulsion, aerodynamics, communication and flight control)
    - Payload
    - Performance
- Technical approach
- Economical approach
- Conclusions and future improvements

4. Basic requirements

The UAV solution proposed must meet the following requirements:

- Surveillance applications
- Flight time between 2h and 12 h
- Mass below 25 kg
- Operation during day and night
- Payload: camera

5. Background

The first step in an engineering project is to study the legal framework in order to design a solution that meets with the regulation involved. The international, European and Spanish legislations related to UAV/RPAS will be mentioned and a general idea of the legal background will be shown. Another important aspect to take into account is the actual market and what technologies have been developed until the moment. This aspect will be treated with a state of the art of the UAV industry. Having an idea of the actual UAV industry will help to focus the study and also to purpose a feasible solution.

5.1. Regulations

5.1.1. Regulations at International level

The ICAO (International Civil Aviation Organization) is a United Nations agency responsible of setting up the principles and regulations of the international air navigation with the objective of promote the development of a secure international air transport. In order to assist the State Members of the Organization to develop national aviation regulations, ICAO publishes the Standards and Recommended Practices (SARPSs).[3]

According to the Article 8 of the Chicago Convention in 1944, pilotless aircrafts can't fly over the territory of a contracting State without special authorization by that State. The contracting State is responsible of insuring that the flight is controlled so that danger to civil aircraft is avoided.

Due to the increasing of UAS technology at the beginning of the new century, in 2007 ICAO build up an Unmanned Aircraft Systems Study Group (UASSG) formed by experts from the Member States, industries and stakeholder groups in order to discuss the impact of RPAS on aviation regulation.

In March of 2011, UASSG published the Circular 328 with the following purposes [4]:

- Inform the global UAS community of the emerging ICAO perspective on the integration of UAS into non-segregated airspace and at aerodromes
- Consider the fundamental differences from manned aviation that such integration will involved
- Encourage other countries to help with the development of ICAO policy on UAS by providing information on their own experiences associated with UAS.

The UASSG were not allowed to publish SARPs due to the status of study group. However, in response to the rapid developments in RPAS technology, in November 2014 the UASSG was elevated to the status of a Panel with the main objective of publishing SARPs on unmanned aircraft by 2018. These SARPs will include guidance on airworthiness, operations and pilot licensing.[5]

5.1.2. Regulations at the EU level

The aviation regulator in Europe is the European Aviation Safety Agency (EASA) that is responsible of the airworthiness and the aircrafts operations in the EU.

The EU Regulations 216/2008 establishes that the EASA is responsible of civil RPAS over 150 kg whereas the Member State authorities are responsible for RPAS – military and civil- below 150 kg.

EASA has already published some documents related with the regulatory frame of UAS[6]:

- Guidance material to support approved Design Organisations that have the objective of selecting the appropriate specifications in order to build the certification basis for RPAS design.
- NPA 2012-10 to transpose the ICAO circulars into Standard European Rules of the Air (SERA).

Since NPA 2012-10 was radically changed, EASA decided to publish a second NPA on the same matter. This new text is the NPA 2014-09.

To propose changes to the existing aviation rules in order to take into consideration the latest developments of drones, EASA has develop the A-NPA 2015-10.

The A-NPA is a proposal for the creation of common European safety rules for operating drones regardless of their weight. It contains 33 proposals with the objective of collecting the safety regulations for commercial and non-commercial activities. It also introduces three categories of operations based on the risk the operation is posing to third parties[7]:

- Open category (low risk)
- Specific category (medium risk)
- Certified category (high risk)

5.1.3. Regulations at Spain level

According to the AESA (*Agencia Estatal de Seguridad Aérea*) the RPAS activity has increased the last months. Therefore, this agency has developed a legal framework to ensure security.

AESA is responsible of regulate drones until 150 kg whereas for drones with a weight above 150 kg the regulator is EASA.

The basic regulations for the professional use are mentioned below [8]:

- The drone must be registered in AESA
- A specific liability insurance for aircrafts is necessary
- Have the pilot license
- Have a valid medical certificate
- It is banned to operate in urban zones

- It is banned to overfly crowds of people
- It is banned to fly at night
- It is banned to fly in controlled airspace
- It is banned to fly close to airports
- It is banned to endanger third parties

For the professional use of drones with MTOW[2] under 25 kg, there is a process that must be followed and delivered maximum 5 days before the start of the operation (art.50.6 Ley 18/2014) in order to be enabled as RPAS operator. The steps that have to be followed are described [9]:

- Request for the realization of test flights that can demonstrate the intended operation according to art. 50.6 of the Law 18/2014 that ensures security.
- Realization of test flights
- Presentation of the prior communication and responsible statement to be enabled as RPAS operator for scientific and technical applications

5.2. State of the art of the UAV industry

The development of the state of the art has been done in order to deeply analyse and evaluate the current technologies involved on UAVs in the actual market as well as study the specifications provided. The most important characteristic of the drones studied can be seen at the following tables. The information has been divided into multirotor and fixed wing UAVs.

Since the UAV market is starting to grow at the present time, most of these models have been developed in the last few years and also some are even starting to be commercialized. Nevertheless, the basic specifications have been tabulated.

The UAVs present very different specifications and different configurations are observed. In terms of propulsion there are two distinct groups: electric and internal combustion propulsion. However, the market trend is the environmental-friendly solution of the electric motor.

An extended review of the state of the art of the UAV industry can be seen in the Annex.

5.2.1. Multirotor UAS

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[2] Although the technical differences between weight (N) and mass (kg) they have been treated as synonyms

Table 1: Multirotor UAS State of the art

Manufacturer	DJI	DJI	3D Robotics
Model	Phantom series	Inspire series	SOLO
Application	Aerial photography and video streaming	Aerial photography and video streaming	Aerial photography and video streaming
MTOW (kg)	1.28	2.94	1.8
Dimensions	350 mm (Diagonal size)	438x451x301 mm	46 cm (Diagonal size) 25 cm (height)
Speeds	5 m/s (ascent) 3 m/s (descent) 16 m/s (Max.)	5 m/s (ascent) 4 m/s (descent) 22 m/s	10 m/s (ascent) 25 m/s (Max.)
Payload weight	-	-	420 g
Propulsion system	Electric motor	Electric motor	880 kV electric motor
Endurance	23 min	18 min	20 min
Range	3500 m	5 km	8 km
GNSS	Yes	Yes	Yed
Operating frequency	2.4 GHz	2.4 GHz 5.8 GHz	2.4 GHz
Price	1 199 € (Phantom 3 Professional)	2 299 €	812 €

Manufacturer	SenseFly	CARTOUAV	Parrot
Model	eXom	MD4-1000	Bebop
Application	High-resolution mapping, 3D modelling and inspection (HD and thermal video imagery)	Traffic control, inspection, audio-visuals, agriculture	Live video streaming and photography
MTOW (kg)	1.8	4.3	0.42
Dimensions	56x80x17 cm	109 cm (between axes)	28x32x3.6 cm

Speeds (m/s)	7 m/s (max. climb rate) 12 m/s (max. speed)	-	13
Payload weight	-	1.2 kg	-
Propulsion system	4 electric brushless motors	Electric motor	4 Brushless engines
Endurance	22 min	60 min	22 min
Range (m)	800	-	300
GNSS	Yes	Yes	Yes
Operating frequency	2.4 & 5 GHz	-	2.4 and 5 GHz
Price	~ 30 000 €	-	399 € 499 € (with control station)

5.2.2. Fixed Wing UAS

Table 2: Fixed wing UAS state of the art

Manufacturer	Brocktek	Brocktek	Latitude
Model	Havoc	Spear	Hybrid UAV
Application	Surveillance, search & rescue, agriculture and infrastructure management	Surveillance, search & rescue, agriculture and infrastructure management	Prototype
Wingspan (m)	4.9	3 – 4.3	-
MTOW (kg)	79	17	16.7
Launch	Manual or Auto Rolling	Manual	-
Take-off distance	-	-	-
Cruise speeds	-	-	20.6 m/s
Stall speed	18 m/s	12.8 m/s	-
Payload weight	20 kg	1 kg (Electric) / 4.5 kg (ICE)	3.6 – 5.4 kg

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Propulsion system	ICE	Electric or ICE	Hybrid (0.5 hp 4-stroke gas engine + electric motor)
Endurance	8 – 18 h	1 h (Electric) / 2.8 h (ICE)	12 – 24 h
Range	-	-	-
Price	-	-	-

Manufacturer	Zala Aero	Zala Aero	Zala Aero
Model	421-08	421-04M	421-16
Application	Surveillance	Video and infrared vision	Monitoring, search & rescue, detection
Wingspan (m)	0.81	1.6	1.62
MTOW (kg)	2.1	4.2	18
Launch	Hand	Catapult	Catapult
Take-off distance	-	-	-
Cruise speeds	65 – 130 km/h	65 – 120 km/h	150 km/h
Stall speed	-	-	-
Payload weight	1 kg	1 kg	3 kg
Propulsion system	Electric motor	Electric motor	ICE
Endurance	100 min	120 min	7 h
Range	15 km	40 km	50 km
Price	-	-	-

Manufacturer	Aeraccess	Thales Group	UAV Factory
Model	GOSHAWK W200	FULMAR	Penguin C
Application	Surveillance and reconnaissance	Search & rescue, surveillance	Surveillance
Wingspan (m)	2	3	3.3

MTOW (kg)	6	20	22.5
Launch	Catapult	Catapult	Catapult
Take-off distance	-	-	-
Cruise speeds	90 km/h	100 km/h	19 – 22 m/s
Stall speed	-	-	-
Payload weight	1 kg	8 kg	-
Propulsion system	Electric motor	ICE	ICE
Endurance	90 – 120 min	6 – 12 h	20 h
Range	-	-	100 km
Price	-	-	-

Manufacturer	UAV Factory	Insitu	Draganfly
Model	Penguin B	Integrator	Tango
Application	Surveillance	Inspection, agriculture, wildfire management, Oil and gas operations, border patrol	Prototype
Wingspan (m)	3.3	4.9	1.5
MTOW (kg)	21.5	61.2	3.94
Launch	Catapult, Runway, Car top launch	-	Catapult
Take-off distance	30 m	-	-
Cruise speeds	22 m/s	28.3 m/s	50 – 60 km/h
Stall speed	13 m/s	-	35 km/h
Payload weight	10 kg (ICE) / 6.6 kg (Electric motor)	18 kg	1.14 kg
Propulsion system	2.5 HP engine / brushless electric motor	ICE	Electric motor

Endurance	20 h (ICE) / 110 min (electric motor)	24+ h	50 min
Range	-	-	-
Price	14 500 €	-	-

Manufacturer	Sensefly	Lehmann Aviation	Lehmann Aviation
Model	eBee	L-A series	L-M series
Application	Agriculture and 3D mapping	Mapping, agriculture, aerial photography	Short range surveillance
Wingspan (m)	0.96	0.92	0.92
MTOW (kg)	0.69	1.15	1.25
Launch	Hand launch	Hand launch	Hand launch
Take-off distance	-	-	-
Cruise speeds	40 – 90 km/h	20 – 80 km/h	20 – 80 km/h
Stall speed	-	-	-
Payload weight	-		350 g
Propulsion system	Electric Brushless DC motor	Electric motor	Electric motor
Endurance	50 min	45 min	45 min
Range	3 km	5 km	5 km
Price	10 560 €	8 990 €	6 990 €

6. Analysis of Design requirements

The first step of the study is to understand the problem in order to justify the need of the product that it is supposed to be developed. Then, the basic requirements need to be identified so that a conceptual design can be done.

6.1. Problem understanding

The current situation of video surveillance systems is not as good as people think. The efficiency of this security systems had been called into doubt recently. Furthermore, in some environments the use of ground security systems is non-viable. Some of this scenarios are large out-door areas that usually are difficult to access.

6.2. Justification

A solution to the problem described above, is the use of UAVs. The main idea is that the security staff can monitor large areas in a short periods of time by using the camera installed on a drone. Also, in environments where it is difficult to access by a ground vehicle the use of surveillance UAVs can facilitate the security tasks. Therefore, the combination of the ground security systems and surveillance drones can create a new concept of security.

The advantages of having UAVs in surveillance applications have been mentioned in order to justify the potential of this study with the objective of solving the limitations of the actual security systems:

1. Aerial surveillance

With drones the opportunity of having aerial cameras is achieved, increasing the effectiveness and solving the limitations of ground systems. One of the most basic problems that ground camera has is the range of vision. However, having a camera in the air provides a new perspective in which is faster and easier to monitor, a feature that is impossible to achieve with the ground security systems.

2. High tech Cameras

Usually, the camera technology used for UAS is more developed that the ones installed at ground security systems. Gimbal stabilisation, EO sensors, object tracking software, 360º HD cameras and thermal imaging for night vision are examples of this state of the art camera technology.

3. Autonomous control

One of the most interesting capabilities that UAV offers is the autonomous control. The flight path can be programmed before the drone takes off, and different flight modes can be set up. This methodology opens an extend range of opportunities like flying around a specific area if something needs to be monitored with closer attention.

This advantages will solve the actual limitations of modern security. However, the design of the UAS needs to be done in order to determine if these capabilities can be accomplished.

6.3. Conceptual design

6.3.1. Design Requirements

In order to develop a conceptual design, the basic requirements need to be analysed in detail. Furthermore, after analysing the problem that is expected to be solved, some design requirements have been added to the ones defined at the beginning of the document:

- Flight time

One of the most important factors for any type of UAV is the flight time. For surveillance applications it is quite important to provide large periods of flight so that the main application of watching out is accomplished even in large areas. As a design requirement, the flight time will be between 2h and 12 h.

- Payload

The payload is the equipment that will allow accomplishing the specific mission. In a surveillance drone, the payload is composed basically by a camera and sensors. For security applications, it is quite important to equip the drone with 360º cameras and also thermals cameras for night surveillance. So as a basic payload requirement, a 360º vision and a thermal imaging camera will be equipped.

- Automatic and manual control

One of the most important innovations that UAV technology provides is the automatic control. As mentioned above, it is vital to be able to program the flight path that the drone must cover before take-off so that later it could fly automatically. However, for surveillance applications, it is also interesting to be able to change automatic control to manual control so that the security staff can control the vehicle in case of an emergency or other special situations. Therefore, as a design requirement, both flight modes need to be provided.

- Weight

Taking into account the regulation study, UAVs with masses below 25 kg have an easier regulation process. Therefore, as a design requirement the UAV will have a mass below 25 kg.

6.3.2. Operability and functional requirements

In order to define what the drone is supposed to do, the different functional requirements have been analysed. Firstly, defining in which environments the UAV is expected to work will help understanding the principal functions. Some possible scenarios have been described:

- Railway network

It is quite often that criminals stole rail cable from the railway network in order to sell copper [10]. This type of crime is very difficult to be prevented due to the large extension of the railway. With the use of a surveillance drone, the railway could be monitored in a short period of time.

- Infrastructures

Any kind of infrastructure such as aqueducts or power stations needs an efficiency security system. Most of this infrastructures are state property so state-owned enterprises are possible targets for using surveillance drones.

After some principal scenarios are mentioned, the functional requirements are described as following:

- Reconnaissance and detection
- Remote monitoring day and night imagery
- Sending emergency signals to ground station

6.3.3. Capabilities

- Portability

Portability is an important aspect to take into account in order to ease the transportation and therefore to promote the use of surveillance drones in different environments. The portability aspect is related to the weight and also to the assembly system in case is implemented.

- GPS Connectivity

In order to have autonomous flight and be able to establish waypoints on the ground station, a GPS connectivity must be provided. It is also needed for the flight control system.

- Performance: Loiter

For surveillance drones, loiter is an interesting flight mode that enables focusing in a small region. The idea of loiter when an anomaly is detected may improve security efficiency.

- Reliability

For any project, reliability is an aspect that should be provided in order to give a good image of the product. Furthermore, for aerial vehicles the importance of avoiding failures increases due to the possible danger that an uncalculated error can produce.

6.4. Initial sizing

6.4.1. Type of UAV selection

Drones can be classified in many categories in reference to different aspects. However, the basic classification is in reference to how the aerodynamic forces are generated. The two possible solutions are fixed-wing and rotary wing drones. In order to start with an initial sizing, it is crucial to decide the configuration of the UAV.

A comparison between both drone configurations has been made taking into account the design requirements for the surveillance application. In the following table, a comparison between rotatory and fixed wing drone can be seen[11]:

Table 3: Fixed wing and multirotor comparison

	Fixed Wing	Rotary wing
Advantages	- Higher speeds - Longer distances - Can carry heavier payload - Low risk of mechanical failure - Minimal maintenance and repair process - Higher endurance - Higher wind resistance	- Vertical take-off and landing - Capacity to hover - Better manoeuvrability - Great object resolution (mm/pixel) - Ease of transport
Disadvantages	- Unable to hover - Need of a runway or launcher to take-off - Due to higher speeds, it has more problems concerning security	- It requires a greater maintenance due to mechanical and electrical complexity - Low endurance

Taking into account the information above, an Ordered Weighted Average (OWA) analysis is performed. The parameters that had been selected for the decision criteria are:

- Endurance

In order to accomplish the design requirement, the flight time must be minimum of 2h. This aspect is critical due to the poor endurances that actual drones in the market have.

- Payload weight

The more payload weight the UAV is capable of carry; the better sensors it will have. The sensors and the camera are the instruments that will ensure the mission success so this factor is essential.

- Price

Providing a competitive price, it is significant when entering to a new market. So the idea of minimising the price has to be taken into account.

- Maintenance cost

Ensuring a low maintenance cost, increases the feasibility of the product. Consequently, is a relevant factor for any aerial vehicle.

- Maneuverability

Another factor that will ensure a better performance is the UAV maneuverability. The possibility of hovering is a very interesting capability that will increase the efficiency of the surveillance operation.

The OWA analysis is presented in the following table:

Table 4: OWA method for configuration decision

	Weight	Fixed wing		Rotary wing	
Criteria	g	p	p·g	p	p·g
Endurance	80	2	160	1	80
Payload weight	80	2	160	1	80
Price	70	1	70	2	140
Maintenance cost	50	2	100	1	50
Maneuverability	70	1	70	2	140
SUM (p·g)	350		560		490
OWA			0.8		0.7

6.4.2. Design Point

In order to develop the initial sizing, some parameters need a starting point value. A realistic approach needs to be develop and consequently, the specifications collected during the state of the art has been taken into account.

To define a feasible range of values for sizing the UAV, the design point is usually found by means of plotting the relations between thrust ratio (T/W) and wing load (W/S) using the equations presented below. Since the UAVs are usually powered using a propeller instead of jet engines, the equivalent term to thrust ratio is power ratio (P/W).[12][13]

- Maximum load/turn

$$\frac{P}{W} = \frac{1}{550\eta}\left[\frac{1}{2}\rho V^3 C_{D_0}\left(\frac{S}{W}\right) + 2K\frac{n^2}{\rho V}\left(\frac{W}{S}\right)\right]$$

(1)

- Endurance

$$\frac{P}{W} = \frac{4}{550\eta}C_{D_0}{}^{\frac{1}{4}}\left(\frac{K}{3}\right)^{\frac{3}{4}}\left(\frac{2}{\rho}\frac{W}{S}\right)^{1/2}$$

(2)

- Cruise

$$\frac{P}{W} = \frac{P_{TO}}{P_{Cr}}\frac{\rho V}{\frac{W}{S}}\frac{1}{\eta}\left[C_{D_0} + \left(\frac{\left(\frac{W}{S}\frac{W}{W_{TO}}\right)^2}{q^2\pi Ae}\right)\right]$$

(3)

- Take-off Distance

$$\frac{P}{W} = \frac{2.44}{550\eta}\frac{1}{g\,d_{to}}\left(\frac{1}{\rho_{SL}C_{L_{max}}}\frac{W}{S}\right)^{3/2}$$

(4)

- Stall condition

$$\frac{W}{S} = \frac{\rho}{2}\,C_{L_{max}}V_{S0}{}^2$$

(5)

Where η is the efficiency, ρ the air density, V the speed, C_{D_0} the parasitic drag coefficient, n the load factor, V_{S0} the stall speed, d_{to} the take-off distance, e the Oswald efficiency, A the aspect ratio, W_{TO} the take-off weight and g the gravity accelereation.

Taking into account the actual market and some common values, the following parameters have been decided:

- Efficiency

For a low Reynolds number framework, like UAV applications, the propellers efficiency is between 0.6 and 0.8. Therefore, the following value have been decided:

$$\eta = 0.7$$

- Density

The density has been calculated at a realistic altitude operation. Taking into account the maximum height of 150 m that European regulations enables[14] and making the assumption of operating at SL, the following density has been calculated according to ISA equations[15]:

$$\rho(h) = \rho_0 \left(\frac{T_0 + a(h - h_0)}{T_0}\right)^{-\frac{g}{aR} - 1} \tag{6}$$

where a is the thermal gradient in K/m, R the gas constant of the air in m^2/s^2 K, T_0 the temperature at sea level, ρ_0 the density at sea level and finally g the gravitational acceleration.

$$\rho(150\ m) = 1.225 \left(\frac{288.15 - 6.5 * 10^{-3}(150 - 0)}{288.15}\right)^{-\frac{9.8}{-6.5*10^{-3}*287} - 1} = 1.21 \frac{kg}{m^3}$$

- Speed

The speed used for the design point of view is the cruise speed. According to the table of the UAVs studied, an average value is around 50 km/h.

$$V = 14\ m/s$$

- Parasitic drag

A typical range of C_{D0} for low Reynolds number is 0.018.[16]

$$C_{D_0} = 0.018$$

- K parameter

The definition of the K parameter of the drag coefficient equation its function of the Aspect Ratio of the wing and the Oswald factor as can be seen in the following equation:

$$K = \frac{1}{\pi A e} \tag{7}$$

The Oswald efficiency factor for a typical joined wing configuration for UAV is between 1.1 and 1.6. An average value of 1.3 has been taken.[16]

$$e = 1.3$$

Usually, for long-endurance UAV, the aspect ratio is high. According to a report of a study regarding the effect of aspect ratio in UAV wings [17], an optimal design for high aspect ratio UAV is of 17.5.

$$A = 17.5$$

Using the previous values, the K parameter can be found as follows:

$$K = \frac{1}{\pi * 17.5 * 1.3} = 0.014$$

- Load factor

One of the man advantages of the UAVs are the capability to realise high load factor manoeuvres that pilots are not even to bear. The load factor it depends basically of the bank angle of the manoeuver. According to a performance flight testing of a small UAV[18], a possible bank angle achieved is about 69°. Therefore, for this bank angle the load factor is around 3[19].

$$n = 3$$

- Take-off distance

Most of the actual fixed wings UAV have a catapult launch system. Therefore, an equivalent take-off distance must be computed.

