PROJECT HADES - ISAE SUPAERO

Progress Report May 2022

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Abstract

Aviation is one of the primary modes of transportation and is likely to keep this title for the forthcoming years. As the aviation industry grows, the need for that growth to be economically, environmentally and socially sustainable is imperative. The aviation industry's swift movement towards sustainable aviation can be seen with the introduction of Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), European Union Emission Trading Schemes (EU ETS) and the objective of major aircraft manufacturers to have hydrogen propelled aircraft operating by 2035.

While the recent trend in the aircraft industry seems to be the electrification of the aircraft, it is not environmentally and economically sustainable. The future of the aviation industry lies in the use of Hydrogen as a fuel. While this trend is still in its nascent stages, it is important to show that such a technology can in fact help the aircraft industry achieve its zero carbon emmission goals.

Keywords : UAV, Hydrogen

Nomenclature

CF *Carbon Fiber*

OD *Outer Diameter*

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

According to the ICAO, the air traffic is estimated to increase by an average of 4.3% per annum in the next 20 years. This growth is not inconspicuous to us as we see an increased number of aircraft taking off or landing in Toulouse. Aviation is responsible for a significant increase in the level of greenhouse gases and with increase in ubiquity of planes, these contributions are bound to increase unless a greener substitute for the current fuel is found. This is where hydrogen as the future of aviation comes into focus.

Hydrogen powered airplanes have already shown successful experimental flights and have paved the way for a net-zero carbon aviation. The use of hydrogen as fuel in short-range aircraft can reduce climate impact by as high 50-90%. Hydrogen has three times the energy per unit mass as compared to traditional fuel and can be generated from renewable sources through electrolysis. There are three ways in which hydrogen can be used as a fuel: fuel cells, hybrid aircraft and combustible fuels.

This innovation however comes with numerous challenges in the form of hydrogen storage, transportation, safety, and regulations. The entire hydrogen architecture right from storage tanks, supply and propulsion systems will have to be developed and further improved subsequently.

The recent advances in electronics, aerodynamics and propulsion have led to aircraft that are faster, have a higher range and are safer. The increased competition among budget airlines have made air transportation more accessible. While on one hand these are the essence of progress, the future that we are striving for, on the other, they have also become a major cause of concern for environmentalists. The call for an environmentally sustainable and greener aircraft has become the need of this hour.

HADES is a project that aims to realise this goal and show it as a proof of concept.

Chapter 2

Aerodynamics

2.1 Constraint Diagram Analysis

The constraint analysis was done by taking into consideration 6 cases which are as follows:

1. Constant Velocity Turn
2. Rate of Climb at Sea Level
3. Take-off ground roll distance.
4. Cruise Airspeed
5. Service Ceiling
6. Maximum Wing Loading

These formulas consisted of various parameters (Table 2.1) which needed to be assumed and following assumptions were based by studying literatures that were related to hydrogen powered airplanes.

By implementing the formulas under these cases and solving for wing loading value and power to weight ratio (since our UAV is propeller based), the Wing Loading was selected to be 131 N/m^2 and the Power to Weight Ratio was 6.5 W/N. This point basically corresponds to the intersection point of curve representing the maximum wing loading and the rate of climb at sea level (Figure 2.1).

Following data was obtained from Code developed on Python:

Planform Area from Aspect Ratio = 1.5 m2
Stall Speed = 13 m/s

Maximum Wing Loading=131.82N/m2
Maximum Wing Loading=13.437308868501528kg/m2
Required Power to Weight Ratio = 6.5 W/N
Required Thrust to Weight Ratio = 0.19450497092809668
Power Required = 1243.4175 W
Thrust Required = 37.20782841369026 N

Parameter	**Symbol**	**Value**
Sea level rate of climb	V_V	2.09 m/s
Sustained turning speed	V_{turn}	25 m/s
Take-off speed	V_{To}	16.66 m/s
Climb speed	V_{climb}	23.33 m/s
Cruise speed	V_{cruise}	31 m/s
Service ceiling rate of climb	$V_{v\ ceiling}$	0.17 m/s
Stall speed	V_{stall}	13 m/s
Zero lift drag coeff.	CD_o	0.025
Minimum Drag Coeff.	CD_{min}	0.03
Drag coeff. At take off	CD_{To}	0.05
Lift Coeff. During cruise	CL_{cruise}	0.215
Max. Lift coeff.	CL_{max}	1.3
Oswald Efficiency factor	e	0.7

Table 2.1: Parameters for the constraint analysis.

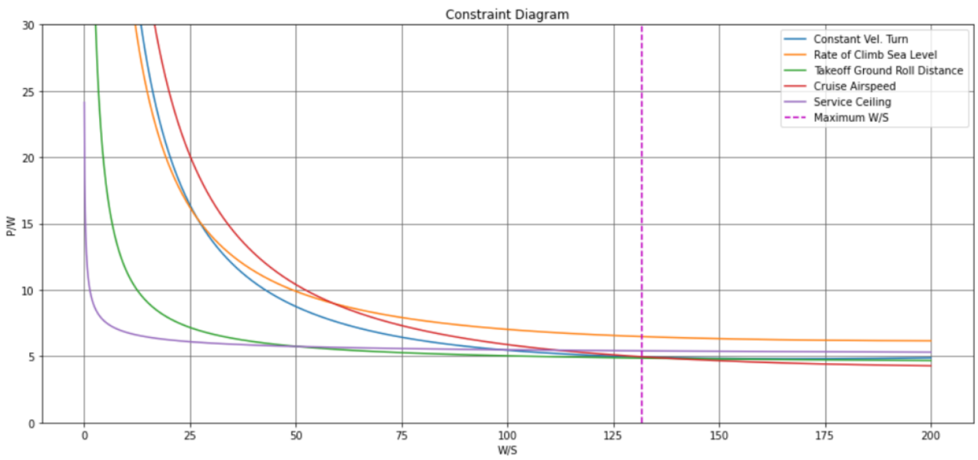

Figure 2.1: Constraints of mission phases on thrust loading and wing loading.

2.2 Airfoil Selection

The airfoil was chosen from well documented airfoils from literature. The endurance demands are not high for the flight mission defined, and the maximum lift coefficient and the drag coefficient were critical parameters.

For the mission, the desired wing lift coefficients are below.

Take-off $C_L = 0.8$
Climb $C_L = 0.45$
Cruise $C_L = 0.25$
Descent $C_L = 1.99$

So as to not overdesign the wing, the maximum achievable CL is considered for an all flaps deployed configuration.

