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Abstract of the PhD Thesis

# Design of Solar Powered Airplanes for Continuous Flight

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## 1. Introduction

The ability for an aerial robot to fly during a much extended period of time has become a key issue and a target of research, both in the domain of civilian aviation and unmanned aerial vehicles. The latter domain takes an increasingly important place in our society, for civilian and military applications. The required endurance is in the range of a couple of hours in the case of law enforcement, border surveillance, forest fire fighting or power line inspection. However, other applications at high altitudes, such as communication platform for mobile devices, weather research and forecast, environmental monitoring, would require remaining airborne during days, weeks or even months. At the moment, reaching such ambitious goals is only possible using electric solar powered platforms. Photovoltaic modules are used to collect the energy of the sun during the day, one part powering directly the propulsion unit and onboard instruments, the other part being stored for the night time.

In order to reach the target endurance, the design of the airplane has to be thought carefully and globally, as a system composed of many subsystems that are continuously exchanging energy. Due to these relationships, each part has to be sized accordingly to all the others. Here, the design method is to engineering what the recipe is to cooking. A good chef can cook an exceptional meal with standard products, whereas his apprentice can miss it completely even using expensive high quality products, simply because a crucial part lies in the combination of all the elements, and not only in their quality. This is especially true for multidisciplinary projects, the case of a solar airplane being an ideal example as it requires knowledge in the fields of aerodynamics, actuators, sensors, electronics, energy storage, photovoltaic, etc.

In 2004, the EPFL/ETHZ Autonomous Systems Lab started the Sky-Sailor project, under a contract with the European Space Agency. ESA had the vision to send to Mars an airplane that could achieve various scientific missions. Compared to other airplane concepts for planetary missions that would be capable of embedding several kilograms for missions limited to a few hours, the goal was here to embed a payload of less than half a kilogram but for missions of weeks, even months, using solar energy. So the objective was to study the feasibility of a solar powered airplane aimed at flying continuously in the atmosphere of Mars. As a first step, the feasibility of continuous flight on Earth was to be studied, with the idea to fly an Earth prototype at altitudes where similarities occur with the red planet.

The present thesis lies within the scope of this project. Its objective is not only to study a fixed design for a well determined mission, but rather to develop a versatile design methodology, that can be used for other projects, with different wingspans or payloads, and rapidly adapted to new technology improvements. The intention is not to focus on aerodynamics only, as this domain was already often covered, but rather to study the sizing relationships between the elements and in particular to develop accurate weight prediction models for all of them. Laws of scaling reveal then clearly what becomes problematic or easier when decreasing or increasing the airplane wingspan.

This thesis concentrates mostly on the conceptual design phase. However, in order to validate the theory through experiments, a full prototype of solar powered airplane was realized, for which the detailed phase is also described. Finally, the prototype that was built has the ability to fly more than 24hours on solar power and completely autonomously in terms of navigation and control.

## 1.1 History of Solar Flight

On November 4$^{th}$, 1974, the first flight of a solar powered aircraft took place on the dry lake at Camp Irwin, California. *Sunrise I*, an unmanned remote controlled aircraft designed by R.J. Boucher from Astro Flight Inc. flew 20 minutes at an altitude of around 100m during its inaugural flight. Despite the poor efficiency of solar cells, score flights of three hours were made during the winter. On the other side of the Atlantic, the pioneers Fred Militky and Helmut Bruss started two years later the construction of their prototypes, *Solaris* and *Solar-HB79*.

After having flown solar model airplanes and proved it was feasible with sufficient illumination conditions, the new challenge that fascinated the pioneers at the end of the 70's was manned flights powered solely by the sun. The first concepts were to use nickel-cadmium battery to store enough energy for short duration flights, as in the case of *Solar One* from Britons David Williams and Fred To in 1978 or the *Solar Riser* of Larry Mauro in 1979. But the crucial stage consisting in flying with the sole energy of the sun without any storage was reached on May 18$^{th}$, 1980, with Dr. Paul B. McCready's *Gossamer Penguin*. Its successor *Solar Challenger* crossed the English Channel one year later. Several remarkable manned solar airplanes followed such as *Solair I*, *Sunseeker* or *Icaré 2*.

In the 90's, the American company AeroVironment, on behalf of NASA, built successive unmanned airplanes with the objective of demonstrating eternal flight at high altitude. The last of the series, *Helios*, had a wingspan of 75m and reached the altitude of 29'524m in 2001. However, it was destroyed during a flight two years later, probably because of turbulence, and never reached its primary objective.

