Multiobjective Optimization for Electric Drives Design in Solar-Powered Ultralight Aircrafts

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Abstract: This paper presents design considerations for a low altitude short endurance electric powered ultralight aircraft with solar panels. The paper focuses on the conversion of the ultralight propulsion system from endothermic into electric, discarding the mechanic and dynamic issues from the design, and addressing the sizing consideration principally on the energy management system components. A tool is presented to optimize the choice of the battery and the panel mass.

Keywords: Power Management, Ultralight Aircraft, Multiobjective Optimization

1 Introduction

The ability to fly without the use of fossil fuels is a strongly pursued objective in recent years, both in the application and in the scientific field. The use of electric ultra light aircrafts in monitoring applications is becoming more and more widespread. Some very important international projects have allowed the construction of aircrafts able to achieve many records, in manned [1,2] and unmanned flights [3,4].

Next to these important international projects, great importance has also been given to the research in the ultralight flights branch. These kinds of flight are widely used in the private aviation field, both for environmental monitoring and hobby activities, thanks to their versatility and ability to be easily guided also by amateur riders. The necessity of having more autonomy is particularly felt in this field, especially in the case of use in the agricultural field for the detection of crops. In such a contest, the transition of the propulsion system from endothermic to electric engines assumes a remarkable relevance, both from industrial and commercial point of view.

This paper studies a model, already present in literature [5], for the design of a long endurance low altitude small aircraft: here this model is developed with the objective of better analyzing the fundamental design. Hence the mechanical sizing and the aerodynamic design are not discussed in the paper, which focus on the choices that lead to the best possible solutions, in terms of energetic autonomy and cost of the aircraft.

2 Model Description

This paper refers to a very simple model of the ultra light aircraft [5], where the elements are the mechanical structure with its given values, as it already exists, the batteries, the solar panels and the propulsion unit: each one will be discussed later. The aerodynamic and energetic relations of the aircraft described here is based on literature [5,6,7,8]. The dimensioning will focus almost exclusively on mass and energy balance, by considering the flight time as a variable that can affect the electrical power generated by solar panels. This dimensioning is so important as the mechanical design, as it can be observed by many literature contributions [9,10,11].

2.1 Irradiance Model

The presence of solar panels will impact on the endurance of the flight, since the photovoltaic conversion acts as an extra power source available on the aircraft. To determine the power available from the solar panels, a model of the solar irradiation is needed. Since a complete solar irradiation model is quite hard and complex to manage at this level of the design, a very simple standard model for the irradiation [12,13] is used. Figure 1 shows the typical irradiation available during the day under optimum weather conditions.

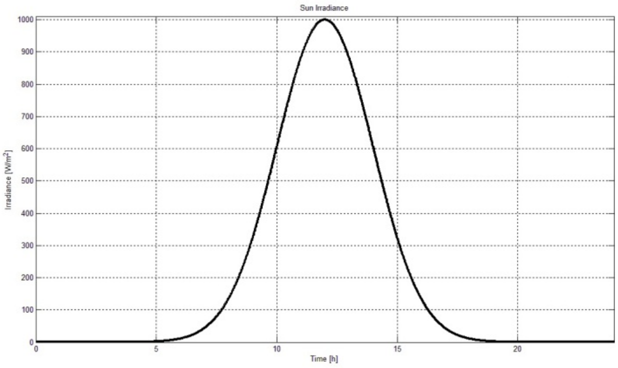

Fig. 1 Approssimation of Irradiance

The Gaussian curve of figure 1 is defined by the following equation:

$$I(t) = Irr_{\max} e^{-\frac{(t-t_c)^2}{2\sigma^2}} \qquad (1)$$

where ***t*** is expressed in hours, $t_c=12$, $\sigma=0.5$.

So the light energy that radiates solar panels during the flight is

$$E_{sun} = \int_{t_0}^{t_0+T_{fly}} Irr(t)dt \qquad (2)$$

where t_0 is the time of takeoff of the aircraft, while T_{fly} is defined as the flight time allowed by the system.

