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DESIGN OF A HYDROGEN POWERED SMALL ELECTRIC FIXED-WING UAV WITH VTOL CAPABILITY

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Abstract. *Most electric small UAVs require large batteries, which lead to increased weight and low endurance. With the current development of new energy sources and emerging technologies, the present work aims to design a fixed-wing UAV with vertical take-off and landing (VTOL) capability using a fuel cell-based propulsion system. The design requirements made by the Portuguese Air Force include a maximum take-off mass of 25 kg and a minimum flight time of two hours. To accomplish these, a conceptual design framework was developed, supported by fast estimates for the disciplines of aerodynamics, structures, propulsion and controls, and a multi-objective optimisation approach led to the initial UAV configuration and sizing. The different discipline models were coupled and multidisciplinary optimisation was conducted to find the UAV optimal design. This process led to a 22 kg aircraft, having a maximum endurance over 3 hours with a 7.2L hydrogen tank, assisted with batteries for VTOL and climb. The results obtained suggest that the application of the hydrogen-powered fuel cell system meets the requirements set, while also proving to be a feasible alternative to conventional solutions.*

Keywords: Fuel cell, Green aircraft, MDO, Multi-objective optimisation, Multi-rotor, Pusher configuration

1 INTRODUCTION

Aircraft design is a branch of aerospace engineering which takes a set of mission requirements and develops a viable solution that bests satisfies them. To do so, it must incorporate knowledge from the different disciplines, namely, aerodynamics, structures, propulsion and control [1].

Despite being an iterative process, the design can be divided into three primary stages: conceptual, preliminary and detailed. It starts with a market study, the analysis of different configurations and trade-off studies between design and requirements are taken into account in the conceptual stage. Then, the configuration selected is fixed and the in-depth design and disciplinary studies of the major components, mostly resorting to computational simulations, take place in the preliminary stage. Finally, in the detailed stage, the structure is fully defined and a prototype is built, where the tooling and construction methods are defined alongside tests of major structural components, ending on a full-scale model to perform flight tests and validate the results [2].

Many energy sources have been tried in aircraft design, being hydrogen a topic of recent research and development progress, despite having already been exhaustively studied as an alternative energy source to fossil fuels for several decades [3].

In the context of seeking innovation in the aeronautical sector, the Air Force Academy Research Centre (CIAFA) started a project to design a class-I fixed-wing small Unmanned Aerial Vehicle (UAV) capable of performing Vertical Take-off and Landing (VTOL) and having a fuel cell as the primary source of energy. The proposed major performance and operational requirements are presented in Tab.1.

Table 1: Performance and operational requirements.

Payload	MTOW	Endurance	Cruise speed	Stall speed	Max TO altitude	Ceiling
2 kg	$\leq$ 25 kg	$\geq$ 2 h	35-45 kts	$\leq$ 25 kts	3000 m	4500 m

This work focuses on the initial steps of the design process, where the goal is to search for a feasible solution and assess its performance. To that end, different possible configurations were studied and the most adequate selected, followed by a market research on similar UAV and adequate propulsion system components (Sec.2), to estimate some of the design parameters. The UAV main mission profile is presented (Sec.3) before the conceptual design methodology is laid down (Sec.4). Then, the initial design point is discussed (Sec.5), followed by optimal trade-off studies (Sec.6). The resulting conceptual design is described (Sec.7), culminating in the current preliminary design progress (Sec.8).

2 CONCEPT GENERATION

2.1 Configuration Selection

A market study was conducted on configurations and methodologies currently used to produce an UAV capable of performing endurance-focused missions, whilst being capable of VTOL, for the expected MTOW category. The main focus was to investigate the advantages and disadvantages of the various configurations available for fixed wing configuration: a) Tail sitter [4] is a simple design, light, less prone to mechanical failures and easy to transport. However, it has low tolerance to lateral wind in VTOL mode and can be difficult to control during landing (Fig.1a); b) Lift+cruise [5] is the most common configuration. The fact that the propulsion system is divided in forward and vertical modes offers greater efficiency for each mode. The downside is the increase in parasite drag and a higher overall dead weight (Fig.1b); c) Tilt rotor [5, 6] has rotors that tilt for vertical or horizontal propulsion. It exhibits good control and stability but has higher structural complexity and reduced propeller efficiency since they are designed to perform both VTOL and horizontal flight (Fig.1c); d) Transwing [7] offers great control and response during VTOL mode and, since the fuselage stays parallel to the ground, the image gathering devices can be always operational. The disadvantages are related with the high complexity of the design: shortage of time and little information regarding the wing root joint mechanism are the main ones (Fig.1d).

(a) Tail sitter [4] (b) Lift + cruise [5] (c) Tilt rotor [6] (d) Transwing [7]

Figure 1: Possible UAV configurations.