UAV factory also manufacturers catapults and as a first approximation, we will use the following function that describes the launch speed as function of the UAV mass:
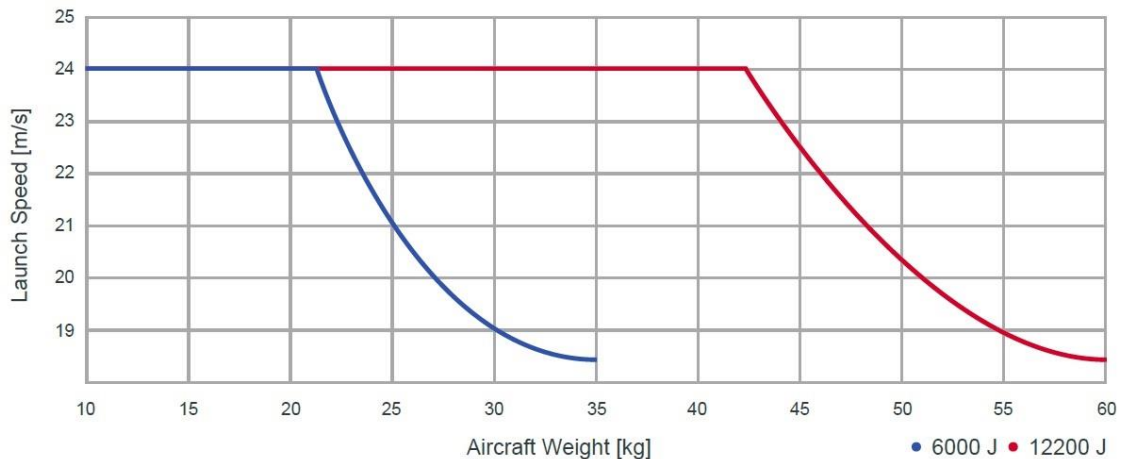
Figure 2: Catapult launch speed vs UAV weight [20]

According to the design requirements, the UAV mass must be below 25 kg. For a 20 kg UAV, the launch speed is 24 m/s. For determine the take-off distance, an energy balance has been made. Knowing that the kinetic energy at the launch instant must be equal to the work made by the power of the motor, it is possible to compute a function that relates the force made by the engine (F) and the take-off distance:

$$\frac{1}{2}mv^2 = F\,\Delta x \tag{8}$$

It is important to take into account that friction forces have been neglected. Using the MATLAB code presented in the Annex, the following graph is obtained:
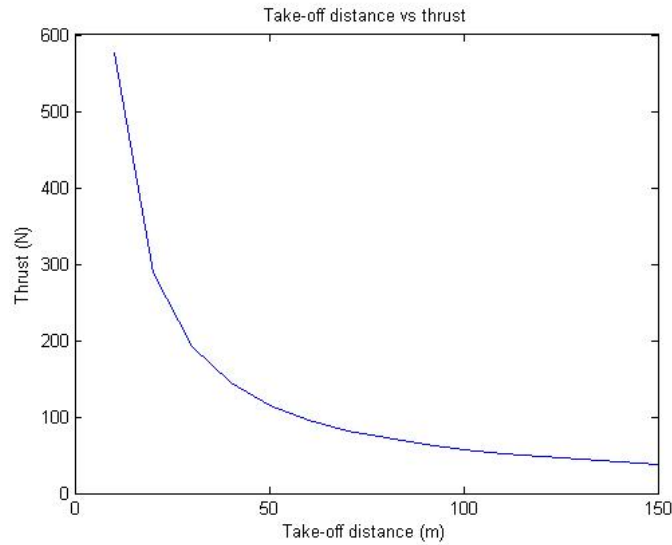
Figure 3: Take-off distance as function of thrust

Although we have an estimated relation between thrust and take-off distance, taking an estimated value of the thrust obtained from the engine will introduce a considerable error. Therefore, a typical value from the market research have been selected. For a 20 kg UAV a realistic take-off distance is[21]:

$$d_{TO} = 30\ m$$

- C_L max

According to the market research, a typical value for the maximum C_L is:

$$C_{L_{max}} = 1.3$$

- Stall speed

For some of the actual UAV models commented above, the stall speed is between 10 and 15 m/s. So an intermediate value has been chosen:

$$V_{stall} = 13\ m/s$$

- W/W_{TO} ratio

This ratio quantifies the relation between the weight just after the take-off and the take-off weight. Usually an unfavourable value is considered:[12]

$$\frac{W}{W_{TO}} = 0.95$$

- P_{TO}/P ratio

This ratio quantifies the power extra needed for take-off. A constant power demanding has been considered:

$$\frac{P_{To}}{P} = 1;$$

With the MATLAB code presented at the Annex, the constraint analysis diagram has been plotted:
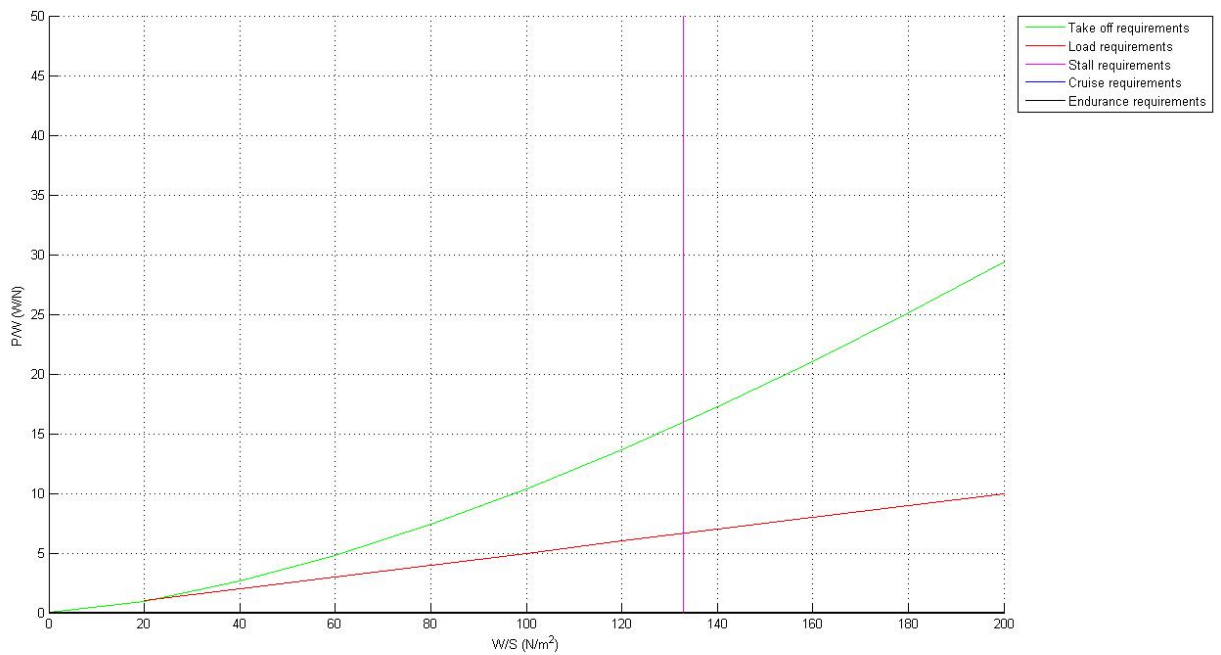
Figure 4: Constraint analysis diagram

As can be seen in Figure 4, the cruise and endurance requirements are not restrictive for the pre-design phase. However, take-off, load and stall conditions had to be taken into account.

The importance of this graph is that the design space is defined. A general tendency used to select the design point is to maximize the wing loading. This is due to the fact that for higher wing loadings, better performance against perturbations. Therefore, the following design point has been selected:

$$\frac{P}{W} = 15 \ \frac{W}{N}$$

$$\frac{W}{S} = 120 \ \frac{N}{m^2}$$

6.4.3. Weight Estimation

Once the design point has been defined, a weight estimation has been made. First, the relation between payload and take-off weight from some fixed-wings drones on the market has been calculated:

Table 5: Payload – MTOW ratio from different UAVs in the market

UAV Model	Propulsion System	PLW/MTOW
Spear	Electric	0,06
Spear	ICE	0,265
Latitude	Hybrid	0,32
Zala 421-08	Electric	0,4762
Zala 421-04M	Electric	0,238
Zala 421-16	ICE	0,167
W200	Electric	0,167
Fulmar	ICE	0,4
Penguin B	ICE	0,465
Penguin BE	Electric	0,31
Tango	Electric	0,29

Although is a compromise solution, the average value has been taken as the pre-design value:

$$\frac{PLW}{MTOW} = 0.29$$

Then, the MTOW can be calculated for different values of payload weight as the following equation shows:

$$MTOW = \frac{PLW}{0.29}$$

Using the design point, a study of the dependence of MTOW with the wing surface and output power has been done:
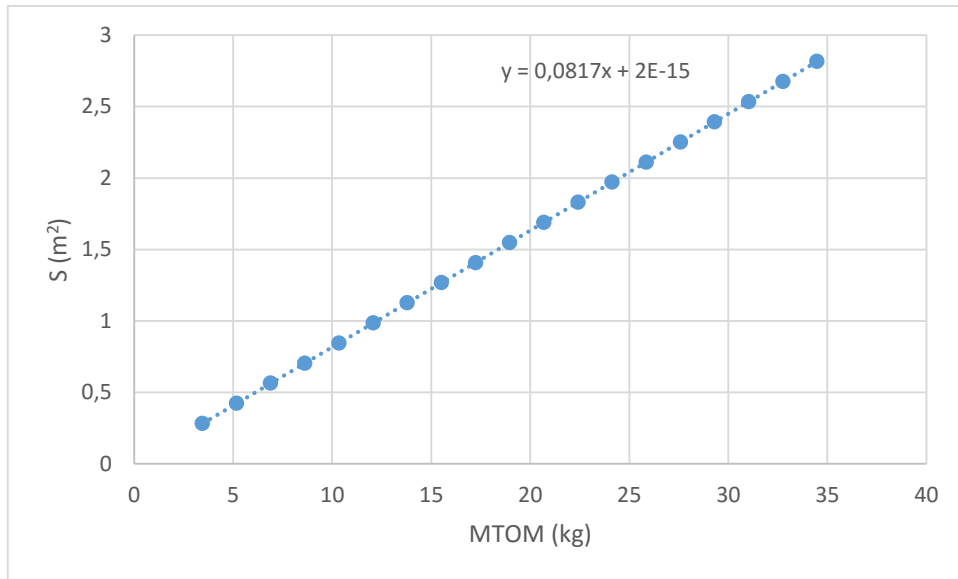
Figure 5: Wing Surface versus take-off mass
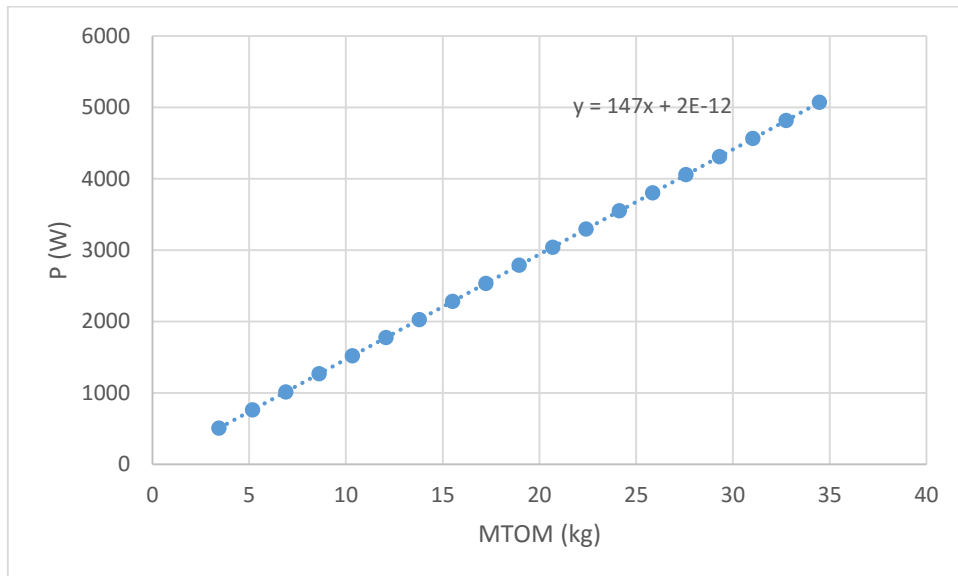
Figure 6: Output power versus take-off mass

With the plots above, a pre-design range of values have been obtained.

7. UAV Solution Proposal

Once the preliminary study had been made, a solution proposal is presented taking into account the design requirements, specifications and constraint analysis. Some important aspects such as the propulsion system, airfoil selection, control station among others had to be studied and propose the best option.

7.1. Propulsion System

There are two aspects to consider when the propulsion system is analysed. First, it is important to study and decide how the thrust will be generated and secondly what will be the power source.

7.1.1. Thrust Generation theory

Most UAVs use propellers to generate thrust. It is important to understand how this type of propulsion system works and consequently a brief description had been made.

The main purpose of the propeller is to transform rotational energy into thrust. There are two basic principles that describes how this energy transformation is done: Newton's third law and Bernoulli's principle.

Newton's third law states that for every action there is an equal and opposite reaction. This principle explains the fact that when the air is pushed downward by the propeller, an upward force is generated. This force is thrust.

The cross section of a propeller blade is an airfoil and therefore, we can apply Bernoulli's principle. The air that flows over the top surface is accelerated and consequently the pressure decreases whereas the air that flows along the low surface of the airfoil increases pressure. This difference of pressure between the upper and lower surfaces generates a lifting force. [22]
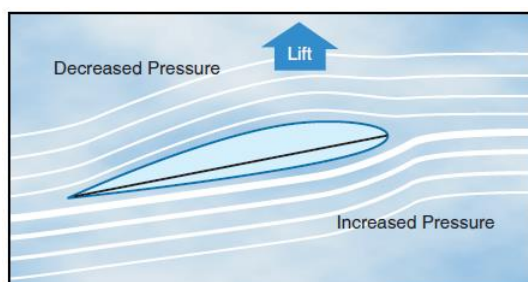
Figure 7: Bernoulli's principle in an airfoil[22]
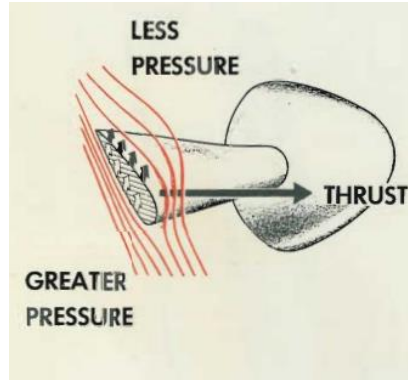
Figure 8: Airfoil on a propeller blade[23]

7.1.2. Power Source

The element that most influences in the mission performance of a UAV is the power source. The two basic aspects to take into account are power and energy density. In order to make clear the difference between both concepts, they have been defined:

- Power density: amount of power per unit of volume or mass. In other words, is the ability to deliver power.
- Energy density: amount of energy stored in a system per unit of volume or mass. In simpler words, is the capacity to store energy.

For a better interpretation, the power density has a decisive effect in maximum speed, flight altitude, rate of climbing and payload capacity. Whereas the energy density has a main impact in the endurance.

The two principal options are internal combustion engines or electrical motors. Powering an UAV with an internal combustion engine is the best option in terms of performance due to the higher power and energy densities in comparison to electrical motors. However, electrical motors provide higher efficiency, quiet operations, low cost investment, and higher reliability.

A summary of advantages and disadvantages between the ICE and the electric motor has been made:

Table 6: ICE and Electric Motor Comparison

POWER SOURCES		
TYPE	**ICE**	**ELECTRIC MOTOR**
ADVANTAGES	Higher Power Density Higher Energy density Long flight times More payload capacity Higher speeds	High efficiency Quiet operations Low cost maintenance High reliability Environmentally friendly Maximum torque No vibrations
DISADVANTAGES	Noisy operations More costs Pollution	Less payload capacity Poor flight times Time to recharge battery

Nowadays, the hybrid technology is being developed and there are some studies about this new concept of propulsion system for UAV. A hybrid propulsion system provides quiet operations, better heat conditions, the battery is able to recharge during flight, need of a smaller ICE than a total gas engine UAV, higher reliability due to the fact of having a back-up power source and also higher efficiencies than ICE and similar to electric motors[24].

In Figure 9, a comparison between different types of electric propulsion system can be seen:
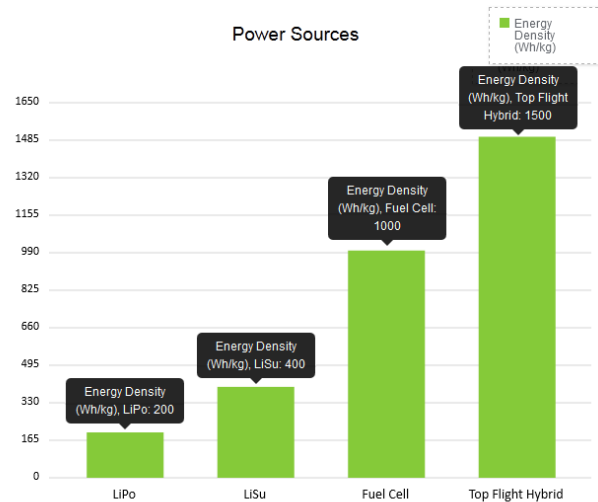
Figure 9: Different propulsion systems comparison[25]

The LiPo batteries are used in 95% of today's UAV. Therefore, by comparing the energy densities, the improvements that hybrid technology is expected to provide are really demanding. This technology is being built up nowadays and consequently it has not been totally developed at the present time. Although this technology is very attractive, it is important to take into account this fact.

Before deciding which type of propulsion system, a brief description of the different types has been made in order to go deeper in the topic.

7.1.2.1. Internal combustion engine

The internal combustion engines can be divided into 4-stroke and 2-stroke engines and in air cooled or water cooled. Also, the rotary engine will be treated separately.

- 4-stroke engine

The four cycle internal combustion engine is the most well-known engine due to the widespread use in the automotive sector. The cycle is made up four processes, as the name implies. The four process are: induction, compression, combustion and exhaust.

- 2-stroke engine

The two-cycle engine is common used in model airplanes although are not as well understood as four-cycle engines. The processes during the cycle are the same but some of them occur simultaneously, as can be seen in Figure 10**.**
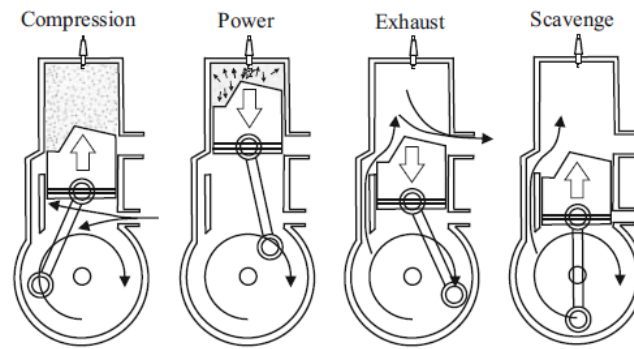
Figure 10: Two-cycle engine process [26]

Both types can be air cooled or water cooled, so the basic difference in terms of performance is that the two-stroke engine has twice as many power strokes on each revolution whereas the four-stroke has half power strokes per revolution. Therefore, the two-stroke engine produces twice the power in unit time at the same rotational speed compared with the four-stroke engine. [27]

Another important fact is that the four-stroke engine has less specific fuel consumption.

A summary of the comparison between both types of ICE can be seen in the following table:

Table 7: ICE 2-stroke and 4-stroke comparison[28]

Parameter	2-stroke	4-stroke
Power per cc engine capacity	76	73
Power-to-weight ratio	2.893	1.727
Engine efficiency	0.654	0.813
Noise level	High	Low
Vibration level	High	Low

- Rotary Engine

The advantage that the rotatory engine presents is the reduction on vibrations, a very important issue related with ICEs. Vibrations are harmful for the sensitive payload system and this type of engine is a possible solution to avoid it.

The main characteristic of rotary engines in comparison to the other two types commented above is the rotor geometrical shape.[26]

29

The main principle that allows the internal combustion in the rotary engine is that the working chamber changes in volume twice per revolution. In Figure 11, a scheme of the cycle can be seen as well as a comparison with a 4-stroke engine:
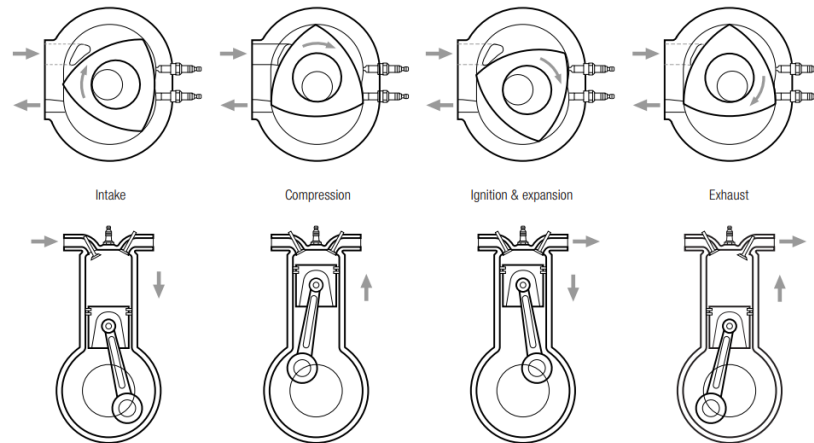
Figure 11: Rotatory cycle scheme[29]

The main advantages of this type of engine have been listed below[29]:

- Small size and light weight
- Flat torque characteristics
- Less vibration and low noise
- Simple structure
- Reliability and durability

7.1.2.2. Electric motors

The electric motors have become an attractive source of propulsion for most of the civil UAV. The two types that are often used for UAV are the standard DC motor with brushes and the brushless motor.

- Brushed DC motors

The basic components of a brushed DC motor are stator, rotor, brushes and commutator.

The stator is in charge of generating the static magnetic field by means of permanent magnets or electromagnetic windings. On the other hand, the rotor, that is composed of windings, can also create a magnetic field. The magnetic poles of the rotor are attracted by the poles of the stator, producing the turn movement of the rotor.

By controlling the switching of the electromagnetic windings, the rotor can turn continuously. The control of the switching is the commutation and for this type of DC motors it is done mechanically using a cooper sleeve and the brushes. [30]
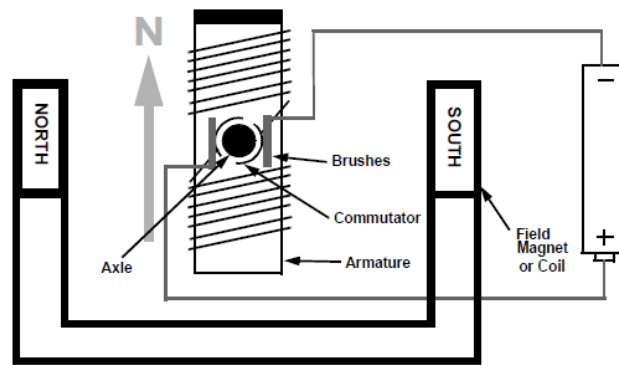
Figure 12: Simple two-pole brushed DC motor scheme[30]

- Brush-less DC motors

This type of motor is used in a wide range of sectors such as aerospace and automotive industry. Compared to the brushed DC motor, the commutation is made electronically.

BLDC motors are a type of synchronous motor, which means that the magnetic field generated by the rotor rotates at the same frequency. The stator consists of electrical steel laminations and windings placed at the slots whereas the rotor is made up of permanent magnets.

The basic configuration of this type of motors can be seen in the following figure:
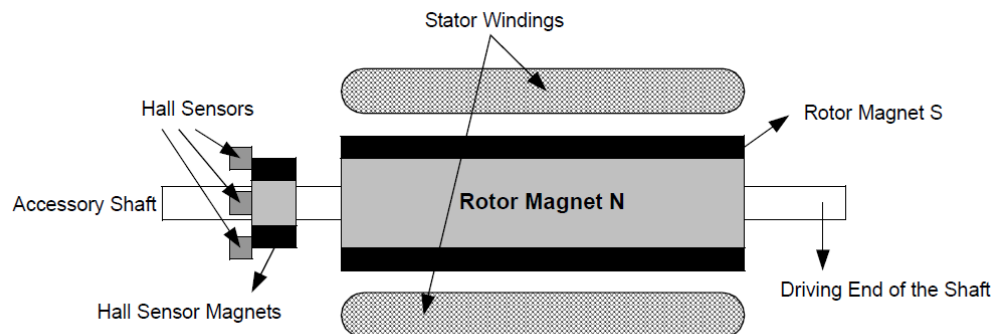
Figure 13: Brushless DC motor components[31]

The main advantages of the brushless motor in comparison to the brushed motor are listed below:[31]

- Better speed vs torque characteristics
- High dynamic response
- High efficiency
- Long operating life
- Noiseless operation
- Higher speed ranges

For all this advantages, and as the market research shows, the brushless DC motor is the most used electric motor for UAV applications.

7.1.2.3. Estimation of the required thrust

The first step to estimate the specifications of the required motor is analysing the specifications.

