Design and Simulation Study of a Hybrid Electric Propulsion System for a VTOL Tilt-Rotor UAV

Daniele Obertino
daniele.obertino@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

November 2021

Abstract

In recent years, development of Unmanned Aerial Vehicles (UAV) combined with Hybrid-Electric Propulsion Systems (HEPS) have emerged as a promising area of research in the aviation field mainly due to the increasing concerns about environmental issues and to the need for more efficient propulsion systems to integrate onboard of novel aircraft concepts, such as Vertical Take-Off and Landing (VTOL) architectures. The increase in mission complexity of both military and civil applications has led to a widespread of these configurations. In this context, hybrid-electric propulsion systems emerge as a solution to the power-matching problem that comes up with these configurations: the power needed for take-off is much greater than the power demand for cruise.

The main focus of this thesis is the design of a hybrid-electric propulsion system for a tilt tri-rotor VTOL UAV. A power-based conceptual sizing approach is adopted to evaluate the propulsion and energy mass of four different architectures (electric, gasoline, hybrid parallel and series) over a reference mission. The results demonstrated that the hybrid solution with a Degree of Hybridization (DoH) of 70% outperforms the other architectures in terms of endurance and range improvements. The series configuration was preferred and thus taken as a reference for the selection of off-the-shelf components. The serial hybrid configuration is critically assessed against the other three considered propulsion concepts. This was conducted maintaining a common mission profile in a simulation environment designed for hybrid VTOL UAVs configurations. The results suggest that the series hybrid-electric solution represents a viable trade-off for this class of UAVs.

Keywords: Hybrid Electric Propulsion, Series and Parallel Architectures, Unmanned Aerial Vehicles, Vertical Take-Off and Landing

1. Introduction

For many decades the mobility in all its means, from ground to sea and up to the sky, has been based on fossil fuels and on the assumption that their supply would last forever. But nowadays it is becoming clearer day after day that this assumption is false. Moreover, environmental concerns are spreading between society, which is increasing the pressure on the authority of each sector to develop new laws and regulations in order to reduce the carbon footprint of mankind.

Therefore, novel ideas and designs for the mobility of tomorrow are being explored. Especially More Electric Aircraft (MEA) concepts are expected to unleash big potential, not only by making the operation more energy-efficient, less polluting, and quieter, but also for an increased design flexibility. [6]. However, the conversion of propulsion systems towards the use of more electric power is still constrained by the technology level of battery which make them impractical. [15] An intermediate step in this process is represented by the implementation of hybrid-electric propulsion systems.

A usual approach to validate new technologies and designs, is to demonstrate their feasibility at a smaller scale and then transfer the results to larger aircraft through a scaling up process. In the same way, this research aims to to assess the feasibility of hybrid-electric propulsion systems on small-scale Unmanned Aerial Vehicles (UAVs) so as to demonstrate the potential of this novel architectures.

The paper is structured as follow: section 2 presents a theoretical overview over the HEPS concepts. Further, the working principle and the way of modelling the main components in a HEPS are introduced. Lastly, several control scheme models are assessed. In section 3 the HEPS simulation framework developed is presented, with the numerical models implemented for each component of the hybrid systems then assembled in the aircraft model. In addition, component-level bench tests and flight campaigns data are used to validate the tool. A complete presentation of the design procedure followed to size the propulsion system of the VTOL UAV is given is section 4, together with the COTS selection, validation and integration on board. In section 5 the hybrid propulsion system designed in the previous section is assessed in more detail through the *MATLAB*$^{®}$ simulation framework, by validating the previous results and exploring trade studies over the mass distribution of the sources onboard in order to obtain the best performances and compare the different propulsion concepts.

2. Theoretical Overview

The concept of operation for a HEPS in a UAV is to combine the power from an electric motor and an another propulsion type in such a way to optimize the efficiency of the overall system and to increase the performance of the vehicle. There are two main hybrid propulsion system architectures: series and parallel, together with the power-split or 'series-parallel'. For the serial hybrid architecture the ICE is completely decoupled from the EM and it does not directly power the propeller. Instead, a separate generator is attached to the internal combustion engine in order to generate the onboard electrical power. The main disadvantage of a series configuration is its inherent losses due to the many energy conversion steps along the powertrain, which strongly decrease the overall efficiency compared to a parallel configuration. On the other hand, a series architecture can mechanically decouple the ICE from the EM and thus the propeller allowing a to control the operational point of the ICE, which can be programmed to operate at the most ideal operating point. Still, it presents a mass penalty which makes it not suitable for micro-UAVs [8]. In a parallel configuration, two power sources are mechanically combined through some form of a mechanical coupling that often consists in a simple clutch to directly drive the propeller. The need of a mechanical coupling device clearly adds a level of complexity to the control of the system compared to the series case and it represents the main disadvantage. However, in standard concepts, thanks to this coupling mechanism, the parallel architecture allows to share the power request between the two sources and to operate the system with a combination of the two. This means that each power source can be sized below the total power requirement while it is not possible in a series configuration. Despite these mass savings, the individual power sources then may not be able to provide sufficient power for the entire operating envelope and in case of more complex architectures, such as VTOL UAVs, this redundancy requirement must always be fulfilled in order to safely perform an emergency landing in the case of a power source failure. Therefore, the advantage of sizing the components for cruise requirements drops [4]. In literature are commonly used the Hybridization Factor for energy (HF_E) and power (HF_P). These parameters give an idea of how the power and energy sources are allocated onboard. In the study of [3], a specific definition of these coefficients for the parallel and series configuration was given according to:

$$HF_{P,ph} = \frac{P_{EM,max}}{P_{max}} \quad (1) \qquad HF_{P,sh} = \frac{P_{EM,max}}{P_{ICE,max}} \quad (2)$$

where $P_{EM,max}$ is the maximum power of the electric motors, P_{max} is the overall power demand and $P_{ICE,max}$ is the maximum power of the ICE.

These parameters need to be used together in order to understand how the sources are actually employed. The HF_E indicates how much of the propulsion system's electric part is used. The most common solutions for small UAV applications are the 2- and 4-stroke reciprocating engines, which convert fluid pressure on a piston into rotating mechanical power on a driveshaft. A two-stroke gasoline engine is typically preferred due to the weight saving coming from the higher power density and improved simplicity, together with slightly lower noise and vibrations.[13] For this category, torque (τ) and Break Specific Fuel Consumption (BSFC), which gives a measure of how efficiently an engine uses fuel to produce work, are frequently used to describe the engine performance, according to their definition in equation 3 and 4. In the formulation P states for the engine power output in $[kW]$, $\dot{m}_f$ is the fuel flow rate in $[gr/hr]$ and rpm is the engine's speed in revolutions per minute.

$$\tau = \frac{P}{2\pi \cdot rpm} \cdot 60 \quad (3) \qquad BSFC = \frac{\dot{m}_f}{P} \quad (4)$$

Their behaviour as a function of the operational rpm is usually mapped by the manufacturers using a dynamometer connected to the output shaft which applies varying braking torque. Since the design of a hybrid-electric configuration can be strongly affected even by small variation of the engine performance, due to its influence on the hybridization factor, it is clear the necessity of an automated and scalable modelling method capable of constructing engine maps in order to explore all the design space and support the components selection.

The Willans line modelling formulation from [14] is a widely applied and verified quasi-static method which allows to predict performance of unknown scaled engines. This parametric approach has been largely used in the automotive field, and it was recently implemented in hybrid electric aircraft simulation and sizing tools. [2]

DC motors are widely spread in the aviation field and especially in the UAV market because of their control simplicity and technological maturity. The brushless DC (BLDC) motors are commonly used in hybrid electric propulsion systems since it offers high reliability and longevity. Moreover, for parallel hybrid applications the BLDC can be used as both a motor and a generator depending on the required operating mode of the system. For correctly operate a BLDC motor, an electronic speed controller (ESC) is mandatory. The main disadvantage of a BLDC motor of requiring a controller is largely outbalanced by its advantages, which include a higher efficiency thanks to the elimination of the brushes that brings to a decrease in friction and heat dissipation. This means that BLDC motors can achieve higher efficiency. The prediction of BLDC performances is way less empirical than for ICE. Fairly accurate results can be obtained by simple equivalent circuits based on fundamental electricity equations with a handful of motor specific constants.[9]

A battery is an electrochemical device that provides electrical voltage and it may be used to store electric energy onboard. Lithium-based battery has a very high specific energy compared to the values of Lead-Acid, Nickel-Cadmium (Ni-Cd) and Nickel-Metal hydride (Ni-Mh) ones. Therefore, Li-based battery are the most common solution in aeronautic applications since the main requirement is to reduce the weight onboard. The value of 200 Wh/kg for current Lithium-ion batteries is not valid for every application. Therefore, a state-of-the-art value of 179 Wh/kg was derived from a database of TATTU Lithium-polymer batteries.

When designing a hybrid electric propulsion system, the propeller connected at the end of the drivechain must be properly sized in order to achieve the thrust requested by the UAV and in the meantime maximize the operational performance of the propulsion architecture. An important trade-off solution can be given by the use of fixed-pitch and variable-pitch propellers. Using a variable-pitch propeller allows to reach higher efficiency values and therefore the performance of the aircraft can be increased thanks to the less power request for the same flight condition. However, the added mass, complexity due to extra parts and risk in failure of the system make it unfeasible for small UAV applications.

In order to correctly predict the performance of the propeller, expressed usually through its efficiency, advance ratio, thrust and torque coefficients, many models have been developed in the literature. A commonly used method is the Blade Element Momentum theory (BEMT) [7].

Another commonly used method to predict propeller performance is the vortex theory. The vortex theory implies the use of the blade-element theory previously described and it is based on the enhanced formulation given by [5] on the minimum energy condition. Powertrain control systems are mainly used to regulate the power flow inside the hybrid electric system in order to achieve the highest possible efficiency of the overall system.