To select the appropriate aircraft configuration for the project needs, an Analytic Hierarchy Process (AHP) was carried out [8]. This process stipulates a set of criteria which are compared among themselves. In this work, the design team defined four main groups: operation, manufacturing, maintenance and innovation. In the operation criterion, the parameters taken into account were aerodynamics, stability and control, endurance, propulsion efficiency, flexibility and redundancy. Regarding the construction criterion, the parameters cost and feasibility were considered. In the maintenance criterion, the parameters were cost, interior access, reliability and transport. Finally, in the innovation criterion, the importance of using new technologies in the design was evaluated, when compared to the requirements and the knowledge available at CIAFA.

A numerical scale ranging from 1 (same importance) to 9 (extremely important) was used to quantitatively compare the different criteria among the different configurations, resulting into matrix arrangements. Firstly applied to the four main categories, secondly, to the several parameters within each main category and finally to the four design concepts to each sub-category. Figure 2 represents, in a multi-level pie chart, the process done with each component weight compared to the others. The inner layer has the four main categories, the middle layer has the subcategories with the color pattern of the corresponding main category, and the external layer represents each configuration classification. The final results are presented on the right, with the lift+cruise configuration proving to be the most suitable for the project requirements.

2.2 Configuration Refinement

Following the choice of a lift+cruise configuration, the tail type as well as the placement of the VTOL and forward mode propulsive systems were defined.

With regard to the placement of the VTOL propulsive system, there were two main solutions identified during the market study: either a design based on a single fuselage with added booms to support the VTOL system, or a design that uses a twin boom

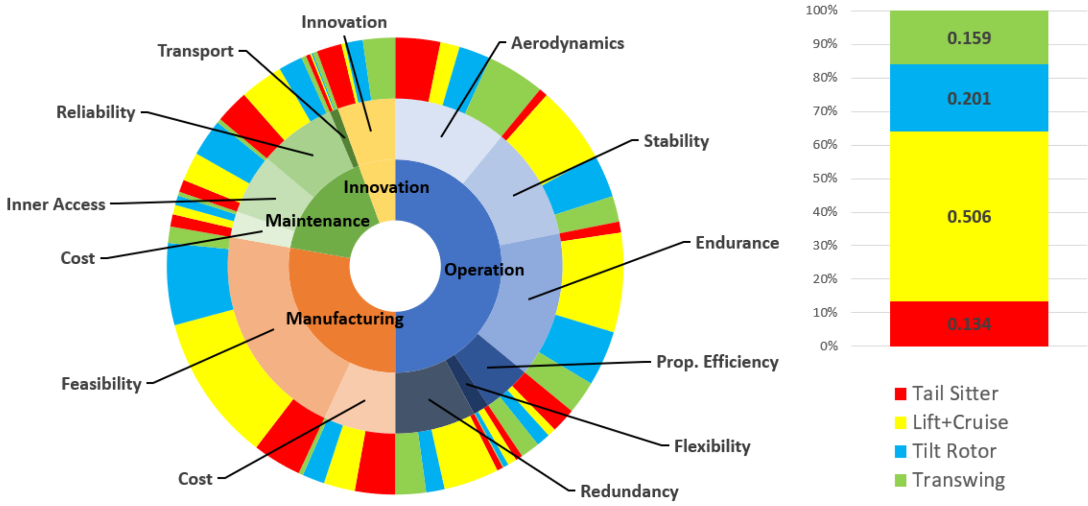


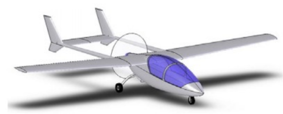
Figure 2: Representation of the Analytic Hierarchy Process for the configuration selection.

configuration where the tail and the propulsive system are both applied [9]. The design team opted for the double boom configuration to reduce the overall weight, since there is no need to create additional structures for VTOL system, and to provide additional structural rigidity [10]. A double boom also gives more freedom for the placement of the forward mode propulsive system, making possible either tractor or pusher configurations.

In terms of tail type, among the various double boom arrangements analyzed, the design team decided that the inverted V-tail had the best characteristics for the project, namely: it is free from the influence of the propeller and wing wakes; it has less surface area, making the least parasite drag possible and becoming less heavy; and it provides good stability in the presence of cross-wind. It is also the most common configuration in UAVs, being the UAV Factory Penguin B or the Ogassa OGS 42 some examples found during the market study (Tab.2). The main drawback of an inverted V-tail is the coupling between longitudinal and lateral modes, making the aircraft control more complex.

Regarding the propulsion for forward flight, there are two configurations possible, tractor or pusher, as illustrated in Fig.3. Since the twin-boom configuration was already

(a) Tractor



(b) Pusher

Figure 3: Forward propulsion system configurations [11].

adopted, the pusher configuration was selected, which is also the most common for this type of UAVs. The pusher configuration provides beneficial payload integration options [9] and better visibility for the gimbal module [11]. In addition, since the propeller wake will not interact with the fuselage, wing or tail, it reduces the overall friction coefficient and, consequently, the UAV total drag [2]. This configuration has two major drawbacks: worse propeller efficiency and displacement of the centre of gravity towards the rear, which in turn implies a longer tail in order to maintain stability and control [2].

2.3 Market Research

With the lift+cruise configuration chosen, a market research of UAVs with similar configuration was done, including UAVs with VTOL capability and UAVs with fuel cell as primary energy source, as summarised in Tab.2.