In 2005, Alan Cocconi's *Solong*, with 4.75m wingspan, achieved a two-day flight using solar photovoltaic energy but also thermal winds. *Zephyr*, by the British company QinetiQ, slightly larger with 18m wingspan, also demonstrated in 2007 flights of 54 hours, partially storing potential energy by gaining altitude during the day and gliding with reduced energy during the night.

## 1.2 State of the art

The history of solar aviation has seen the realization of exceptional airplanes, manned or unmanned, that showed outstanding capacities and broke records but for which the design process is never explained or is kept confidential. On the other side, there is a literature of more than thirty papers covering the subject of solar powered airplane design. However, the majority of them always stayed at a theoretical level and do not include the realization of a prototype that could validate and add far more credibility to the theory. Also, many studies are very local, only taking into account a precise wingspan and being therefore not applicable to different sizes.

## 1.3 Contributions

This thesis focuses on the design of solar powered airplanes. We propose a new design methodology and we want to address the problems that were highlighted in the last section. The contributions lie on four pillars:

- **Simplicity**: the first objective is to develop a method that is clear, complete and still very simple, which is not contradictory. For this purpose, it is completely analytical and uses mathematical models that are not discrete but continuous. It shows the real tendency of physics and does not for example interpolate physical effects using a polynomial without any physical significance. Hence, the reader can very easily output a valid conceptual design in only minutes with the help of the short Matlab program given in the appendix.
- **Large design space**: the methodology is not only valid for a limited range of wingspan or weight, but remains applicable to a large scale of solar airplanes, from the tiny MAV to the manned aircraft. To reach this goal, the mathematical models of the subparts, for example the weight or the efficiency of electric motors according to their power, was not only studied in a limited domain, but over a very large scale, for some models with up to 7 orders of magnitude, showing on the same graphics a tendency that encompasses motors from 1mW to 10 kW. Combining this very large final design space with the analytical character of the methodology, it allows

achieving sensitivity analysis on certain parameters and for example point out what are the emerging problems when up or down-scaling.

- **Concrete and experienced based:** the mathematical models and the various technological parameters used in the methodology are based on real and practical cases. Large sets of empirical data that we then interpolated were preferred to theoretical estimation that proved to be sometimes far too optimistic leading to unrealistic designs.

- **Flexibility and versatility:** the method contains exactly 30 parameters, either linked to mission or technology, which can be easily modified to evaluate the sensitivity of a solution with a change in mission or with a technology improvement. As well, the method can be used to design not only an airplane that achieves 24 hours continuous flight, but also for many other scenarios; one that stores its electrical energy into potential energy gaining altitude or another one that would have an endurance of a few hours, flying only during the day time. We will even present the design of such an airplane flying not only on Earth, but in the atmosphere of our neighbor planet, Mars.

Another contribution of this thesis is the realization of a fully functional unmanned solar airplane. In fact, our design methodology was not limited to a theoretical study only verified with simulations, but it was validated through the realization of a real prototype and flight experiments. The airplane, named Sky-Sailor, was designed on paper to fly more than 24 h at the beginning of the project. Four years later, in June 2008, it successfully reached its objective with a flight of more than 27 h, confirming the effectiveness of the method. For its building, the idea was to combine the theoretical knowledge available in a university with the impressive practical experience of model-making experts. Finally, this thesis has the modest ambition to draw up a state of the art on solar aviation from its beginning until now, referencing the major scientific papers on the subject and trying to summarize the history of solar flight and its major contributors. An exhaustive list of 91 solar airplanes flown to date for which it was possible to obtain technical information is also given in appendix.

## 2. Conceptual Design Methodology

The conceptual design methodology constitutes the theoretical heart of this thesis. Whether it is intended to achieve surveillance at low altitude or serve as a high altitude communication platform, a solar aircraft capable of continuous flight needs to fly at constant altitude. In fact, the first one would be useless for ground surveillance at high altitude and the second one wouldn't cover a sufficient area at low altitude. For this reason, we concentrate the following study on straight level flight only, storing the surplus of solar energy in the battery. Other scenarios, such as storing energy through potential energy in altitude or using ascending thermals, will be discussed afterwards.

Our methodology is based on two simple balances, which are represented in figure 1.

- **Weight balance:** the lift force has to be equal to the weight of all the elements constituting the airplane
- **Energy balance:** the energy that is collected during a day from the solar panels has to be equal to or higher than the electrical energy needed by the airplane.