The airfoil meeting all requirements is the Wortmann FX 76-MP-120 with ailerons at 60% chord and maximum deflection angle of 12° (more information can be extracted from Figure 2.2).

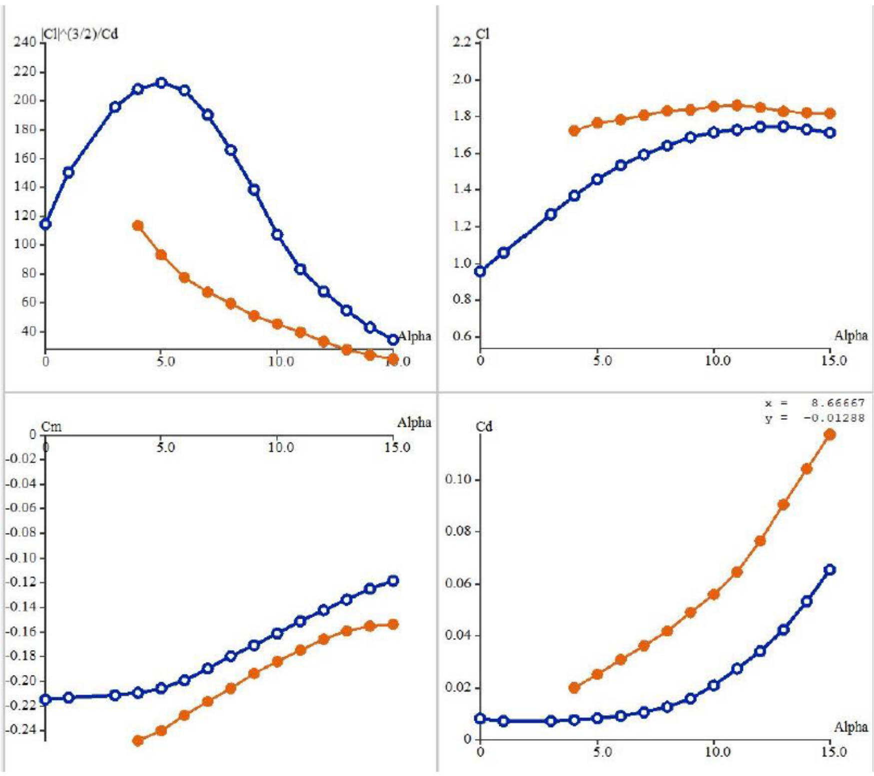

Figure 2.2: Clockwise from top, aerodynamic endurance, lift, pitching moment and drag for the Wortmann FX 76-MP-120 airfoil. Results are plotted for the clean airfoil (blue) and the flapped airfoil (orange).

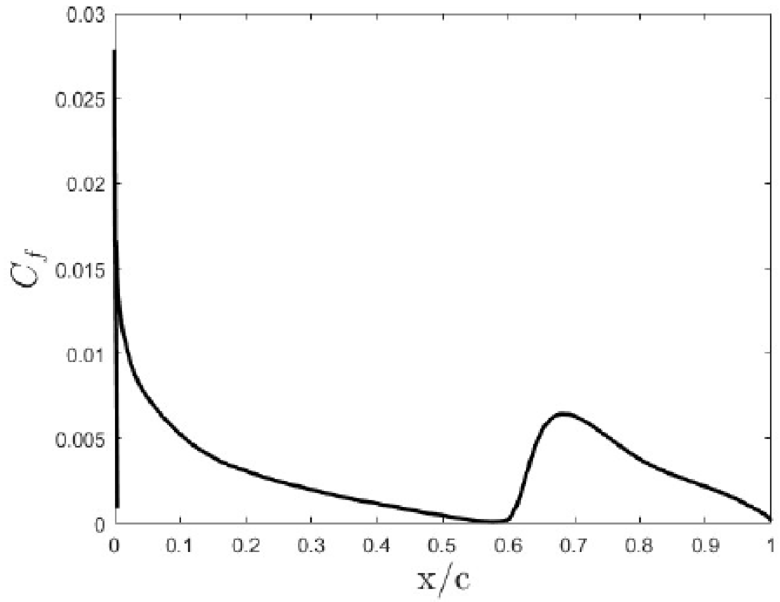

Figure 2.3: Friction coefficient plot at Re = 800,000. To be consulted for separation, transition and reattachment locations on the airfoil.

The plot above indicates where the ailerons can be placed for maximum aerodynamic advantage.

2.3 Wing Design

Sizing of the wing was based on the ratios taken from the previous report of HADES. The taper ratio was taken to be 0.34 and wing box ratio of 0.46, since extensive research was carried out by the previous team.

The parametrical study was performed with the software AVL with the Viscous Drag modification. The input variables are presented below.

Wingbox fraction $\frac{b_{wingbox}}{b_{wing}}$ **[-]**	0-0.5
Taper ratio [-]	0-0.65

Table 2.2: Input variables for parametrical study.

The most efficient configuration provided by the AVL parametrical study was:

Taper Ratio = **0.34**
Wing Box Ratio = $L_{wingbox}/b_w$ = **0.46**

From the wing box ratio which is the ratio between wing box length and wingspan (since the wingspan was already selected to be 3m from the requirements and limits specified in the EASA handbook for UAV's) the resulting **wing box length is 1.38 m**.

From the constraint analysis of the UAV, the **wing area needed is 1.5** m^2. Based on this wing planform area and the taper ratio, the **root chord = 0.608 m** and **tip chord = 0.206 m** were determined. This planform is illustrated below.