The first parameter to estimate is the minimum required thrust. This parameter is independent of the altitude, however, it depends on the speed as can be seen in the following figure. For higher speeds, higher is the altitude to reach the minimum required thrust.
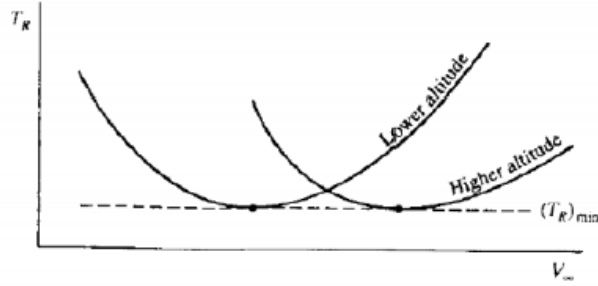
Figure 14: Thrust vs speed and altitude effect[32]

For estimating the thrust, the rate of climb is used. The rate of climb it depends on difference between available power and required power as can be seen in the following equation:

$$ROC = \frac{P_A - P_R}{W} \tag{9}$$

For propeller aircrafts, the available power is usually considered constant, so for a UAV it will also be used such simplification. Therefore, the highest ROC take place when the power required is lowest, in other words, at the point of maximum efficiency (L/D).

To calculate the required thrust the following equations can be used:

$$ROC = \frac{T \cdot V - D \cdot V}{W} \Rightarrow T = \frac{ROC \cdot W}{V} + D \tag{10}$$

$$P = T \cdot V \tag{11}$$

However, the rate of climb is a difficult parameter to estimate. Therefore, the design point is used for determine the maximum thrust required.

Considering a maximum weight of 20 kg, so that the maximum weight allowed of 25 kg in not overpassed, the following data from the aerodynamic study and the constraint analysis is obtained:

$$V_{\max\left(\frac{L}{D}\right)} = 33\frac{m}{s}$$

$$P_{20\,kg} \cong 3\,kW$$

Then, the estimated required thrust at maximum L/D is calculated:

$$T = \frac{P}{V} = \frac{3000\,W}{33\,\frac{m}{s}} \cong 90\,N$$

7.1.2.4. Decision

Once the different possibilities have been studied, selecting the option that best fits within the design requirements can be made. A simple method to schematically show the best option is by means of an OWA analysis.

First we describe the parameters that need to be taken into account:

- Endurance

One of the design requirements is to ensure a flight time between 2 and 12 h. Therefore, is important to select an option that allows this requirement.

- Efficiency

Efficiency is always a main parameter that needs to be maximized in propulsion systems.

- Performance

Selecting the option that allows a better performance, in other words, the type of system that will ensure better power loading.

- Price

How much it will cost is always an issue that need to be taken into account in order to design the best solution with minimum cost.

- Maintenance cost

The cost of fuel or electricity needs to be taken into account. A comparison between the prices of fuel and electric eGallon can be seen in Figure 15.
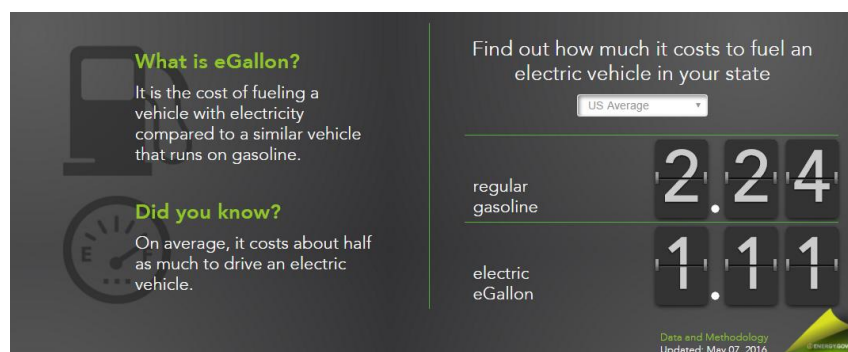
Figure 15: Comparison between eGallon Price and gasoline Price in the US[33]

- Payload capacity

The power source is directly related to the payload capacity. So it is quite important to select a solution that ensures a great payload capacity in order to install better sensors and cameras.

The results of the OWA analysis can be seen in the following table:

Table 8: OWA method for selecting the power source

	Weight	ICE		Electric Motor	
Criteria	g	p	p·g	p	p·g
Endurance	80	2	160	1	80
Efficiency	60	1	60	2	120
Performance	70	2	140	1	70
Price	70	1	70	2	140
Payload capacity	70	2	140	1	70
Maintenance Cost	60	1	60	2	120
SUM (p·g)	410		630		600
OWA			0,77		0,73

The most critical design requirement for selecting the propulsion system is the endurance. Electric motors are gaining importance in the actual UAV market, however for ensuring a minimum of 2h of flight time the only feasible solution is an internal combustion engine or a hybrid propulsion system. As was mentioned before, the hybrid technology is being developed at the present time so it has not been considered.

As was described before, the possible internal combustion engines are 2-stroke, 4-stroke and rotary engines. The rotary engines for UAV are quite heavy in comparison with the pistons engines. In order to keep the weight as low as possible, the rotary engines have been discarded.

From Table 7, it can be observed that the 2-stroke engine has better power-to-weight ratio and power capacity than the 4-stroke, ergo, it is a better option in terms of power specifications. However, the 4-stroke engine is a better option in terms of efficiency, fuel consumption, noise level and vibrations. For a surveillance drone, minimising the vibrations that the engine produces will provoke less damage generated by vibration.

Although the better power specifications of 2 -stroke engines, using a 4-stroke has been decided.

Taking into account that the MTOW needs to be lower than 25 kg and according to Figure 6, an approximated value of 3000 W engine have to be chosen. Another important aspect is the engine weight. In order to limit the search, the maximum weight allowed is about 3 kg.

The market research of 4-stroke engines can be seen in the Annex. The specifications of the engines considered adequate for the study can be seen in the following table:

Table 9: Comparison of UAV engines

	FT-300[34]	**RCV Engine**[35]
Capacity	49 cc	70 cc
Speed range	-	2000 – 10 000 rpm
Power Output	3 kW at 7000 rpm	4 kWat 8500 rpm
Fuel Consumption	-	330 g/kW h
Weight (kg)	1.828	2.7

Due to power requirements, a minimum of 3 KW for the power output is needed. Comparing the engines that meet the restriction, it can be observed that the FT-300 has the best power-to-weight ratio. However, the RCV 70 cc UAV engine, has been selected due to the wider range of speeds.

7.1.3. Propeller

The design of the propeller is one of the most difficult tasks due to the complexity of rotor aerodynamics. However, some basic parameters have to be defined.

The most common way to classify the propellers is by the number of blades. From a general point of view, the lower the number of blades the higher is the propeller efficiency. Discarding the one-blade propeller due to balance problems, the best option in terms of aerodynamics is the two-blade propeller. However, if the demanding thrust is high more blades will be needed thereby decreasing efficiency.

Some estimations should be made in order to determine the number of blades, the diameter and the pitch.

From Roskam Airplane Design book[36], the following equation to estimate the propeller diameter is used:

$$D_p = \sqrt{\frac{4\,P_{max}}{\pi\,n_p\,P_{bl}}} \tag{12}$$

Where P_{max} is the maximum power, n_p the number of propeller blades and P_{bl} the power loading per blade. To estimate the P_{bl} value, some different ranges are defines depending on the type of aircraft. The aircrafts that appear in Roskam that resembles more to UAV are the homebuilt airplanes, with a P_{bl} between 1 and 3,2 hp/ft^2. An average value of 2 hp/ft^2 have been considered. For having a high efficiency propeller, the number of propeller blades have been set at 2. Finally, the P_{max} considered is 4 hp taken into account the weight estimation.

The diameter obtained is:

$$D_p = \sqrt{\frac{4 \cdot 4\,hp}{\pi \cdot 2 \cdot 2\,\frac{hp}{ft^2}}} = 1.3\,ft \Rightarrow D_p = 0.4\,m$$

Another important parameter to take into account is the propeller pitch, defined as the distance that the propeller advances in one revolution[37]. The following figure schematizes the propeller pitch definition:
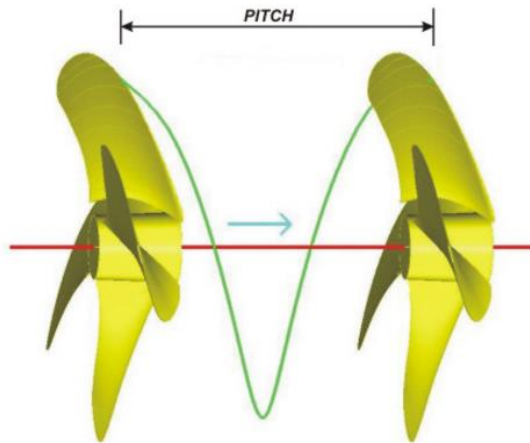
Figure 16: Propeller pitch scheme[37]

The propeller pitch is directly related to the blade angle of attack and there are two types: geometrical pitch and effective pitch. The geometrical pitch is the theoretical distance that the propeller makes in one revolution and the effective pitch the real distance that makes. The effective pitch is lower than the geometrical due to propeller slippage in the air.
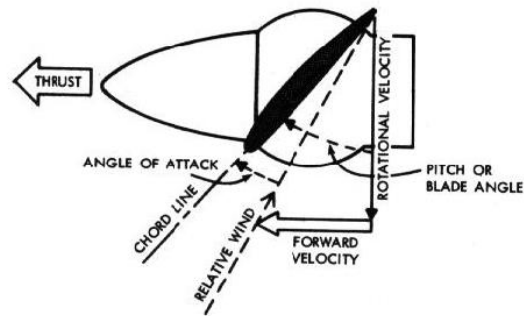
Figure 17: Blade angle of attack[38]
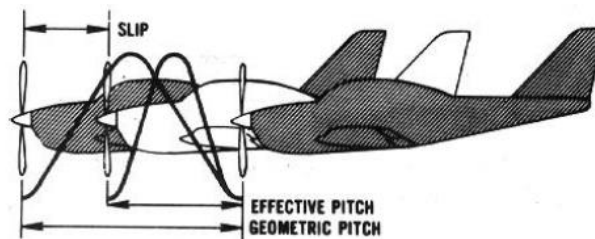
Figure 18: Difference between effective and geometrical pitch[38]

The angle of attack seen by the blades of the propeller changes with the aircraft velocity so that selection the pitch value is a complex decision. Thus, the pitch will be selected so that the main requirements are ensured, although it is not the most effective solution.

From section 3.1.2.3., the estimated required thrust is 90 N. Using a propeller selector software, the following specifications have been calculated[39]:

Figure 19: Propeller selector software

The UAV propeller manufacturers do not provide many information of their products due to the fact that they design it taking into account the client requirements. Therefore, it should be decided in future considerations.

7.1.4. Engine and propeller location

The two basic options regarding the location of the propulsion system are pusher and tractor configuration. A brief description of the advantages and disadvantages of each configuration have been done.

- Pusher configuration

In this configuration the propeller is situated at the back of the fuselage. The main advantage that provides good stability due to the fact that the wings are not affected by the propeller wash. However, since the clean air does not arrive to the propeller, the thrust is affected.

- Tractor configuration

The main advantage of having the propeller situated at the front of the UAV is that a non-disturbed air arrives directly and consequently a more efficient thrust is generated. The drawback of this configuration is that the propeller wash affects the aerodynamic efficiency and also the surface controls.

The contribution of the tractor configuration disadvantage is more important than the pusher configuration drawbacks. Therefore, the pusher configuration is selected.

7.2. Aerodynamics

7.2.1. Airfoil selection

The purpose of this section is finding the most efficient airfoil in order to obtain the best performance of the UAV. The first step is to define the simulation conditions.

- Simulation conditions

A possible range of Reynolds number needs to be computed with equation (13). Taking into account the market research and some assumptions, some maximum and minimum values for the parameters of the following equation have been taken.

$$Re = \frac{\rho V c}{\mu} \tag{13}$$

- Density

The sea level density has been considered as the maximum value. The minimum value is the density at the maximum height allowed by regulations, approx. 150 m.

- Speed

According to the market research, a maximum speed of 40 m/s and a minimum of 13 m/s have been taken.

- Chord

The chord depends on the wing configuration. However, since the UAV have to be as small as possible so that the maximum weight allowed is not overpassed, a range between 0.2 m and 0.6 m has been considered.

- Viscosity

As viscosity is usually expressed as function of temperature, a range of temperatures has been taken. The maximum is sea level temperature, 288.15 K, and to take aware of the possibility of flying in extremely cold conditions a minimum of 270 K has been considered. Using a gas viscosity calculator, the air viscosity values have been calculated.[40]

The following table summarizes all the simulation conditions:

Table 10: Simulation conditions

	Velocity (m/s)	Height (m)	Density (kg/m3)	Chord (m)
Minimum value	13	1500	1,06	0,2
Maximum value	40	0	1,225	0,6

	Temperature(K)	Viscosity(kg/m·s)	Reynolds
Minimum value	270	$1,72 \cdot 10^{-5}$	$1,6 \cdot 10^{5}$
Maximum value	288,15	$1,812 \cdot 10^{-5}$	$1,6 \cdot 10^{6}$

- Decision criteria

The criteria used for selecting the best airfoils is:

- Thickness greater as possible due to structural restrictions
- Having a consistent angle of attack for maximum efficiency
- Level of efficiency as high as possible
- Stall speed as much different as possible to cruise speeds

- Airfoil simulation

For UAV applications, the low Reynolds airfoils are the most commonly used. Using the XFLR5 software, the following low Reynolds airfoils have been analysed.

For analysing the airfoils a wing of 3 m of wingspan and 0.2 m of chord has been used. The results are shown in the following table.

Table 11: Results of airfoil simulation

Airfoils	AoA max Cl/CD	Max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	Thickness (%)
NACA 4415	1,5	34,869	0,54	0,015	-0,231	31,45	15
NACA 4418	2	32,372	0,598	0,018	-0,246	29,88	18
NACA 2415	2,5	34,679	0,44	0,013	-0,158	34,84	15
NACA 2418	3	32,535	0,496	0,015	-0,173	32,8	18
NACA 23012	4,5	32,254	0,538	0,017	-0,144	31,5	12
NACA 23015	4	30,164	0,499	0,017	-0,135	32,71	15
NACA 23018	3,5	28,934	0,458	0,016	-0,125	34,13	18
Clark-Y	1,5	38,599	0,48	0,012	-0,198	33,34	11,72
Gemini	3	35,027	0,477	0,014	-0,161	33,46	15,37
e169	5,5	33,529	0,53	0,016	-0,132	31,73	14,4
e205	2,5	37,595	0,463	0,012	-0,16	33,98	10,47
e387	1,5	38,529	0,469	0,012	-0,192	33,74	9,07
s8036	3,5	34,26	0,516	0,015	-0,165	32,17	16

In terms of aerodynamic performance, the Clark-Y is the best airfoil and has a thickness greater than 10%. For this reasons, it has been selected as the UAV airfoil.

7.2.2. Wing configuration

The different possible wing configurations have been described in order to analyse them and chose the better option.

7.2.2.1.   Canard configuration

This configuration is characteristic for having the wings and vertical stabilizer at the rear and a smaller horizontal stabilizer in the front. Canard configuration increases performance against stall, however they are complex to design and it may experience stability problems.

7.2.2.2.   Flying wing

It consists on a tailless fixed-wing aircraft without fuselage that produced a low drag profile. The main problem for this type of aircrafts are controllability and stability issues.

7.2.2.3.   Conventional

This is the simplest configuration and the most used one due to the resemble with standard aircrafts. It has a fixed wing near the front of the fuselage and vertical and horizontal surfaces in the rear of the vehicle.

7.2.2.4.   Blended wing

It is a type of fixed wing aircraft were the wings are smoothly blended into the fuselage and so there is no clear dividing line between fuselages and wing. It can be tailless or not. This configuration performs a good lift to drag ratio. However, the complexity of the design makes it difficult to manufacture.

7.2.2.5.   Tandem

This configuration consists of two wings, one at the front and other at the rear. The main advantage of this wing configuration is that produces high values of lift. However, the main drawback is the weight.

7.2.2.6.   Biplane

As the tandem configuration, it consists of two wings but stacked one above the other. With this configuration high lift is produced but as the tandem, weight is the main issue.

7.2.2.7.   Decision matrix

In order to select the best option, a decision matrix has been made. The parameters that have been taken into account are listed below:

- Weight

 One of the design requirements is to keep the total weight under 25 kg. Therefore, it is the most important parameter.

- Portability

The wing configuration should be one that allows easy transportation of the vehicle.

- Complexity

It is important to design a low complex vehicle in order to reduce manufacturing costs.

- Performance

The wing configuration needs to allow the design requirements and so issues like take-off, maneuverability, stall speed, etc are taken into account.

- Stability and controllability

The wing configuration needs to be as stable as possible in order to ensure the success of the mission without experiencing problems.

The following table illustrate the final decision.

Table 12: Decision matrix Wing configuration

	Weight	Canard	Flying Wing	Conventional	Blended Wing	Tandem	Biplane
UAV Weight	30	6	9	7	8	5	5
Portability	20	7	6	7	5	7	8
Complexity	20	7	6	9	5	8	8
Performance	20	7	6	7	5	7	8
Stability and controllability	10	7	6	8	5	6	7
TOTAL	100	67	69	75	59	65	70

The best configuration option taking into account the parameters described above is conventional. The advantages that this configuration enables are a combination of simplicity and good performance and a light structure.

7.2.3. Wing position

There are three possible configurations:

- High wing

This configuration is the best option in regards of high lift and consequently for short take-off. In terms of stability, is stable against perturbations.

- Mid wing

Mid wings are the most used configuration in civil aviation due to highest velocities and good lift and stability performances.

- Low wing

In comparison to high wings, low wings have higher speeds and good maneuverability. However, for take-off are not the better options and they need high take-off distances.

According to the market research, the most common used position is high wing. This is due to simplicity, easy to assemble and high lift that helps to take-off easily. Therefore, the high wing configuration have been selected.

7.2.4. Tail configuration

The tail configuration is an important part of the UAV that have the objective of provide stability. However, there are some related issues such as weight and portability that need to be taken into account.

Some typical UAV tail configurations are described:

- Cruciform tail

This configuration consists of a horizontal tail that intersects the vertical tail approximately by the middle. One of the principal advantages is reducing the effects of the downwash.

- V tail

The V tail is a non-conventional configuration that replaces the horizontal and vertical tail with two surfaces set in V-shape. Although it is not the better option in terms of stability, is a good option to minimise weight. Another advantage is that produces less drag.[41]

- T-tail

The t-tail configuration consists of a vertical tail and the horizontal tail mounted at the top, forming a T-shape. With this configuration, the tail is well kept out from the disturbed airflow behind wing and fuselage and therefore downwash effects are avoided. The main drawback for this configuration is the more complex design and it does not work so good in low speed vehicles.

- Twin tail

The twin tail, also known as H-tail, it consists on a horizontal surface just at the rear of the fuselage and two vertical surfaces located each one at the edge of the horizontal tail forming a H-shape. The main advantage of the H-tail configuration is that keeps both vertical surfaces out of the current of air created by the propeller allowing better control of the vehicle.

- Conventional tail

The conventional tail is the most used configuration due to good results in stability and easy design. It consists of a vertical tail mounted on the fuselage and a horizontal stabilizer crossing the fuselage.

- Inverted-V tail

It is very similar to the V-tail design but can be a good option to minimize weight. Another principal advantage is that provides stabilisation in cross wind situations, increases structure rigidity and allows coordinated turns without ailerons.[42]

In order to choose one of the tail configurations explained above, a decision matrix have been made. The decision criteria parameters are described:

- Stability and control

The main function of the tail is to provide control surfaces so that the aircraft can be stabilised. Some of the configurations are more stabilised than others and therefore needs to be taken into account.

- Weight

Minimizing the weight is always an important factor. A maximum weight of 25 kg is allowed so a tail configuration as lighter as possible need to be chosen.

- Portability

Some configurations can ensure an easy assembly system in order to facilitate transportation.

- Complexity

It is important to find simplicity in the designs of the different part of the UAV so that manufacturing costs can be keep it as low as possible.

- Performance

For tail selection, the performance will take into account if the configuration avoids downwash effects and other aspects. In other words, that the UAV can operate without experiencing problems.

The decision matrix can be seen below:

Table 13: Decision matrix for tail configuration

	Weight	Cruciform	V-tail	T-tail	Twin tail	Conventional	Inverted-V
UAV Weight	25	7	9	7	6	7	8
Portability	15	7	6	9	5	8	6
Complexity	10	5	7	5	6	8	7
Performance	20	7	7	7	8	8	7
Stability and controllability	30	7	7	8	8	8	7
TOTAL	100	68	73,5	74	68,5	77,5	71

The conventional configuration is the best option due the combination of simplicity, lightweight tail and good stabilising performance.

7.2.5. Wing Geometry

7.2.5.1. Selection of the planform

There are many different planforms in the market and the selection is not trivial. Therefore, a brief study of the different options has been made. Although the criteria for selecting the planform is based on aerodynamic purposes, structural problems need to be taken into account. The following table summarizes the advantages and disadvantages of each wing planform.[43]

Table 14: Study of the different planforms

Planform	Advantages	Disadvantages
Rectangular	- Easy to manufacture - Most commonly used	- Bad aerodynamic and structural performance
Elliptical	- Minimum induced drag planform - Good structural behaviour	- Complex manufacturing process (expensive)
Tapered	- Almost the same efficiency as the elliptical wing - Low induced drag - Easy to manufacture - Requires less reinforcements in the wing tip allowing weight reduction	- Stall stars at the wing tips
Mix[3]	- Trade-off between tapered and rectangular planform (good structural and aerodynamic behaviour combined with the property that stall is displaced to the central area of the wing) - Used for propeller aircrafts	- Worst behaviour against stall than elliptical wings

The mix planform is the best option for propeller propulsion UAVs and it is also characterised for having good aerodynamic and structural behaviour. In the actual market, this planform is commonly used, so we can prove that is a feasible solution. Due to this reasons, the mix planform is selected for the UAV study.

7.2.5.2. Wingspan

For selecting the wingspan, some simulations with the XFLR5 software has been done. The range of wingspans simulated corresponds to the maximum and minimum values of the market research. The results are presented in the following table:

---

[3] Rectangular shape from the root to a certain point and then a tapered section until the wing tip

Table 15: Study of the wingspan

Wingspan (m)	Max C_L/C_D AoA (°)	Max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	V_{stall} AoA (°)
0.8	1	18.08	0.257	0.014	-0.126	33.51	20
1	1	20.115	0.284	0.014	-0.136	29.65	17.5
1.5	1.5	25.062	0.367	0.015	-0.160	24.09	14
2	1.5	28.933	0.401	0.014	-0.171	21.03	12
2.5	1	31.927	0.382	0.012	-0.168	18.83	11
3	1	34.197	0.397	0.012	-0.173	17.11	10.5
3.5	1	35.962	0.409	0.011	-0.177	15.86	10
4	1	37.433	0.419	0.011	-0.180	14.66	10
4.5	1.5	38.635	0.474	0.012	-0.194	13.94	9.5

The results show that the lift-to-drag ratio increases with wingspan whereas the stall velocity decreases. These tendencies and the rate of change can be seen in the following graphs:
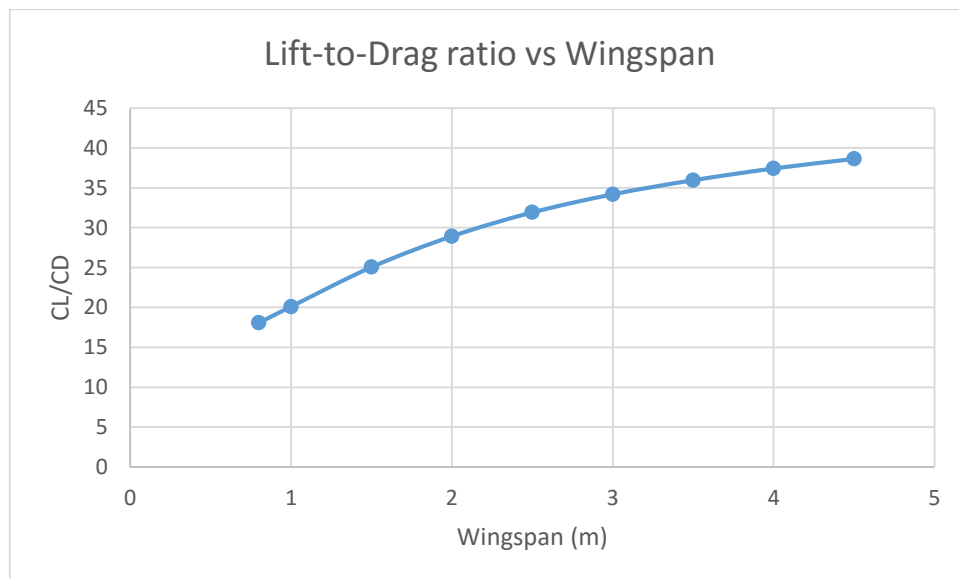
Figure 20: Lift-to-Drag vs wingspan graph
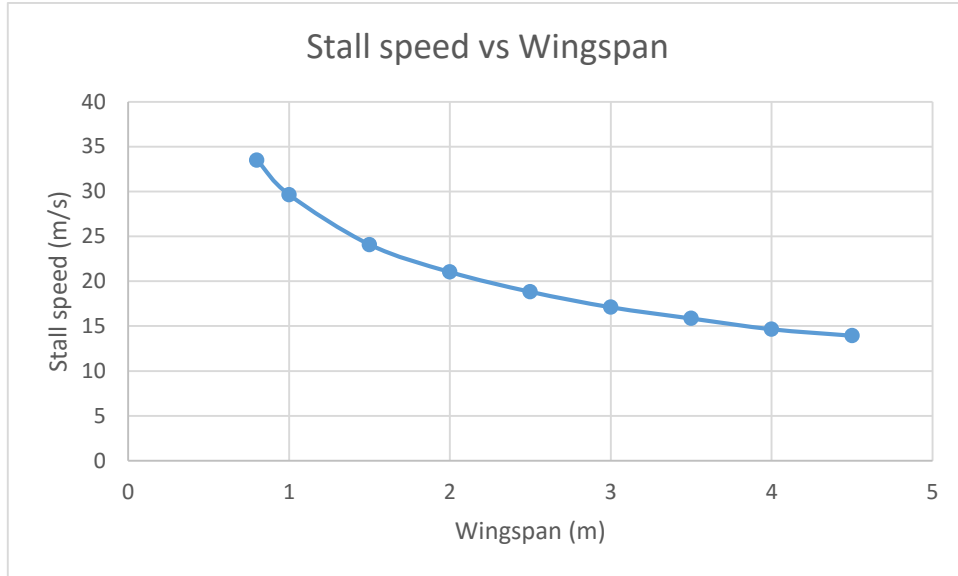
Figure 21: Stall speed vs wingspan graph

The rate of change of the values decreases with the wingspan. In other words, the curves decrease more rapidly for lower wingspan values. Between 3 and 4 m of wingspan, the curve is smoother.