2.2 Mass

As regards the model of the masses and energies required for the flight at the level, the report [5,6,7] considered is the one which studies the flight level to the stalling speed, at which the aircraft is subjected to two forces, the lift *L* and the drag *D*, which must balance:

$$L = C_L(\rho/2)SV^2 \qquad D = C_D(\rho/2)SV^2$$

Here C_L and C_D are respectively the lift and drag coefficients, ρ the air density, S the wing area and V the airplane relative speed, which is similar to the ground speed if one assumes no wind. The drag coefficient is the sum of the airfoil drag C_{Da}, the parasitic drag of non-lifting parts that will be neglected here, and the induced drag C_{Di} than can be estimated by:

$$C_{Di} = \frac{C_L^{\,2}}{e\pi AR} \qquad (3)$$

Following the Schrenk's Method [14], where *e* is the Oswald's efficiency factor and *AR* the aspect ratio of the wing, i.e. the ratio between the wingspan *b* and the chord.

2.3 Power need analysis

According to the previous relations, the power needed to keep the aircraft fly at a constant quote is defined as:

$$P_{level} = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{(mg)^3}{S}} \sqrt{\frac{2}{\rho}} \qquad (4)$$

Using the relation between S, b and AR, we can rewrite:

$$P_{level} = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{2ARg^3}{\rho}} \frac{m^{3/2}}{b} \qquad (5)$$

The total mass of the aircraft is determined by the sum of the structure mass and the masses of the batteries and solar panels, which are the elements that have to be sized to achieve the goals of the design.

To obtain the total power consumption, it is necessary to consider also the efficiencies of the engine and the propeller.

As regards the estimation of the mass of the propulsion unit, different models have been proposed in the literature [8,15], describing the motor, the power unit and the gearbox, but in general they also propose to reduce the relation between the power and the mass of the motor to a linear relationship of this type:

$$m_{prop} = k_{prop}P \qquad (6)$$

where $0.0045 < k_{prop} < 0.01$ according to the type of engine selected.

2.4 Power system sizing

The energy produced by the solar panels during the flight, always under optimum atmospheric conditions, can be defined as

$$E_{solar} = S\int_{t_0}^{t_0+T_{fly}} \eta_{solar} Irr(t)dt \qquad (7)$$

where S is the solar panels surface mounted on the aircraft structure, and η_{solar} is the conversion efficiency of the solar panels.

As regards the accumulation of energy in the batteries, depending on the selected technology for the battery, the charge density varies, and also the specific cost of the battery. The energy available at time t_0 is therefore:

$$E_0 = E_{batt}(t)\big|_{t=0} = k_{batt} m_{batt} \qquad (8)$$

where m_{batt} represents the mass of batteries installed on the system, while k_{batt} is the energy density of the same, expressed in Wh/kg.

The flight time will therefore be dependent on the initial charge of the battery and the power required at the level flight, partially offset by the photo-generated power from the solar panels present on the wings.

$$T_{fly} = \eta_{disch} \frac{E_0}{P_{level} - \eta_{ch} P_{SOL}} \qquad (9)$$

The solar power itself is dependent on the time of flight (as well as starting from the take-off), because it determines the amount of solar power that the panels will be irradiated from.

As regards the engine, instead, it must be able to express a mechanical power sufficient to ensure the flight at high altitude, for which the power delivered by the engine is compared with the mechanical power required, and the exit logic of this comparison can assess the feasibility of the project with the chosen data.

$$P_{av} = \eta_{motor} \eta_{prop} \frac{m_{prop}}{k_{prop}} \qquad (10)$$

Finally, the cost is estimated as a linear combination of the cost of individual components of the project (battery, solar panels and motor), with an initial cost consisting of the cost of the structure of the aircraft.

$$Cost = m_{struct} + c_{batt} m_{batt} + c_{solar} S + c_{prop} m_{prop} \qquad (11)$$

So imposing previous reports, we get a system like the one shown here:

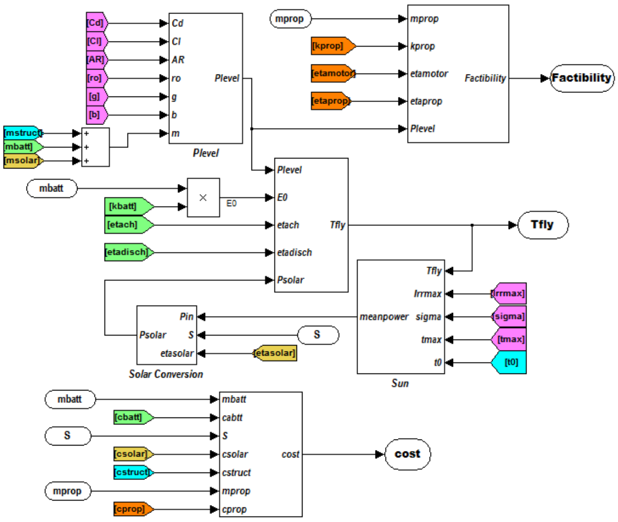

Fig. 2 Simulink Model for the Time of Flight and Cost Calculation

In this Simulink model all the variables described are introduced: the total mass is calculated as the sum of the structure mass, the battery mass and the solar panels mass. The block “P_{level}” calculates the power needed for the level flight; the block “Sun" evaluates the total power that irradiates on the solar panels during the flight (eqn. 2), while the block “Solar Conversion” calculates the electric power sourced from the panels during the flight. These two blocks realize a static algebraic loop with the block “T_{fly}” that calculates the output parameter. This algebraic loop does not carry a problem, from an analytical point of view, since the variables involved in the loop are not causing any division by zero, but in the numerical resolution, it could cause an error for some particular input values, due to the software algorithm used to solve it. Therefore, during the MATLAB simulation, a specific routine has been employed to avoid this kind of errors. The other blocks, “cost” and “Factibility”, calculate respectively the Cost of the design and its Factibility: the Factibility output is a Boolean variable, whose value depends on the comparison between the power needed for level flight and the power available from the propulsion unit. If the available power is higher than the required one, this variable has a True (or 1) value, otherwise is False (or 0).

The input “mbatt”, “S” and “mprop” are the three input variables of the objective function for the design optimization. The constant values used in the model are derived from literature [4,5,10,15-20], and showed in the following tables:

Physical Parameters
(magenta labels in Simulink model)

Description	***Parameter***	***Simulink name***	***Value***	***Unit***
Lift Coefficient	C_L	*Cl*	0.8	-
Drag Coefficient	C_{Da}	*Cda*	0.013	-
Oswald's factor	e	*e*	0.9	-
Gravity acceleration	g	*g*	9.8	m/s^2
Maximum Irradiance	Irr_{MAX}	*Irrmax*	1000	W/m^2
Time	t_{MAX}	*tmax*	12:00	h
Standard deviation for Irradiance	σ	*sigma*	0.5	h
Air Density	ρ	*ro*	1.1655	kg/m^3

Table 1. Physical parameters of the model

Battery Parameters
(green labels in Simulink model)

Description	***Parameter***	***Simulink name***	***Value***	***Unit***
Battery Energy Density	k_{batt}	*kbatt*	140	Wh/kg
Efficiency of battery charge	η_{ch}	*etach*	0.98	-
Efficiency of battery discharge	η_{disch}	*etadisch*	0.98	-
Specific cost of battery	c_{batt}	*cbatt*	65.8	€/kg

Table 2. Battery Parameters of the model

Solar Panels Parameters
(yellow labels in Simulink model)

Description	***Parameter***	***Simulink name***	***Value***	***Unit***
Efficiency of solar panels	η_{solar}	etasolar	0.15	-
Mass density of solar panels	k_{solar}	ksolar	0.54	kg/m^2
Specific cost of solar panels	c_{solar}	csolar	108	€/m^2

Table 3. Solar panel parameters of the model

Propulsion Unit Parameters
(orange labels in Simulink model)

Description	***Parameter***	***Simulink name***	***Value***	***Unit***
Mass to power ratio	k_{prop}	*kprop*	0.008	kg/W
Efficiency of motor unit	η_{motor}	*etamotor*	0.85	-
Efficiency of propulsion unit	η_{prop}	*etaprop*	0.85	-
Specific cost of propulsion unit	c_{prop}	*cprop*	125	€/kg

Table 4. Propulsion Unit parameters of the model

Structure Parameters
(cyan labels in Simulink model)

Description	***Parameter***	***Simulink name***	***Value***	***Unit***
Aspect Ratio	AR	*AR*	4	-
Wingspan	b	*b*	8	m
Structure mass	m_{struct}	*mstruct*	140	kg
Departure time	t_0	*t0*	10.5	h
Structure cost	c_{cost}	*ccost*	4000	€

Table 5. Structure parameters of the model

3 Using the model for design and optimization purposes

The choice of the energy management components for an ultra-light aircraft is driven by two goals:

1. the maximization of the energetic autonomy of the aircraft, in order to achieve the maximum flight length;
2. the minimization of the overall cost of the aircraft.