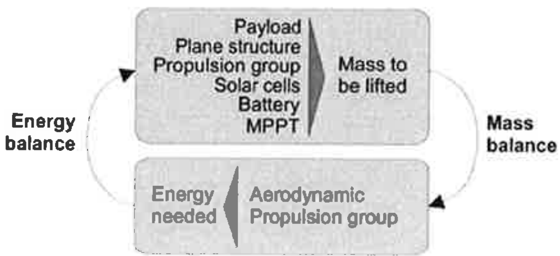


**Figure 1:** Energy and mass balances

From here on, and considering the type of mission and the payload to embed, there are two different methods to achieve the airplane conceptual design:

- The **discrete and iterative approach** consists in selecting a first set of components (motor, solar panels, battery, etc.) based on pure estimation of the final required power or on previous designs. Then, having their total mass, the wing surface and propulsion group can be sized. Having chosen a precise motor, gearbox and propeller, we can calculate the power needed for level flight. This value is then compared with the power available from the previously selected solar generator, and so on. An iterative process takes place, refining selections, improving the design at each step and ending hopefully with a converging solution.
- The other approach, developed in this thesis, is an **analytical and continuous approach** that consists in establishing all the relations between the components with analytical equations using models describing the characteristics of each of them. This method has the benefit of directly providing a unique and optimized design, but requires very good mathematical models. In the present case, an important effort will be made to have these models as accurate as possible on a very wide range, so that the methodology can be applied for solar MAVs as well as for manned solar airplanes.

Following this second approach, the expression of the power needed for an aircraft at level flight was established and the irradiance modeled, which allows to compute the daily solar energy available. Then, mass prediction models had to be developed for all the airplane elements. Whereas the mass of a battery is linear to its capacity, modeling the mass of the airframe is a more complex formula based on surface, aspect ratio and fabrication technology. Finally, all these models can be combined to express the design loop presented above mathematically. This is represented graphically in figure 2 and summarizes the design problem of any solar powered airplane aimed at continuous flight, with thirty parameters:

- 25 technological parameters, the energy density of the energy storage solution for example.
- 5 mission parameters that are the air density given by flight altitude, the day and night duration, depending on the time and the location, and the mass and power consumption of the payload.
- The wingspan, the aspect ration and the airplane total mass are the 3 variables that will be investigated during the optimization process.

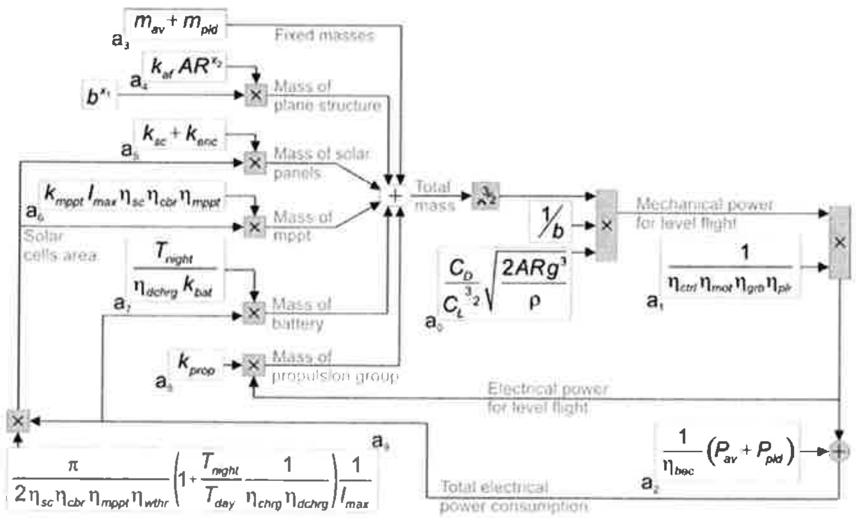


**Figure 2:** Schematic representation of the design methodology

Solving the loop analytically, the final equation can be expressed as a cubic equation (1) with variable $m^{1/2}$, $m$ being the airplane total mass. A non-complex solution exists only if inequality (2) is verified. For a defined set of parameters, this inequality defines exactly the feasibility of continuous solar flight or not.

