

Designing a Hybrid Electric Powertrain for an Unmanned Aircraft with a Commercial Optimization Software

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ABSTRACT

The design of a hybrid electric powertrain requires a complex optimization procedure because its performance will strongly depend on both the size of the components and the energy management strategy. The problem is particularly critical in the aircraft field because of the strong constraints to be fulfilled (in particular in terms of weight and volume). The problem was addressed in the present investigation by linking an in-house simulation code for hybrid electric aircraft with a commercial many-objective optimization software. The design variables include the size of engine and electric motor, the specification of the battery (typology, nominal capacity, bus voltage), the cooling method of the motor and the battery management strategy. Several key performance indexes were suggested by the industrial partner. The four most important indexes were used as fitness functions: electric endurance, fuel consumption, take-off distance and powertrain volume. A design able to fulfill all the targets set by the industrial partner was found using an elimination-by-aspect approach applied to the overall Pareto front. The results of the algorithm were post-processed and some metrics were used to evaluate the performance of the genetic algorithm in solving the proposed optimization problem.

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INTRODUCTION

Hybrid Electric Propulsion Systems (HEPS) are of increasing interest in the development of efficient aircraft powertrains [1], particularly for Unmanned Aerial Vehicles used for surveillance tasks. In fact, HEPSs allow the UAV to fly in electric mode thus reducing its thermal, acoustic and smoke signature.

HEPS are characterized by the usage of two energy storage systems, usually a fuel tank and a battery. The usage of the batteries also allows the optimization of the operating point of the engine that can also be downsized. In fact, engines are usually designed to meet the high requirements of thrust at takeoff but, for the most part of the mission (cruise), they work at part load. HEPS can be classified into parallel and series powertrains. In the case of series configurations [2], the mechanical drive path that moves the propeller is connected to an electric motor while the internal combustion engine is used to drive a generator. The electric power to the motor is the algebraic sum of the battery power and the engine/generator power. The series configuration is suitable for low-speed, high-torque applications but it is less efficient than the parallel one, where both the engine and the motor are mechanically connected to the drive train [2]. Moreover, it requires larger batteries and electric machine [3].

HEPS for UAVs were studied numerically in [2, 3, 4, 5, 6] and tested experimentally in [7]. A test flight was performed with a hybrid electric aircraft [8] and a reduction of fuel consumption of 30% with respect to the conventional gasoline engine was estimated but very limited information was given about these powertrains. HEPS

unfortunately require an increasing of complexity, mass and volume that are critical issues in the aircraft field where reliability and power density are the main goals.

In HEPS, the power management of multi-source operation is also critical. The supervisory control strategies for hybrid electric powertrains are usually classified into four categories [9]: numerical optimization, analytic optimal control theory, instantaneous optimization and heuristic control techniques. Heuristic Control Techniques are rule based and require a very low computational cost [2]. They can be based on Fuzzy Logic controllers [10]. Other approaches use the Bellman's Principle or, in general, Dynamic Programming to perform a global Numerical Optimization. The main drawback is the heavy computational burden and the necessity to have a full knowledge of the power request versus time. Finally, the analytic optimal control searches for the optimal solution using a simple mathematical model for the powertrain [11]. Harmon et al. [6] proposed a Neural Network Controller which assigns relative importance between the use of gasoline, electricity and recharging. In the present investigation, a rule-based strategy was used to keep low the computational time. More complex strategies will be taken into account as further investigation.

In the case of road vehicles, the simulation of hybrid electric powertrains is usually performed with backward simulation codes. Donateo et al [12-13] developed, implemented and validated a tool named PLA.N.E.S. to evaluate the benefits and the disadvantages of advanced powertrain for aircraft by adapting the unified model