In order to maximize the performances of each component these control strategies must be critically studied and adapted to the case of application. In fact, especially for small hybrid UAVs implementing this new combined type of propulsion, the control strategy is strongly linked to the features of the aircraft and its mission profile, therefore it should be carefully selected in order to optimize the working synergy between the units and thus to minimize the fuel consumption. These deterministic methods clearly must rely on some prior knowledge of the system.

3. HEPS Simulation Framework

The fundamental purpose of the framework, is to evaluate the performance of conventional and novel hybrid FW-VTOL UAV configurations. Thus, in order to allow the user to sweep mission parameters, features of the components and to test different control strategies, the platform is structured in a modular chain, keeping each model independent and separated from the others, so that single parts can be exchanged or updated to meet the top level aircraft requirements (TLARs) in the most effective way. This is achieved by employing an object oriented approach.

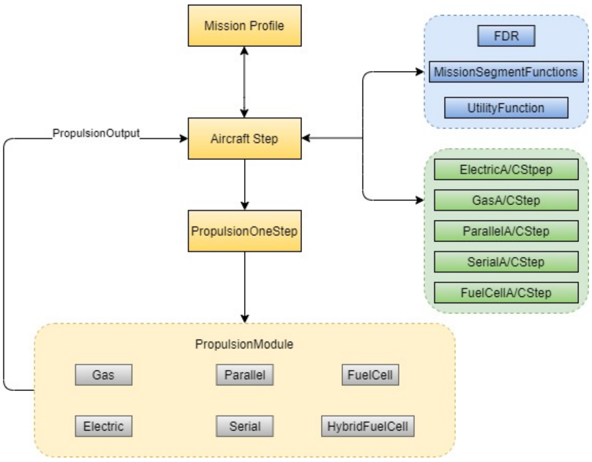

Figure 1: Flowchart of the information between the various modules of the simulation platform.

The flowchart displayed in figure 1, shows the iterative backward-looking architecture of the framework.

The mission profile is the starting point of the simulation, from which at every time-step the performance of the powertrain are then evaluated in the lower levels of the code. This module is the one where the features of the aircraft under analysis, together with the mission parameters, are specified and given in input to the tool. The framework allows the user to select from a variety of flight conditions, which can be combined in the most creative way in order to explore the behaviour of the concept being tested. Finally, the user can set the time step of each segment to increase or reduce the resolution of the simulation.

The operational data specified by the user are sent to the aircraft class, which loads the aerodynamic characteristics and structural properties of the system. Utility and mission functions are linked to define boundary conditions which are fundamental in the computation of the forces acting on the aircraft. Finally, a Flight Data Recording (FDR) system saves the variables of interest for final interpolations and plotting purposes.

Depending on the propulsion system selected, the aircraft module receives components data and properties for the architecture and accordingly, it activates the right propulsion module. This function generates the specific output to that subclass and then sends back the information to the aircraft module. The process iterates at each time-step until the end of the mission.

3.1. Aircraft Mechanics

The first step of the backwards energy state model implemented is to determine the thrust requirements for the specific flight condition according to the aircraft mechanics, which are then translated into power requirements inside the components modules. A variety of mission segments is available in the tool and for the majority of them the UAV is assumed to be in trimmed steady state and as a 2-Dimensional point mass on which vertical and horizontal forces act to achieve the equilibrium of the system. Since the overall performance rather than transient behaviour modelling of the UAV are the main focus, the previous assumption is deemed acceptable and the study maintains his legitimacy.

3.2. Battery Model

The modelling and characterization of Li-Po has been explored in the past by a research group at University of Victoria [12]. The charging and discharging curves of LiPo were developed according to the equations 5 and 6, proposed by *MathWorks MATLAB*$^{®}$ for the Simulink environment.[11]

- Charging ($I_n < 0$)

$$V(I_t, I_n) = V_0 - \frac{K \cdot Q \cdot I_n}{I_t + 0.1Q} - \frac{K \cdot Q \cdot I_t}{Q - I_t} + A \cdot \exp(-\beta \cdot I_t) \tag{5}$$

- Discharging ($I_n > 0$)

$$V(I_t, I_n) = V_0 - \frac{K \cdot Q \cdot I_n}{Q - I_t} - \frac{K \cdot Q \cdot I_t}{Q - I_t} + A \cdot \exp(-\beta \cdot I_t) \tag{6}$$

Thanks to constant rate battery discharging tests, the exponential voltage coefficient A, the exponential capacity coefficient β and the polarity voltage K required by the model to describe the exponential zones of the voltage output drop were assessed and uploaded. The internal properties of the batteries, such as the nominal voltage V_0, the internal resistance and the capacity Q, were normalized with respect to the number of cells to ensure the scalability of the model. Thus, the nominal current I_n (A), the current request and the time-step, which defines the extracted capacity I_t (Ah), and the battery size (number of cell in series), are required as input to compute the output voltage V.

Based on the sign of the current in input, the charge mode or discharge mode is activated and thus the state of charge (SOC) of the battery can be evaluated.