$$m - \underbrace{a_0 a_1 (a_7 + a_8 + a_9 (a_5 + a_6))}_{a_{10}} \frac{1}{b} m^{\frac{3}{2}} = \underbrace{a_2 (a_7 + a_9 (a_5 + a_6)) + a_3}_{a_{11}} + a_4 b^{x_1} \quad (1)$$

$$a_{10}^2 a_{11} \frac{1}{b^2} + a_{10}^2 a_4 b^{x_1 - 2} \le \frac{4}{27} \quad (2)$$

## 3. Application of the design Methodology

The Sky-Sailor project started with the objective to prove the feasibility of continuous flight, over 24 hours. This flight should be feasible during the 3 summer months, embedding a 50g payload consuming 0.5W, representing a small camera and its transmitter. With a flight altitude of 500m and a location in central Europe, the mission parameters are set. The technological parameters were chosen according to the state of the art in the various domains.

Considering a certain set of airplane wingspans and aspect ratios, the design methodology consists now in testing the inequality that defines if the continuous flight is possible or not. In the case of a positive answer, all the dimensions, masses, speed characteristics, powers, etc. can be calculated for the designed airplane. Figure 3 shows for example the mass distribution between the various airplane elements for an aspect ratio of 13. Interestingly, below 2.3m wingspan the surface of solar cells is insufficient and above 4.7m the weight of the airframe, that varies in a cubic manner with the wingspan, becomes too high. Finally, a wingspan of 3.2m, which optimizes the flight altitude, was selected, leading to a predicted airplane total mass of 2.55kg.

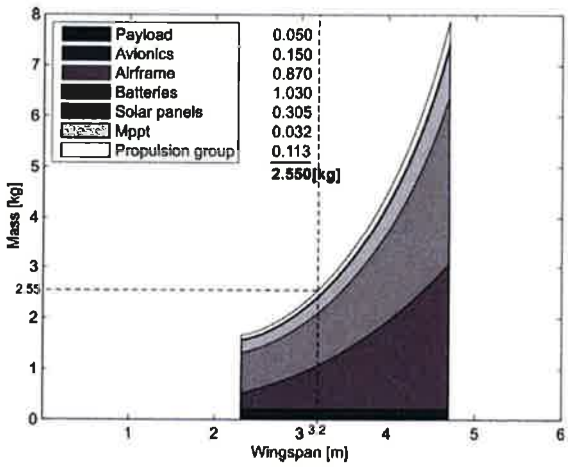


**Figure 3:** Mass distribution considering an aspect ratio AR of 13. The values for a wingspan of 3.2m corresponds to the Sky-Sailor Design.

## 4. Sky-Sailor Realization and Testing

According to the results of the design methodology application, a fully functional prototype was built within the framework of this thesis. The general configuration of the airplane is a 3 axis motorized glider. The structure is made of composite materials and was built with the help of a world expert in ultra-lightweight high performance model sailplanes.

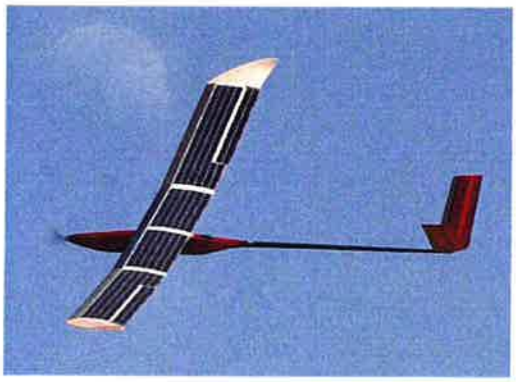

**Figure 4:** The Sky-Sailor prototype during a long endurance flight test

The wing is covered by 216 silicon flexible solar cells with 17% efficiency, offering a total maximum power of 90W. A dedicated electronic circuit, with an efficiency of 97%, was developed for the efficient management of this power and the safe charge of the battery. Using the latest lithium-ion technology, the battery still represents more than 40% of the airplane total mass. As can be noticed when using the design methodology presented above, energy storage is clearly the main limiting factor to the development of long endurance airplanes. The propulsion group was studied in order to have a combination of elements that reach the highest efficiency at nominal flight conditions. A customized brushless motor drives a low speed, large diameter carbon propeller through a gearbox for a power consumption of only 14W at level flight. All these elements are represented in figure 5 where one can observe that only 11% of the sun's energy is converted into mechanical energy for the airplane propulsion.