approach proposed in [14]. This approach is widely used in the automotive field [15,16] but quite new for aircraft applications. In the present investigation, the PLA.N.E.S. code was combined with a many-objective optimization environment (Modefrontier 4.4 [16]) to perform the optimization of powertrain specification and battery management strategy with respect to four key performance indexes. Genetic Algorithms (GAs) were chosen among the tools implemented in Modefrontier because of their robustness and their capability to deal with many-objective optimizations [33]. Moreover, they are simple to use and to combine with existing simulation codes without significant modifications and their efficiency is independent of the nature of the problem (i.e. linearity, type of design variables, type of constraints, discontinuities of the search space, etc.). Genetic algorithms can be easily applied to multi-objective problems due to their intrinsic parallelism. Examples of application of multi-objective genetic algorithms in the design of an hybrid electric road vehicle can be found in Hu et al. [19] and Donateo et al. [20]. In the previous work of the author in the automotive field [20], the usage of Multi-Criteria Decision Making was also proposed for the choice of the final configuration from the multi-dimensional Pareto front. In the present investigation, the choice of the final solution was performed with an elimination-by-aspect procedure thanks to the user friendly displaying tools available in Modefrontier.

THE AIRCRAFT MODEL

The investigation was performed in collaboration with an industrial partner that furnished essential details on the specification and the performance of the UAV otherwise quite impossible to find. Because of a confidentiality agreement the performance of the aircraft will be given in a dimensionless way in the present investigation.

The UAV has an aspect ratio (b^2/S) equal to 12 and a wing load $W_0/S = 815.4 \text{ N/m}^2$ (where b is the wing span, S the wing area and W_0 the takeoff weight). A typical mission of the aircraft in its surveillance task was drawn from the information given by the industrial partner (available data) and is shown in Fig. 1, in arbitrary units. The mission is defined in terms of time histories of altitude, true air speed and auxiliaries power request.

The aircraft was modelled with a backward approach with a in-house simulation software named PLA.N.E.S. The simulation approach is briefly explained here. Detailed information about the code and its validation can be found in [13]. The mission is discretized with a time-step of 60s, except for the takeoff and landing phases where a time-step of 1 s is used. The time histories of speed (V) and altitude (z) are used to calculate, at any time step, the thrust to be delivered by the powertrain. The thrust is obtained by considering the balances of the forces acting on the aircraft in the lift (L) and drag (D) directions [20]:

$$L = W \cos \gamma - \frac{W}{g} V \frac{d\gamma}{dt} = \frac{1}{2} c_L \rho S V^2 \quad (1)$$

$$D = T - W \sin \gamma - \frac{W}{g} \frac{dV}{dt} - \mu W = \frac{1}{2} c_D \rho S V^2 \quad (2)$$

Where W is the instantaneous weight of the aircraft, T the required thrust, c_L the lift coefficient, ρ the density at the current flight level, g is the acceleration of gravity, S the wing area and γ is the angle of climb ($\sin \gamma = \frac{V}{dz/dt}$).

The rolling force μW depends on the runway through the friction coefficient μ and is zero in flight while the gravitational force $W \sin \gamma$ is zero at land and in steady flight.