3.3. Propeller Model

Through the propeller model, the thrust requirements determined in the aircraft dynamic model are translated into torque, rpm and thus power demand at the propeller shaft. These parameters are then passed to the selected propulsion branch, in which a matching loop is used to find the operational point capable to fulfill the inputs. Thus, the accuracy of this starting point is of extreme relevance for the correct evaluation of the components performance. Regardless the method selected, the simulation logic of the propeller model relies on the non-dimensional terms C_T and C_P, which are the thrust and power coefficient, respectively. These terms describe the main performance characteristics of the propeller, in terms of shaft power P and produced thrust T, as shown in equations 7 and 8, where ρ is the air density, n represents the revolutions per second, and D is the propeller diameter.

$$C_T = \frac{T}{\rho \cdot n^2 \cdot D^4} \tag{7}$$

$$C_P = \frac{P}{\rho \cdot n^3 \cdot D^5} \tag{8}$$

3.4. Electric Motor Model

As common practice, a simplified Kirchhoff's Law equivalent circuit is used to model brushless DC motors performance. Its characterization relies on the three main parameters: motor constants K_V, which describes the proportionality between the motor revolution per minute and its voltage [rpm/V], the no-load current I_0 in amps [A] and the internal resistance R_m measured in ohms [Ω], as displayed in figure **??**. These are loaded in the circuit to determine the key performance parameters for the electrical side of the tool, such as the current drawn from the battery, the voltage level of the battery and the throttle setting. To solve the circuit, several relations are defined.

3.5. Internal Combustion Engine Model

The normalized formulation of the method relies on only two engine parameters: displacement V_d $[m^3]$ and piston stroke S $[m]$. These are used to express the torque and rotational speed of the engines in terms of mean effective pressure p_{me} $[Pa]$, which describes the engine's ability to produce mechanical work, and mean piston speed ν_m $[m/s]$. The literature [14] suggests to use the following parametrization to define the Willans line coefficients:

$$\begin{cases} p_{me} = [e_0(\nu_m) - e_1(\nu_m) \cdot p_{ma}] \cdot p_{ma} - p_{mloss}(\nu_m) \\ e_0(\nu_m) = e_{00} + e_{01} \cdot \nu_m + e_{02} \cdot \nu_m^2 \\ e_1(\nu_m) = e_{10} + e_{11} \cdot \nu_m \\ p_{mloss}(\nu_m) = p_{mloss0} + p_{mloss2} \cdot \nu_m^2 \end{cases} \tag{9}$$

Where e_{00}, e_{01}, e_{02}, e_{10}, e_{11}, p_{mloss0}, p_{mloss2} are engine characteristic parameters usually obtained by multiple linear regression from benchmark engine test data.

The minimum is found by setting the partial derivatives with respect to e_{00}, e_{01}, e_{02}, e_{10}, e_{11}, p_{mloss0}, p_{mloss2} equal to zero. Once these parameters are defined, the scaling procedure can be implemented. In figure 2, a comparison between the experimental brake mean effective pressure (BMEP) and the corresponding values resulting from the application of Willans line model for the DA35 is highlighted. The result presents a satisfactory accuracy, with a good fitting as proven by the value of the coefficient of determination, equal to 0.9462.

The information extracted from the model allows the simulation framework to return estimates for engine torque, power, BSFC or RPM based on inputs for any scale of engine within the modelling range. Finally, its main advantage lies on the possibility to select the optimal component by sweeping only the engine displacement and piston stroke.

3.5.1 Ideal Operating Line Strategy

The basic concept behind the hybrid state controller implemented for both the serial and the parallel HEPS in the next section, is the application of the Ideal Operating Line (IOL). The IOL of an engine is defined as the trend smooth line on the fuel consumption map, interpolating the combinations of each torque and rpm points that corresponds to the lowest BSFC. Its generation was embedded inside the ICE model, where thanks to the Willans method the BSFC-Torque-RPM maps of the selected engine can be determined and then, through a minimization algorithm that discretizes the points of lowest possible BSFC for each torque-rpm combinations, the IOL is extrapolated by means of a third order fit polynomial regression throughout the engine's operating range. In this way, for a standard hybrid mode, the controller determines the engine torque and rpm conditions along the IOL and thus the BSFC value for the operating point. Based on the power request, this result is then used as an input to calculate any remaining power that needs to be covered by the support of the EM.

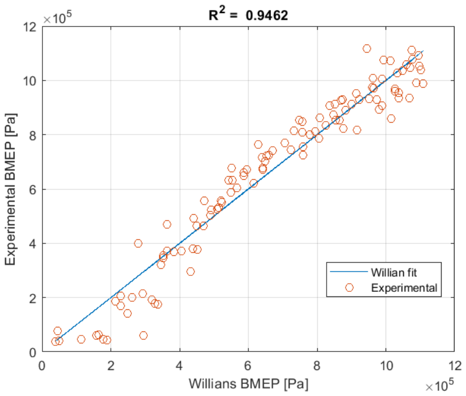

Figure 2: Desert Aircraft 35 experimental and simulation data comparison.