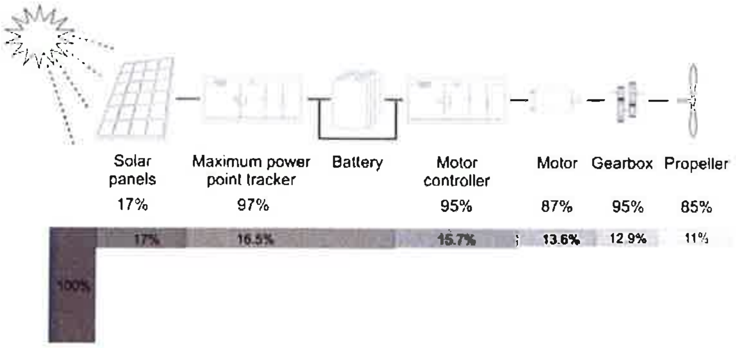


**Figure 5:** Energetic chain of the Sky-Sailor with cumulated efficiencies

A lightweight and low power consumption autopilot system was also developed for the autonomous navigation and control of the airplane (Figure 6). It contains a GPS, an inertial measurement unit, as well as altitude and speed pressure sensors. They are interfaced to a micro controller unit that drives the motor and the control surfaces to follow autonomously a predefined trajectory. A dynamic model of the airplane was established for the simulation and tuning of various control techniques, prior to testing with the real prototype. The possibility to control the aerial robot manually was also implemented, especially for the landing phase.

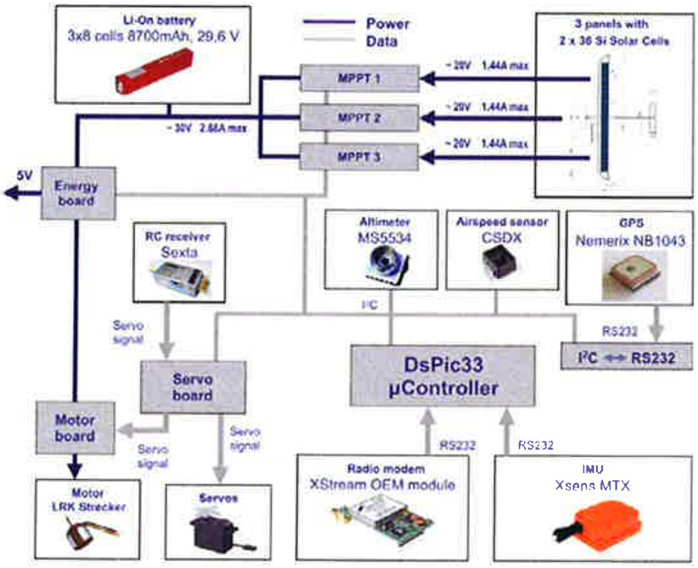


**Figure 6:** Schematic of the autopilot system

On the ground, a control station receives five times per second through the radio modem all the sensors data and energy information from the airplane. A graphical user interface was realized that reproduces a tridimensional view of the flight on a map and virtual flight instruments (Figure 7). The trajectory can be modified and sent to the airplane that will immediately react.

**Figure 7:** Screenshot of the graphical user interface

From 2004 to 2008, several flight experiments took place for the successive validation of the different parts of the airplane. On the 20$^{th}$ of June 2008, the Sky-Sailor took off at 12h33 for an attempt to demonstrate continuous flight over more than a day. With good irradiance conditions but some turbulence, it flew the entire afternoon, recharging its battery with the only energy of the sun. After dusk, the battery was the unique source of energy available and it slowly discharged during the night. In the early morning at 6h10, the solar panels started progressively to supply power again. Only one hour later, they gave enough energy to supply the motor and the avionics entirely, but also to charge the battery that still had 5.8% of capacity. The morning saw again turbulent atmospheric conditions which required more power to the motor and led to a longer battery charge. However, at 15h35 on Saturday 21$^{st}$, the battery was completely full, ready for a new night cycle. That proved the feasibility of continuous flight using solar energy only. The airplane landed some minutes later after a flight of more than 27 hours. With an average speed of 32.3 km/h (8.97 m/s), it covered more than 874 kilometers. Considering take-off and landing phase, the flight was achieved at 98.9% in autonomous mode. This flight was the world first demonstration of solar continuous flight without the use of thermal winds and at a constant altitude.