This section shows how the proposed model can be profitably used, in conjunction with an optimization algorithm, to obtain information about the most effective dimensioning choice.

In the objective functions, the input are the battery mass, the solar panel extension and the propeller mass. As the cost is a linear combination of this three variables, it is obviously increasing with the increase of each single variable.

The flight autonomy, instead, has nonlinear dependence from the two variables (we considered the propeller mass only for the cost, as it is something already included in the structure mass), and in particular we observed that the relation T_{fly} - m_{batt} is a non-monotone function, with a maximum dependent on the m_{batt}/m_{tot} ratio, as it is shown in the figure below.

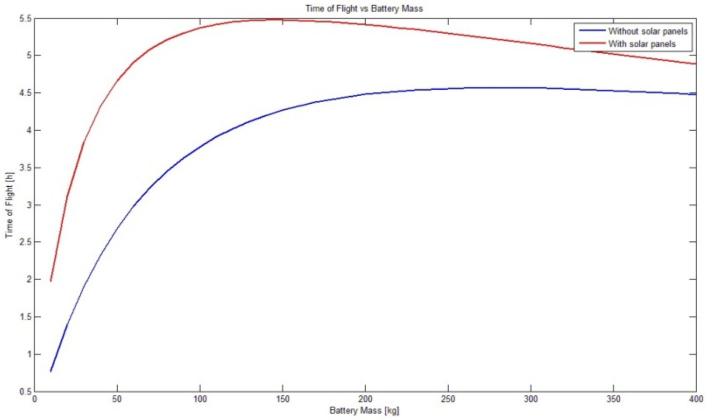

Fig. 3 Time of Flight vs. Battery mass relation

For both goal optimization, in order to translate the issue of the problem into a multiobjective minimization function, we introduced a performance figure, named T_{land}, defined as the time-length of the day in which the aircraft is not flying:

$$T_{land} = 24 - T_{fly} \tag{12}$$

With this performance figure, we are now able to perform a multiobjective optimization, using different algorithms. We used the MATLAB global optimization toolbox to perform the optimization: the objective function has a three element vector as input, which are the battery mass, the panels surface and the propulsor mass. In the Simulink model, the propulsor mass is used to value the factibility of the design, that is true if the mechanical power provided by the propulsion unit is enough to power the aircraft. If this condition is not satisfied, the performance parameters (T_{land} and cost) are maximized at the values, respectively, 24 h and 24 k€. The choice of the maximum value for T_{land} as 24h was obvious, since the goal of the project is to predict the autonomy for short flying, while the value of 24k€ for the maximum cost has been considered suitable, since it means that the cost of the electrical parts will exceed 5 times the cost for the structure. However, this value does not affect the simulation results, and it could be changed if needed, in case of a restricted budget.

The results given by the multiobjective optimization algorithm shown in figure highlight the Pareto Front for the studied issue.

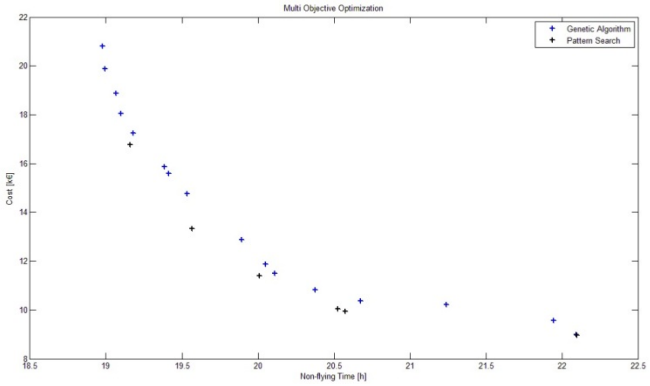

Fig. 4 Pareto front obtained from the multiobjective optimization algorithms

***m_{batt}* [kg]**	***S* [m^2]**	***m_{prop}* [kg]**	***Cost* [k€]**	***T_{land}* [h]**
31.261	0.810	27.334	9.561	21.944
37.203	7.587	28.441	10.822	20.379
60.210	6.843	33.404	12.876	19.892
132.831	7.995	50.198	19.878	18.993
80.930	7.823	45.560	15.865	19.384
34.724	6.794	26.864	10.377	20.674
50.367	7.214	30.231	11.872	20.049
72.928	7.555	41.230	14.768	19.536
113.725	7.842	45.845	18.061	19.101
46.911	7.363	29.023	11.510	20.112
30.083	0.009	24.098	8.993	22.095
37.233	3.615	27.023	10.218	21.239
99.239	7.975	46.748	17.235	19.181
84.101	7.405	41.979	15.581	19.412
117.756	7.936	50.102	18.868	19.067
137.336	7.998	55.163	20.796	18.978

Table 6. Optimization results obtained with Genetic Algorithm.