4. HEPS Sizing Analysis

In order to carry out an evaluation analysis of the propulsion system, the employed aircraft needs to be defined. The aim of this work is to design the propulsion system of a FW-VTOL UAV, named 'Eusphyra', featuring a canard and tilt-rotor configuration shown in figure 3, which was developed at CFAR in collaboration with DRDC. The implementation of a tilting rear rotor mechanism was done to reduce the power installed on board, to optimize the usage of the components and thus to reduce the overall weight, as explained in [10]. Moreover, the '80-20' configuration, as stated before, refers to the relative position of the rotors compare to the centre of gravity, which directly affects the thrust distribution, prioritizing an excess of thrust in the rear propeller in order to maximize the top speed and cruise performance. The Maximum Take-Off Mass (MTOM) is set to 25kg due to current Canadian legislation on non-recreational UAV system operations. The first necessary step to formulate the sizing problem is to identify and establish the top level aircraft requirements (TLARs), their level of

Figure 3: Eushyra tri-rotor CAD model.

importance and priority. This is essential in order to obtain the main drivers of the sizing methodology.

Mission Parameters	
Cruise speed	35 m/s
Cruise time	4 h
Cruise altitude	60 m
Dash speed	60 m/s
Dash range	25 km
Hover and Transition	30 s

Table 1: Mission data.

The main characteristics of each segment of the mission profile are summarized in table 1. The idea is to simulate what would be an actual Intelligence, Surveillance and Reconnaissance (ISR) mission, which is usually employed in the military sectors for small unmanned aerial vehicles. This type of mission assumes: a vertical take-off from the ship's helipad up to the cruise altitude; a hold in hover to maneuver the UAV toward the region of interest; forward transition, whose time was estimated from the flight test of the scaled version previously discussed; dash out to overcome strong arctic winds; cruise leg where information is gathered with the magnetic sensor and eventually enemies or intruders are identified; finally a return back to base following the same segments.

A new sizing process was considered. Similar studies in the literature for electric VTOL configurations [16], propose a power-based sizing approach. Starting from the computation of the power requirements at the rotors and propellers, these are used to size the pairing electric motors. However, the inclusion of hybrid systems makes the study a multi-variable problem since there is a more complex powerchain with different possible combinations of the components that need to be taken into account. The main drivers of the computational analysis, are in the forms of power requirements to overcome mechanical, electrical and propeller efficiencies of the aircraft.

Table 2 summarizes the condition of minimum power for VTOL with a total area of $\sum A_i = 1\ m^2$ at a climb speed V_c of 2 m/s, and for FW, where a constant propeller efficiency value η_p of 0.85 is assumed as a conservative estimation [1].

	T/W	**Front[W]**	**Rear[W]**
VTOL	1.05	303.253	3950.84
	1.4	432.33	5640.24
	η_p	0.85	
FW	Cruise	568.29	/
	Dash	2434.84	/

Table 2: Required power and area distribution.

Overall, the trade-off between size of the rotors and minimum theoretical total power consumption leads to a diameter of the front rotors close to the $0.5m$ maximum value prescribed and a rear rotor with a size way smaller the $1m$ limit.

From the computation of the maximum power requirements of the aircraft, the sizing process of the propulsion system could start.

To find the best suited propulsion system for the configuration, four architectures are defined and compared through the evaluation of their performance, mass and energy consumption along the baseline mission selected.

In order to size each propulsion system in terms of dimensions, masses and power output, a sizing script based on the models presented before has been implemented in the simulation environment. In order to simplify the comparison for the hybrid architectures, a common definition of the hybridization factor (HF) is given as:

$$HF = \frac{P_{max,EM,tilt}}{P_{max,EM,tilt} + P_{max,ICE}} \tag{10}$$

Where $P_{max,EM,tilt}$ is the maximum power request computed in table 2 for the rear rotor, and $P_{max,ICE}$ is the maximum power of the ICE mounted onboard. Due to many unknown on the supports, mass of the tilting mechanism and losses along the different drivechains, several conservative considerations were taken into account for efficiencies values and additional weight factors according to [3]. The results obtained from the sizing process of the different propulsion systems over the baseline mission profile are discussed and compared. The propulsion mass has a decreasing trend with the HF until a value of 0.7, clearly visible for the parallel case, where a minimum of overall propulsion mass is reached. This HF breakpoint can be attributed to the best balancing of three main factors: battery mass, ICE size and fuel consumption. After this point, the propulsion mass tends to increase due to the higher battery mass, related to the fact that the engine reaches a size where even during the dash mode, the battery needs to deliver a big amount of power to support it, and therefore due to the low energy density of this unit the overall mass rapidly increases. Also the fuel consumption reaches a saturation point after which it is not possible to further reduce the BSFC. Similar considerations can be made for the electric and gasoline architectures. With all these considerations in mind, a series hybrid electric architecture featuring an HF of 0.7 is selected as the best trade-off between all the possible solutions and it is taken as a reference system for the market components selection performed afterwards.

A survey of the available options in the market was performed in order to obtain a first components selection for the propulsion system of the Eusphyra. For the battery pack, the selection of LI-Po Max Amps 5.45Ah. Between the many suppliers such as Tattu/GensAce, this one was selected due to the higher value of energy density, equal to 180 Wh/kg.