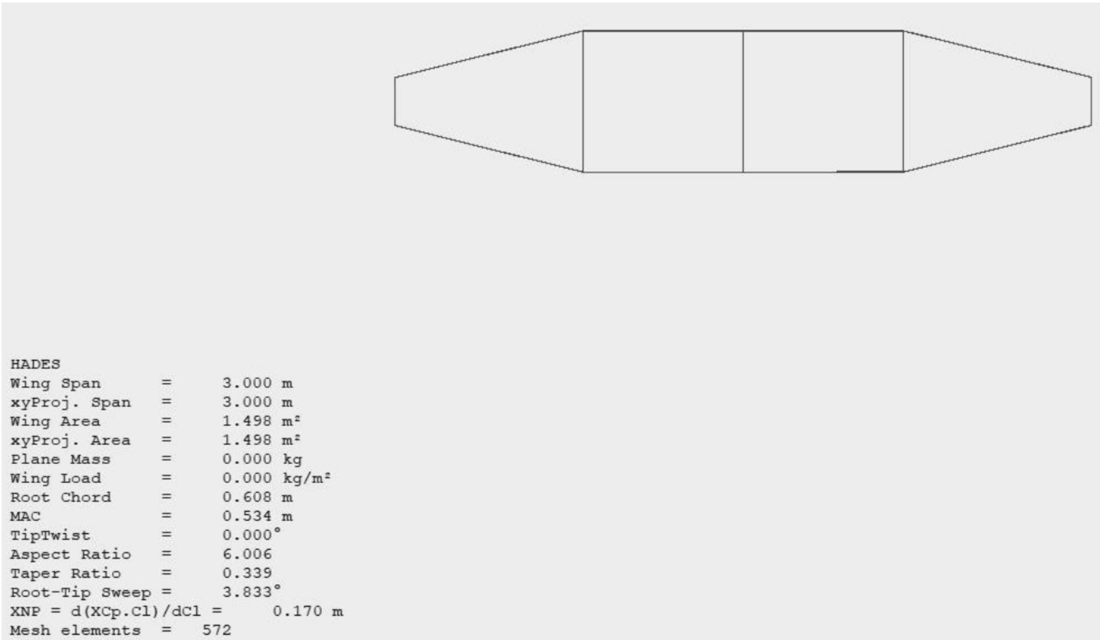

Figure 2.4: Clean wing planform with dimensions as constructed in XFLR5.

From the C_f plotted in Figure 2.3 and the conventional planform area fractions (12-25%) for ailerons, the aileron placement has been tentatively determined as shown below.

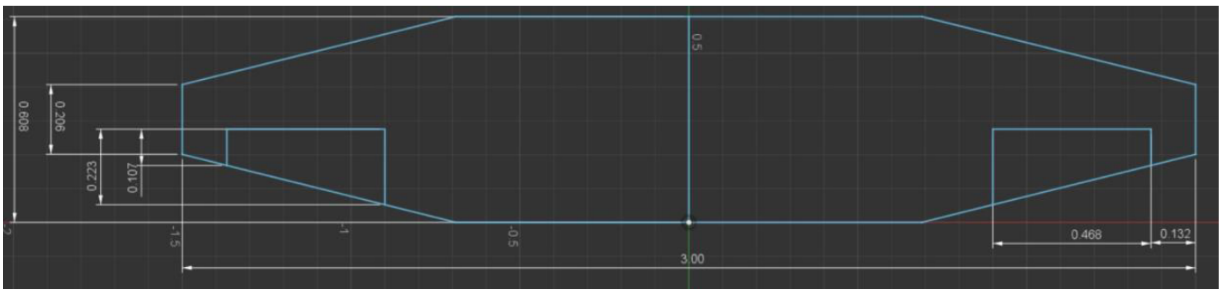

Figure 2.5: Wing planform with ailerons/flaps.

The performance for this wing is analysed for the cruise speed of 31 m/s and presented in the graphs below.

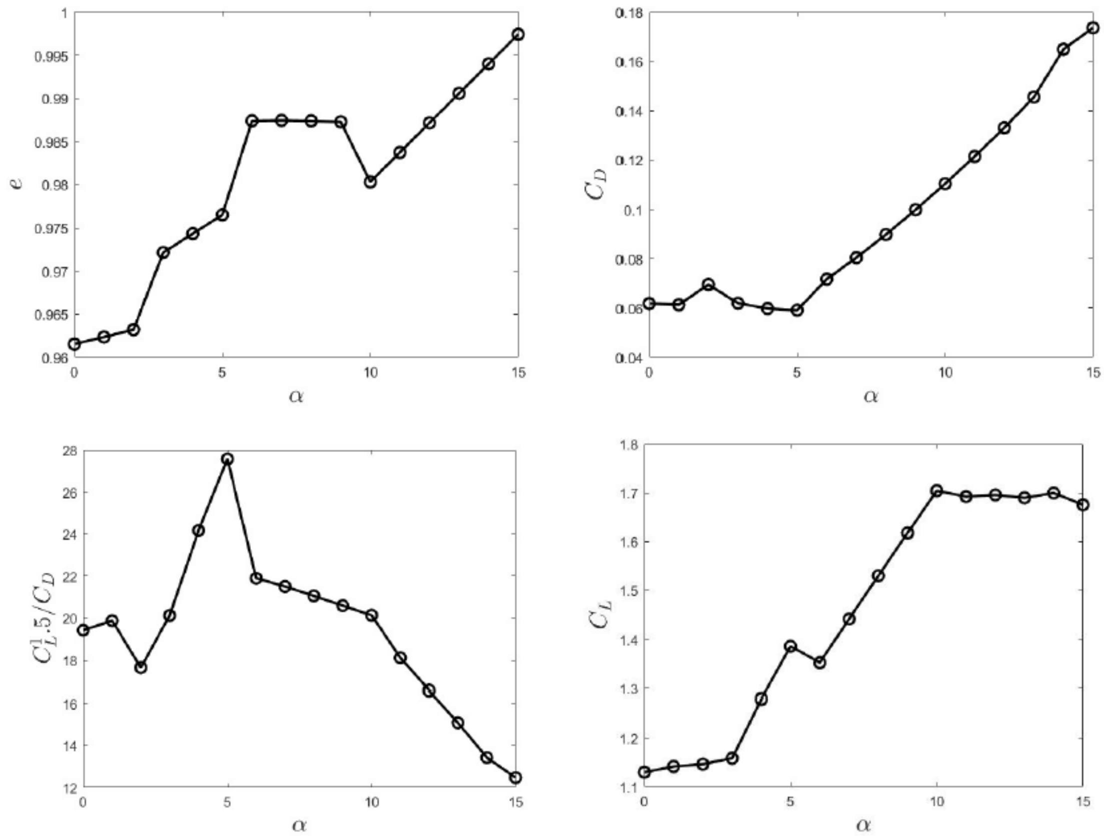

Figure 2.6: Clockwise from top, aerodynamic efficiency, drag, aerodynamic endurance, lift for the wing design.

Chapter 3

Structures

The values obtained from the design team are used to build the CAD model for the tapered wing. The half wing span is 1500 mm with taper ratio of 0.34.

Figure 3.1 gives the overall idea of the wing which will be manufactured using wood (balsa) and carbon fiber layup (in selective places).