Table 2: Market study of similar UAVs.

VTOL UAV	MTOW	Propulsion sys.	Structural weight	Empty weight
Ogassa OGS42V	36 kg	hybrid	-	22.0 kg
MMC Griflion M8	12 kg	electric	5.5 kg	-
Alti Transition	18 kg	hybrid	5.8 kg	11.8 kg
UAV fuel cell powered	MTOW	Fuel type	Structural weight	Endurance
Sparkle Eagle Plus - VTOL	21 kg	hydrogen	12.5 kg	5 h
Top Engineering Falcon-V	18 kg	hydrogen	6.5 kg	3 h

Other studies were carried out to estimate initial parameters used during the conceptual phase. Regarding the VTOL motor, based on an MTOW of 25 kg, a configuration with 4 electric motors providing sufficient power at 80% of their maximum rating, the power-to-weight ratio was estimated based on components available at T-Motor manufacturer [12] as summarised in Tab.3. For the forward mode motor, another power-to-weight ratio value

Table 3: Market study of VTOL motors.

Motor	Power @80%	Weight	Power to weight ratio
P80IIIPin KV100	2335.0 W	0.649 kg	3.598 kW/kg
V605 KV210	1827.5 W	0.310 kg	5.895 kW/kg
V505 KV260	1451.2 W	0.215 kg	6.750 kW/kg
V602 KV180	1147.4 W	0.300 kg	3.825 kW/kg

was assumed and based on MTOW, cruise speed, required thrust and on the reference [13], motors capable of producing around 1500 W of continuous power were analysed. The market research includes motors from T-motor [12] and Hacker [14] manufacturers, as presented in Tab.4. These studies allowed for the estimation of the power-to-weight ratio,

Table 4: Market study of motors for forward flight mode.

Motor	Rated Power	Weight	Power-to-weight ratio
Hacker A60-5S V4	1591 W	0.595 kg	2.674 kW/kg
Hacker A60-5XS V4	1870 W	0.480 kg	3.896 kW/kg
T-Motor AT4125 long shaft	1554 W	0.355 kg	4.378 kW/kg

for both VTOL and forward motors, that will be used further as initial data estimates during the conceptual design Tab.6.

2.4 Fuel Cell System

The main focus of the project is the design of a small fixed-wing UAV with a fuel cell as a primary source of energy. A fuel cell is an electrochemical equipment that directly converts chemical energy from a supplied fuel into electrical energy. Its primary parts consist of two layers, the anode and the cathode, where the oxidation and reduction occurs, respectively. Between the layers, there is an electrolyte material that works as a barrier, allowing ions to flow, while forcing the electrons to move out of the electrolyte, thus generating electricity [15].

There are different fuel cell types, depending on the the electrolyte material, being the Polymer Electrolyte Membrane Fuel Cell (PEMFC) the most common in UAVs [16]. This uses a polymer membrane as an electrolyte material and runs on hydrogen, as schematically shown in Fig.4.

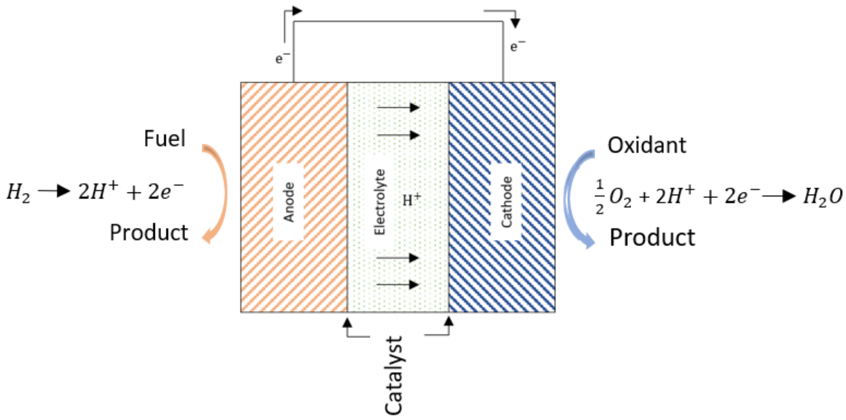


Figure 4: Schematic of $H_2 - O_2$ PEMFC (adapted from [17]).

A market research was done to evaluate the characteristics of different fuel cells to be used as a starting point in the conceptual design. This led to the identification of two models from Intelligent Energy [18] that meet the project requirements, as listed in Tab.5: a single IE-Soar™ 800W cell or two IE-Soar™ 650W cells mounted in parallel.

Table 5: Market research of fuel cells.

Fuel cell model	IE-Soar 800 W	IE-Soar 650 W (x2)
Rated Power [W]	800	1300
Mass [kg]	0.930	1.620
Power-to-weight ratio [W/Kg]	860.2	802.5

Hydrogen can be stored in different forms depending on the fuel cell operation - compressed gas, liquid, chemical or physical absorption [19]. Compressed hydrogen is the most common in UAVs applications, where it is kept at high pressure (35 to 70 MPa) on cylindrical fuel tanks made of composite materials [16]. The tanks present a considerable mass when compared to the quantity of hydrogen they store, as attested in Fig.5 that shows the hydrogen to tank mass ratio of different tank capacities from different suppliers.