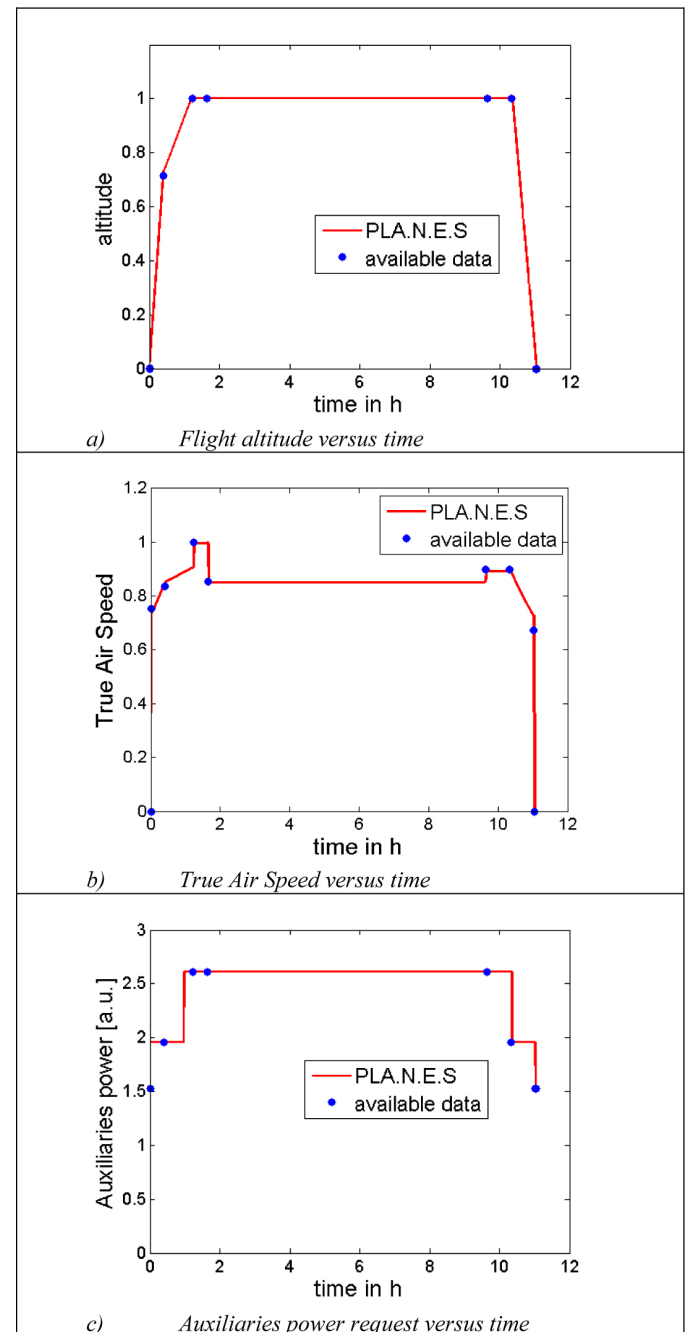


Fig. 1. Time histories of altitude, speed and auxiliaries power request along a typical mission of the UAV

The following drag polar was assumed for the UAV 21:

$$c_D = 0.025 + 0.0279c_L^2 \quad (3)$$

The thrust obtained from (2) is used to calculate the thrust power THP at any time step as:

$$THP = T \cdot V \quad (4)$$

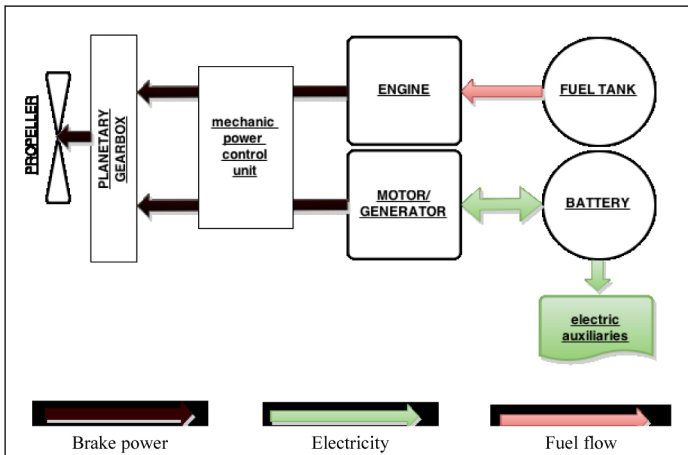


Fig. 2. Energy flows in the hybrid electric powertrain

The thrust power is generated by the propeller that is connected to a planetary gear box. The gear box is used to perform the power-split between the engine and the electric machine. The flows of mechanical, electric and chemical energy in the proposed powertrain are shown in Fig. 2. The engine receives chemical energy from a fuel tank whose size is not changed in the optimization. The motor/generator is linked to a battery whose correct specification is critical for the performance of the aircraft.

At any time step, a supervisory controller has to decide among the following operational modes:

1. Thermal (the engine produces all the power required by the propeller);
2. Electric (the propeller shaft power is generated by the motor using the battery as only energy source);
3. Charging (the engine generates the power to move the propeller and to charge the battery while the electric motor works as a generator);
4. Power-split (both the engine and the motor generate mechanical power that is delivered to the propeller).