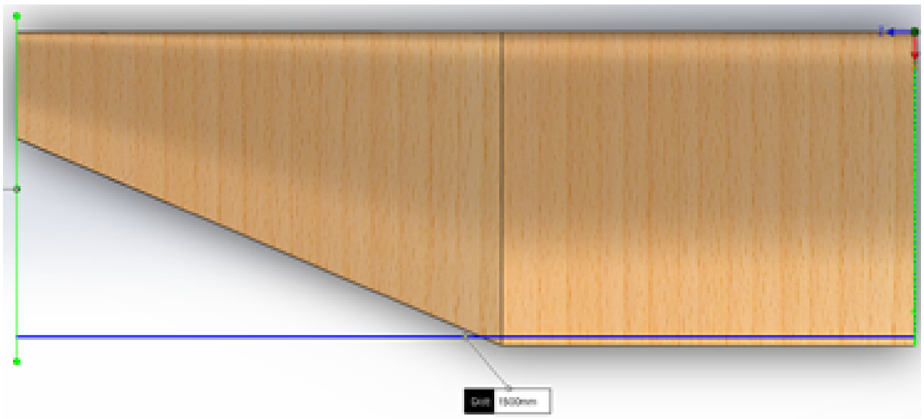

Figure 3.1: Illustration of the complete wing.

Moving to the internal structure, the ribs (Figure 3.2) will be manufactured individually using balsa. For now, 4 mm thick ribs seem to be strong enough which will be obtained using laser cut. The ribs will have blanking to improve the strength and reduce the overall weight of the structure. The analysis on type of blanking will be carried out in the next iteration.

Next, we move on to the assembly of the wing. Since it is a tapered wing, it is difficult to have a continuous spar or web passing through all the ribs. Hence, a wing box type of design will be preferred as shown in Figures 3.3 and 3.4.

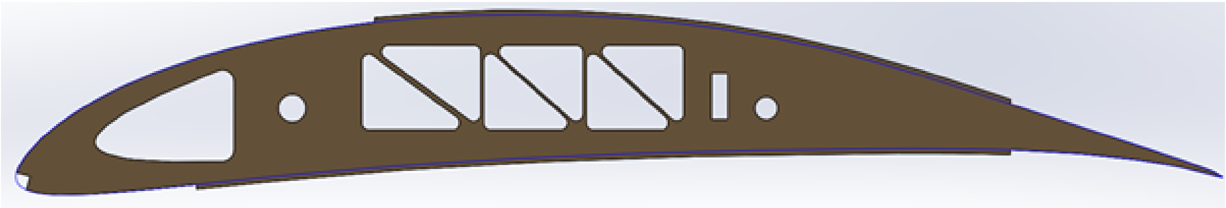

Figure 3.2: View of the initial rib design.

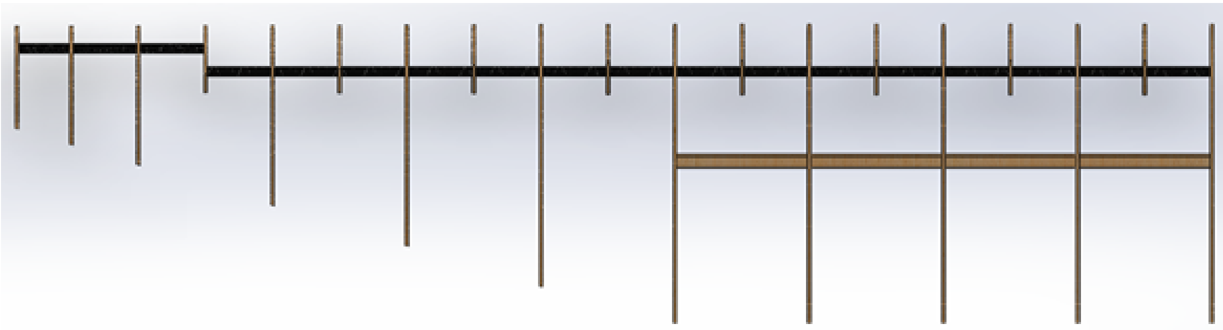

Figure 3.3: Top view of the wing.

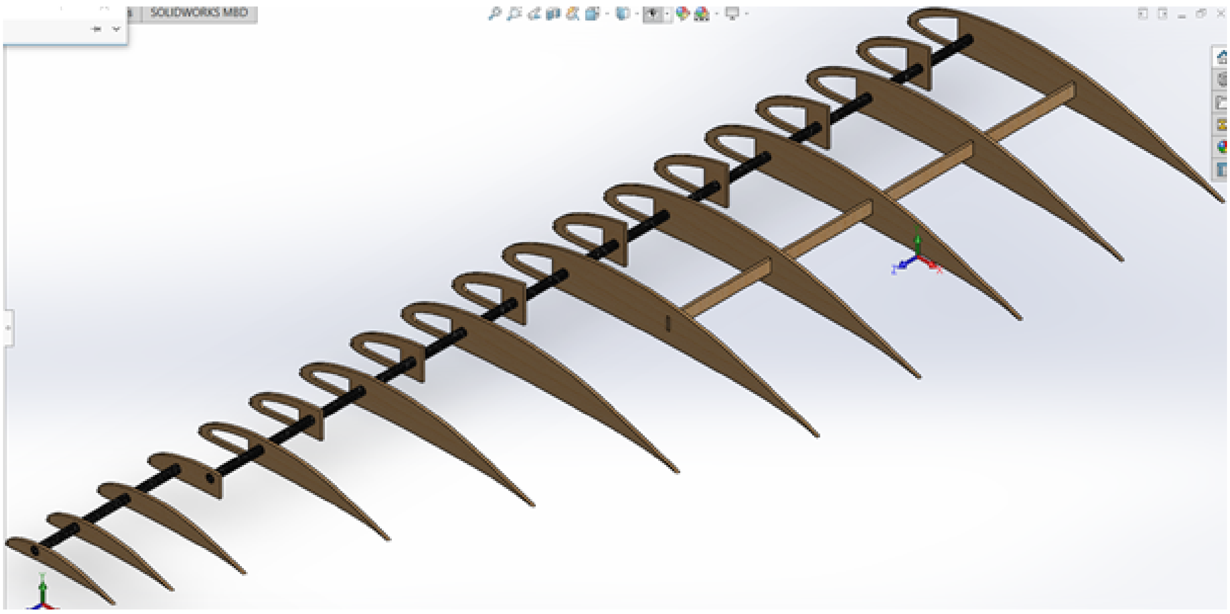

Figure 3.4: Isometric view of the wing.