3 MISSION PROFILE

The stated requirements and target performance criteria are based on typical mission scenarios. The main mission profile of the developed UAV, set by the design team, starts with a vertical take-off, followed by a vertical climb at 2 m/s (1-2). This phase is pursued by hover (2) coupled with an acceleration in forward mode (2-3), for a total of 45s, to transition from VTOL to forward fight. A climb phase succeeds, divided into two parts: first a high-gradient climb with 2.5 m/s vertical speed to overcome possible high altitude

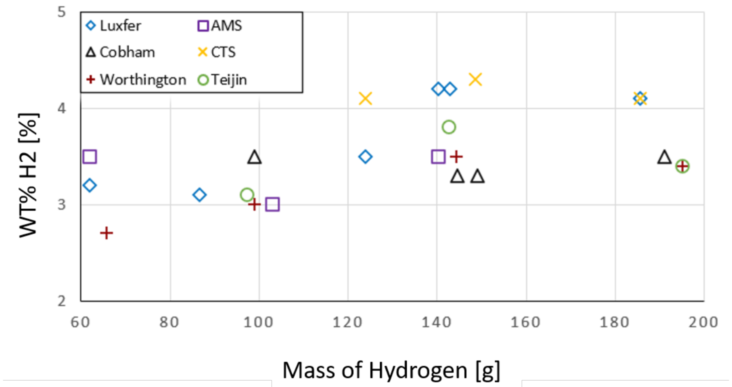


Figure 5: Hydrogen to tank mass ratio of different tank capacities (adapted from [20])

obstacles (3-4), then a low-gradient climb to allow a higher speed closer to cruise speed (4-5). Subsequently, two cruise phases occurs (5-6 and 7-8), encompassing the main mission - loiter - in between (6-7). These cruise segments will be set between 35 and 45 knots according to requirements. As cruise ends, the UAV initiates the descent (8-9), until it starts the landing circuit for 5 minutes (9-10). When ready to land, the UAV starts the hover phase to do the transition (10), followed by the vertical descent at 1 m/s (10-11). The described mission profile is sketched in Fig. 6.

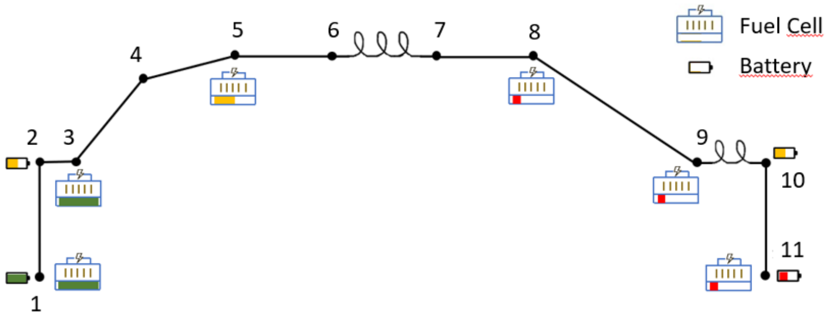


Figure 6: Main mission profile.

A strategy for operating each segment was sought: the fuel cell used in forward flight mode is sized to produce enough power during level flight; an additional battery is sized to be used in the vertical climb and vertical descent phases.

4 CONCEPTUAL DESIGN METHODOLOGY AND INITIAL DATA

The design methodology consisted of using a numerical tool developed by the authors together with a multi-objective optimisation algorithm to perform trade-off studies that assess the impact of some design decisions on the overall project.

A flowchart of the developed numerical tool developed is represented in Fig.7. The methodology and design process is based on Gundlach [9] with some additional considerations from other authors.

For the conceptual design, some initial parameters of the UAV must be set, encompassing different areas, based on available state-of-the-art data. The market studies conducted form the basis for some of the values considered regarding the airframe but also motors, propellers and fuel tanks. Avionics data is based on a similar CIAFA aircraft. Special care was taken when estimating C_{D_0} since the presence of the VTOL propulsion system