***m_{batt}* [kg]**	***S* [m^2]**	***m_{prop}* [kg]**	***Cost* [k€]**	***T_{land}* [h]**
30.000	0.000	23.981	8.972	22.100
30.000	7.996	24.900	9.950	20.575
31.045	8.000	25.125	10.047	20.526
45.574	8.000	28.311	11.402	20.008
66.000	8.000	33.000	13.332	19.566
101.596	8.000	41.723	16.764	19.158

Table 7. Optimization results obtained with Pattern Search Algorithm

Figure 4 shows clearly that the algorithm offering the best solutions for the present problem is the Pattern Search algorithm, that gives non dominated solutions, though these solutions are sparely distributed in the solution space and most of them are very close to the bounds of the solution space, while the genetic algorithm offers many intermediate solutions, that are clearly dominated by the Pattern Search ones.

After this multiobjective optimization has been performed, some solutions have been studied in order to have information about the different design behavior. In particular a consideration concerned the sun irradiance: the whole model optimization has an optimum condition for the sun irradiance as a parameter; the change in weather condition could cause a variation of the performance of the aircraft designed with an optimization based on the fully illuminated daylight conditions.

Even if the optimization has been intended to achieve a configuration that could allow the longest time of flight with the lowest cost, the behavior of the various designs strongly depends on the chosen configuration when external parameters vary from the standard condition used in the optimization. This is shown in figure 5. In this case the reduction of sun irradiance results in a reduction of the time of flight: the configuration that is less sensitive to this external variation in terms of normalized time of flight is the Solution D, that is the most expensive one, while the most sensitive, the Solution A, is the cheapest one. The configuration C is less sensitive than A and B, even if it is cheaper: this is due to the genesis of the solution C, characterized by a strong imbalance towards the cost minimization, despite the time of flight. Though the configuration C is not really affected by the sun radiation reduction, it is not a good native solution in terms of time of flight.

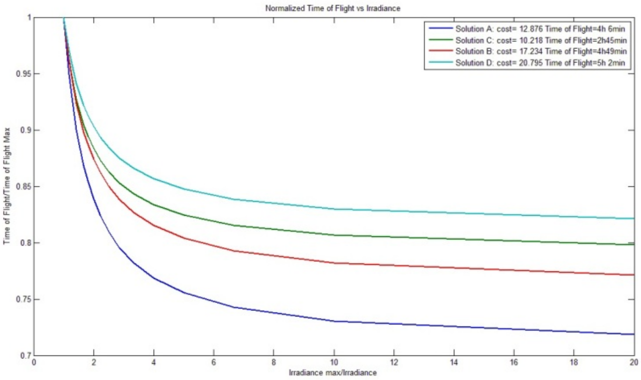

Fig. 5 Time of Flight variation vs. Maximum Irradiance

Design	***m_{batt} [kg]***	***S [m^2]***	***m_{prop} [kg]***	***Cost [k€]***	***T_{fly} [h]***
A	60.210	6.843	33.404	12.876	4h 6'
B	37.232	3.615	27.022	10.218	2h 45'
C	99.239	7.974	46.747	17.235	4h 49'
D	137.336	7.997	55.163	20.795	5h 2'

Table 8. Configurations selected for the Sun Irradiation variations behavior.

4 Conclusions and future developments

In this paper a well known model for Electric Airplanes have been discussed and developed in order to make it suitable for the sizing of the electrical elements of an already existing aircraft. A Simulink model have been realized for the simulation of the design with various input parameters, and finally an objective function have been written to apply many MATLAB algorithm from the optimization toolbox and the Pareto front has been detected. The result of this work is a design tool that, even in this first development stage, could be useful to convert an aircraft or an aircraft fleet from an endothermic propulsion system to an electric one. Future developments will necessarily undergo a better and deeper description of the model, and a wider parameter choice, to make this tool more effective in terms of complete design.

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