An OD of 12 mm spar made of CF will pass from the root rib till the 4^{th} last rib. In order to have structural rigidity, a 2^{nd} spar of same OD but different length is attached. In the initial ribs, a web of 20x5 mm^2 is placed. Sheeting on both front and back of the ribs will be there which will help in maintaining the profile of the wing along with the longerons that will pass through all the ribs.

Initial analysis on wing bending and force distribution will be carried out from now so as to optimize the structure of the wing. CF-balsa-CF ribs will be manufactured wherever strength is required e.g. ribs where the servos will be attached, root and tip ribs.

Note: Currently all pictures are for left wing. Right wing will be identical one.

Chapter 4

Control and Embedded System

The control and embedded system of the drone are divided into two parts the Autopilot Hardware and the Ground Control Station. The Overall System Architecture of the Drone control is shown in Figure 4.2.

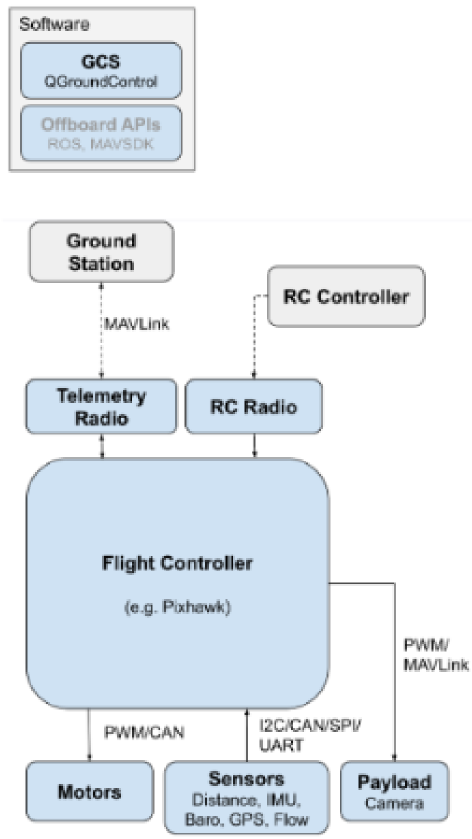

Figure 4.1: Overall System Architecture of the Drone control.

4.1 Autopilot Hardware

The term autopilot is referring to the complete system that will enable the UAV to autonomously take off and fly from waypoint to waypoint. There are many different components to an autopilot system including the flight controller, the telemetry, and the GPS. The overall system and its main components are shown in Figure 4.2. Most of the equipment comes from HolyBro due to its reliability, familiarity with its products, and price points.

Figure 4.2: Main autopilot hardware components [1].

4.1.1 Flight Controller

The flight controller components of the autopilot system include the main processor, the power management board, the GPS, and the ESC (electronic speed controllers).

The Processor is used to execute the autopilot commands and to run the flight control software. The Pixhawk4 32-bit processor is chosen and is compatible with the PX4 firmware. PX4 uses sensors to determine vehicle state (needed for stabilization and to enable autonomous control). The system minimally requires a gyroscope, accelerometer, magnetometer (compass), and barometer. A GPS is needed to enable all automatic modes, and some assisted modes.

The power module and distribution are provided by a single Power Management Board, which provides power to the autopilot and ESC through a Li-Po battery. It is used to convert the battery voltage to a low voltage better adapted for the autopilot system. In addition, it is able to communicate to the PX4 firmware on the battery's voltage and the current supplied to both the flight controller processor and the motors. This is essential in monitoring the battery's charge and knowing how long the UAV can continue to fly. The Pixhawk 4 PM07 power module is chosen as it is compatible with the Pixhawk4 main processor.

The GPS module is a necessary component of the flight controller system. It allows the processor to estimate the UAV's position and fly from waypoint to waypoint autonomously. The Pixhawk 4 GPS module chosen includes a UBLOX M8N module, an IST8310 compass sensor, a safety switch, and an LED indicator. The UBLOX M8N is able to receive up to 3 GNSS, such as GPS and GLONASS, which provides a more accurate position estimation.

The ESCs are used to ensure the correct speed of the UAV's motors. The flight controller processor inputs a command to the ESC to increase or decrease the voltage supplied to the motor. AXION RC ESC 18A for Brushless motors, 5-10 Ni-xx, 2-3 Li-Po cells was chosen which is compatible with the PX4 firmware, processor, and power management board. PX4 drones are mostly commonly powered by Lithium-Polymer (LiPo) batteries. The battery is typically connected to the system using a Power Module or Power Management Board, which provides separate power for the flight controller and to the ESCs (for the motors).

4.1.2 Telemetry radio

MAVLink is a very lightweight messaging protocol that has been designed for the drone ecosystem. PX4 uses MAVLink to communicate with QGroundControl (Autopilot system discussed in a later section), and as the integration mechanism for connecting to drone components outside of the flight controller: companion computers, MAVLink enabled cameras, etc.

The telemetry comprises a set of two paired modules, one in the air and one on the ground to send and receive data from the UAV. The on-ground module can be combined with a ground station to monitor the UAV in flight and set new objectives. In order to be compatible with the Pixhawk4 flight controller chosen and also taking into consideration EU requirements that forbid 915 MHz, the Holybro 500mW Telemetry Radio V3 433 MHz is chosen.

4.1.3 RC Controller

As a safety precaution, it is imperative to have a second independent source of control for the UAV. An additional RC receiver and transmitter are required for manual control.

It consists of a remote control unit that uses a transmitter to communicate stick/control positions with a receiver based on the vehicle. The receiver must be compatible with the transmitter, the PX4 firmware, and the flight controller processor. Therefore, the FrSky ultra mini receiver R-XSR is chosen alongside the FrSky Transmitter Taranis X9 Lite.

4.2 Autopilot System

Flying the simulation with the ground control station is closer to the real operation of the vehicle with the QGroundControl application and hence was chosen. This is the open-source software that will enable pixhawk calibration, mission planning, and control for any MAVLink-enabled drone.

QGroundControl to load PX4 onto the vehicle control hardware and set up the vehicle, change different parameters, get real-time flight information and create and execute fully autonomous missions. It includes PX4 firmware, Standard plane Airframe, Sensor calibration, Radio setup, Flight modes, Power and Safety setup (see Figure 4.3).