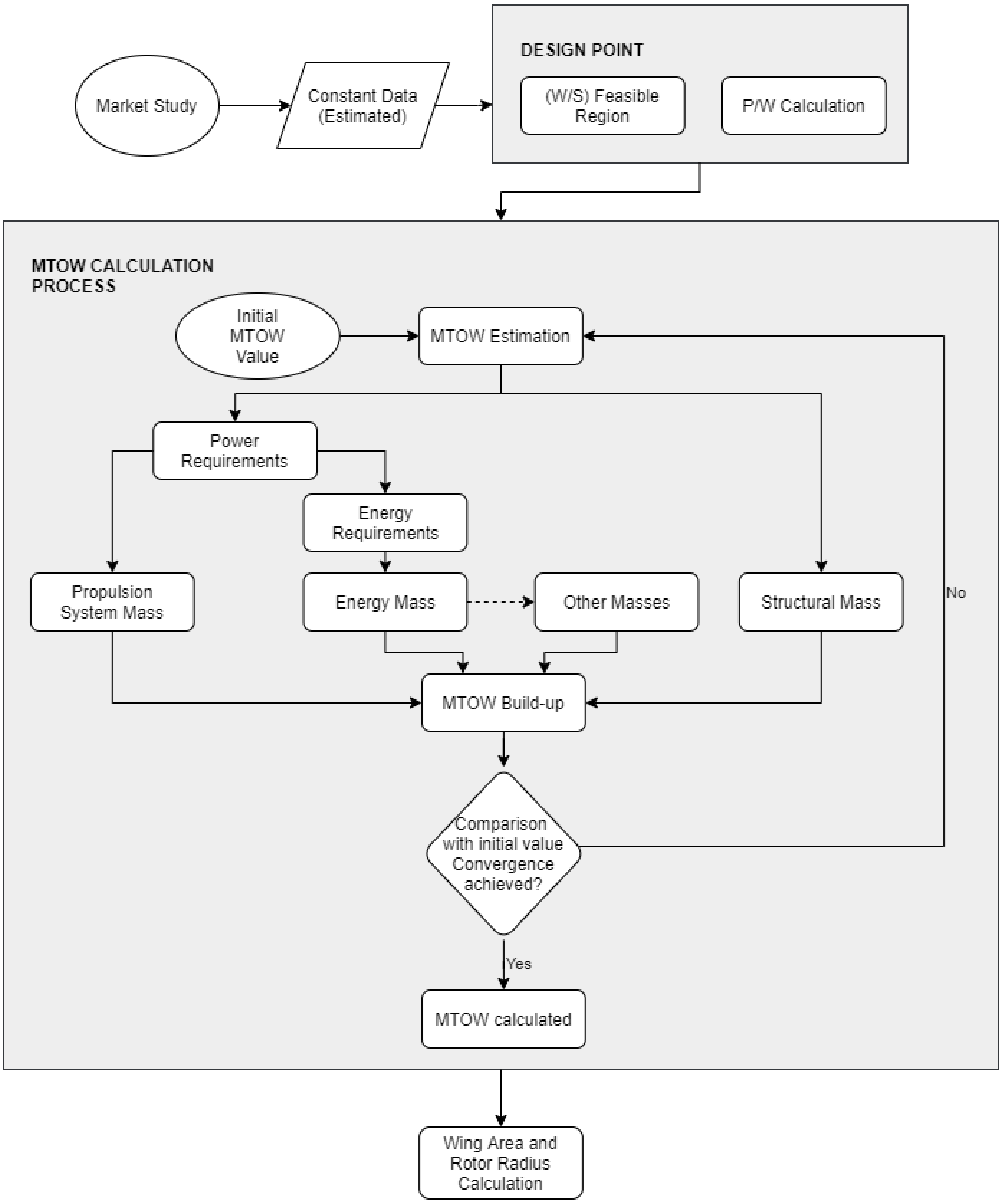


Figure 7: UAV conceptual design methodology.

increases drag at horizontal flight. Table 6 summarises all the UAV initial parameter values. Some of them will be used at the design point phase while others during the weight build-up (Sec.5)

5 DESIGN POINT AND WEIGHT BUILD-UP

With the initial data defined, the design point is found for forward flight (power loading as a function of wing loading) and for vertical flight (power loading vs disk loading).

The wing loading is subjected to a set of constrains imposed by design proposal, those being the stall condition and the maximum ceiling. The power loading for each forward flight segment of the mission profile is computed through a simple performance equation

Table 6: UAV initial parameter values.

Parameter	Value	Parameter	Value
Airplane base drag coefficient - C_{D_0}	0.04	Forward motors power-to-mass ratio	3.5
Oswald efficiency factor - e	0.75	VTOL motors power-to-mass ratio	4.5
Maximum lift coefficient - $C_{L_{max}}$	1.3	Batteries safety factor	0.3
Structural factor	0.35	Batteries specific energy density	160 Wh/kg
Propeller efficiency - η_{pr}	0.65	Electric system efficiency	0.85
Induced power factor - k_i	1.2	Hydrogen-to-tank mass ratio	0.035
Rotor solidity - σ	0.10	Hydrogen low heating value	120 MJ/kg
Rotor profile drag coefficient - $C_{d_{0(rotor)}}$	0.012	Avionics power requirement	80 W
Fuel cell efficiency	0.4-0-5	Avionics and cabling mass	2.5 kg

considering the rate of climb (ROC) [2], applicable for climb and level flight,

$$\left(\frac{P}{W}\right)_{min} = \frac{1}{\eta_p}\left[ROC + \frac{\rho V^3 C_{D_0}}{2\left(\frac{W}{S}\right)} + \frac{2K\left(\frac{W}{S}\right)}{\rho V}\right], \tag{1}$$

which considers the base drag coefficient and the induced power factor,

$$K = \frac{1}{\pi\ AR\ e}\,. \tag{2}$$

For the vertical flight stages, that include vertical climb, hover and vertical descent, a disk loading value is defined. Each flight condition has its own power loading equation [21], using the momentum theory for hover and vertical climb (V_y representing the vertical climb speed),