For the EM-propeller pairs for front and rear propellers, T-motors was chosen as many static thrust test data are available and past projects at CFAR have proven their consistency. The criteria behind the selection of the P60 KV170 and U13-II KV130 was due to current and voltage compatibility with the battery pack. According to the modelling, the ICE size and power specifications for the 0.7 HF case perfectly matched the performance and dimension of the single cylinder two-stroke engine by Desert Aircraft DA35, that has been largely studied and tested at UVIC CFAR. Therefore, also in view of its good fitting inside the fuselage, it was selected. The S676-500U-21 produced by Sullivan was chosen owing to its good specifications of minimum amount of space and mass, together with the availability of power and efficiency curves from the manufacturer. Finally, the PMU SGENS-100A-01 was selected in order to control and merge the current coming from the generator and battery sides in such a way as to give the power for propulsion to the tilting rear EM-propeller and, eventually, to charge the battery.

The same study, iterated before with the support of the mass and power models for the components, is now repeated with the data coming from the market selection. Therefore, the baseline mission profile, is again simulated for the four propulsion system architectures. Still, conservative factors are kept in order to account for the mountings, inefficiencies and extra mass of the tilting mechanism.

The results for the mass budget distribution portrayed in figure 4 resemble the ones obtained in the fully computational simulation analysis. For all the cases, a small underprediction below 10% over the total mass of the propulsion systems is obtained from the tool, with the exception of the electric case that results slightly lighter thanks to the higher energy density of the battery pack selected. This overprediction can mainly be associated to an oversizing of the front motors, due to voltage compatibility and propeller size matching issues.

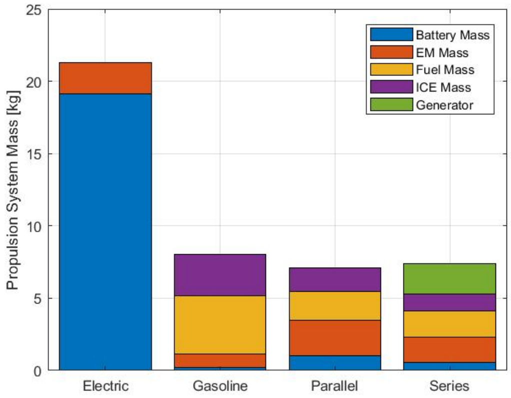

Figure 4: Mass breakdown of the four designed propulsion systems.

5. Mission Performance Evaluation

In this chapter, by feeding the Eusphyra aerodynamic and structural characteristics into the aircraft simulation environment the series hybrid propulsion system previously designed is critically assessed against the other architectures.

The first set of simulations run had the purpose to demonstrate the results coming from the sizing process. By dropping some of the assumptions made in order to conservatively estimate the power demand, such as on the propeller efficiency or operational rpm, a more realistic behaviour of the propulsion system components is expected along the stated mission profile. The exploration of the theoretical performance of the different propulsion systems is conducted with the goal to achieve the same flight time for all the configurations, with the propulsion weight left as free variable according to the values defined in the sizing process.

To better understand the power requirements computed from the propeller model for the four architectures along the flight path, the electric system power profile for the 4h cruise mission is shown in figure 5. This system can be taken as a reference and used as a minimum requirement since the electric propulsion has the least number of efficiency losses along the powerchain and thus consumes less power.

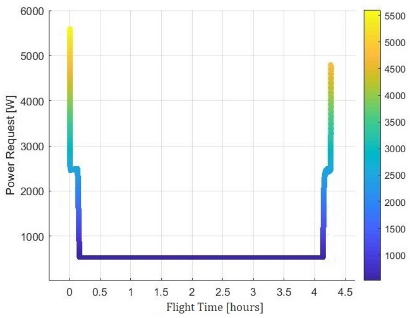

Figure 5: Total power demand for the Electric configuration.

Two efficiency terms to evaluate and compare the configurations are defined: the energy and propulsion efficiencies in $[hr/kg]$. The first one relates the flight time and the weight of the main energy source on board and it shows how efficiently the resource is consumed in order to achieve the prescribed targets. The second one gives an idea of the dry weight of the propulsion system installed to complete the mission.

The electric aircraft configuration leaves only $0.1kg$ for the structure and avionic masses, making this solution unfeasible. Both series and parallel hybrid aircraft configurations are penalized compared to gasoline concept in terms of propulsion efficiency values because of the additional weight of extra components. However, since the engine of the ICE only configuration results oversized for the majority of the mission, its energy efficiency is less than half of the one from the series and parallel hybrid solutions, which take advantage of the smaller-sized combustion engine that during the low-power requirement cruise segment performs at a lower BSFC, according to the OOP or IOL strategy implemented. This lead to a 56% and 51% of fuel mass savings for the series and parallel hybrid aircraft, respectively. Finally, between the two hybrid configuration, the series shows a 13.8% increase in dry weight due to extra generator mass, but the improved control logic can lead to 11% savings in fuel burnt and 4% reduction in CO_2 emission, thus reducing its operational cost and environmental impact.