In the present investigation the following rule-based strategy was used. Mode 1 is used when the batteries' State of the Charge (SOC) is below a certain limit (SOC_{min}) and the engine is not able to charge the batteries. Mode 2 is used when the SOC is above the SOC_{min} and the electric drive is able to sustain the flight without the usage of the engine. In the case of modes 3 and 4, there is a further degree of freedom in the amount of power to be generated by the engine. This power depends on the discharge and recharge currents of the battery

along the mission that are the only two parameters of the supervisory controller included in the optimization. If the engine and/or the batteries are not able to sustain the power request with the available SOC, the software returns an error flag. In the present version of the code the errors are summed up in the mission to quantify the ability of the proposed powertrain to follow the pre-loaded mission. A correction will be considered in the future to take into account the lack of power as in the automotive simulation code Advisor [15]. The electric power is assumed to be negative when the battery is in charge. The battery state of charge is allowed to vary between 20% and 90%. The SOC limits were implemented because, in operating conditions, charging up to 100% or discharging up to 0% can involve to a plating of electrodes with consequent inhibition of active materials and irreversible loss of the internal capacity [22,23].

The outputs of the supervisory control strategy are:

1. The speed and the torque of the engine;
2. The current to/from the electrochemical storage system.

In the present investigation the gearbox is modelled as a simple mechanical power split device with a mass of 20kg and a efficiency of 0.9. The sizing of the gear boxes has not been yet completed for the difficulty to retrieve literature data on mass and volume of the gearbox as a function of the nominal power and speed of engine and motor. Also the propeller is modeled as a black box with the following values of efficiency: 0.65, 0.7 and 0.8 at takeoff, climb/descent and cruise, respectively. The mass of the propeller is also assumed constant for all the designs. Scaling methods are considered for the most critical components of the hybrid powertrain, namely the engine, the motor and the battery.

Scaling the engine

The scaling parameter of the engine is assumed to be its nominal power. According to the nominal power, the model calculates the displacement, the nominal speed, the mass, the volume and the efficiency of the engine. The efficiency is obtained by using sea-level and altitude performance maps of a two-stroke diesel engine with a nominal power or 128kW [24]. The maps contain the torque and the specific fuel consumption (bsfc) of the engine for different values of speed and Air-Fuel Ratio (AFR) with AFR=18 corresponding to the full load conditions. Fig. 3 shows the performance maps of the reference engine at 0 and 3000m. More details on the numerical simulation of the diesel engine used to obtain the maps can be found in [24].

To adapt the maps to a different engine size, the torque was scaled with the displacement and the engine speed with the stroke thus obtaining maps of Brake Mean Effective Pressure (BMEP) versus mean piston speed. This scaling method is widely used in literature for the design of hybrid electric powertrains [14]. Recently Sorrentino et al. [25] validated the model by scaling a gasoline engine from 38.5 to 25kW and a diesel engine from 102.6 to 67.2 kW. When increasing the engine power, the nominal speed of the engine is decreased to preserve the piston mean speed, while the displacement is increased to achieve the same mean effective pressure as shown in Fig. 4.

The mass of the scaled engine can be calculated with linear correlations as proposed in literature [26]. For four stroke diesel engines, the mass M_{ICE} and the specific fuel consumption at takeoff ($bsfc_{t.o.}$) are a function of the engine brake power:

$$M_{ICE} = 6.88(HP_{ICE})^{0.61} \quad [kg] \quad (5)$$

$$bsfc_{t.o.} = 329(HP_{ICE})^{-0.062} \quad [g/kWh] \quad (6)$$

where HP_{ICE} is the brake engine power in Horse Power. These correlations [26] despite being based on a report of the NASA published in 1981, correctly predict the fuel consumption of the 128kW engine at 2000rpm and AFR=18 (presumed takeoff conditions) while the mass is overestimated. For the two-stroke engines used in the present investigation, the power to mass ratio of the engine will be assumed equal to 1.0 kW/kg as for the 128kW engine. The volume of the engine was assumed independent of its nominal power.

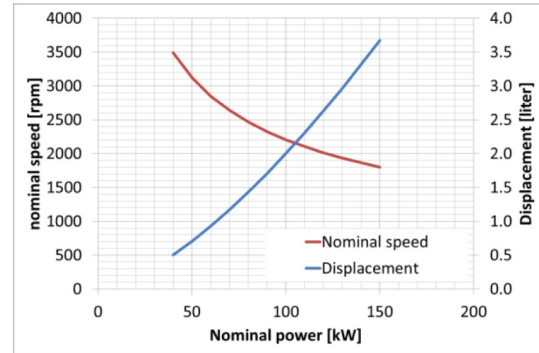


Fig. 4. Displacement and nominal speed of the engine versus nominal power

To take into account the effect of engine size on its maximum bsfc, the efficiency maps of Fig. 3 could be corrected by applying eq. (6) to every engine operating point. In the case of the 80kW engine the corrected bsfc would be about 3% larger than the bsfc of the 128kW engine. For this reason, the effect of engine size on the nominal bsfc was neglected in the present investigation but will be taken into account in the after retrieving data of modern diesel engines.