$$\left(\frac{P}{W}\right)_{hover} = k_i\sqrt{\frac{DL}{2\rho}} + \frac{\rho V_{tip}^3}{DL}\left(\frac{\sigma C_{d_{0_{rotor}}}}{8}\right) \text{ and} \tag{3}$$

$$\left(\frac{P}{W}\right)_{vertical\ climb} = V_y - \frac{k_i}{2}\left(V_y - \sqrt{V_y^2 + \frac{2DL}{\rho}}\right) + \frac{\rho V_{tip}^3}{DL}\left(\frac{\sigma C_{d_{0_{rotor}}}}{8}\right), \tag{4}$$

and, due to the low descent velocity, experimental curve-fitting expression for the vertical descent segment, considering the descent speed lower than twice the induced velocity at the rotor plane,

$$\left(\frac{P}{W}\right)_{vertical\ descent} = V_y + v_{i,d}\ k_i + \frac{\rho V_{tip}^3}{DL}\left(\frac{\sigma C_{d_{0_{rotor}}}}{8}\right), \tag{5}$$

with

$$v_{i,d} = v_h\left[k_i - 1.125\left(\frac{V_y}{v_h}\right) - 1.372\left(\frac{V_y}{v_h}\right)^2 - 1.718\left(\frac{V_y}{v_h}\right)^3 - 0.655\left(\frac{V_y}{v_h}\right)^4\right]. \tag{6}$$

The aircraft weight can be divided into four main contributions: structural (related to airframe), propulsion systems (accounts for the weight of the motors, ESCs and propellers/rotors), energy part (includes the batteries and hydrogen weight) and other weights (includes some fixed weight components such as avionics, cabling, servos, payload, fuel cell system, and a variable weight such as the hydrogen tank since its size depends on the hydrogen mass required). Referring to Fig.7, the MTOW calculation process required an initial estimate for each of these.

The structural weight is simply defined as as fraction of the MTOW because of the lack of information at the conceptual phase that does not allow an estimate of the airframe weight based on the aircraft dimensions.

The propulsion weight is obtained through a ratio between the power output of the electric motor and its weight. The motors are selected based on the required maximum output power, computed from the power loading equations at the design point multiplied by the initial MTOW estimate. The forward and VTOL motors have different properties, as such power-to-weight ratios and power requirements. A safety factor of 15 % is applied to the maximum power requirement (for both flight operation modes) to account for estimates inaccuracies and additional power requirement due to sudden events like wind gusts.

The energy weight calculations are based on the power requirements and duration of each flight phase, being the power consumption of the avionics also considered. As mentioned previously, vertical flight segments are purely powered by battery while horizontal flight has hydrogen as its energy source. Additionally, the fuel cell maximum output cannot provide enough power for certain segments (climb), so the additional battery is considered for those cases. With this in mind, some hydrogen is accounted to recharge that battery to account for additional peak power demand. Moreover, a safety margin is considered for the battery and additional hydrogen to serve as reserve. The battery and hydrogen mass is determined by applying the specific energy density of Li-Po batteries and the low heating value of hydrogen. The total hydrogen mass is then used to compute the mass of the tank needed to store it.

The total weight is then build up by summing the group estimates together, and compared with the previous estimate. A correction is applied based on the difference between the two and the process is repeated until a stopping criteria is met: either the absolute difference is less than one gram or the number of iterations exceeds 50.

Knowing the converged MTOW, the wing area and rotor area (and consequently rotor radius) are determined with the wing loading and disk loading, respectively.

6 OPTIMAL TRADE-OFF STUDIES

To assess the impact of some early design decisions on the overall UAV design, two main objectives were considered: MTOW and endurance. The multi-objective constrained optimisation problem was posed in the standard form

$$\begin{array}{rll} \text{minimise} & f_m(\boldsymbol{x}), & m = 1, 2 \\ \text{subject to} & g_j(\boldsymbol{x}) \leq 0, & j = 1, ..., J \\ & x_i^L \leq x_i \leq x_i^U, & i = 1, ..., n\,, \end{array} \tag{7}$$

where six design variables were considered, as listed in Tab.7.

The objective function can be written in vector form as

$$\boldsymbol{f}(\boldsymbol{x}) = [MTOM(\boldsymbol{x}), -Endurance(\boldsymbol{x})]^T \tag{8}$$

and the inequality constraints as

Table 7: Design variables for the multi-objective optimisation problem.