The influence of the main mission parameters over the aircraft performance is then analysed. Each segment of the baseline mission is isolated and evaluated in order to determine the behaviour of the UAV for a VTOL only, dash only and cruise only mission. The energy sources onboard are redistributed in order to maximize the range and flight time of the configurations for the specific application. The first study involves a mission simulation mainly focused on the cruise segment for the four architectures. After the vertical take-off, hover and transition phases, a constant cruise condition is maintained as long as the combination of the remaining fuel load and battery SOC is higher than the required energy to transition back and land.

By taking out the dash requirement, it is possible in the hybrid configurations to redistribute the mass available for fuel and battery. The results show a general increase of the flight time and range. Compared to the previous results, the electric architecture reaches almost 90% extra mission time and 63% of additional range. The concept gaining the least advantage in this study is the gasoline one. The increments in time and distance flown are only 10% and 9%, respectively. Finally, both hybrid concepts reach a significant 52% and 48% increase in flight time with only 30% and 28% of increase in the fuel mass, taken from the reduced battery weight.

The four architectures are then simulated on a purely dash mission, besides the necessary phases to take-off and transitioning. The goal is to reach the maximum flight time and range with the aircraft at its top speed conditions. In order to better operate the hybrid configurations in this high power demand scenario, the mass allocated for fuel and battery has been revised, favouring the latter to reach a balanced configuration. The results give an idea of how strongly the dash requirement impacts on the sizing and selection of the components for the configuration. The hybrid architectures that were optimized for cruise conditions are the most affected by it. The main constraint in this case is given by the use of battery to support the engine. Because of that, out of the settled $9kg$, a large part of the mass available is taken by the batteries leading to 1/10 the values of flight time reached in the standard mission. Both the series and parallel concepts behave much more as the electric solution rather than the gasoline one, which outperforms them with a factor higher than 2 for the time flown. These considerations are supported by the energy efficiency, which shows a higher value for the gasoline.

For the last simulation case, the performance of the four systems during axial operations are assessed. The classic vertical take-off is followed by a stationary hover. Generally, the mission time achieved for all the configurations is much lower than any other case. This can be attributed to the extremely high power request, as well as to the fact that the multirotor operations were not a main TLAR, and therefore the design itself results inefficient for these phases. The considerations previously made for the *dash only mission* can be applied almost in the same way to this case. Because of the high power request and the need to draw a big amount of energy from the battery, the hybrid architectures show even lower performance than the electric one, since additional mass penalties are brought by the extra components and thus less battery capacity can be reallocated. For those, a maximum hover time of $15min$ can be accomplished. The gasoline configuration shows by far the best performance, since only a small part of the power is given by the battery. Thus, it is capable to reach $50min$ in air.

To conclude the mission performance study, in case in the future the Eusphyra might extends its application to a package delivery market, or in general to evaluate its carrying capabilities, a payload versus flight time extrapolation analysis for the standard mission profile is conducted. Trends for each architecture are displayed in figure 6; the electric case was left out since it would appear only as a short segment in the bottom-left corner and its unviability has been largely demonstrated before. Clearly, since the structural components, avionic, support and propulsion mass are defined, the available mass for payload is related to the fuel and battery mass onboard. In view of that, an increase in payload obviously leads to a reduction in the flight time. From the slope of the curves, it is also possible to deduce which system is most efficient in mission time. As largely stated before, the series hybrid configuration is optimized for this phase, thanks to its improved control logic, but the penalties coming from the extra components suggest that, if mechanically feasible, the parallel architecture should be preferred for short flight legs.

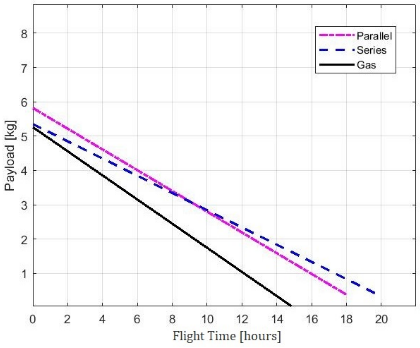

Figure 6: Payload versus flight time.