For aerodynamic purposes, the best option is 4.5 m. However, the higher the wingspan the higher the wing surface and consequently more weight. In order to keep the weight as low as possible and taking into account the smooth change in values from approximately 3 m, a wingspan around 3 m has been taken.

7.2.5.3. Aspect ratio

Once the wingspan is selected, the effect of the aspect ratio in the UAV performance can be studied. The aspect ratio is defined as follows:

$$AR = \frac{b}{c} = \frac{b^2}{S} \tag{14}$$

where b is the wingspan, c the average chord and S the wing area.

The wingspan value is fixed from 7.2.5.2 so for different chords combinations, the AR effect will be studied. The wing is divided in 2 sections: one rectangular and the other tapered as can be seen in Figure 22.
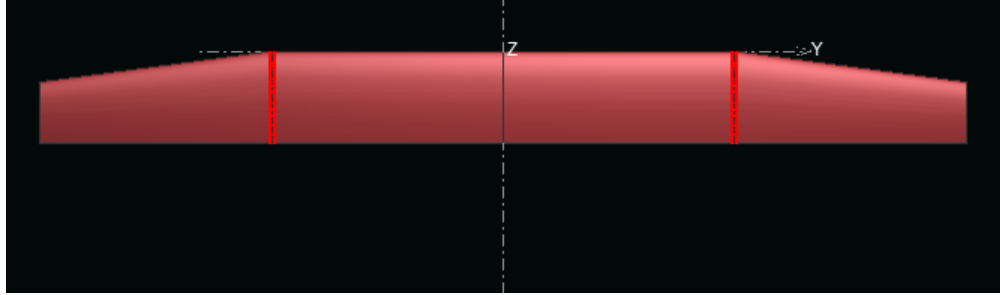
Figure 22: Wing geometry model

The rectangular section length has been fixed to 1.5 m. The following table summarizes the results of the simulations:

Table 16: Results of the simulation for different wing geometries

c_{root} (m)	c_{tip} (m)	AR	Max C_L/C_D AoA (°)	Max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	V_{stall} AoA (°)
0.3	0.2	10.9	1	36.364	0.413	0.011	-0.21	17.5	10.5
0.3	0.15	11.4	1	37.273	0.420	0.011	-0.22	17.77	10.5
0.3	0.1	12	1	37.945	0.425	0.011	-0.24	18.41	10
0.3	0.05	12.6	1	38.424	0.427	0.011	-0.24	19.95	8.5
0.25	0.2	12.6	1	37.656	0.421	0.011	-0.2	18.97	10
0.25	0.15	13.3	1	38.780	0.429	0.011	-0.22	19.3	10
0.25	0.1	14.1	1	39.697	0.436	0.011	-0.24	19.7	10
0.25	0.05	15	1.5	40.356	0.488	0.012	-0.27	21.41	8.5
0.2	0.15	16	1.5	40.161	0.486	0.012	-0.23	21.3	9.5
0.2	0.1	17.2	2	41.432	0.546	0.013	-0.27	21.43	10
0.2	0.05	18.5	2.5	42.456	0.603	0.014	-0.31	22.94	9
0.15	0.1	21.8	2.5	43.874	0.608	0.014	-0.27	24.34	9.5
0.15	0.05	24	2.5	45.475	0.619	0.014	-0.31	25.78	9

In order to analyse the tendency and the rate of change of different parameters with the AR, the following graphs can be seen:
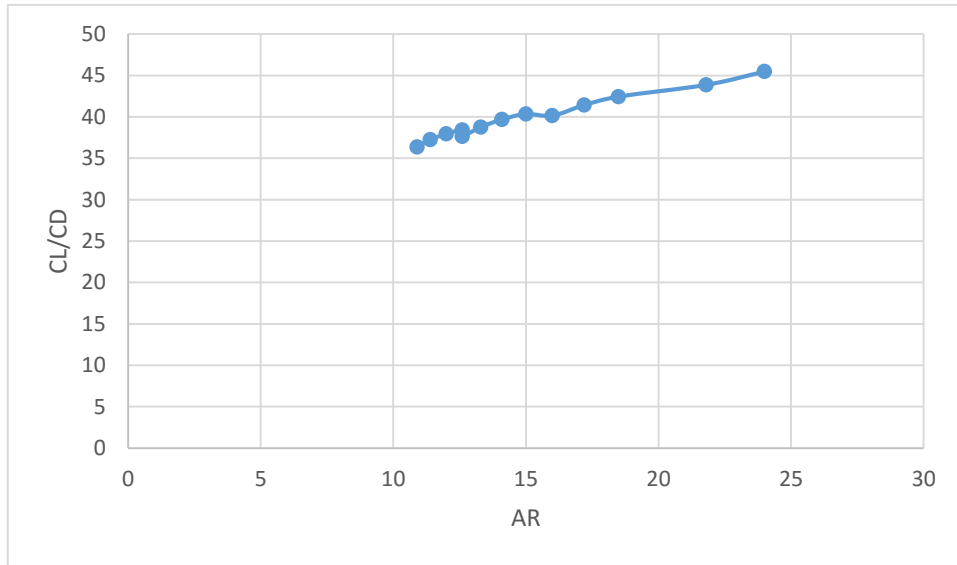
Figure 23: Lift-to-Drag ratio variation with the AR of the wing
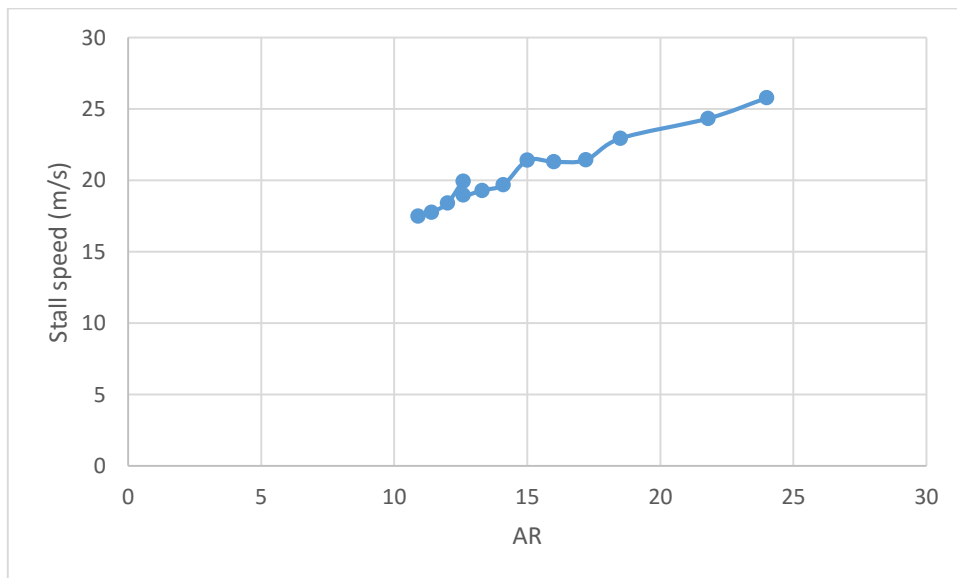
Figure 24: Variation of the stall speed with the AR of the wing

The tendency is to maximise the C_L/C_D and minimise the stall speed. The higher the AR the higher the C_L/C_D but also the higher the stall speed is. For wings with aspect ratios between 15 and 17, a stabilization in the stall speed can be observed. Therefore, an AR of 17 is the best option in order to obtain the best aerodynamic performance. The final wing design parameters can be seen in the table below.

Table 17: Final wing parameters

c_{root} (m)	c_{tip} (m)	AR	Max C_L/C_D AoA (°)	Max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	V_{stall} AoA (°)
0.2	0.1	17.2	2	41.432	0.546	0.013	-0.27	21.43	10
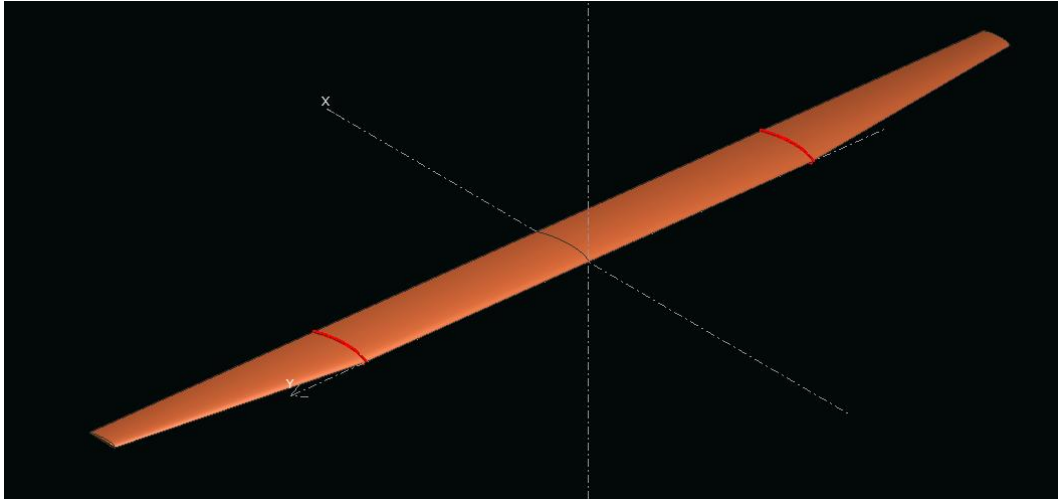
Figure 25: Final Wing Design

7.2.6. Stability and control

Stabilizers have an essential role in a UAS. For any type of aerial vehicle, the vertical and horizontal stabilizers need to be well design in order to ensure stability during flight as well as control. For a UAV, the control operations are done automatically by means of the autopilot calculations. In the following points, a solution for both stabilizers have been provided. These stability and control proposals have been calculated and designed using the 3D Panel Method, that the XFLR5 software provides.

7.2.6.1.   Conventional configuration tail

In 7.2.4, the conventional tail configuration was selected due to the simplicity, lightweight configuration and it is known that it provides good stability performance. It consists of a vertical tail mounted on the fuselage and a horizontal stabilizer crossing the fuselage.

Figure 26: Example of UAV with conventional configuration tail[44]

7.2.6.2. Horizontal stabilizer

The horizontal stabilizer can be considered as a small wing that has the purpose of providing longitudinal static stability. As a starting point, an example of a UAV with conventional tail configuration and with similar wingspan and reasonable weight values has been taken as a model. The UAV taken as reference is the Spartan Phoenix, a fire surveillance drone designed by San Jose State University. This UAV has a wingspan of 3.1 m and a weight of 11.3 kg. The dimensions of the horizontal and vertical stabilizer can be seen in Figure 27.
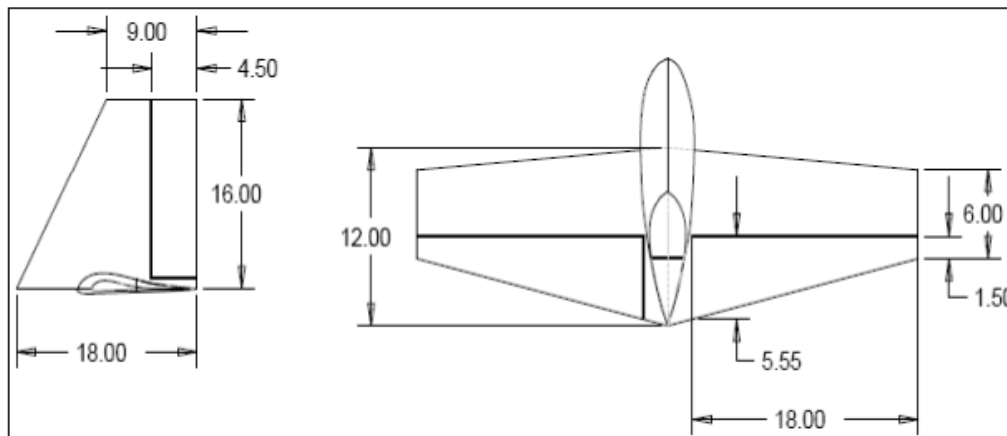
Figure 27: Spartan Phoenix horizontal and vertical stabilizer dimensions[45]

The next step is to select an airfoil. For Low-Reynolds numbers, the horizontal stabilizer airfoils are usually symmetrical. This is due to the fact that the symmetrical airfoil is a solution of compromise when the aerial vehicle needs to fly at different speed ranges and attitudes like UAVs. The following airfoils have been simulated with the same conditions as the wing and with a fixed geometry in order to compare them in equal conditions. The best known symmetrical airfoils are

NACA ones. Therefore, the study has been limited to NACA airfoils. The fixed geometry used for the airfoils study can be seen in the following figure.

	y (m)	chord (m)	offset (m)	dihedral(°)	twist(°)	foil	X-panels	X-dist	Y-panels	Y-dist
1	0,000	0,300	0,000	0,0	0,00	NACA 0024	13	Cosine	19	-Sine
2	0,450	0,150	0,150		0,00	NACA 0024				
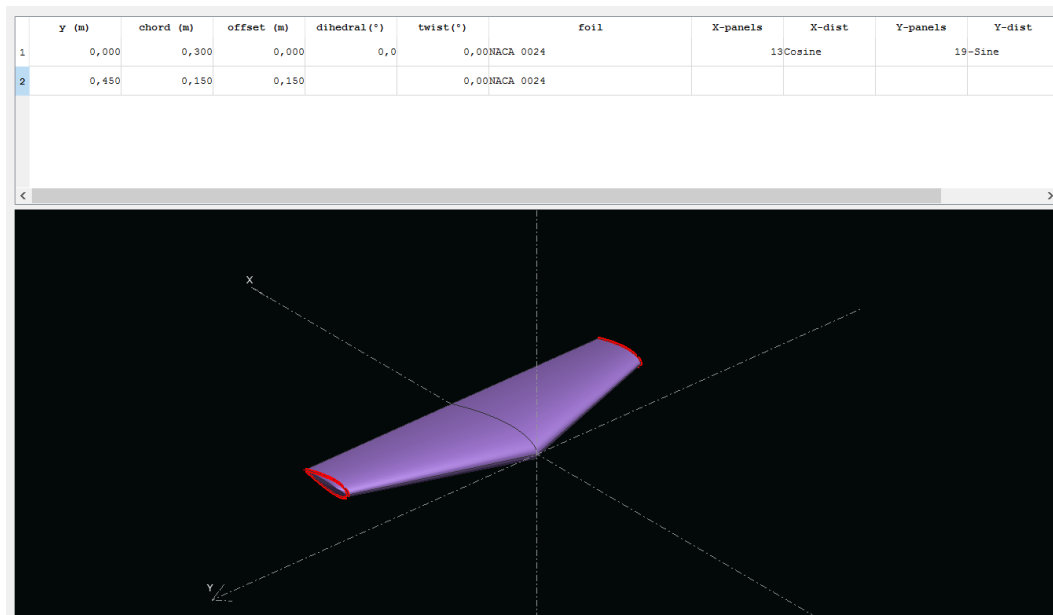
Figure 28: Horizontal stabilizer first iteration geometry

Table 18: Horizontal stabilizer airfoil siimulation

Airfoils	AoA max C_L/C_D (°)	max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	$C_{L\,max}$
NACA 0012	4.5	22.7	0.30	0.013	-0.157	37.54	1.122
NACA 0015	4	21.9	0.27	0.012	-0.141	36.42	1.193
NACA 0018	4	20.6	0.27	0.013	-0.142	36.24	1.205
NACA 0021	4.5	19.5	0.31	0.016	-0.162	36.52	1.186
NACA 0024	4.5	18.4	0.31	0.017	-0.163	36.83	1.166

The stall speed values are approximately the same for all the NACA airfoils simulated. However, the difference between the maximum C_L/C_D values have to be taken into account. Therefore, the selection of the horizontal stabilizer will only be

determined by comparing the different efficiency values. The result of the simulation shows that the most efficient airfoil is NACA 0012.

Once the airfoil is selected, the geometry of the horizontal tail needs to be studied. The length has been fixed to 0.9 m, the same value as Spartan Phoenix UAV, in order to simplify the study. So the variable parameter in this second simulation is the taper ratio. The taper ratio is defined as follows:

$$\lambda = \frac{c_{tip}}{c_{root}} \tag{15}$$

Different combination of tip chord and tip root have been proved. Furthermore, the wing has been added to the simulation so that the contribution of both can be taken into account. The distance between the wing and the horizontal stabilizer has been fixed to 1,6 m, that t is coinciding with the Spartan Phoenix UAV.
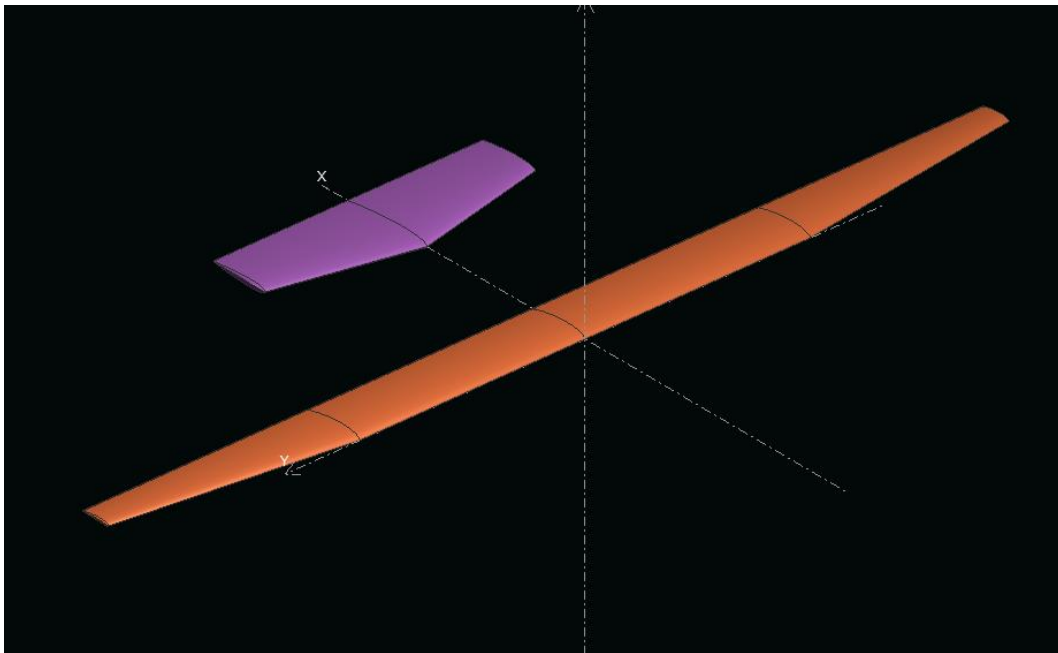
Figure 29: Wing and horizontal stabilizer simulation

The results of the simulation can be seen in the following table.

Table 19: Simulation wing and horizontal tail changing taper ratio

C_{root} (m)	C_{tip} (m)	AoA max C_L/C_D (°)	max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	V_{stall} angle (°)
0.3	0.2	3.5	37.810	0.718	0.019	-0.643	20.36	10
0.3	0.15	3.5	37.920	0.714	0.019	-0.617	20.44	10
0.3	0.10	3	37.957	0.653	0.017	-0.490	20.54	10
0.25	0.2	3.5	38.130	0.714	0.019	-0.597	20.44	10
0.25	0.15	3.5	38.203	0.710	0.019	-0.570	20.53	10
0.25	0.10	3	38.216	0.649	0.017	-0.451	20.63	10
0.2	0.15	3.5	38.504	0.706	0.018	-0.519	20.64	10
0.2	0.10	3	38.469	0.645	0.017	-0.408	20.75	10

The stall speed does not change appreciably, therefore the stall speed is not considered on the criteria for selecting the horizontal stabilizer. However, in terms of efficiency the best chord combinations are 0.2 m for the root and 0.15 m for the tip. Finally, in order to provide longitudinal stabilization, the C_m should be null for the angle of maximum efficiency of the wing and tail configuration. Furthermore, the slope of the C_m - α graph should be negative. In order to adjust the C_m so that it goes null for the angle of maximum efficiency, the tilt angle has been modified by the trial and error method.

The tilt angle that adjust the C_m to 0 at the maximum angle of efficiency is -2.55°. The following C_m - α graph has been obtained with this simulation and it can be observed that at 3.5° (angle of maximum efficiency) the C_m is almost null.
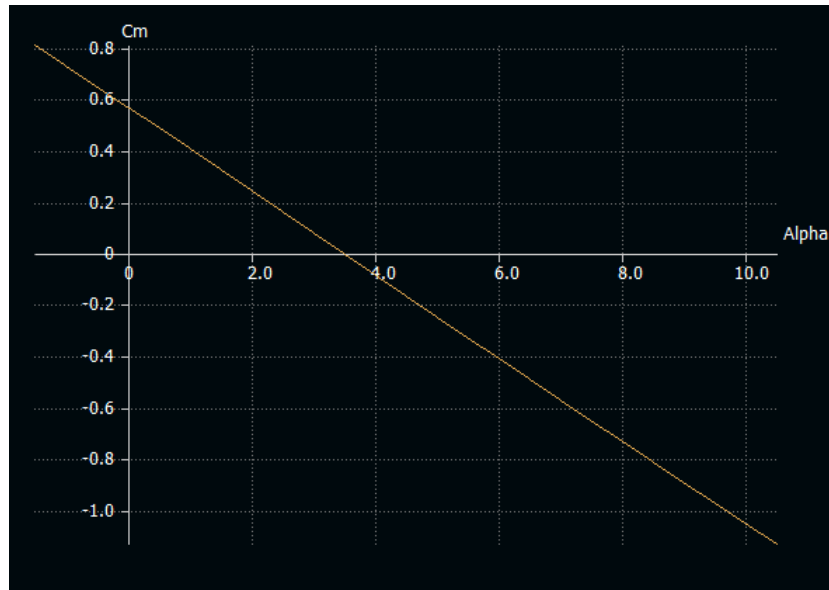
Figure 30: C$_m$ - α graph for the configuration wing - horizontal tail with tilt angle of -2.05°

The slope of the graph above is negative. Therefore, it can be concluded that is a stable configuration. The slope of the linear function has been calculated:

$$C_{m_\alpha} = \frac{-0.4 - 0}{6 - 3.5} = -0.16 \tag{16}$$

The slope calculated is quite high. This means that the reaction to perturbations will no occurred too smoothly. However, it is stable and for a pre-design phase is an affordable value.