Design var.	Description	Lower bound	Upper bound	Units
x_1	Disk loading, W/A	100	350	N/m^2
x_2	Wing loading, W/S	100	250	N/m^2
x_3	Wing aspect ratio	5	12	-
x_4	Loiter time	2	∞	h
x_5	Stall speed	26	32	kts
x_6	Operational speed	30	45	kts

$$\boldsymbol{g}(\boldsymbol{x}) = \left\{ \begin{matrix} MTOM(\boldsymbol{x}) - 25 \\ -E(\boldsymbol{x}) + 2.5 \\ b(\boldsymbol{x}) - 4.0 \\ P_{\text{Con. Mode}} - P_{\text{nominal}} \\ m_{\text{fuel}} - m_{\text{Tank}} \\ V_{\text{stall}} - V_{\text{Op}} + 8 \end{matrix} \right\} \begin{bmatrix} kg \\ h \\ m \\ W \\ g \\ kts \end{bmatrix} \leq 0\,, \tag{9}$$

where $g_1(\boldsymbol{x})$ sets the maximum MTOW; $g_2(\boldsymbol{x})$ sets the minimum endurance; $g_3(\boldsymbol{x})$ constraints the maximum wingspan; $g_4(\boldsymbol{x})$ imposes that the required power at all times must be less than the fuel cell nominal power when flying in forward flight mode; $g_5(\boldsymbol{x})$ forces the total amount of hydrogen needed to be within the tank capacity; and $g_6(\boldsymbol{x})$ establishes that minimum operational speed should be at least 8 kts higher than the stall speed.

With the problem defined in Eq.(7), the *Pymoo* open-source optimisation framework was used [22]. The Non-Dominated Sorting Genetic Algorithm (NSGA-ii) was selected for its multi-objective handling, which sorts the individuals in the population by rank. The objective function vector is evaluated using the numerical tool developed by the authors (Fig.7). The stopping criteria is defined with design variable ($x_{tol} = 10^{-4}$), objective ($f_{tol} = 10^{-3}$) and constraint violation ($x_{cv} = 10^{-6}$) tolerances. In case the algorithm is not able to meet these, a maximum of 150 generations are run.

Several trade-off studies were performed running the *Pymoo* framework with the numerical analysis tool (Fig.7), using the parameters defined in Tab.6.

Considering the first four design variables in Tab.7, all constraints but $g_5(\boldsymbol{x})$, and a fuel cell with a nominal power of 800 W, the optimisation problem is solved and the Pareto-front (with rank 1 or non-dominated solutions) obtained is shown in Fig.8.

Three optimal solutions were selected for comparison purposes: one corresponding to the lightest UAV (MTOW=19.2 kg); an intermediate solution (MTOW=19.7 kg); and the heaviest solution (MTOW=20.4 kg). The mass of hydrogen varies between 120 and 130 g. The maximum required power to be supplied by the fuel cell corresponding to each solutions is represented in Fig.9, which shows that there is always an excess of power as imposed by the constraint g_4. Nevertheless, the power margin in each solution is small, being largest for the lightest solution.

Due to the uncertainty in estimating some key parameters needed to assess the power required, particularly the aircraft base drag coefficient C_{D_0}, solutions with larger power margins were searched. To do so, instead of using a ratio to estimate the fuel tank mass based on the fuel mass, two distinct tanks were chosen: a large tank with dry mass of 4.3 kg and a capacity for 185 g of H_2; and a small one of 3.3 kg with 148 g hydrogen capacity.

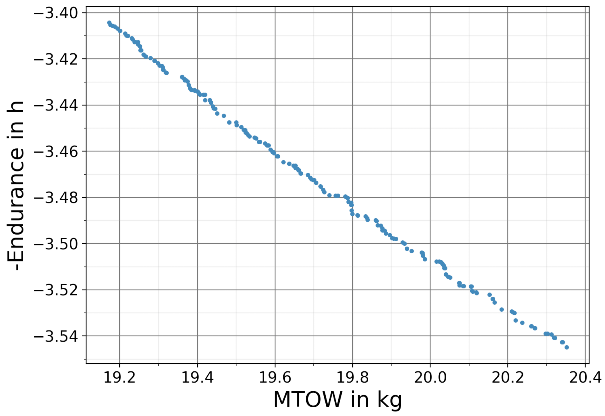


Figure 8: Optimal trade-off solutions

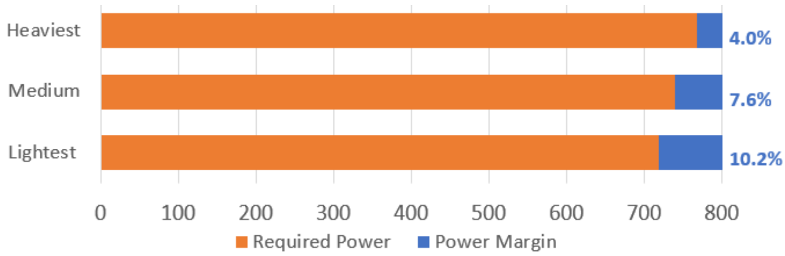


Figure 9: Maximum required power in level flight.

The small tank and the 800 W fuel cell are used in one problem formulation and the large tank with a 1300 W is used in another. For the lightest configuration, two additional design variables were added to the optimisation problem, stall speed and operational speed (x_5 and x_6 in Tab.7) and the constraint g_5 added to guarantee that the mass of hydrogen can be held in the tank, Eq.(9). For the heavier configuration, the constraint g_5 was added as well, with $m_{\text{tank}} = 175\,\text{g}$, Eq.(9) but no additional design variables were considered. After comparing the two different set of solutions, it was concluded that, if the wingspan constraint is to be satisfied, then any solution in the obtained Pareto-front of the heavier configuration will have a larger MTOW and smaller Endurance when compared to any other optimal solution of the smaller configuration.