Scaling the Electric Path

The design of the battery is performed according to three parameters:

- The type of battery (1 or 2);
- The nominal capacity (C_{nom});
- The number of elements in series (N_{ser})

Table 1. Specification of the batteries

Parameter	Battery 1	Battery 2
Rated Voltage [V]	3.7	3.6
Max Voltage [V]	4.2	4
Cut-off Voltage [V]	2.7	2.8
Max continuous current in discharge [A]	$5C_{nom}$	$2.2C_{nom}$
Peak current [A]	$10C_{nom}$	$5C_{nom}$
Max continuous current in charge [A]	$3C_{nom}$	$1C_{nom}$
Energy density [Wh/kg]	134.5	149
Energy volumetric density [kWh/m ³]	140	172
Power density [kW/kg]	0.67	0.33

Two technologies were considered for the batteries with a trade-off between higher energy density (battery 2) and higher power density (battery 1) [27]. Their specifications are reported in of Table 1.

The following model proposed in literature for automotive applications [23] is used for the battery.

At any time step, the supervisory control decides the power of the battery (P_{batt}). The corresponding battery current is calculated as:

$$I(t) = \frac{V_{oc}(t) - \sqrt{V_{oc}(t)^2 - 4R \cdot P_{batt}(t)}}{2R}$$

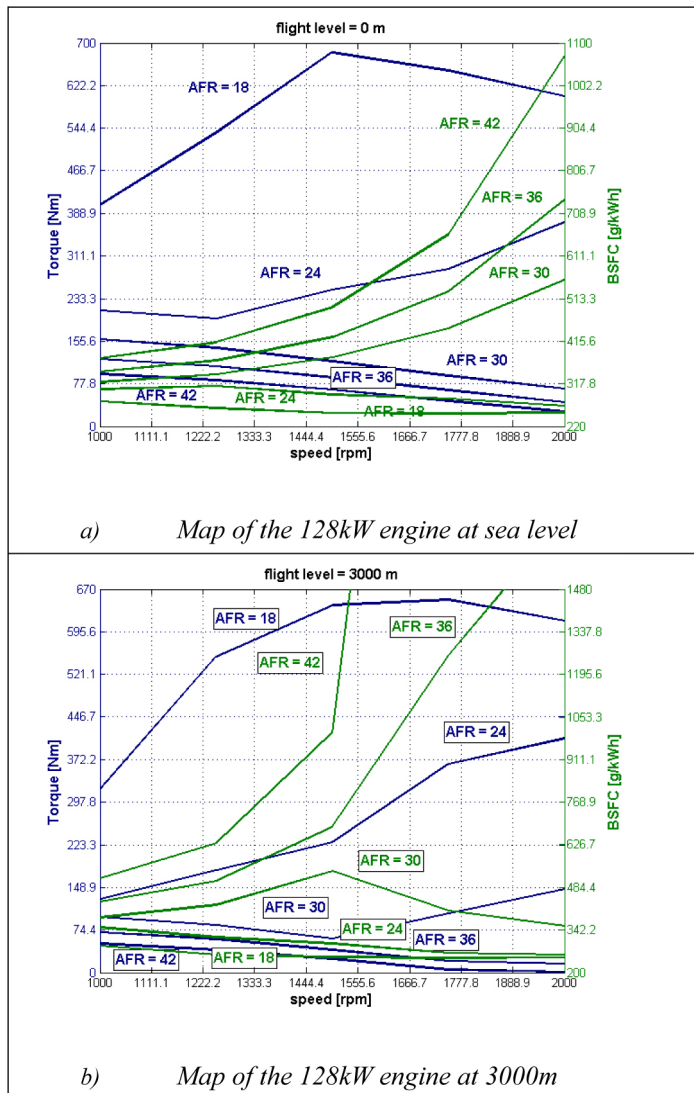


Fig. 3. Performance maps of the reference engine at different flight altitudes