7.2.6.3.   Vertical stabilizer

As in the horizontal stabilizer, the first step is selecting the airfoil. It is quite common in general aircrafts that the airfoils used for vertical and horizontal stabilizers are both NACA symmetric airfoils.[46] So the following NACA airfoils have been simulated with XFLR5 and the results obtained have been tabulated in the table below. The geometry of the vertical tail has been fixed using the values of the Spartan Phoenix and the wing and the horizontal tail have been considered in the simulation.
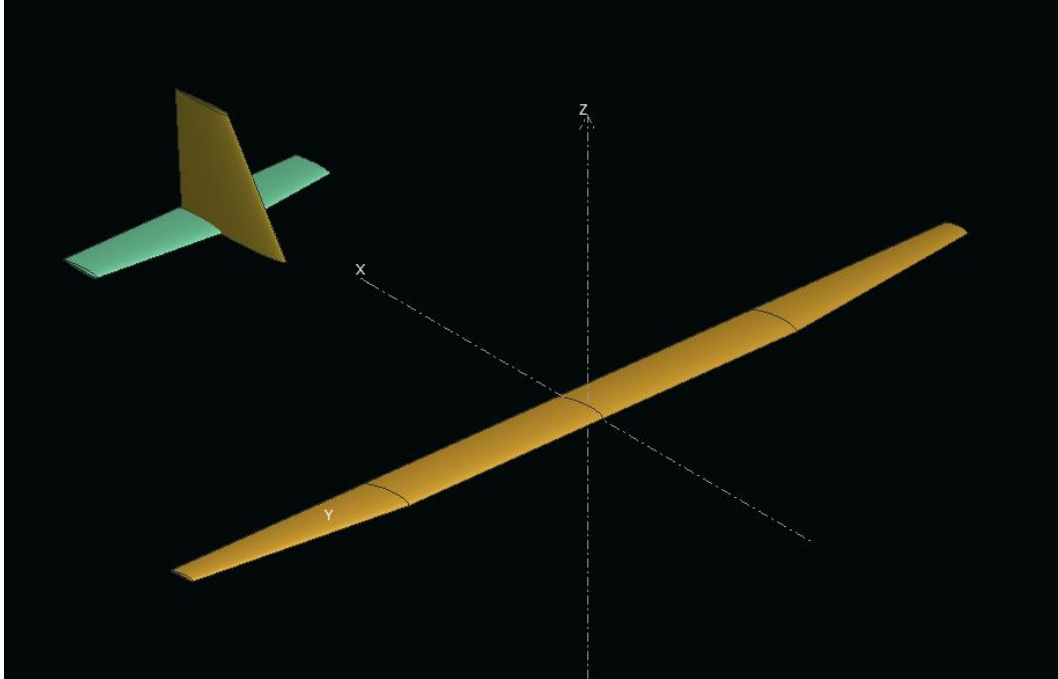
Figure 31: Simulation for selecting the vertical stabilizer airfoil

Table 20: Airfoil vertical stabilizer simulation for the configuration wing, horizontal and vertical stab

Airfoils	AoA max C_L/C_D (°)	max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	V_{stall} angle (°)
NACA 0008	4	33.990	0.705	0.021	-0.084	20.66	10.5
NACA 0009	4	33.881	0.705	0.021	-0.084	20.66	10.5
NACA 0010	4	33.746	0.705	0.021	-0.084	20.66	10.5
NACA 0012	4	33.439	0.705	0.021	-0.084	20.66	10.5

The results for the different airfoils tested are quite similar. This is due to the fact that the vertical stabilizer does not have a considerable effect in the whole UAV configuration. However, it is interested to note that the C_m is close to 0 for the angle of maximum efficiency. Although the difference between these airfoils is almost negligible, the most efficient solution is using NACA 0008.

Once the airfoil is fixed, the geometry has been studied. An important parameter to take into account for the vertical stabilizer is the tail volume coefficient. This coefficient is expressed as follows:

$$v_v = \frac{S_v \cdot L_v}{S_w \cdot b} \tag{17}$$

Where S_v is the elevator surface, L_v is the distance between the leading edge of the wing and the leading edge of the elevator, S_w is the wing surface and finally b the wingspan. The values fixed in equation *(17)* are:

- $S_w = 0.525$ m^2
- b=3 m

The unknown parameters are the elevator surface and the distance between leading edges. Since the length of the vertical stabilizer has been decided to be fixed at the same value as the reference UAV model, the taper ratio is the variable parameter regarding to the elevator surface. Before, starting to analyse the effect of the vertical taper ratio tail, an experimental consideration has been taken into account. It is proved that for gliders the tail volume coefficient must be between 0.02 and 0.025 [36]. Therefore, for a UAV the tail volume coefficient needs to have the same order of magnitude.

Some combinations for the root and tip chords with different L_v values have been studied in order to select one that can give a reasonable value for the tail volume coefficient. For further information of the results of the study, see the Annex.

The criteria for selecting the vertical tail configurations that will be simulated is trying to minimize the tail volume coefficient in order to provide a feasible design based on the limited glider range commented above. The geometries selected and their corresponding simulation results can be seen in the following table.

Table 21: Results of the simulation for different vertical tail geometries

C_{root} (m)	C_{tip} (m)	L_v (m)	AoA max C_L/C_D (°)	max C_L/C_D	C_L	C_D	C_m	V_{stall} (m/s)	V_{stall} angle (°)
0.25	0.15	1.3	3.5	35.264	0.653	0.019	-0.002	20.60	10.5
0.25	**0.1**	**1.3**	**3.5**	**35.383**	**0.653**	**0.018**	**-0.002**	**20.60**	**10.5**
0.25	0.1	1.4	3.5	35.383	0.653	0.018	-0.002	20.60	10.5
0.25	0.1	1.5	3.5	35.383	0.653	0.018	-0.002	20.60	10.5

The most efficient geometry is the 0.25 – 0.1 m chord combination. Since the distance between leading edges does not affect to the results of the simulation, the one that has the minimum tail volume coefficient has been selected.
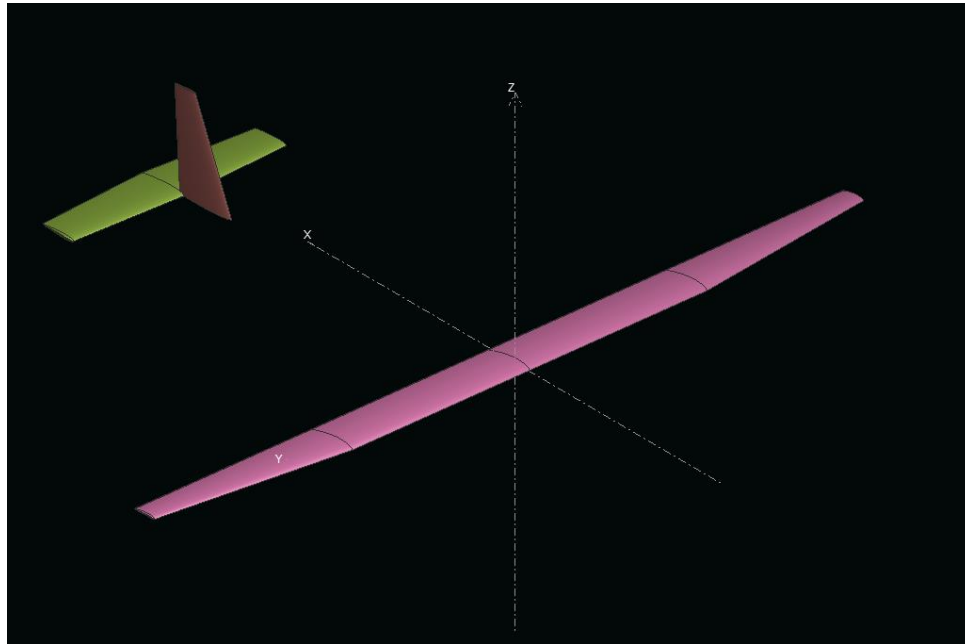
Figure 32: Final tail configuration

7.2.6.4.   Control surfaces

- Aileron

The ailerons are responsible of the roll control movement. This lateral control is achieved through the deflexion of control surfaces in the trailing edge of the wing. This deflection allows a change in the airfoil curvature, that it is translated in a reduction or increment of lift. For example, if the desired roll movement is toward the right, the aileron of the left will be deflected downward to increase curvature and consequently increase the lift produced by the left wing. Whereas the right aileron will be deflected upward so that the lift is reduced in the right wing, creating a roll moment towards the right. The deflections of the ailerons are done automatically by the commands transmitted by the autopilot based on instantaneous calculations.

The design of the ailerons follows a complex method and it can be considered out of the scope for a preliminary solution proposal.

- Elevator

The elevators are the control surfaces situated on the final section of the horizontal stabilizer. There are responsible of generating a pitch control moment. The

longitudinal control is achieved by deflecting the horizontal tail surface upwards or downwards. For creating a pitch moment that increases the angle of attack, the elevator should be deflected upwards so that it produces a lift reduction in the tail and consequently the tail will fall ant the nose of the UAV will move upwards. If the desired control moment is decreasing the angle of attack the reverse process is needed.

The design of the elevator follows a complex method and it can be considered out of the scope for a preliminary solution proposal.

- Rudder

The rudder is the control surface responsible of the yaw control. It is situated at the final part of the vertical stabilizer. For turning the nose of the aircraft to the right, the rudder should be deflected to the right so that a force in left direction is created generating a yaw moment to the right.

The design of the rudder follows a complex method and it can be considered out of the scope for a preliminary solution proposal.

7.3. Communication system and Ground Control Station

The communication system is one of the most critical subsystems of the UAS. A failure in the communication links between the air vehicle and the control station will be traduced un the inability to accomplish the objectives of the UAV mission.

The communication system consists of an uplink that transmits commands from the ground control station to the UAV and a down-link that transmits the data from the UAV to the ground station.

The main functions of the communications links are:

- Controlling the flight of the UAV
- Receive and process the data from the payload sensors
- Ability to control the operation of the payload

The basic specifications that should be defined for the UAS communication system are[27]:

- Data rate: amount of data transferred per second by a communication channel. It is measured in bytes per second (BPS)
- Bandwidth: difference between the highest and lowest frequency. In other words, the width of the band of frequencies that the communication channel uses

7.3.1. Communication Media

The communication media is the communication channel used for linking the aerial vehicle with the ground control station[47]. There are different possibilities[27]:

- Fibre-optics

Fibre-optics communications are a good option to take into account due to the efficient and fast way to transmit large amount of data. The fibre-optic is usually used to communicate the ground control station and the antenna. The information sent to and from the UAV is a critical parameter that determines the success of the mission. Therefore, high bandwidth and rapid transmissions over long distances need to be provided. Fibre-optics can provide the bandwidth and transmission capabilities required so it is a well-positioned candidate. [48]

- By Laser

This communication media consists on propagating light in the air so that data can be transmitted wirelessly. Although the advantages that this type of communication provides, it has some important drawbacks such as atmospheric absorption that limits the range. This technology is being developed in order to reach a feasible solution but nowadays is not often used.

- Radio communications

The radio communications are the most common solution for this type of systems. In other words, is the most feasible wireless solution. This is the main reason why it will be the communication media implemented.

7.3.2. Data link

As was mentioned before, the data link is one of the most critical parts of the systems. Therefore, it is quite important to define the main functions of the data link and make a preliminary study. The communication media selected for the data link is radio frequencies as can be seen in 7.3.1.

- Functions

The data-links functions for an UAV are illustrated in Figure 33 and described as follows:

- Uplink: is the communication link in which the ground control station is the transmitter and the UAV the receiver. A bandwidth of a few kHz is needed and it is basically used for sending controls to the aerial vehicle.
- Downlink: is the communication link in which the UAV acts as the transmitter and the ground control station as the receiver.
- GPS link: in order to provide a navigation system so that information about the position is obtained, a GPS link needs to be ensured.
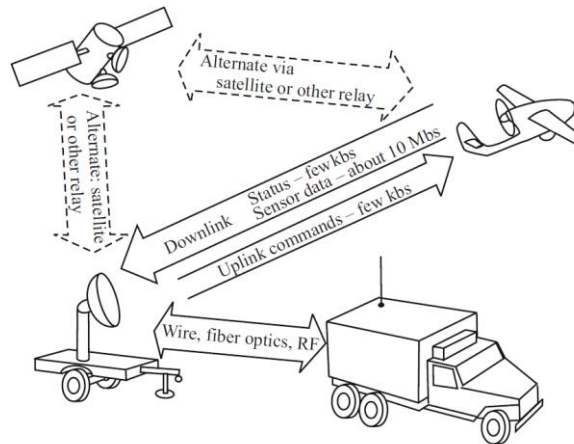
Figure 33: Data-link functions[26]

- Subsystems

The data-link is typically divided into different subsystems described as follows:

- UAV subsystems

In the UAV there 2 subsystems placed, the Air Data Terminal (ADT) and the antennas. The ADT consists of a radio frequency (RF) receiver and transmitter, modems to encode the digital information for transmission and processors if compressing the data is required. [26]

- Ground control station subsystems

The ground data terminal consists of antennas, RF receiver and transmitter, modems and processors to reconstruct the data compressed.

- Frequency selection

In UAV missions, the rates of data that are usually transmitted are high and consequently higher radio frequencies are needed. These higher radio frequencies have the disadvantage that they not have the ability to be refracted, requiring a direct and uninterrupted line-of-sight (LOS) between the transmitter and the receiving antennas. [26]

For selecting the range of frequencies is important to take into account that low frequencies are easier to propagate but with a poor data rate. On the other hand, the higher the frequencies the higher the capability of carrying data rates. However, the LOS increases and consequently the power required to transmit the data is also higher.

Before selecting the range of frequencies, the RF spectrum has been studied. The width of the RF spectrum goes from 3 kHz to 300 GHz and it can be divided as follows[26]:

Table 22: RF spectrum

Band Name	Frequency	Wavelength	Applications
Very Low Frequency (VLF)	3 – 30 kHz	100 – 10 km	Maritime Navigation signals
Low Frequency (LF)	30 – 300 kHz	10 – 1 km	Navigational aids
Medium Frequency (MF)	300-3000 kHz	1 km – 100 m	AM radio
High Frequency (HF)	3 – 30 MHz	100 – 10 m	Aircraft communications
Very High Frequency (VHF)	30 – 300 MHz	10 – 1 m	Aircraft communications
Ultra High Frequency (UHF)	300 – 3000 MHz	1 m – 100 mm	Aircraft radars, TV broadcast, Wireless LAN, Mobile phones
Super High Frequency (SHF)	3 – 30 GHz	100 – 10 mm	Space and satellites communications, Microwave systems
Extremely High Frequency (EHF)	30 – 300 GHz	10 mm – 1 mm	Radio Astronomy

For a civil UAS, the typical frequencies used for the different data links and transmission can be seen in Figure 34.
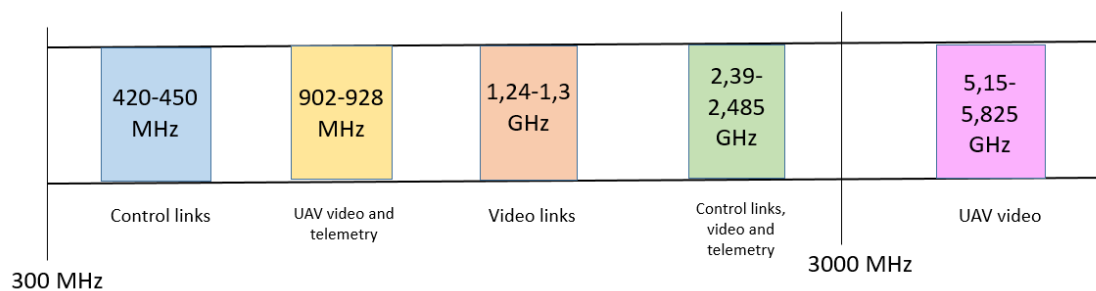
Figure 34: Frequencies generally used for UAV applications

In order to select a feasible frequency band, the following table summarizes the advantages and disadvantages of the most used in communication systems.

63

Table 23: Advantages and disadvantages of RF bands[49]

Frequency Band	Advantages	Disadvantages
430 MHz	- Multiple channels - Less range distortion due to weather - Less multipath distortion	- Do not enable video broadcast - Legal power transmitted restrictions
900 MHz	- Enables video broadcast - Low cost	- EU legal power transmitted restrictions - Interferences due to wide use (WLAN, phones, etc.)
2.4 GHz	- Enables video broadcast - Low cost	- Interferences due to wide use - LOS operational requirement - Legal restrictions
5,8 GHz	- Enables video broadcast - Small transmitting antennas	- LOS operational requirement - Range affected by air humidity - Expensive cost

Due to the high data rate needed for the UAV mission (Video broadcast), high frequencies are needed. The typical ones used in the market are 2.4 GHz and 5.8 GHz. The most potential problems that need to be avoided are interference issues, that can cause loss of control and flyways. A feasible solution is to avoid having two frequencies in the same band. Therefore, the most typical configuration used for civil UAV are combining 2.4 GHz with a 5.8 GHz link.[50]

- Data rate

The data rate is the number of bits transmitted per second through a digital transmission system, so is the speed of data transmission. For video streaming, the data rate needed is quite high. The minimum data rate for a good performance surveillance camera is 20 Mbps, however if more definition is needed the data rate can reach values of 2 Gbps. Therefore, the data rate depends on the camera and a value can't be assumed.

The bandwidth is the difference between the highest and the lowest frequency of a signal. This concept is very related to data rate and in some fields of communication can be used as synonyms[51]. The higher is the bandwidth, the higher needs to be the data rate. In applications where video streaming is the main function to be developed, the bandwidths are excessive and consequently, a data processing task has to be provided in order to accomplish bandwidth compression.

The analysis of the data processing system has been contemplated as out of the project scope and therefore it is an issue that can be developed in future considerations.

- UAV Antenna

Regarding to the direction of propagation, there are two types of antennas:

- Omnidirectional: antenna that transmits signals in all directions with uniform power.
- Gain antenna: it concentrates the beam power in one direction. With this antenna the effective radiated power increases. However, the antenna must be always sending the data in the direction of the receiver, that will be mounted in the aerial vehicle. This requirement introduces complexity to the system due to the fact that pointing commands need to be send.

In order to avoid complex solutions and after a brief market research, omnidirectional antennas are the most used for civil applications. The main parameters to select the antenna are the frequency band in which they can send signals, the gain and finally the weight. Taking into account the range of frequencies selected for the data link (2.4 GHz and 5.8 GHz), some antennas in the market can be seen below. The main manufacturers consulted are Cobham[52] and Pharad[53].

Table 24: Market research Antennas

Frequency (GHz)	Gain (dBi)	Weight (g)	Size (mm)
1 - 6	2 (Nominal)	190	134x59 ⌀
2 - 18	2 (Nominal)	600	104x39 ⌀
1.7 - 6	1.3 (1.8 GHz) 3.1 (4.2 GHz)	5.7	63.5x35.5x0.2
0.8 - 6	2.4 (0.8 GHz) 4.3 (1.5 GHz) 5 (6 GHz)	75	130x23x114
0.8 - 6	2.4 (0.8 GHz) 4.3 (2.4 GHz) 5.2 (5.8 GHz)	5.7	125x51x0.2
0.225 - 6	0 (200 MHz) 2.1 (0.6 GHz) 2.7 (0.9 GHz) 3.1 (2 GHz)	29	340x260x0.2

	4.1 (3.6 GHz)		
	5.7 (5.8 GHz)		

- Radio Modem

It is necessary to provide an on-board radio modem in order to transfer and receive the data. Therefore, the data link between the aerial vehicle and the ground control station is established.

The idea is to have a transceiver on-board and at the ground control station so the data communications are accomplished. The less expensive solution is using XBee telemetry kit, an open-source telemetry module. It requires configuration and installation but is a low cost solution for creating Radio Private Networks.
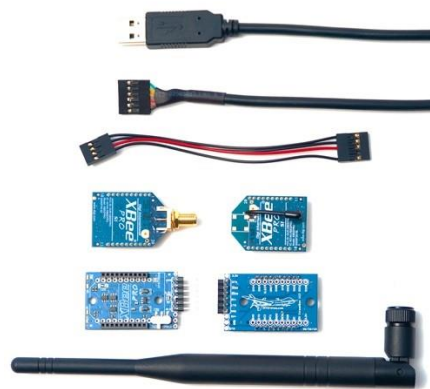
Figure 35: Radio Telemetry kit for 2.4 GHz[54]

The price for the radio telemetry kit is of 115€. [54]

7.3.3. Ground Control Station

7.3.3.1.   Functions and components

The ground control station is the main subsystem for controlling unmanned vehicles. The functions of a GCS can be divided into planning and operation functions[26]. The planning functions are:

- Design of flight routes (waypoints)
- Study of the mission area using maps
- Imposing mission requirements such as altitude, speed, etc.
- Process the planning messages

On the other hand, the operation functions are listed below:

- Launch, control and recover the UAV
- Control and monitoring of the payload
- Monitoring UAV position (GPS)
- Change mission planning requirements
- Display sensor data received from the UAV

- Save useful data

The basic components for a GCS can be seen in the following figure:

Figure 36: Example of portable GCS **[55]**

For civil applications, the most used GCS are portable and are composed by the following items:

- Antennas to receive and transmit data
- Computer where the software would be installed
- Screen Display for monitoring some sensor data
- Batteries to provide power to the GCS and the corresponding power status display
- Joystick to control the UAV
- GPS antenna
- Electronic compartment where data links, video receivers, data acquisition devices and data storage drives can be installed
- Set of interfaces for other devices: USBs, Ethernet, video inputs, serial ports, VGA, microphone, audio

3.3.3.2. Software

The software selection depends on the flights modes desired and mission requirements such as video streaming, flight planning, return to launch site among others. In order to have a first approximation of what the software should provide, the principal functions and flight modes have been described.[56]

- Map planner

As was commented above, the possibility to design the route before starting the mission is one of the main functions of the GCS. By using waypoints, the route can be programmed and, in some cases, some basic parameters can also be fixed.

- Camera control

Capturing images manually or generate a photo/video survey plan so that the camera can do it automatically.

- Stabilize mode and automatic mode

Changing from autonomous flight to manual control flight needs to be ensured. This allows inspection when an alarm is activated.

- Altitude hold mode

This flight mode maintains the UAV altitude constant.

- Return to launch mode

The purpose of this flight mode is that the UAV can return autonomously to the launch site if it gets out of the line of sight. It is a security measure.

- Landing mode

A function that sends the command of landing the UAV.

- Alarm mode

If the UAV detects an anomaly, an alarm signal needs to be sent to the GCS. Then the software should provide a sensory stimulation so that the user can act to prevent any trouble.

There are different types of ground control station. The most used ones are RC that use a smartphone or a tablet as the device for the software and video streaming. As a more professional option, there are GCS that use laptops, extra screens, etc. An example of these last GCS can be seen in Figure 36. In order to maintain the costs as low as possible the simpler control stations have been selected.

The problem of selecting it from a market research is that the manufacturers design their own controllers and in consequence they only work with specific drones. However, in order to estimate the cost of the GCS, it has been considered a 1000 € laptop, a 1000 € data link and a 1000€ software.

7.4. Payload

7.4.1. Introduction

The payload consists of all the instruments needed for the development of the mission. Therefore, all the equipment necessary to fly, navigate and recover are not considered as payload. The most common payloads are cameras.

The payload selection criteria is based on the mission requirements. Therefore, the objectives of the mission needs to be clearly detailed. Furthermore, the weight is the most critical parameter while selecting the instruments. The trend is minimising the weight but generally better quality instruments are heavier. Due to this inconsistency, the decision of the payload is not trivial.