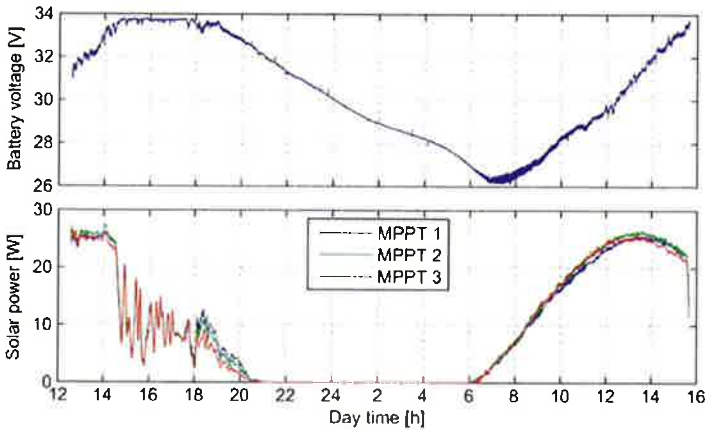


**Figure 8:** Evolution of the battery voltage and the power supplied by the solar panels during the 27 h flight

## 5. Scaling Considerations and Other Designs

After having shown one application of the methodology that was validated through the realization of a prototype, this last chapter aims at presenting additional designs at different scales, in order to emphasize the portability of our methodology, but also the limitations of solar power when scaling up or down. The analytical character of the design method and its mathematical models allow investigating these scaling issues on the different airplane elements. The cases of solar micro aerial vehicles, manned solar airplanes and high altitude long endurance platforms are presented. Furthermore, we also discuss special airplanes or flight configurations that could enhance the flight duration, such as using altitude to store potential energy or use swiveling solar panels to track the sun.

## 5.1 Solar Micro Aerial Vehicle

There is a growing interest for Micro Aerial Vehicle and several projects have been started in the two last decades in this domain with various study goals, such as aerodynamics, system design, obstacle avoidance, bio-inspired algorithms, etc. Unfortunately, what all these prototypes have in common is a poor endurance that rarely exceeds 15 to 20 minutes. For this reason, solar energy could be a solution.

Even if the airplane structural mass scales down in a favorable manner, they are several negative effects when decreasing the size of a solar airplane. On the aerodynamic side, the low Reynolds numbers induce a significantly lower lift to drag ratio and propeller efficiency. Considering the propulsion group, the scaling down of electromagnetic motors is not favorable either. On figure 9, our model covering more than two thousand motors shows clearly that even if we can consider the mass to power ratio as constant for good quality motors, the efficiency tends to drop dramatically below 1W. Also, the small curvature radius of MAVs wings makes the integration of fragile solar cells more difficult. Additionally, the energy density decreases for small batteries because of the increasing percentage of packing material. Finally, the electronics and more specifically the sensors see important limitations to their miniaturization.

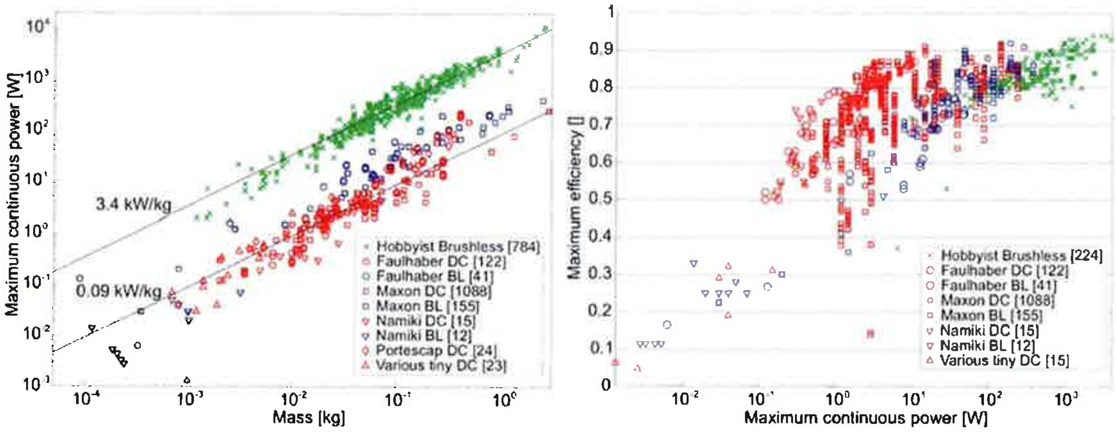


**Figure 9:** Power to mass ratio and maximum efficiency of 2264 commercial motors

All these points impact negatively the technological parameters (efficiencies, energy densities, etc.) of our conceptual design methodology. Using these new parameters, the first result is that it is impossible to find a configuration that can fly continuously over 24 hours at the MAV size, even without any payload in summer. This accomplishment is already a real challenge at the UAV size, thus with the lower efficiencies and aerodynamic problems at MAV size, this infeasibility becomes understandable. However, the methodology can be slightly modified to design an optimal MAV that flies only during the day. This showed very good results and ended with the realization of two prototypes of 77cm wingspan.