7 FINAL CONCEPTUAL DESIGN

With the smaller configuration, a Pareto-front was obtained with the different optimal trade-off solutions. Because the fuel mass is small compared to the total UAV mass (200 g compared to 19 kg), there is no reason for flying without the hydrogen tank completely full. The selected final design corresponds to the lighter configuration with 800 W fuel cell and the hydrogen tank fully topped off at the start of the mission.

After analysing all estimates made by the analysis tool, a market search was conducted to select appropriate motors, propellers and batteries. The general characteristics of the final configuration are summarised in Tab.8.

As expected, the total UAV weight increased when the ratios were replaced by the actual components since all the batteries and motors had to be rounded up to the nearest commercially available component. The propulsion system mass is comprised of four V605 KV210 motors coupled to 22x7.4 propellers to power the VTOL and hover segments, and

Table 8: General characteristics of the UAV final configuration.

Description	Value	Description	Value
Stall Speed	28 kts	Op. Speed	36 kts
Wingspan	4 m	Propulsion sys. mass	2.60 kg
Wing area	1.372 m^2	Energy sys. mass	7.23 kg
Payload	0.9 kg	Structural mass	7.56 kg
Endurance	3h20min	MTOW	21.6 kg

one AT 5220-A 20 25-CC motor with a 19x10 propeller to power the forward flight. The energy system includes: two Li-Po 6S batteries, one coupled to the fuel cell system and another used solely to power the VTOL and hover segments; a 7.2 L hydrogen tank and a single fuel cell with 800W nominal power.

8 PRELIMINARY DESIGN PROGRESS

In order to have a more refined design than the one presented in the conceptual phase, the wing, tail and fuselage preliminary design is conducted. The methodology followed is based on Corke and Sadrey, with considerations from other authors regarding design for UAVs [1, 9, 23].

The wing structure is divided into three panels: one rectangular in the middle and two tapered ones at the tips. To meet the maximum lift coefficient estimated previously, SG6042 airfoils are chosen, which also have good aerodynamic efficient at cruise conditions.

The fuselage is shaped around the hydrogen tank and it is sized to accommodate all the necessary components, distributed along its length.

The tail arm length of the inverted V-tail is based on the total aircraft length and the symmetric NACA 0008 airfoil is selected for the stabilizers, that generate a downward force at cruise.

Figure 10 represents the initial CAD model of the design with the preliminary considerations stated before.

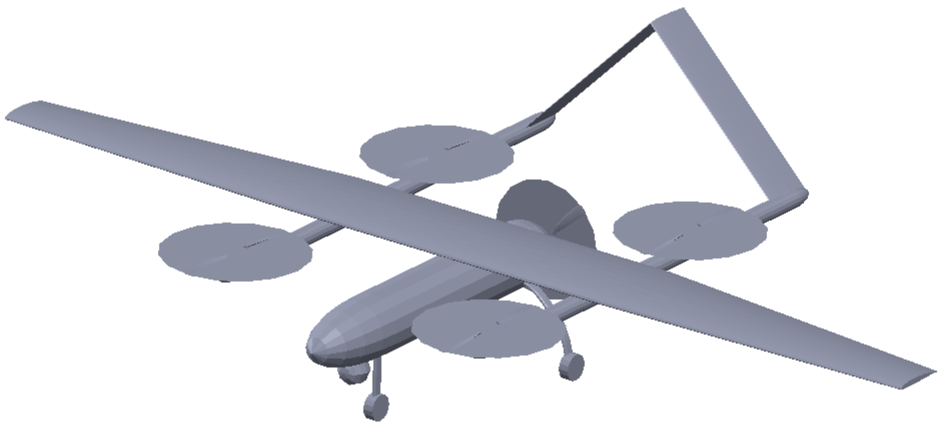


Figure 10: CAD model of the UAV following considerations from preliminary design.

9 CONCLUSIONS

During the conceptual and preliminary design of the UAV, some challenges were found using hydrogen as energy source: the fuel cell efficiency is highly dependent on its power output level; the maximum available power is too small for some flight stages, such as VTOL or hover; and the tank empty weight represents a very large portion of the MTOW.

Market studies were done to define initial parameter values that were used by the developed numerical analysis tool to perform the initial sizing. It followed a multi-objective optimisation to compare different optimal trade-off solutions with respect to MTOW and Endurance.

After selecting the most suitable solution, the estimates computed served as guidance in the choice of some key components commercially available, such as motors and batteries. With more realistic values for MTOW and power consumption during flight, the analysis tool was re-executed and the general UAV characteristics were obtained for the conceptual design. Some progress has been made in preliminary design, having produced a CAD model that represents the final design in some detail.

Future work include further analyses with higher fidelity computational methods to complete the preliminary and the detailed design. The project end goal is to build and fly the proposed concept for validation and refinement purposes.

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