7.4.2. Mission requirements

As commented in 6.3, the typical mission requirements for a surveillance UAS are:

- Recognition: Determining which class an object belongs to. For example, the sensor needs to differentiate a tank from a person.
- Detection: Determining objects of interest. As an example, if there is some movement, the UAV needs to measured it and detect it.
- Video streaming during day and night: Allowing the user to watch the video recorded by the camera.
- Panoramic view of 360°

7.4.3. Description of the payload

According to the mission requirements, the principal payload for a surveillance UAS are day and night-vision cameras with IR imaging. The technology related with camera sensors had experienced a rapid growth in the last years. Therefore, in the actual market it can be found both cameras, day and IR night-vision, in one device. They also incorporate object tracking software and HD streaming.

Taking into account the mission requirements, the following characteristics should be provided by the camera:

- Gyro-stabilized gimbal

Nowadays, nearly all UAV cameras are gyro-stabilized. This means that by using a gimbal, the image is stabilized automatically due to the free rotation about a single axis.

- Multi-sensor

As commented above, in the actual market multi-sensor cameras can be found. The main sensors that needs to be provided are the Electro-Optical sensor and the IR sensor.

The EO sensors are able to convert light rays into electronic signals so that it can be read by an instrument. This type of sensor enables the UAV to detect movement. [57]

On the other hand, the IR sensors are necessary for night surveillance. There are two types of night-vision cameras based on IR sensors: image enhancement and thermal imaging.
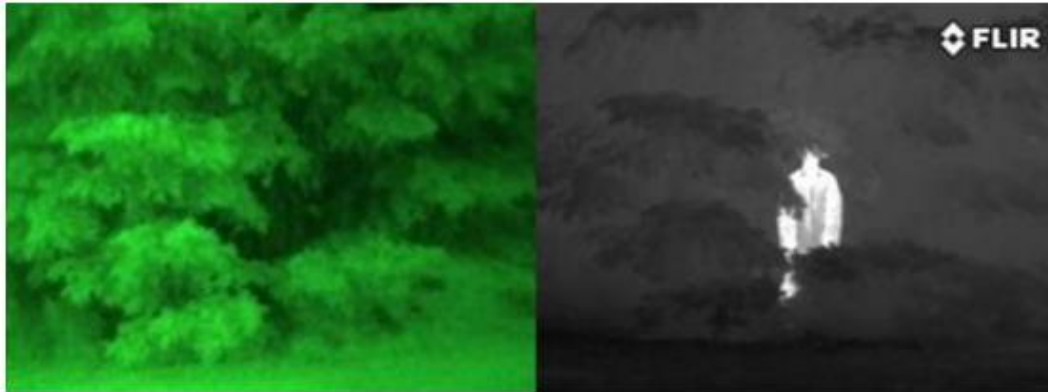
Figure 37: Comparison between image enhancement (left) and thermal imaging (right)[58]

Both types of night vision work in different ways. Thermal imaging captures the upper portion of the infrared light spectrum. Any object emits in this infrared light as heat. In this way, hotter objects emit more of this light than cooler ones. Thermal imaging is achieved by using lens that are able to focus the infrared light emitted by all the objects in view and by using a phase array of infrared detector elements, a temperature pattern called thermogram is created. This temperature pattern is transformed into electric impulses and finally into data for the display.

Image enhancement is able to collect tiny amounts of light, including the lower portion of the infrared light spectrum, and amplifies it. These type of cameras uses a photocathode to convert the light photons into electrons. Then, then electrons are amplified by means of a microchannel plate and finally hit a screen coated with phosphors that transforms the electrons again into photons. The green image is due to the phosphors. [59]

Regarding to surveillance applications, the thermal imaging cameras are one of the most effective devices. While image enhancement only amplifies the tiny light of objects during night, thermal imaging enables detection in many different

scenarios[58]. For example, it can detect persons that are hidden or view through smoke. The different in effectiveness can be seen in Figure 37.

Once the different night-vision sensors are described, it can be concluded that thermal imaging is the best option.

- On-board Image processing

This specification is related to the communication system. The on-board processing enables reducing data rate so that the data link requires lower bandwidths.

- Electronic video stabilization

It is of extreme importance that the camera includes electronic video stabilization. Electronic video stabilization consists on algorithms that modules the camera motion in order to correct the images. Therefore, it removes all the vibrations generated by the UAV and the wind.

- Object tracking

The function of video tracking is to allocate a moving object over time. While tracking a target, the camera is able to hold it in the centre of the vision and zoom it. This is done by means of localization algorithms.

7.4.4. Market research

Taking into account the payload description, a market study for different UAV cameras has been done.

- Epsilon 140 dual Sensor Payload

Figure 38: Epsilon 140 **[60]**

Table 25: Epsilon 140 specifications[60]

Epsilon 140 Specifications	
Weight (kg)	1.5
Size (mm)	Ø140 x 189
Camera Rotation	360 ° (Azimuth) -90° to +45 ° (Elevation)
Power	8 W (15 W peak)
Input Voltage	10 – 16 V
Digital Video Output	720p HD output
Object Tracking	Yes
Software stabilization	Yes
Resolution	720p HD
EO sensor	Yes
Optical zoom	30x
IR night sensor	Yes
IR resolution	640x480
Human target detectability	2000 m
Price[61]	≈ 40 000 €

- UAV VISION CM100

Figure 39: CM100 [62]

Table 26: CM100 Specifications[62]

CM100 Specifications	
Weight (kg)	0.8
Size (mm)	Ø100 x 129
Camera Rotation	360 ° (Azimuth) ±115 ° (Elevation)
Power	12 W
Input Voltage	9 – 36 V
Digital Video Output	1280 x 720
Object Tracking	Yes
Software stabilization	Yes
Resolution	1280 x 720
EO sensor	Yes
Optical zoom	30x
IR night sensor	Yes
IR resolution	640x480

The price of the CM100 was requested to the manufacturer UAV Vision and the information received can be seen in the table below:

Table 27: CM100 prices

Product	Description	Price USD
CM100	Gimbal with EO Sensor only	$26,459
336 IR	Gimbal with EO and 336 IR Sensor	+$3,818
640 IR	Gimbal with EO and 640 IR Sensor	+$7,852
KLV	KLV Data	+$361
OT	Object Tracking	+$6,170
GEO-S	GEOLock Standard	+$5,050
AIS	Aerial Information System Software	+$4,290

- Zenmuse XT Thermal camera

The Zenmuse camera was designed for the DJI Inspire UAV. However, FLIR Systems Inc. had developed a new version that incorporates thermal vision. The specifications can be seen in the following table.

Figure 40: Zenmuse XT[63]

Table 28: Zenmuse XT Specifications[63]

Zenmuse XT Specifications	
Weight (kg)	0.6
Size	136 mm (W) x 125 mm (H) x 131 mm (D)
Camera Rotation	360 ° (Azimuth)
Power	19.5 W (25 W peak)
Digital Video Output	4096x2160
Resolution	4608x3456
CMOS sensor	Yes
Digital zoom	4x
IR night sensor	Yes
IR resolution	640x512
Price[64]	10 170 €

As can be seen, the technology involved in these type of cameras is really demanding. Therefore, the prices can reach values of 20 000€. Although the type of camera that should be implemented in the solution have been described, for the economical approach study will be considered as an extra equipment.

7.5. Flight Control System

7.5.1. Introduction

The flight control system consists of all the sensors and hardware/software needed for perform a controlled flight. It consists of a microprocessor, sensors and input/output pins.

The sensors such as gyroscopes, accelerometers, barometer and GPS collects data and by means of a microprocessor, calculations are made and if any correction is needed, it is done automatically.

7.5.2. Sensors

The sensors used for the flight control system are described below:

- Gyroscope

The main application of the gyroscope is to measure angular changes in the three angular axes and later by using a software this information is transform into a position. The most commonly used are the vibrating structure gyroscopes due to the affordable price, the small size and the ease to buy. It is based in Coriolis acceleration, that is induced when the system is rotating. [65]
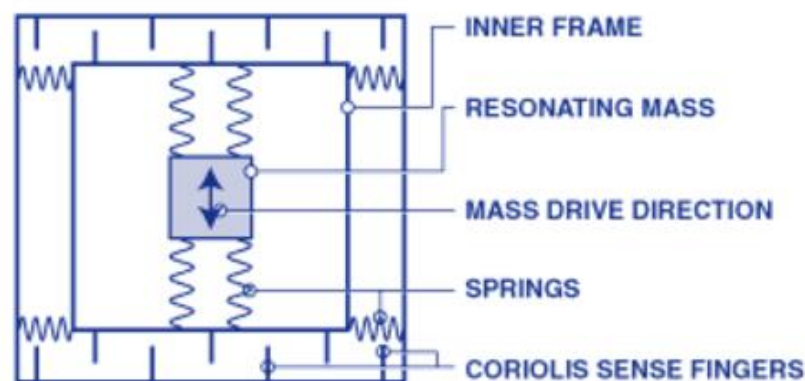
Figure 41: Vibrating structure gyroscope scheme[65]

The mass is pushed up or down by the Coriolis force. When the mass is closer to a Coriolis sense finger, a potential difference is produced and consequently the angular velocity is measured.

- Accelerometer

This sensor is used for measure linear acceleration in the three axis. In stationary conditions the accelerometers mark 9.8 m/s, due to the force of gravity that all object on Earth experience. The measurement unit used by the accelerometer are g's that is equal to 9.8 m/s^2. Therefore, at stationary conditions the accelerometer should mark 1 g. Due to the fact that they can detect gravity, the accelerometers can inform to the computer of which direction is down. In this way, as an inclinometer, the accelerometer plays an important role for stabilizing the UAV. [66]

- Compass

Compass are used for detect the direction of the drone with respect to the north magnetic. As the sensors explained above, this sensor can also be used in the three axis. [66]

- Inertia Measurement Unit

The IMU is an electronic device that combines the three sensors explained above. It contains 3-axis accelerometers, 3-axis gyroscope and in some cases 3-axis magnetometers. The accelerometer is in charge of measuring the non-gravitational acceleration in the three axis and combined with the gyroscope, that measures pitch, yaw and roll, the UAV current position can be measured by means of a computer that is constantly calculating. The main drawback of this type of device is the cumulative error. Due to the fact that the system is continually uploading the data, if there is a measurement error this is accumulated. The most common solution is to add the magnetometers to assist calibration and consequently a better performance for dynamic orientation calculation is achieved.[67]
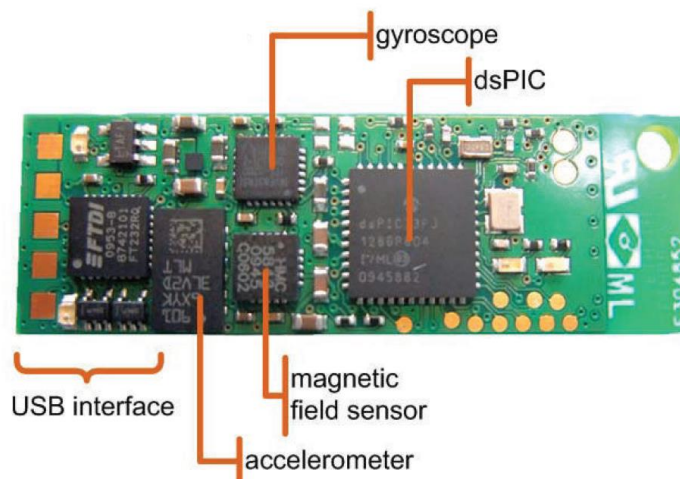
Figure 42: IMU[67]

- GPS

As was commented in 7.3, the GPS uses the signals transmitted by a number of satellites in order to determine the geographical location. It is quite often that the flight control system incorporates a GPS chip that acts as a receiver.

- Barometer

The barometer can be used for calculating height from atmospheric pressure measurements. Most flight controllers combine the pressure measurements with the GPS altitude to calculate an accurate height.

7.5.3. Autopilot

The autopilot or flight computer collects the information through the sensors and directs automatically the flight by monitoring using the control surfaces.

7.5.4. Architecture

A simplified way to schematize the different connections in a flight control system is by means of a block diagram. The following diagram is a simplification that shows how the flight control system works.
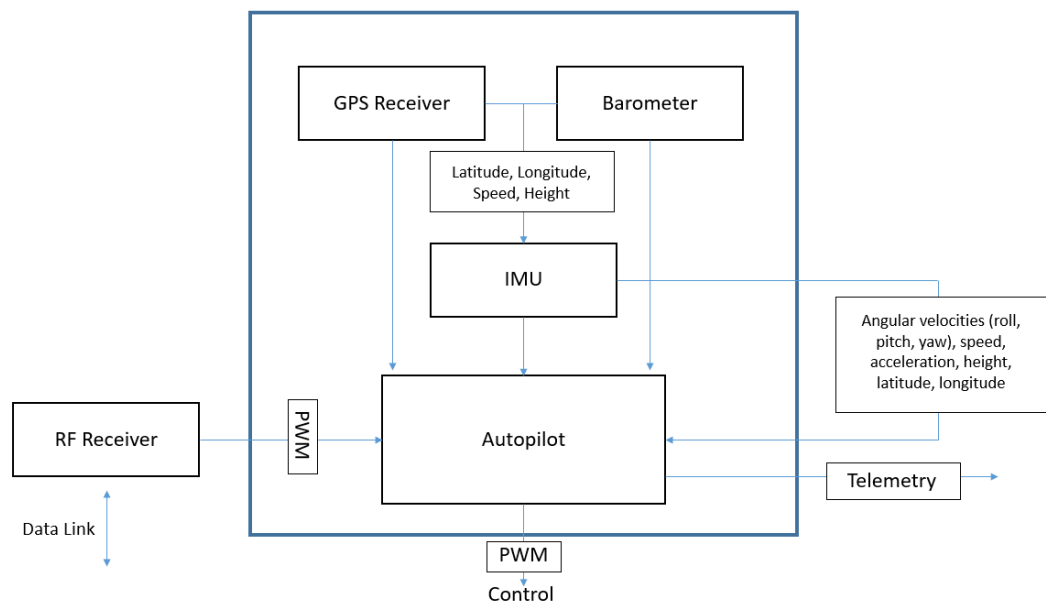
Figure 43: Flight control system architecture

The GPS receives from the satellite latitude, longitude and speed data. Furthermore, by using the barometer, accurate height data of the vehicle is measured. This data is transferred to the IMU that calculates the angular velocities and the accelerations. Finally, all the data is received by the flight computer that

monitors the trajectory and calculate the corrections needed. These corrections are implemented and therefore an autonomous control is achieved.

7.5.5. Market study

- Commercial Autopilots

A market study of autopilots for UAV have been developed in order to analyse what specifications provide. It is quite often that the autopilot includes all the sensors commented above, therefore the term autopilot it refers to the computer and sensors.

In Spain there are important companies that manufacturer autopilots worldwide. One of these industries are UAV Navigation located in Madrid. The autopilots that this company manufactures have been proved in really extreme conditions such as controlling drones that reach 700 km/h. Therefore, the technology involved on their products is quite innovative and very well considered in the global market. [68]

The specifications of two basic autopilots from this company have been summarized.

Vector

The Vector is the most advanced autopilot that UAV Navigation have designed. The characteristic that makes this autopilot so special is reliability. Although a sensor failure takes place, the vector can continue developed his functions by estimations of attitude and position.

Figure 44: UAV Navigation VECTOR Autopilot[69]

Table 29: VECTOR specifications **[69]**

VECTOR Autopilot specifications	
Weight (g)	180
Size (mm, H x W x L)	45 x 68 x74.5
Flight control	Fully automatic, multi-waypoint, 3D flight-plan following
Axis	3 (roll, pitch, yaw)
Auto take-off/landing	Yes
Gyro-stabilization	Yes
Power Consumption (W)	2.5
Supply	9V to 36V DC
Number of Flight Control CPU	2
GPS Antenna connection	50 Ohm SMA Female
PWM rate	50 Hz or 200 Hz
PWM signal	1ms to 2ms high

AP04

This autopilot has been successfully used in many UAVs since 2004 and it suits in all kind of UAVs (rotatory and fixed wings).

Figure 45: APO4 Autopilot[70]

Table 30: AP04 specifications[70]

AP04 Autopilot specifications	
Weight (g)	173
Size (mm, H x W x L)	45 x 68 x74.5
Flight control	Fully automatic, multi-waypoint, 3D flight-plan following
Axis	3 (roll, pitch, yaw)
Auto take-off/landing	Yes
Gyro-stabilization	Yes
Power Consumption (W)	2.5
Supply	9V to 36V DC
Number of Flight Control CPU	2
GPS Antenna connection	50 Ohm SMA Female
PWM rate	50 Hz or 200 Hz
PWM signal	1ms to 2ms high
Altimeter (AIR DATA SYSTEM)	0 to 6000m
Max acceleration	10G
Max angular rate	300°/s
Magnetometer attitude compensation	Yes

Another important Spanish manufacturer is Embention, based in Alicante. This company started its activity by designing autonomous bombs. However, this technology was later applied to designing UAVs and nowadays they are one of the references in the industry.

Veronte Autopilot

The autopilot they have designed it is composed of the flight computer and all the sensors needed. Therefore, they manufacture the complete flight control system. The sensors included in the Veronte autopilot have been tabulated:

Table 31: Veronte Autopilot list of sensors[71]

Veronte Autopilot sensors	
Static pressure	15 – 115 kPa
Dynamic pressure	4 kPa (@290 km/h & SL)
Accelerometers (3 axes)	±6 g in maintained maneouvre
Rate-gyroscopes (3 axes)	±300°/s
Magnetometers (3 axes)	±6 Gauss (compensated)
GPS	4 Hz receiver
Voltage sensor	-
Temperature sensor	-

The specifications can be seen in the following table:

Table 32: Veronte Autopilot specifications[71]

Veronte Autopilot specifications	
Weight (g)	200
Size (mm, L x W x H)	69 x 53 x 49
Control surfaces	Aileron, flap, elevator, rudder, gas, etc.
Flight modes	Fully autonomous flight, assisted control and manual control
Data Links	900 mHz/ 2.4 GHz/ Other
Power Consumption (W)	4
Supply	6.5V to 36V DC
Number of Flight Control CPU	2

- Open-source Autopilots

The purpose of the open-source autopilot projects is to create a start point data about the flight control system so that the UAV industry can grow faster. Uploading the autopilot code and explaining how to build it up, they promote the interest of

UAV in society. Nowadays, there are a lot of people who design their own UAV and they use the open-source autopilot design. One of these open-source project has been described below.

Paparazzi UAV

Paparazzi is a complete open-source hardware and software for UAS. The autopilot, GCS and monitoring software using a bi-directional datalink is included. A scheme of the different components that the Paparazzi project include in the design can be seen in Figure 46.
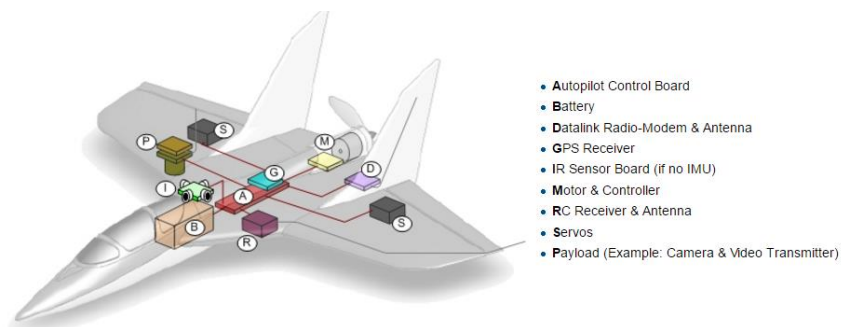
Figure 46: Paparazzi components[72]

There are many different autopilot versions. One of the most completed versions is Lisa/S, developed by Delft University of Technology. The specifications of Lisa/S can be seen in the following table.
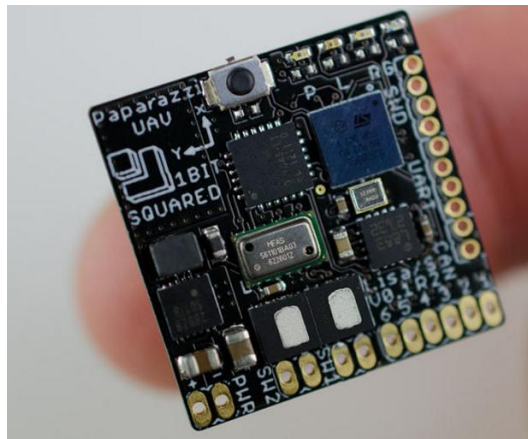
Figure 47: Lisa autopilot[73]

Table 33: Lisa/S specifications[74]

Lisa/S Autopilot specifications	
Sensors	
IMU (3 axis) Magnetometers Barometer GPS	
Weight (g)	2.8
Size (mm, L x W x H)	20 x 20 x 5
Price	385 €
Supply	2.3V to 5.5V

The Autopilot system considered for the solution is the Lisa/S due to the low price in comparison with the commercial ones.

7.6. Power supply

7.6.1. Power requirements

Providing an on-board generator system is of crucial importance due to the energy consumption that the flight control system and payload have. Taking into account the market research on payload cameras and autopilots, the following power requirements are needed:

Table 34: Power supply specifications

Supply	9 – 36 V
Power Consumption	15 W

7.6.2. Battery selection

For a UAV application, the batteries that supply power to the different instruments such as payload cameras and the flight computer need to combine high capacity with lightweight design. The actual batteries that offer these two characteristics are lithium polymer batteries.

For selecting the battery, some calculations need to be done. The specification of a LiPo battery designed for UAV applications can be seen in the following table:

Table 35: Tattu LiPo battery pack specifations [75]

Tattu LiPo Battery Pack specifications	
Capacity	9000 mAh
Voltage	14.8 V
Weight	809 g
Dimensions	208x73x25 mm
Price	120 €

With the power supply requirements, the following calculation have been made:

$$Power\ system\ requirement = 15\ W$$
$$Battery\ voltatge = 14.8\ V$$
$$Battery\ capacity = 9\ Ah$$
$$Voltatge\ system = \frac{15\ W}{14.8\ Ah} = 1.0135\ A$$
$$Time\ of\ power\ supply = \frac{9\ Ah}{1.0135\ A} = 8.9\ h$$

It can be concluded that the battery is able to supply power to the UAV for a large duration mission.

7.7. Landing Gear

The function of the landing gear is to bear the impact loads during the landing phase and to provide directional control during take-off. In terms of performance, the landing gear increases drag during flight.

According to the market study, one of the most frequently method for launching is the use of catapult. Therefore, the landing gear needs to be removable in case the take-off is done by catapult.

The different types of landing gear have been described below:

- Tricycle

This configuration provides the UAV of good stability when rolling. However, it has the drawback that aerodynamically introduces a source of drag considerable.

- Conventional landing gear

It consists of two main wheels at the forward part of the fuselage, by the centre of gravity and a small wheel or skid at the tail. It is compatible with catapult launcher. The main drawback is that the directional control is not as good as for the tricycle.

In order to save weight and to have the most efficient configuration, the conventional landing gear has been selected.

After a brief market research, the possibility to buy the landing gear separately has been difficult to find. Therefore, needs to be design it for the specific mission. Although it has been considered out of the scope, a description of the materials used and a weight estimation has been done.

The materials used for an UAV landing gear are basically aluminium for the bars and the wheels.

Figure 48: Example of landing gear [76]

Taking into account the typical density of the aluminium 6061(2.7 g/cm^3)[77] and the possible dimensions of the landing gear (70 cm x 5 cm x 0.5 cm), a 0.5 kg is obtained for the main bars. Adding a 100 g per wheel, an estimated weight of 0.7 kg is obtained.[78]

7.8. Structure

The design of the internal structure is considered out of the scope of the study. However, the materials that are used for the UAV construction have been described.