## 5.2 Manned Solar Airplane

Having discussed the feasibility at a much reduced size, we go now in the other direction and consider the scenario of a manned or high altitude solar airplane, embedding scientific or communication instruments. In this case, most of the technological parameters see a positive change, from the aerodynamic lift to drag ratio to the efficiencies of all the propulsion group elements.

Unfortunately, the single part that doesn't scale up in a positive manner is the airframe mass. The models used to predict the airframe mass depending on the aspect ratio and the wingspan were so far only local models. The data of 515 radio-controlled and manned sailplanes were used to create our own model that shows a clear cubic tendency between airframe mass and wingspan, whereas a quadratic tendency was too often used in the literature, leading to unrealistic designs.

The application of our methodology shows that the airframe becomes precisely the problem when up scaling. Considering our mathematical model represented on figure 2, we isolated the airframe weight and searched for the tendency it should have in order to make solar continuous flight feasible at any wingspans. This is represented with the green zones on figure 10 that is probably the most important figure in this thesis. It shows the cubic model that was explained above, superposed to 86 solar airplanes flown from 1974 to 2008. Interestingly, our sailplane model crosses these zones only in the UAV domain.

This demonstrates mathematically why it is easier to build a solar airplane that achieves continuous flight at the UAV size than at the MAV or at the manned size. At high wingspan, far lighter construction techniques have to be found, very often at the expense of fragility. When having a look at the large solar airplanes built so far, they are precisely trying not to follow the cubic law, but trying to be lighter and enter the feasibility zone. This is especially true for the Helios and the future Solar Impulse.