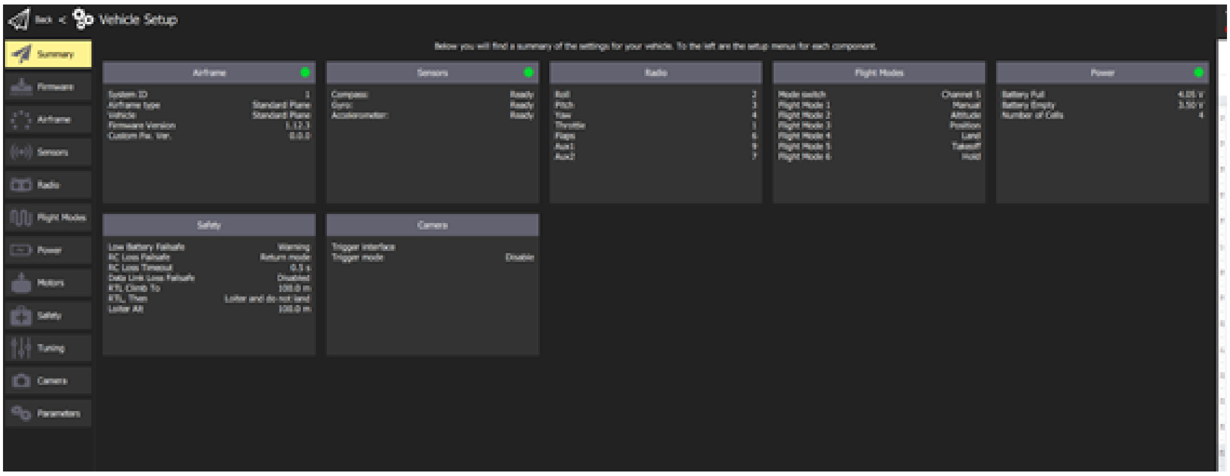

Figure 4.3: QGroundControl menu summary.

4.3 Connections

The RC transceiver is connected with the Sbus port and Bound with the joystick as shown in Figure 4.4.

The Radio setup is calibrated in the ground control as shown in Figure 4.4.

The connection to pixhawk is shown in Figure 4.6.

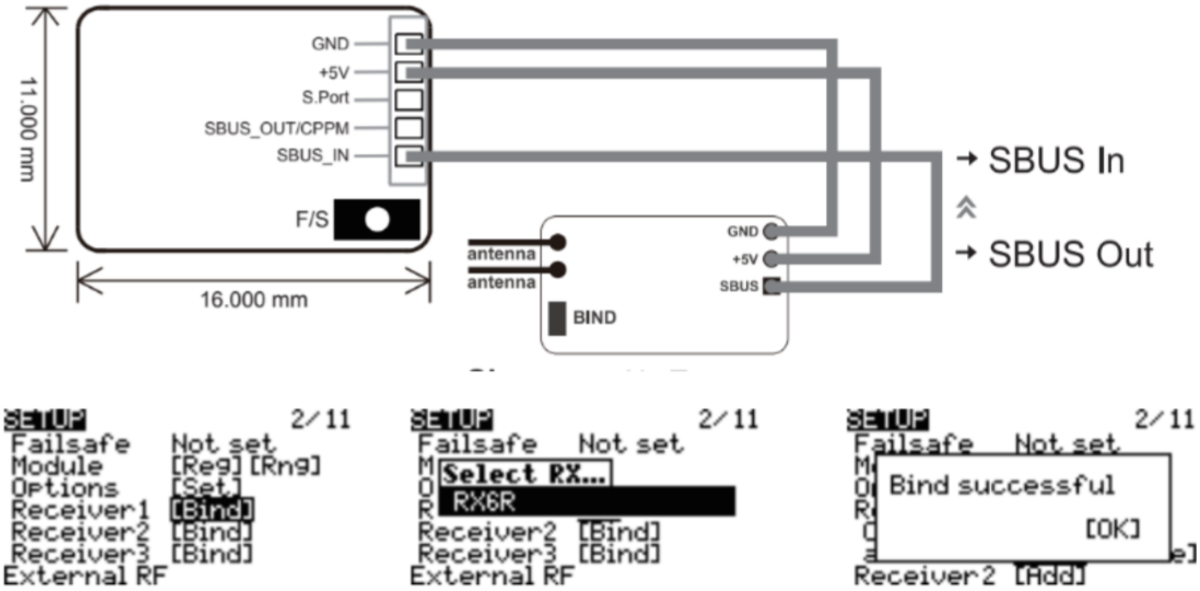

Figure 4.4: RC transceiver connection diagram [1].

Figure 4.5: Radio setup in QGroundControl.