7.8.1. Wings

The structure of the wing consists basically on a front spar, a rear spar, the ribs and the skin panel. The internal structure of an UAV wing can be seen in Figure 49.
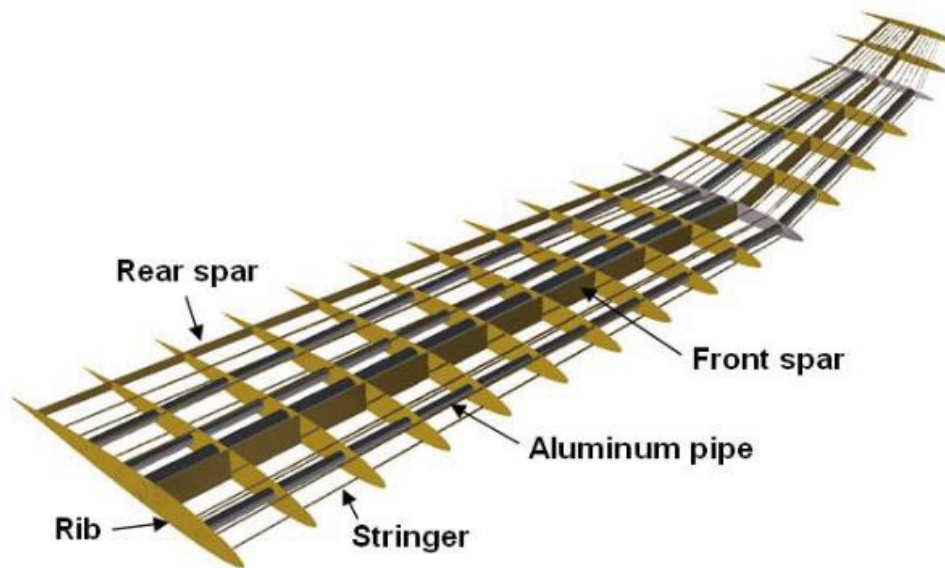
Figure 49: Example of the internal structure of an UAV wing[79]

One of the materials that suits better for the front spar is the carbon fibre. The main advantage related to the carbon fibre is that it has high strength and low weight. For the ribs and the rear spar, balsa wood is commonly used. This type of wood can be very lightweight and conserves a high strength. It also absorbs the vibrations quite well and can be easily worked. [80]

Finally, the internal structure is covered by a composite skin. The most used composites are fiberglass and carbon fibre. However, due to the fact that carbon fibre is much more expensive, the fiberglass is a better option. [81]

The material used for the reinforcements is also fiberglass composite.

7.8.2. Fuselage

The fuselage consists of a semimonocoque structure that consists on the formers linked longitudinally by the stringers and finally the skin that covers all this internal structure. The materials used are the same as the wings. Thus, composite materials predominate.

7.8.3. Tail

Finally, the tail can be considered as a wing so the internal structure is equal. However, only one spar is needed. Regarding to the tailboom that goes from the fuselage to the tail, a carbon fibre tube can be used.

7.9. Assembly system

The design of the assembly system it is also considered to be out of the scope. However, a main description has been made in order to provide the general idea that needs to be developed in future works.

The high wing configuration allows the independence between the fuselage and the wing. Therefore, an assembly system for putting together the wing with in the fuselage needs to be ensure it. The wing itself, needs to be separated between 2 parts as the 3 m wingspan is difficult to transport.

Regarding to the tail, the tailboom that connects it with the fuselage has to be able to be disassembled so that they can be transported separately. This needs to be ensured due to the length of the tailboom. Also an assembly system between the horizontal and vertical tail will facilitate the carrying.

An example is presented in order to illustrate a feasible assembly system. The following UAV is Penguin B model, commented at the market research.
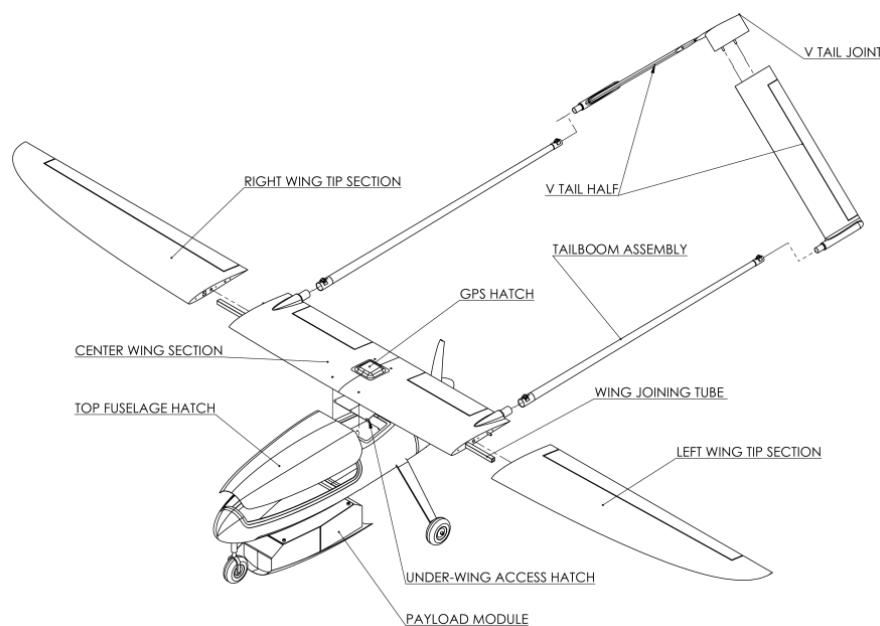
Figure 50: Assembly system of the Penguin B UAV[82]

7.10. Performance

Some performance parameters must be calculated in order to study later the feasibility of the solution proposed by comparing with other UAS on the market. The following parameters will be studied:

1) Stall velocity
2) Range and Autonomy
3) Turning
4) Take-off
5) Landing

7.10.1. Weight budget

In order to calculate the different parameters, a weight estimation is needed. The MTOW was fixed at 20 kg. This value was selected taken into account the market

research and trying to design a UAV similar to Penguin B, the fixed-wing UAV with the higher endurance. However, after the solution is proposed a weight budget needs to be done in order to verify the MTOW considered at the beginning of the study.

The most important weight related to the critical parameter of flight time is fuel weight. For Penguin B UAV, the fuel tank is about 7.5 L. The engine selected works with JP8 fuel, that has a density approximately of 0.8 kg/L.[83] So an estimated fuel weight has been calculated:

$$W_f = 7.5\ L \cdot 0.8\frac{kg}{L} = 6\ kg \tag{18}$$

Some considerations regarding the materials weight have been taken in order to calculate an approximate weight of the UAV.

- Fuselage

Taking into account the dimensions of the fuel tank, the payload camera and the flight control system, the following fuselage has been considered in order to estimate a price:
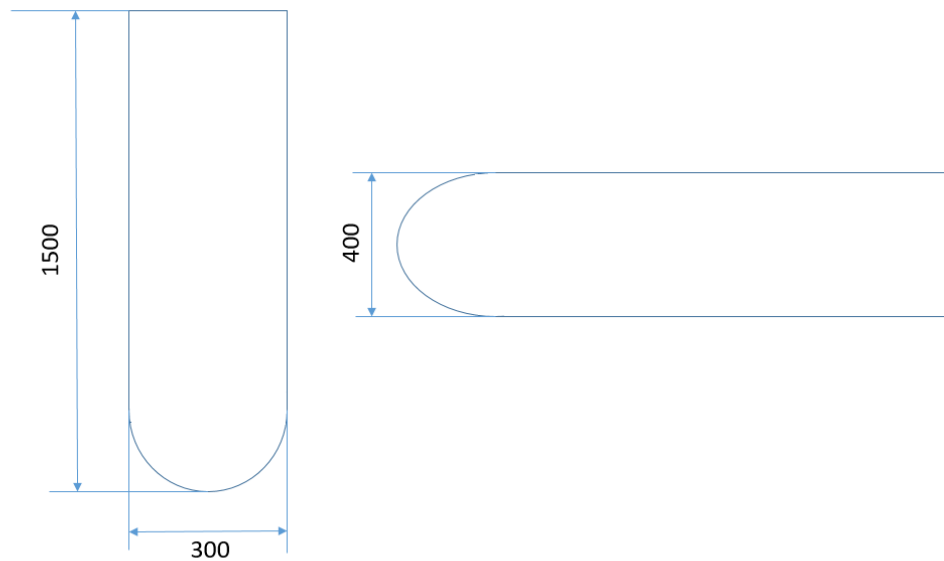
Figure 51: Fuselage estimated dimensions (dimensions in mm)

The approximated fuselage surface that needs to be covered by GFRP is of 2.3 m². Considering a thickness of 0.7 mm we obtain a volume of 0.0016 m³. Since the GFRP has a density of 2100 kg/m³, the skin weights 3.38 kg.

The internal structure cannot be estimated without a previous design. However, an internal structure mass of 2 kg has been considered. The material used for the semimonocoque structure is CFRP. This assumption is a guess that can introduce a source of error. Thus, a verification needs to be done in future improvements. The total weight of the fuselage is of 5.38 kg. This total weight includes the CFRP tube that joints the tail with the fuselage.

- Wing and tail

The surfaces for the wing and tail calculated by the XFLR5 software can be seen in the following table:

Table 36: Surfaces calculated in the XFLR5 software

Wing	$0.525 \ m^2$
Vertical stabilizer	$0.07 \ m^2$
Horizontal stabilizer	$0.16 \ m^2$

Considering a skin thickness of 0.7 mm, a total GFRP volume of $5.29 \cdot 10^{-4} \ m^3$ is obtained. Taking into account the GFRP density, the total skin weights 1,1 kg. For the internal structure, 2 carbon fibre front spars of 1.5 m each with a cross section of 2 cm of diameter has been considered. Thus, the total volume is 942 cm^3. Taking into account the CFRP density of 1600 kg/m^3, a total spar weight of 1.5 kg is obtained. For the ribs and the rear spars, that are made of balsa wood, an estimation cannot be done. Thus, the assumption of 2 kg of balsa wood is done.

Table 37: Weight estimation

Payload weight	1.5 kg
Flight control system	0.2 kg
UAV modem	0.15 kg
Fuel weight	6 kg
Engine	2.7 kg
Power supply	0.8 kg
Structure estimated weight	
Fuselage	5,4 kg
Wing and tail	4.6 kg

TOTAL	21.35 kg

Since the estimated weight is close to the MTOW fixed at the beginning of the study, for the following performance calculations it has been used a 20 kg value.

7.10.2. Stall Velocity

The stall velocity is the velocity achieved in the point where an increase of angle of attack leads to a decrease of lift coefficient. The angle of attack at which this occurs is the critical angle of attack and the lift coefficient is maximum. The unexpected fall of the lift coefficient is due to the fact that the boundary layer is detached, producing an extreme increase of drag and lift loss.

To calculate the stall speed, the lift equation is used. It is determined by calculating the speed for the maximum lift coefficient as (19) shows. The lift force can be considered equal to the weight for a horizontal flight.

$$W = L = \frac{1}{2} \cdot \rho \cdot S \cdot V^2 \cdot C_L \tag{19}$$

and the stall speed can be expressed as:

$$V_{stall} = \sqrt{\frac{2 \cdot W}{S \cdot \rho \cdot C_{L_{max}}}} \tag{20}$$

The stall speed can be calculated using the sea level air density, the weight estimated and the maximum lift coefficient from the last XFLR5 simulation.

$$V_{stall} = \sqrt{\frac{2 \cdot 20 \, kg \cdot 9{,}81 \frac{m}{s^2}}{0{,}525 \, m^2 \cdot 1{,}225 \frac{kg}{m^3} \cdot 1.4328}} = 20.636 \frac{m}{s}$$

7.10.3. Range and endurance

A simply way for calculating the maximum range and endurance of the UAV is using the Breguet equations for a propeller aircraft. Although this method is an idealization, it gives an approximated idea of the capabilities of the UAV. The Breguet equations are[84]:

$$x_{emax} = \frac{E_m}{c_p} \cdot \eta_p \cdot \ln\left(\frac{1}{1 - \frac{W_f}{W}}\right) \tag{21}$$

$$t_{max} = \frac{E_m}{c_p \cdot V_{Bi}} \cdot 3^{3/4} \cdot \left(\frac{1}{\sqrt{1 - \frac{W_f}{W}}} - 1 \right) \tag{22}$$

Where:

- x_{emax} is the maximum range
- $E_m = C_L/C_D$ is the maximum efficiency
- C_p is the specific consumption of the engine
- η_p is the propeller efficiency
- W_f is the fuel weight
- t_{max} is the endurance
- V_{Bi} is the velocity at maximum efficiency

The specific consumption data can be founded in the engine specifications, the maximum efficiency is known from the last XFLR5 simulation, the propeller efficiency has been fixed to 70%, the fuel weight ratio from the weight estimation and the velocity at maximum efficiency from the XFLR5 simulation. Therefore, the endurance and range are calculated.

First, the specific power consumption is calculated by using the following equation[84]:

$$c_p = \frac{\varphi \cdot g}{P_m} \tag{23}$$

where φ is the mass consumption, g the gravitational acceleration and P_m the engine power.

Using the engine information presented in 7.1.2.4, the specific power consumption is calculated:

$$c_p = \frac{\varphi \cdot g}{P_m} = 330 \frac{g}{kW\,h} \cdot \frac{1\,kg}{10^3\,g} \cdot \frac{1\,kW}{10^3\,W} \cdot \frac{1\,h}{3600\,s} \cdot 9.8 \frac{m}{s^2} = 9 \cdot 10^{-7} \frac{1}{m}$$

Therefore,

$$x_{emax} = \frac{35.383}{9 \cdot 10^{-7}} \cdot 0.7 \cdot \ln\left(\frac{1}{1 - 0.3}\right) = 9.8 \cdot 10^6\,m \cong 9800\,km$$

$$t_{max} = \frac{35.383}{9 \cdot 10^{-7} \cdot 30.57} \cdot 3^{3/4} \cdot \left(\frac{1}{\sqrt{1 - 0.3}} - 1 \right) = 5.72 \cdot 10^5\,s \cong 160\,h$$

The results obtained are not realistic. This inconsistency in the results may be due to the fact that the Breguet equation is not a good approximation for UAVs, that operates at low Reynolds number and does not necessary perform large horizontal flights during the mission.

In order to have a more realistic view of the endurance that of the UAV proposed will ensure, a conceptual and simplified calculation has been made. Considering that the engine works all the time at maximum power, the mass flow rate for the JP-8 fuel is:

$$\varphi = 330\,\frac{g}{kWh} \cdot 4\,kW = 1320\,g$$

The maximum fuel weight is about 6 kg according to the weight budget. Therefore, the endurance at maximum power requirement is:

$$t_{P_{max}} = \frac{6000\,g}{1320\,\frac{g}{h}} = 4.5\,h$$

Half power requirement has been also studied:

$$t_{\frac{1}{2}P_{max}} = \frac{6000\,g}{330\,\frac{g}{kWh} \cdot 2\,kW} = 9\,h$$

This flight time is an approximation and it only gives the idea that the design requirement of having an autonomy between 2 and 12 h is accomplished. In real performance, there are many different factors that have to be taken into account. However, for a preliminary study this value can be considered.

Considering that the UAV flies at constant speed, a very simple calculation can be made to give an idea of the range. Taken into account the market study, a general cruise speed of 60 km/h has been considered:

$$Range = 4.5\,h \cdot 60\,\frac{km}{h} = 270\,km$$

This value is an ideal range that it is impossible to be reached. The range in a UAV is determined by the range of the communication link. However, if the communication link is interrupted, the UAV will be able to travel this distance and therefore needs to be taken into account.

7.10.4. Turning

As was commented during the design requirements, the UAV has to be able to loiter. A way to analyse the maneuverability of the vehicle is calculating the turn rate and the turn radio.
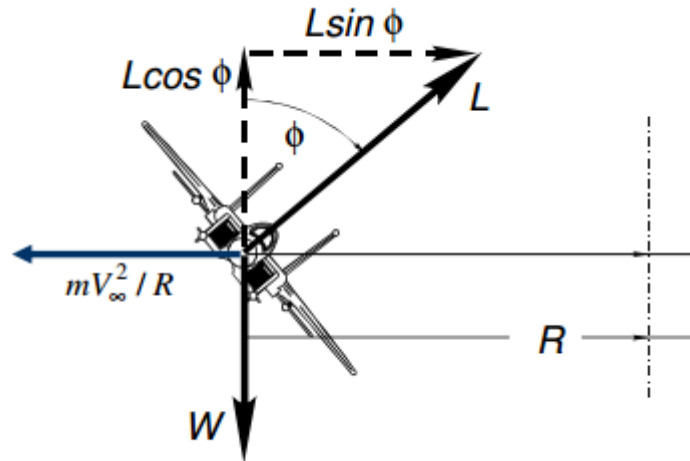
Figure 52: Distribution of forces during a turn[85]

An important parameter to take into account for the turning analysis is the load factor:

$$n = \frac{L}{W} = \frac{L}{L \cdot cos\phi} = \frac{1}{cos\phi} \tag{24}$$

where ϕ is the bank angle.

The turn rate can be expressed as[86]:

$$\dot{\psi} = \frac{g\sqrt{n^2 - 1}}{V} \tag{25}$$

Finally, from Figure 52, the equation for the turn radius is obtained:

$$L \sin\phi = m\frac{V^2}{R} \Rightarrow R = \frac{W}{L}\frac{V^2}{g \sin\phi} = \frac{1}{n}\frac{V^2}{g \sin\phi} \xrightarrow[\sin\phi = \sqrt{1-\frac{1}{n^2}}]{} R = \frac{V^2}{g\sqrt{n^2 - 1}} \tag{26}$$

With the results obtained in the last XFLR5 simulation, an analysis of the turn rates and turn radius have been done. The values for SL altitude and different bank angle angles can be seen in the Annex. However, the following table have been attached in order to comment the results obtained.

Table 38: Turn rate study for a bank angle of 45°

$\phi = 45$ °			
AoA (°)	V (m/s)	$\dot{\varphi}$ (°/s)	R (m)
0	49.41	11.38	248.86
0.5	44.53	12.62	202.13
1	40.86	13.76	170.19
1.5	37.98	14.80	147.04
2	35.63	15.78	129.41
2.5	33.67	16.69	115.56
3	32.01	17.56	104.45
3.5	30.57	18.39	95.26
4	29.31	19.18	87.57

With these results, an idea on how much it will take the UAV to loiter a specific area is obtained. As an example, for a turn of 45° with an angle of attack of 4 ° it takes 20 s to perform a complete turn. It can be considered a good time for overlooking a target during the UAV mission.

In order to study the effect of altitude in the turn radius, the following modification has been made:

$$R = \frac{2W}{\rho S C_L g \sqrt{n^2 - 1}} \tag{27}$$

The modification done consists on expressing the speed as function of the altitude by the lift coefficient equation. For an altitude of 1000 m the results obtained are the followings:

Table 39: Turn rate study for a bank angle of 45° at an altitude of 1000 m

$\phi = 45°$			
AoA (°)	V (m/s)	$\dot{\varphi}$ (°/s)	R (m)
2	35.63	4.23	139.93
4	29.31	5.14	94.80
6	25.51	5.90	71.83
8	22.92	6.57	57.93

The higher the UAV flies, the higher the turn radius. However, the difference between both turn radius is about less than 10 m.

7.10.5. Take-off

According to the UAV market study, the most used launch method is by catapult. However, a first approximation of the take-off distance has been made.

7.10.5.1.   Take-off distance

Take-off can be divided into three stages: ground roll, transition to climb and climb as can be seen in Figure 53. In order to compute the whole take-off distance, the three different stages need to be computed separately.
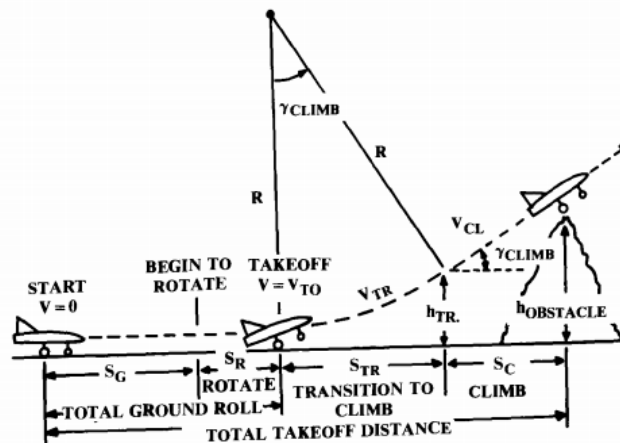
Figure 53: Different stages during take-off[86]

- Ground roll segment

The ground roll segment is divided in two distances: S_G and S_R. S_G can be calculated using the equation presented in [86]:

$$S_G = \frac{1}{2g} \int_{V_i}^{V_f} \frac{d(V^2)}{K_T + K_A V^2} = \frac{1}{2gK_A} \ln\left(\frac{K_T + K_A V_f^2}{K_T + K_A V_i^2}\right) \quad (28)$$

Where:

$$K_T = \frac{T}{W} - \mu \quad (29)$$

$$K_A = \frac{\rho}{2\frac{W}{S}} (\mu C_L - C_D) \quad (30)$$

Since the integration is solved for a constant thrust, an average value needs to be taken. This average value is the thrust at 70% of V_{TO}.

For small aircrafts, the time spent in the rotate stage can be approximated to 1s, therefore the S_R is equal to V_{TO}.

According to [86], the typical values for the friction coefficient μ of an asphalt runway are between 0.03 and 0.05.

- Transition to climb

For general aircrafts, the climb speed during the transition segment is 1.3V_{stall}. During this stage, the UAV describes a circular trajectory. The radius of this turn can be computed by the following equation:

$$R = \frac{V_{TR}^2}{g(n-1)} = \frac{V_{TR}^2}{0.2g} \approx 0.205 V_{stall}^2 \quad (31)$$

For calculate the distance S_T, the climb angle at the end of the transition needs to be computed. The following equation is used:

$$\sin\gamma = \frac{T-D}{W} \cong \frac{T}{W} - \frac{1}{L/D} \quad (32)$$

While the transition distance is:

$$S_T = R\sin\gamma = R\left(\frac{T}{W} - \frac{1}{\frac{L}{D}}\right) \quad (33)$$

The horizontal distance travelled is:

$$h_{TR} = R(1 - \cos\gamma) \quad (34)$$

- Climb

Finally, the last segment is calculated. The horizontal distance travelled during the transition stage is used for calculating S_C:

$$S_C = \frac{h_{obstacle} - h_{TR}}{\tan \gamma} \tag{35}$$

For a UAV application, the S_c can be considered null due to the fact that there is not obstacle that force the drone to overpass it.

The MATLAB code attached at the annex has been implemented in order to calculate the whole take-off distance.

The results obtained are:

$$S_{Ground\ Roll} = 28.73\ m$$

$$S_{Transition} = 63.94\ m$$

$$d_{TO} = 92.66\ m$$

The ground roll segment obtained is very similar to the roll distance for the UAV Penguin B, therefore it can be concluded that the results are realistic.

7.10.5.2. Catapult

As was commented above, the more used method for launching commercial UAVs is by means of a catapult. When the catapult is used for the take-off, the landing gear is no longer used, allowing a lighter TOW. Also, using it instead of a normal take-off, increases reliability due to the fact that the UAV will not suffer the friction loads and will avoid damages occurred by possibly obstacles in the runway. Therefore, is the most secure take-off method. Thus, the life of the product can be extended.

There are many different catapults in the market. Some examples have been studied:

- UAV Factory 6 KJ Portable Pneumatic Catapult

Table 40: UAV Factory Catapult specifications[20]

Rail Length	4 m
Maximum Launching Energy	6000 J
Maximum UAV weight	35 kg
Maximum Launch speed	24 m/s
Input Voltage	11 – 16 VDC
Weight	110 kg

- Aeromapper UAV Launcher

Table 41: Aeromapper UAV launcher specifications[87]

Rail Length	2.8 m
Weight	5 kg
Price	$1400

7.10.6. Landing

7.10.6.1.   Landing distance

For the calculation of the landing distance, the equations used for the take-off distance are used. The scheme of the landing phase can be seen in the following figure:
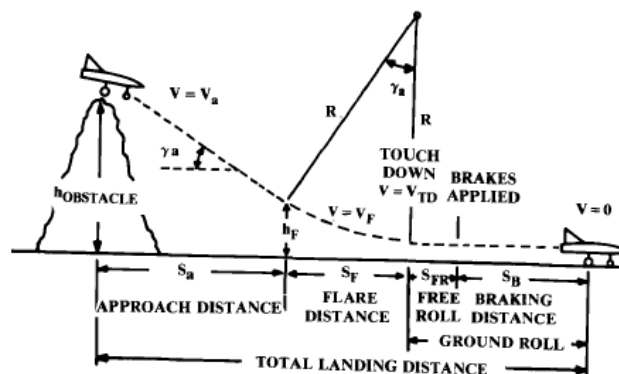

Figure 54: Landing phase scheme [86]

The first stage is approach. The approach distance can be calculated using equation *(35)* with a speed equal to 1.3 times the stall speed. For the take-off analysis, the $h_{obstacle}$ was considered zero. However, for landing calculations the approach distance is of special interest. Therefore, a $h_{obstacle}$ of 15 m have been considered.