6. Conclusions

Within the scope of this Master's Thesis work, the hybrid-electric propulsion system for a tilt tri-rotor VTOL UAV to be used by DRDC to conduct magnetic reconnaissance operations was designed and evaluated. A powerbased sizing process and a HEPS simulation framework were used to compare different architectures. First, the improvement of the HEPS simulation platform developed in the MathWorks MATLAB environment was done. The scalability and adaptability of the numerical models for the propulsion system was the main driver of the research, giving a higher degree of flexibility to the tool. The framework has now available multiple options for the definition of the propeller performance, a EM model, the implementation of the Willans line method (to model ICE of theoretically any size), a fuel cell model and energy management strategy for both serial and parallel hybrid. Then, a preliminary sizing code with the purpose to implement a conceptual design analysis of the different options for the propulsion system of the aircraft under study was conducted. For the hybrid cases, the serial hybrid-electric with a HF equal to 0.7 was obtained as best trade-off solution. Knowing the power request, the theoretical size and mass of the components, a market research was conducted. The data of the components selected were passed to the sizing tool in order to compare the results with a satisfactory matching. Finally, an overview of the aircraft performance was established from a theoretical point of view by means of the simulation framework. The results showed that for any condition, the electric version could achieve the smallest range and endurance, thus it could still be employed for short missions if the requirements of operating totally carbon emission free and with a substantially lower noise profile would be brought up. The hybrid versions show the biggest advantages in a cruise only condition, with over 11 hours of flight achievable thanks to the possibility of operating the UAV in stealth and recharge mode. Whereas, for dash and axial segments, the gasoline solution could lead to higher endurance. Lastly, the UAV capacity of carrying payload for the longest time was assessed, with the parallel hybrid solution being advantageous for shorter times and the serial hybrid best suited for endurance over 10 hours. Four areas for further research were identified and will be discussed here. The first biggest disadvantage is the lack of an user-friendly interface. A big contribution to the simulation tool would be building this interface, potentially through the use of MATLAB GUI. Another solid improvement would be adding more features to the models, giving different level of abstraction based on the purpose of the study. It is also suggested that more simulations are run and that a deeper tuning and validation of the models is done if additional test bench or flight campaigns are performed in the future. The work developed in this thesis was purely theoretical, being only validated through the use of computational tools. Thus, even if an actual design combining COTS was presented, more research and testings should be done about the challenges of integrating the different sources selected and their compatibility before proceeding with the purchase. The conversion of the present parallel hybrid electric test bench to a serial configuration must be performed. Testing a wide range of mission profiles is critical to the complete characterization of the system, as steady-state measurements do not fully encapsulate a UAV system's performance. The detailed design and optimization of the HEPS for implementing into the Eusphyra must be done. The end goal of this research must be the integration of the concept into this , testing this way the propulsion architecture in a real-world scenario and collecting helpful test data along the flight tests.

Acknowledgements

Acknowledgements

References

[1] EPI Inc.. Propeller Performance Factors. `http://www.epi-eng.com/propeller_technology/selecting_a_propeller.htm`. Accessed: 21 september 2021.

[2] T. Donateo and A. Ficarella. Designing a Hybrid Electric Powertrain for an Unmanned Aircraft with a Commercial Optimization Software. *SAE International Journal of Aerospace*, 10, aug 2017.

[3] D. Finger. *Methodology for Multidisciplinary Aircraft Design under Consideration of Hybrid-Electric Propulsion Technology.* PhD thesis, RMIT University, dec 2020.

[4] D. F. Finger, C. Braun, and C. Bil. A Review of Configuration Design for Distributed Propulsion Transitioning VTOL Aircraft. In *Proceedings of the 2017 Asia-Pacific International Symposium on Aerospace Technology*, pages 1782–1796, 2017.

[5] S. Goldstein and L. Prandtl. On the vortex theory of screw propellers. *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, 123:440–465, 4 1929.

[6] M. Hepperle. Electric Flight - Potential and Limitations. In *Energy Efficient Technologies and Concepts of Operation*, 2012.

[7] J. Ledoux, S. Riffo, and J. Salomon. Analysis of the Blade Element Momentum Theory. 2020.

[8] W. Lu, D. Zhang, J. Zhang, T. Li, and T. Hu. Design and implementation of a gasoline-electric hybrid propulsion system for a micro triple tilt-rotor VTOL UAV. In *2017 6th Data Driven Control and Learning Systems (DDCLS)*, volume 10, pages 433–438. IEEE, 2017.

[9] D. Lundström, K. Amadori, and P. Krus. Validation of Models for Small Scale Electric Propulsion Systems. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition.* American Institute of Aeronautics and Astronautics, jan 2010.

[10] B. Luís. Design and Development of a Magnetic Anomaly Detection Unmanned Aerial Vehicle. Master's thesis, Instituto Superior Técnico, 2019.

[11] MathWorks. Battery block for implementation of a generic dynamic model. `https://www.mathworks.com/help/physmod/sps/powersys/ref/battery.html`. Accessed: 27 august 2021.

[12] J. Matlock, S. Warwick, P. Sharikov, J. Richards, and A. Suleman. Evaluation of energy efficient propulsion technologies for unmanned aerial vehicles. *Transactions of the Canadian Society for Mechanical Engineering*, 43(4):481–489, 2019.

[13] E. Mattarelli, G. Cantore, and C. Alberto. Advances in The Design of Two-Stroke, High Speed, Compression Ignition Engines. In *Advances in Internal Combustion Engines and Fuel Technologies.* InTech, 2013.

[14] G. Rizzoni, L. Guzzella, and B. Baumann. Unified modeling of hybrid electric vehicle drivetrains. *IEEE/ASME Transactions on Mechatronics*, 4(3):246–257, 1999.

[15] B. Saha, E. Koshimoto, C. C. Quach, E. F. Hogge, T. H. Strom, B. L. Hill, S. L. Vazquez, and K. Goebel. Battery Health Management System for Electric UAVs. In *2011 Aerospace Conference*, pages 1–9, 2011.

[16] A. R. Serrano. Design methodology for hybrid (VTOL + Fixed Wing) unmanned aerial vehicles. *Aeronautics and Aerospace Open Access Journal*, 2(3):165–176, 2018.