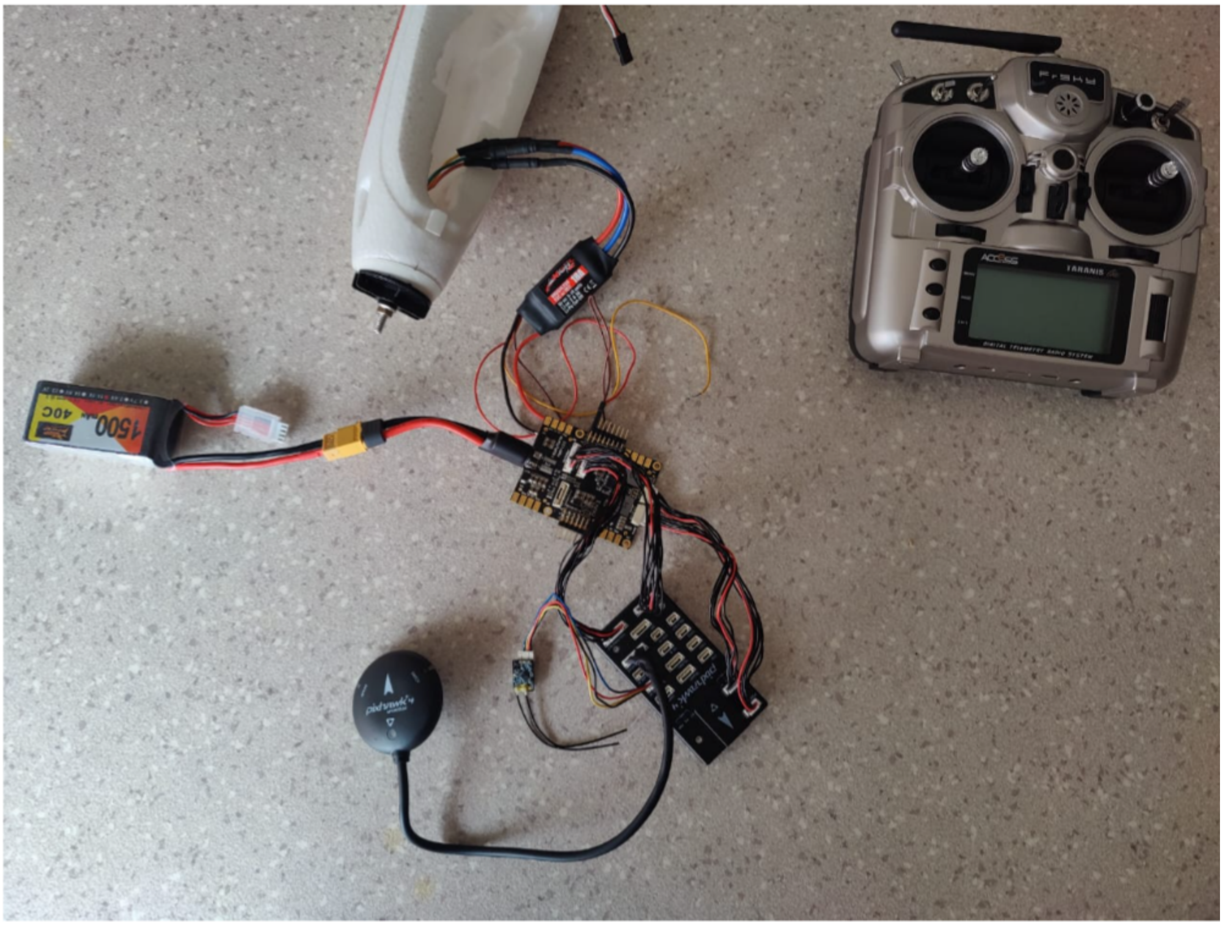

Figure 4.6: Overall connections of the UAV.

4.4 Future Work

For successive iterations in the design, the sizing of control surfaces will need to be carefully performed, as they play an important role both in terms of aerodynamics and structural performance. For a start, they influence directly the aerodynamic coefficients thus having and impact in the control of the UAV. Furthermore, they represent a change in the design of the wing and new equipment, such as servos, needs to be fitted in its structure. In addition, their effect in phenomena such as flutter or divergence can also represent a challenge for the designers.

In this sense, the control and embedded system department will propose a sizing in accordance with the stage of the design, as a different degree of accuracy will be needed. The main parameters to be determined are: the planform area ($\mathrm{S_i}$), the chord to span ratio ($\mathrm{c_i/b_i}$), the maximum deflecion ($\pm\delta_\mathrm{i}$) and wingspan location ($\mathrm{b_{p,i}}$) [2]. They can be observed, in the case of ailerons, on Figure 4.7 and some reference values can be found in Table 4.1.

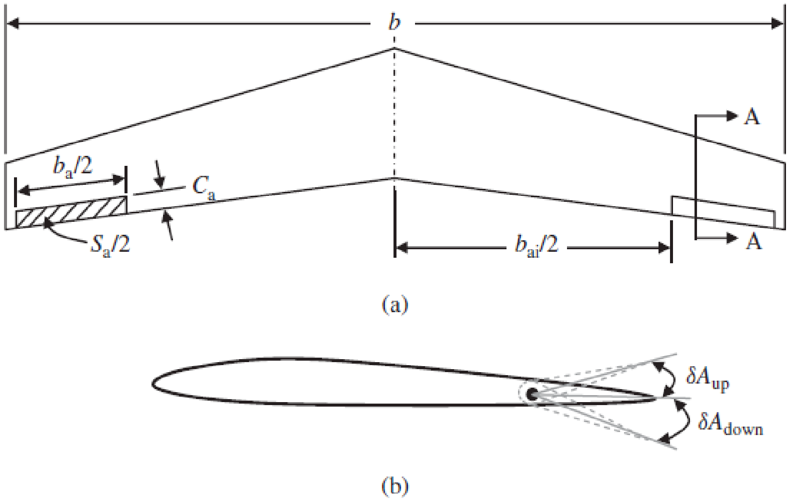

Figure 4.7: (a) Top and (b) side view of the ailerons [2].

Parameter	Aileron	Elevator	Rudder
S_i/S	0.05-0.1	0.15-0.4	0.2-0.35
b_i/b	0.2-0.3	0.8-1	0.7-1.0
$b_{p,i}$/b	0.6-0.8	0.0-0.2	0.0-0.3
c_i/c	0.15-0.25	0.2-0.4	0.15-0.4
δ_i	$\pm 30°$	$+20°, -25°$	$\pm 30°$

Table 4.1: Range of usual values for control surfaces found on the literature [2, 3].

In the early stages of the design, empirical methods can be followed to provide a first approximation. Then, the use of panel methods and CFD would be needed to achieve more precise values of the aerodynamic coefficients estimation, which together with flight dynamic simulations can be used to improve the design. There are also existing sizing software to simplify the study, for instance Hurricane [3].

Eventually, the necessary equipment to ensure the correct operation of the control surfaces will also be depicted, based on the literature review and on the products available in the market.

Chapter 5

Systems and safety

5.1 Mission Objective

To design an autonomous Unmanned Aerial Vehicle (UAV) powered by hydrogen fuel cell capable of flying for $>=$ 2 hours.

5.2 Literature Survey

A brief literature review was carried out to understand the previous design trends and capabilities (Table 5.1).

5.3 Market Survey

The existing products were identified and listed in Table 5.2.

5.4 Mission Profile

The UAV takes-off from the ground.

The UAV clears an obstacle height and initiates climb to the cruise altitude.

After attaining the cruise altitude, the UAV either cruises or loiters over the region of interest.

Once the mission objective is fulfilled, the UAV descends and lands.