The second stage is flare. During the flare the UAV changes from the approach speed to the touchdown speed that can be assumed 1.15 times the stall speed. Thus, the flare speed can be estimated in 1.23$V_{stall.}$ Finally, by means of the equations used for the transition to climb in the take-off analysis, the flare distance is calculated.

The ls stage is the ground roll that can be divided into the free roll and the breaking distance. The initial velocity during this phase is the touchdown speed and the finally velocity is zero. By using the same equations as in the take-off ground roll, the landing ground roll distance is calculated. The thrust generated in the ground roll segment has been considered zero and the friction coefficient has been increased to 0.5 due to the effect of brakes.

For the calculations, the landing weight considered is 85% of the MTOW and since the thrust and the drag at the starting point of the approach are unknown so a normal approach angle of 3° has been taken.

Using the MATLAB code presented in the Annex, the following results are obtained:

$$S_{approach} = 277.63 \, m$$

$$S_{flare} = 17.19 \, m$$

$$S_{Ground \, Roll} = 26.18 \, m$$

$$d_{TO} = 321 \, m$$

7.10.6.2. Alternative methods for landing

The landing phase is a critical issue for an UAV. According to the market study and as commented above, UAV are usually design to operate without the use of a landing gear. This is due to the fact that having a large runway is not available in most of the cases. Therefore, alternative methods for landing need to be studied. Two of these methods have been described.

- Parachute

One possible method is the use of parachute in order to descent to ground with low speed so that the UAV does not suffer damage. This solution needs to be taken into account while designing the fuselage due to the fact that the parachute has to

be stored on-board. It is a feasible solution but it also risky due to the dependence in weather conditions.

Figure 55: Parachute landing method[88]

- Vertical Net

This recovery method consists of a net suspended between two poles. The net is also suspended by a structure to hold the UAV above the ground when gets trapped into it. The design of the net is not trivial due to the fact that it needs to distribute the forces that the UAV generates when get trapped. Although is a more complex solution than the parachute, it is more secure and do not depend in uncontrollable factors such as weather conditions. Also extra weight and possible structure modifications are avoided.
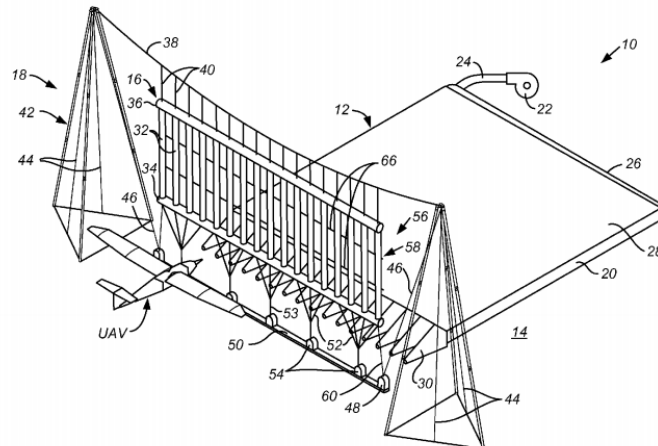
Figure 56: Patent regarding a net recovery system[89]

- Belly landing

It is quite often the use of the underside of the fuselage for landing when a landing gear is not incorporated. This type of landing introduces a risk of damage. However, reinforcements of composite materials on the belly of the fuselage are

used in order to reduce this damage. Since this landing configuration is the lightweight solution, it has been decided to classify the landing gear as an extra equipment and to provide reinforcements to the UAV so that it can land with this method.

8. Feasibility study

Once the solution is proposed, analysing if it is possible to be implemented is essential for any project. There are two approaches while studying a project feasibility: the technical and economical.

8.1. Technical approach

Before starting to manufacture a product, a study that determines if the proposed solution can be carried out with the actual technologies have to be done.

8.1.1. Functional factors

- Utility

The fundamental utility of the UAS proposed is aerial surveillance. This objective is basically accomplished by providing a camera and a communication system that ensures video streaming. Although the principal idea is simple, its design is not trivial. However, video streaming communications is a well-studied technology and by means of a modem and antennas, the data link can be stablished. Therefore, the main purpose of the UAS is feasible to be achieved. Furthermore, as the market study showed, this video streaming is already implemented in some of the most used drones at the present time. The development of camera technologies has experienced a tremendous growth in the last 10 years and nowadays buying lightweight cameras with good image quality is affordable to almost everyone.

The principal utility needs to be complemented with the design of an aerial vehicle. This is not any impediment to the project due to the fact that the aircraft design is an engineering field highly developed and the wide available information and software facilitates the task. However, in unmanned vehicles there is an extra complexity due to the lack of pilot that requires the implementation of an on-board flight computer and sensor system so that corrections during flight can be done automatically.

The technical knowledge involving sensors is also highly developed due to the fact that there are used in almost all the engineering fields. Regarding the flight computer, there are enterprises that are dedicated to write the algorithms that allows the corrections needed during the flight as well as following waypoints, obstacle avoidance among others. Therefore, the actual technology related to automatic control is within the reach of a UAS project.

With respect to the ground control station, the actual laptops or even a mobile phone are able to monitor the UAV during flight with the use of specific software. As was described in the solution proposal point, open-source software is an example of the feasibility of the ground control segment.

To sum up, one of the reasons why the application of UAV is experiencing a growth is due to the simplicity involved in their designs. Therefore, it can be concluded that with the actual technology, the UAV solution proposed can be implemented.

- Monitoring and maintenance

UAV maintenance and equipment monitoring is an important factor to take into account for security purposes. For any flying machine safety and reliability need to be ensured. Therefore, the UAV needs to be designed so that the different parts can be easily tested as well as replaced in case of failure. Then, an assembly system should be provided so that the maintenance and monitoring can be done. However, it is considered out of the scope of the project and needs to be develop in future works.

- Ergonomic factors

The UAV will have an estimated empty weight about 11 – 14 kg and a maximum take-off weight of 20 kg. The main dimensions are:

Table 42: Main dimensions considered for the UAV proposed

Wingspan	3 m
Length	$\cong$ 2 – 2.5 m (depending on the fuselage)
Height	$\cong$ 1 m (depending on fuselage and landing gear)

Although the high values of the dimensions, the assembly and disassembly system will be able to facilitate its transportation, making feasible the use of the UAV in many different scenarios.

- Legal factors

The main requirement that facilitates the legal adaption of the UAV is to have a mass below 25 kg. As was commented below, the MTOW was fixed to 20 kg. Therefore, the design is adapted to the legal requirements regarding weight aspects.

Another important aspect concerning legislation is the frequency used for the communication link. In the communication system description, the frequencies selected for the data link were 2.4 GHz and 5.8 GHz. According to the CNAF, the Spanish legal instrument that assigns the different radio services to a frequency band, these frequencies are reserved to industrial, scientific and medical applications.[90]

Since the UAV has been designed for surveillance, it can be considered as an industrial application and consequently it fits in the legal framework.

8.2. Economical approach

In order to analyse whether the solution proposed can fit into the UAV market, the costs have to be calculated so that the sale price can be estimated. Then, by comparing with other UAS projects it will be determined whether it is possible to manufacture it at an affordable price.

8.2.1. Raw Materials Cost and pre-design cost

The cost of the items presented on the UAV solution proposal section have been tabulated. Some of the prices have to be estimated due to lack of information.

Table 43: Costs of the solution proposed

Item	Price
UAV	
Propulsion system	
RCV engine	500 €
Propeller	29 €
Fuel tank[61]	1200 €
Raw materials	
Balsa wood	$15{,}625 \frac{€}{kg} \cdot 2 \text{ kg} = 31{,}3 €$
GFRP[91]	$3{,}44 \frac{€}{kg} \cdot 4{,}5 \text{ kg} = 15{,}5 €$
CFRP[91]	$97 \frac{€}{kg} \cdot 3{,}5 \text{ kg} = 339{,}5 €$
Flight Control System and Communication System	
Autopilot (Lisa/S)	385 €
XBee modem	28 €
Power supply	
On board generator system	120 €
UAV platform	**2 639 €**

Payload	
Payload camera	26 300 €
UAV with payload	**28 939 €**
Ground Control Station	
Ground Control Station	3 000 €
TOTAL GCS	**3 000 €**
TOTAL UAS	**31 939 €**
TOTAL UAS without payload	**5 589 €**
Extra equipment	
Pneumatic catapult	20 950 €
Landing gear[61]	910 €

The cost of the hours worked during the development of the study are also considered.

Table 44: Cost engineering of the pre-design phase

Hours worked	300 h
Price per hour	15 €/h
Total	**4 500 €**

8.2.2. Estimation of UAV cost

For the calculation of the price, the payload as well as the extra equipment, has not been considered due to the increase of the final costs. Therefore, a basic UAV platform without its payload will be offered to the client as the main product. Since the GCS do not involve any manufacturing process, the price will be added to the final price but with a benefit percentage.

For the calculation of the total cost of the project, the method considered in Roskam book[36] have been followed. However, due to the fact that this book was published 1986 and it is for commercial and military aviation, the calculations have been estimated in a more realistic way.

8.2.2.1. Investment

The investment needed for the development of the project can be estimated as the research, development, test and evaluation cost. It involves all expenses from preliminary design until the certification. The following estimations have been done:

- Engineering cost

The pre-design phase costs were estimated in Table 44. A total of 4500 € was obtained.

Considering a 2 aeronautical engineer team, the expected time for the development of the final design is of 2 years. The tasks that need to be done in the future have been described in section 11.

The engineering cost can be seen in the following table.

Table 45: Engineering cost of the design phase

Engineering cost of the design phase	
Number of engineers	2
Salary	42 000 €/year
Time	2 years
TOTAL	**168 000 €**

- Development support and testing cost

The development support and testing costs involves the material, propulsion and wind tunnel tests. In order to calculate it, the experimental equation proposed in Roskam book [36] have been used:

$$C_{test} = 0.008325(W_{ampr})^{0.873}(V_c)^{1.89}(N_{rdte})^{0.346}(F_{diff}) \tag{36}$$

where W_{ampr} is the Aeronautical Manufacturers Planning Report and can be calculated as the empty weight minus the battery, engine and flight computer weights; the V_c represents the cruise speed of the aerial vehicle that in the case of the UAV is considered the maximum efficiency speed (30.57 m/s); N_{rdte} is the number of UAV used for testing and 4 units have been considered and finally F_{diff} is a factor that takes into account the difficulty of the project that can be equal to 1.

After making the calculations, the following result is obtained:

$$C_{test} = 2085 \text{ €}$$

- Flight test cost

The flight test cost can be computed as the sum of the engines, propeller, battery, communication system, flight computer and material costs multiplied by the number of UAV used for testing. Then, the hours worked in the development of the flight tests multiplied by the € rate per hour. The hours worked have been estimated with the considerations presented in Roskam and the cost per hour has been considered of 20 €/h. A quality cost can be also estimated as the 13% of the human resources costs.

$$C_{flight\ test} = 4 \cdot (2639\ \text{€}) + 1.3 \cdot 320\ h \cdot 20\frac{\text{€}}{h} = 18\ 876\ \text{€}$$

- Research, development, test and evaluation cost profit and finance

In order to obtain a profit of the RDTE phase and to take into account an extra finance to deal with the running costs, these costs needs to be computed. Both are calculated as the 10 % of the RCTE cost.

Then the total RDTE cost it can be computed:

$$C_{RDTE} = \frac{4\ 500 + 168\ 000 + 2\ 085 + 18\ 876}{0.8} = 241\ 826\ \text{€}$$

The value of this cost can be considered as the initial investment needed. Therefore, a final investment of 245 000 € have been considered.

8.2.2.2.   Manufacturing cost

All the cost related with manufacturing the total number of units during the production phase have to be estimated. The following costs are involved:

- Engineering and design cost

It takes into account the engineering design work during the manufacturing process. It can be computed as the 30 % of the total engineering cost calculated in the RCTE cost:

$$C_{man_{eng}} = 0.3 \cdot (4\ 500 + 168\ 000) = 51\ 750\ \text{€}$$

- Production cost

In order to calculate the total cost of manufacturing a UAV, the method proposed in Roskam[36] has been used. It is based on using the flight test costs but with a higher € rate per hour and for the number of drones that are expected to be sold during all the manufacturing phase. The considered number of UAV sold are 200 in 10 years.

$$C_{prod} = 200 \cdot \left(2639 + \frac{320}{4} \cdot 35\frac{\text{€}}{h} \cdot 1.3\right) = 1\ 255\ 800\ \text{€}$$

- Financial cost

As in the RDTE cost, the 10% of the total manufacturing costs is added.

The total cost for the manufacturing process is:

$$C_{MAN} = \frac{1\,225\,800 + 51\,750}{0.9} = 1\,419\,500\ \text{€}$$

8.2.2.3. Estimation of the UAV price

An approximated value for the sale price can be calculated as follows:

$$Price = \frac{C_{RDTE} + C_{MAN}}{200} = \frac{241\,826 + 1\,419\,500}{200} = 8\,307\ \text{€}$$

This price corresponds to the price only of the UAV without payload and GCS. Adding the costs of the GCS and adding a 20 % of benefits, the price for the whole UAS but without a payload is:

$$Price_{UAV+GCS} = 8\,300 + 1.2 \cdot 3\,000 = 11\,900\ \text{€}$$

8.2.3. Positioning in the actual market

Some professional UAS prices that have similar mission requirements have been tabulated in order to compare them with the costs of the solution proposed.

Table 46: Professional UAV prices

Penguin B [92]	14 500 € (without payload)
LP960 full system [93]	6 990 €
Lehmann Aviation L-A series full system[94]	8 990 €
HBS Skywalker UAV[95]	4 000 €
HBS FX61 PRO[95]	3 100 €
SenseFly eBee UAV [92]	10 560 €
NOVA F7200[96]	13 480 €

Professional UAVs are really demanding in economic terms. The minimum price for a complete UAV system is around 4000 €. Furthermore, these prices are mostly for electric propulsion UAVs that performs between 30 min and 2 h of flight. If a higher flight time is desired, ICE propulsion is needed and the price can exceed the 15 000 €.

It can be concluded that the price of the solution proposed fits on the market, with a competitive price. However, the payload camera proposed during the

development can increase two times the price calculated. Although it is the best option for professional surveillance applications, giving the chance of selecting a more affordable camera is the most feasible solution.

9. Environmental impact study

The main objective of an environmental impact study is to decide to proceed with the project or not by taking into account the environmental impacts. There are different areas that needs to be considered while studying the drones environmental impact. The first point is about the pollution created by the UAV due to the ICE. Then, a study of how the drones can be used for the environmental sector has been done.

- Pollution

Since the UAV proposed works with an ICE, contaminating gases are emitted. Due to this reason, the general market trend is electric propulsion. However, the autonomy that ICE provides is necessary for some applications.

Moreover, this type of drones can substitute operations that generally are carried out by ground vehicles. Thus, since the UAV engines contaminates less than a car, it can be understood as a decrease of contaminating emissions.

However, an increase of the technology involved in electric propulsion needs to done in order to make electric UAV have a large endurance.

- Environmental monitoring

The civil applications of drones are innumerable and some of them are related to environmental monitoring. The first application is agriculture drones. This drones are capable of increasing the efficiency of the farms and, most important, to reduce the use of pesticides.

On the other hand, surveillance UAV can be also used for wildlife conservation. One example of the efficiency of drones for the sake of environmental monitoring is the Ranger Drone[97]. This drone has succeeded in the prevention of poaching.

To sum up, the use of drones for environmental applications have to be promoted in order to raise public awareness about the benefits that this type of industry can provide.

Another important issue is materials recycling. The materials used in the solution proposed are composites. Although there are more difficult to recycle than others, the possibility of manufacturing the composite waste can be considered.

10. Security considerations

While developing a project, the security is an important issue to take into account. In the UAV sector, the security problems are creating an international debate. The recent incidents involving drones with commercial aircrafts are an example of security mechanisms that must be incorporated.

The no-fly zones include basically airports and flying fields where manned aircrafts operate at low altitude [98]. Some UAV manufacturers, like DJI, offers a flight mode that avoids entering in such banned zones. The idea is to be able to set in the software of the GCS the banned areas. Then, when the drone detects that is entering to one of these zones, using the GPS receiver, it will automatically land.

Regulation are in process of building up a new legal framework in order to avoid such dangerous operations. Drones need to be used in areas where the probability of harming others is very low, and this no-fly mode proposed is a feasible solution.

Therefore, the implementation of security mechanisms need to developed in future improvements.

Furthermore, the communication system is a critical issue while developing a UAV. Interferences can make unable the telemetry link and therefore loss the complete control of the aerial vehicle. In order to avoid this interference problems, the data links used in the communication system have different band frequency. Thus, if one of the links becomes inoperable the other can still be used. Furthermore, a study of the different risks involving the communication links have to be done.

11. Organization and planning of the future work

During the development of the proposed solution, there are many aspects that have been considered for future improvements. However, an organization and planning scheduling needs to be done in order to make clear the future of the study.

Table 47: Planning scheduling of future tasks

Task	Preceding Task(s)	Approximated duration (h)
Structural Design	-	200
Design of control surfaces	-	150
Validation of the aerodynamic results	-	100
Design of the assembly system	Structural Design	100
Data compression and treatment analysis	-	150
Study of the risks in the communication system	-	100
Electrical system design	-	200
3D Model	All previous tasks	200
Construction of prototypes	All previous tasks	400
Flight tests	All previous tasks	100
Design modifications	All previous tasks	300

After all the tasks described in the table above are done, the manufacturing process will be able to start. The estimated duration until the start of manufacturing is 2 years.

12. Conclusions and future work

During the development of the study, some conclusions have been drawn. The most important ones concerning specific and general aspects have been outlined.

First, a brief study of the legal framework was made in order to obtain a general idea of the environments in which an UAV can operate. It has been found that the actual regulations cover general aspects regarding the operation of drones but do not differentiate between the types of UAV neither the applications that are able to perform. Furthermore, they limit the use of UAV to very restrictive zones due to the fact that flying in urban areas or near an airport is totally banned. Another important feature that has to be taken into account regarding surveillance applications is that night operations are illegal. It is clear that with the actual regulation, implementing a surveillance UAV is a very complex task. Therefore, a change in the legal framework needs to be done in order to promote the expected growth of the UAV industry and also to make feasible the use of drones for commercial purposes.

Another aspect to consider before the solution proposal is the state of the art of the UAV industry. With the market research, a general idea of the technology involved in the design of a UAV was obtained. It also shows the market trends towards the multirotor configuration and the electric propulsion. Moreover, the analysis of the different specifications is essential in order to give some initial values, that have been used as a starting point during the pre-design phase.

Once the background has been studied, the analysis of the design requirements and the initial sizing has been made. The first step is to understand the problem that is expected to be solved. The main innovation that a surveillance drone provides is the opportunity of monitoring a specific zone from a more effective point of view as well as operability in areas of difficult access. Then, taking into account the capabilities that must be ensured, the design requirements have been defined. The conceptual design consisted of selecting the type of UAV. The two possible alternatives are multirotor and fixed wing drones. Concerning the design requirements, the most critical parameter to fulfil is endurance. A minimum of 2h needs to be ensured. After studying the advantages and drawbacks of each configuration, it has been found that fixed wing UAV has higher flight times.

The selection of the type of drone, allowed the development of an initial sizing. By means of a constraint analysis, a range of values concerning power and weight specifications has been established. It is important to note that the maximum weight available is 25 kg in order to facilitate the regulation process.

The second part of the study is the UAV solution proposal. During this section, the different subsystems have been presented and the alternatives have been studied. Then, the solution that best fits within the design requirements has been selected.

The first subsystem studied is propulsion. There are two very different alternatives: internal combustion engines and electric motors. From the state of the art, it can be observed that the most usual option is electric propulsion. However, since the endurance needs to be minimum of 2h, the ICE was the only viable option. Nevertheless, this decision is the most demanding in terms of weight and price. The propeller has also been considered and the basic specifications such as the diameter and blade pitch have been determined.

An aerodynamic study has been developed in order to propose an efficient wing and tail configurations. The methodology followed has been to simulate the different possibilities with the XFLR5 software, that is based on the 3D panel method. With this method the airfoil, wingspan, planform and geometry of the wing and tail has been decided. Taking into account the results of the simulation, a mix planform with a 3 m of wingspan has been obtained. However, some characteristics have been determined by analysing the different options and choosing the one that better meets the design requirements. An example is the wing position, that in order to ensure an assembly system, the high wing was the most appropriate configuration.

Another crucial design studied is the communication system. It has been observed that the communication media used for establishing the data links are radio communications. A study of the advantages and drawbacks of the different frequencies has been made in order to select the best one. It has been determined that the best frequency band for surveillance applications where video broadcast has to be ensured, is 2.4 GHz. However, due to security considerations, providing a second link in a different frequency band (5.8 GHz) has been decided.

In order to develop the mission requirements, a payload has to be installed in the UAV. For surveillance applications, it consists of a camera. Taking into account the UAV capabilities, some specifications such as 360° panoramic view and thermal imaging need to be ensured. After a brief market research, it can be observed that the camera prices are along the 20 000 €. Thus, the payload is the most critical subsystem regarding economical purposes.

One of the main characteristics that makes drones such an attractive technology is the automatic control system. The basic working principle has been analysed and some examples in the market have been described. In order to keep the costs as low as possible, the most economical autopilot has been selected.

Although the structural design has been considered out of the scope of the study, the materials used for designing a UAV have been described. It can be observed that the structure is made totally of composite materials, where carbon fibre and fiberglass are the most commonly used.

With all the decisions made during the solution proposal, some calculations concerning the performance of the drone have been made. First, an estimated weight has been calculated. A maximum take-off mass of 20 kg was considered. Then, the different phases of the flight have been studied. For take-off and landing the possibility of adding a landing gear as an extra equipment has been considered. Thus, the take-off and landing distances have been calculated. However, catapult and belly landing are the methods considered for the solution proposed.

In order to verify the design requirement of endurance, the autonomy has been calculated. Although some simplifications have been made, the value obtained verifies the fulfilment of the requirements considered at the beginning of the study. As an example of the results obtained, for a half power requirement the estimated flight time is about 9 h.

On the other hand, a feasibility study has been developed in order to determine if the implementation of the solution proposed is possible. Regarding technical aspects, the technology involved in the UAV is viable. In fact, one of the characteristic that makes UAV such an attractive sector is the simplicity involved.

After proposing the solution, an economical study has been made. By estimating the costs of the raw materials and the manufacturing process, the total price of the UAV has been calculated. It has to be noted that the catapult, the landing gear and the payload had been considered as extra equipment. By comparing with other UAS prices in the market, it can be concluded that the solution proposed fits in the UAV market. A price about 12 000 € for the UAV with the ground control station has been obtained.

Last but not least, the environmental impact study and the security considerations have been taken into account. The most important fact concerning this last section of the study is that the UAS proposed can be used for environmental applications such as the prevention of poaching.

As a final conclusion, the study can be considered satisfactory due to the fact that the different objectives proposed have been accomplished. However, some important points of the design of a UAS remain outstanding for future improvements.

First, the internal structure has to be designed and simulated with Finite Element Method. Regarding to the internal structure, the assembly system needs to be developed and tested.

Then, the aerodynamic results obtained during the study need to be verified by means of a CFD software. Also the control surfaces have to be designed in order to ensure control.

Besides, a 3D model using CATIA or SolidWorks needs to be build up so that the drawings can be obtained. Moreover, the communication system is a relevant aspect that has to be analysed carefully. Thus, a study of the data compression and treatment as well as an appraisal of risks has to be done.

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