All this is illustrated in Figure 5.1

Name	Authors	Year	Summary
The NederDrone: a hybrid lift, hybrid energy hydrogen UAV	C. De Wagtera , B. Remesa , E. Smeura , F. van Tienena , R. Ruijsinka , K. van Heckea , E. van der Horsta	2020	Developed by TU Delft. Hybrid energy concept. VTOL tail sitter configuration (offers more endurance than multicopter design). 12 propulsion units. Hygrogen fuel cell from Intelligent Energy 800 W pressurised cylinder. The paper included mass formula for hydrogen fuel cell. High level overview of design.
A fuel cell powered unmanned aerial vehicle for low altitude surveillance missions	N. Lape∼na-Rey ,*, J.A. Blanco , E. Ferreyra , J.L. Lemus , S. Pereira, E. Serrot	2017	Designed by Boeing Research & Technology Europe. Fixed wing glider configuration, MTOW of 11 kg. Hybrid powered. Endurance of around 4 hours. PEM Hydrogen Fuel cell. High level discussion of avionics architecture and design. Useful information regarding challenges and lessons learnt.
Design and development of a fuel cell-powered small unmanned aircraft	Taegyu Kim, Sejin Kwon	2012	Small fixed wing UAV weighing 1.5 kg. Useful for small UAV design, internal component placement. Aimed at 3h of endurance. Talks about temperature issues with PEM hydrogen fuel cell.

Table 5.1: Literature review on previous UAV.

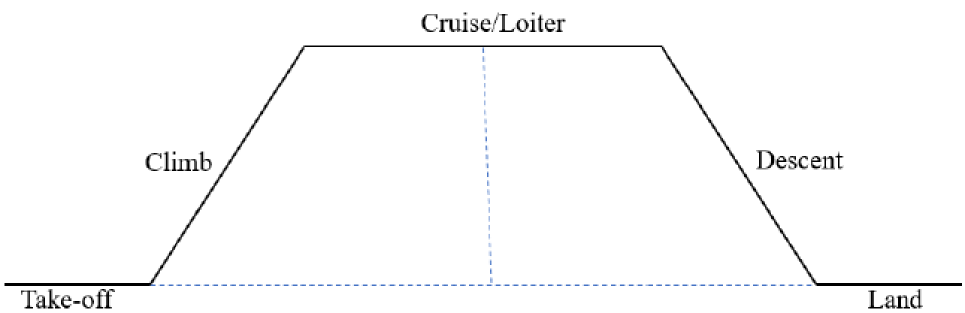

Figure 5.1: Mission profile drawing.

Drone	Type	Endurance	MTOW	Payload	Reference
Thales & ZenT	Quadcopter	2 hours			[4]
DS30	Multicopter	120 min (without payload), 80 km	24.9 kg	5 kg (max)	[5]
DJ25	Fixed wing VTOL	330 min			[6]
Skylle 1550		150 min	21 kg	10 kg (max)	[7]
Delair					[8]
Nederdrone	Fixed Wing		13 kg		[9]

Table 5.2: Summary of the market survey performed.

5.5 Requirements

The requirements for the UAV are divided into two categories: design (Table 5.3) and safety (Table 5.4). The design requirements have been derived from initial feasibility analysis and the safety requirements are derived from the EU regulations relating to the UAS (Unmanned Aerial System) operations.

5.5.1 Design Requirements

Req ID	Requirement	Rationale
1.01	The UAV shall be able to fly for a minimum of 2 hours.	Based on UAVs available in the market, the endurance was chosen unanimously.
1.02	The UAV shall not exceed a cruise altitude of 120 m AGL.	Regulation document Annex-Part B-(1-b)
1.03	The UAV shall have a wingspan less than 3 m.	-
1.04	The UAV shall have a wing area of 1.29 m^2.	From feasibility analysis
1.05	The UAV shall be powered by a hydrogen fuel cell with an energy density >= 500 Wh/kg.	From feasibility analysis
1.06	The UAV shall weigh no more than 20 kg.	From feasibility analysis
1.07	The UAV shall be able to carry a payload of at least 5 kg.	

Table 5.3: Design requirements to be fulfilled.

5.5.2 Safety Requirements

These requirements have been derived from 'Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft'. According to this document, the UAV can operate under three categories: Open, Specific, Certified based on the requirements it meets. For the current system of interest i.e., UAV, the operations must be performed under 'Specific' category due to the following aspect:

- "Where one of the requirements laid down in Article 4 or in Part A of the Annex is not met, a UAS operator shall be required to obtain an operational authorisation pursuant to Article 12 from the competent authority in the Member State where it is registered."
- The requirement not being met in Article 4 is – "during flight, the unmanned aircraft does not carry dangerous goods and does not drop any material". The dangerous goods include:
  - explosives (mass explosion hazard, blast projection hazard, minor blast hazard, major fire hazard, blasting agents, extremely insensitive explosives)
  - gases (flammable gas, non-flammable gas, poisonous gas, oxygen, inhalation hazard)
  - flammable liquids (flammable liquids; combustible, fuel oil, gasoline)
  - flammable solids (flammable solids, spontaneously combustible solids, dangerous when wet)
  - oxidising agents and organic peroxides
  - toxic and infectious substances (poison, biohazard)
  - radioactive substances
  - corrosive substances

  Since, the UAV shall be hydrogen powered, which is a flammable liquid, the UAV must be considered under 'Specific' category and the following requirements have been considered for this category.

Req ID	Requirement	Rationale
2.01	The UAV shall operate with maximum characteristic dimension up to 3 metres in VLOS over controlled ground area except over assemblies of people.	Part-B UAS.SPEC.020 Operational declaration – (1-a)
2.02	The UAV shall operate with maximum characteristic dimension up to 1 metre in VLOS except over assemblies of people.	Part-B UAS.SPEC.020 Operational declaration – (1-a)
2.03	The UAV shall operate with maximum characteristic dimension up to 1 metre in BVLOS over sparsely populated areas.	Part-B UAS.SPEC.020 Operational declaration – (1-a)
2.04	The UAV shall operate with maximum characteristic dimension up to 3 metres in BVLOS over controlled ground area.	Part-B UAS.SPEC.020 Operational declaration – (1-a)
2.05	The UAS operator shall be required to obtain an operational authorisation pursuant to Article 12 from the competent authority in the Member State where it is registered.	Article 5 – (1)
2.06	When applying to a competent authority for an operational authorisation pursuant Article 12, the operator shall perform a risk assessment in accordance with Article 11 and submit it together with the application, including adequate mitigating measures.	Article 5 – (2)
2.07	The UAV operator shall obtain certification from the competent authority.	Article 7
2.08	While in flying in autonomous mode, the UAV shall have the capability of switching to manual mode by the remote pilot.	For the safe recovery of the UAV
2.09	The UAV shall have Return to Home capability in case of any error (such as GPS loss).	

Table 5.4: Safety requirements to be fulfilled.

Chapter 6

Proposed timeline

Chapter 7

Team organization and inventory

Chapter 8

Conclusion

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