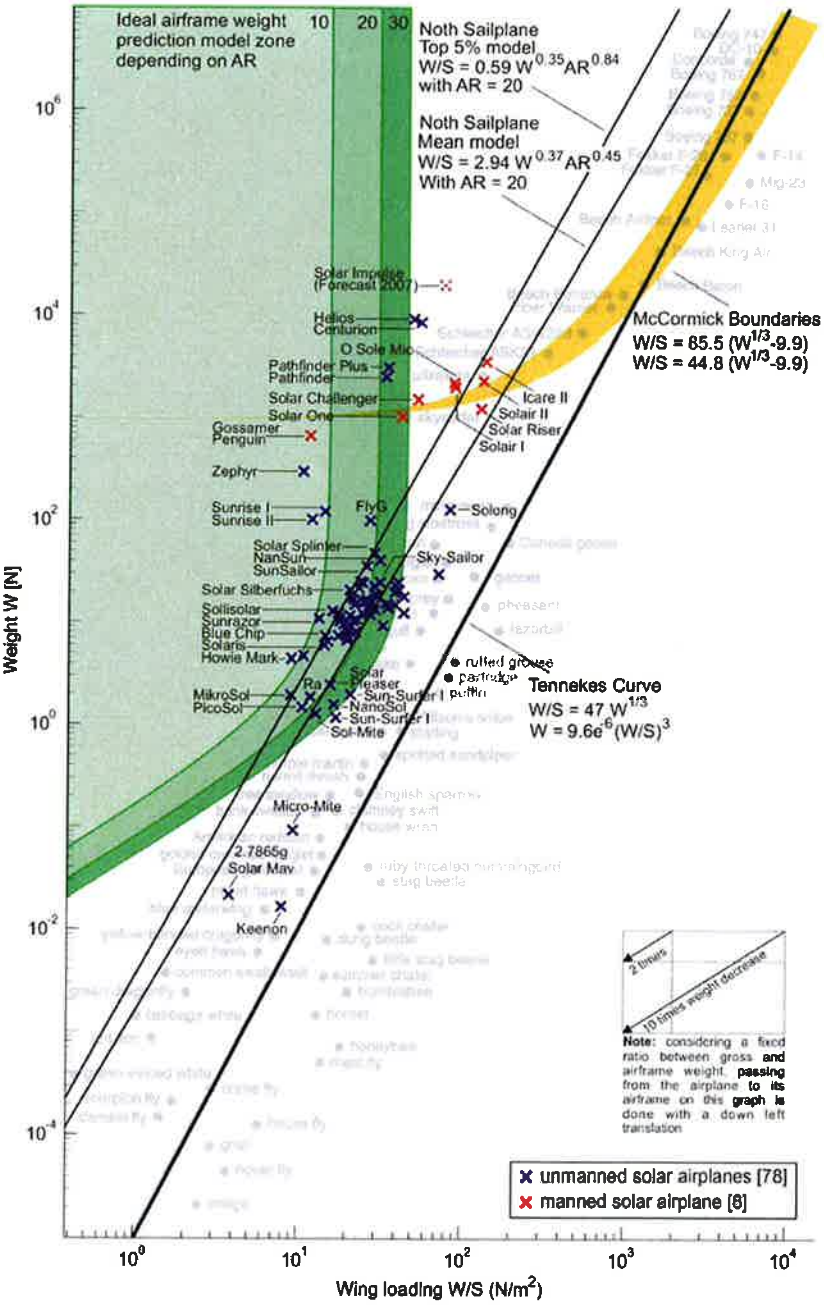


**Figure 10:** Representation of the airframe mass models interpolated from 515 sailplanes, superposed to 86 solar airplanes flown from 1974 to 2008. The green zones represent the ideal airframe weight prediction model for a solar airplane aimed at continuous flight.

# 6. Conclusion

## 6.1 Main achievements

This thesis presented a new methodology for the conceptual design of solar powered airplanes. It has the advantage to be very versatile and usable for a large range of dimension, from UAVs with less than one meter wingspan to manned airplanes. It is purely analytical and based on the concepts of energy and mass balances during one day using mathematical models that put the sizing of all elements on the airplane in relation.

The methodology was used for the conceptual design of a prototype that would embed a small payload and with the objective to prove the feasibility of continuous flight. Following the obtained design, a prototype was built and fully tested. Named Sky-Sailor, it validated the theoretical part of this thesis through experiments and proved the efficiency of the design methodology by achieving a flight of more than 27 hours using solar power only. This achievement is a record for a UAV that doesn't use altitude gain or thermal updrafts.

The design methodology being valid over a wide range of dimensions, a part of this thesis was also dedicated to study the scaling of solar airplanes and thus to clearly identify what becomes problematic at large or small dimensions.

## 6.2 Outlook

The experience gained during this thesis allows us to foresee the direction that solar aviation will take and the applications that it might cover. It is obvious that the technologies involved in the construction of solar powered airplanes will see many improvements these following years, with the growing need of green solutions for transportation, consumer electronics, etc.

**Figure 11.** Forest fire monitoring with a swarm of solar powered airplanes

The first solar powered airplanes used for concrete applications will probably have a size between 3 to 6 m. In fact, it was proved that this range is optimal and allows already now continuous flight with the current technologies. Moreover, applications such as law enforcement, border surveillance, forest fire fighting or power line inspection would require a payload of not much more than 1 kg what is precisely the capacity in such wingspan range.

At the MAV range, improvements will be necessary before seeing flying robots of the size of a hummingbird, powered by the sun only. The low Reynolds number will always be a limiting factor, but with more efficient solar cells and propulsion group elements, added to better energy storage, the dream should once come true. Miniaturization of the electronics and the avionics will also play a major role.

At large scale, we observed that with the current state of technology, embedding a human person or for instance a payload of 150 kg for a perpetual flight imposes a huge wingspan and requires a very lightweight wing that turns out to be fragile. The first limitation also comes from the sun irradiance that even with 100% efficiency solar cells would never provide enough power to not only carry the passengers, but also a minimum of comfort, which implies a lot of additional weight. Linked to this, the cubic tendency of the airframe's weight is not compensated by the square tendency of the solar cells surface. The large surface of solar cells needed leads then to impressive wingspans. Also, we observed that the speed of a solar airplane doesn't exceed 50 km/h making trips last several days instead of hours as with an actual airliner. That lets us believe that solar propulsion has a future for transportation only for trips that don't exceed 24 hours and for one or two persons onboard. Even in this case, a more efficient solution would still consist in collecting solar energy from large surfaces of solar panels on ground installations and use this energy in a concentrated form, stored in a battery or a fuel cell, on a fast and efficient electric aircraft. For solar HALE platforms anyway, it is different as the objective is not to transport something from A to B in a minimum of time but rather to ensure the presence of a given payload at a certain location and altitude during months or years. In this case, solar energy makes sense but significant improvements in energy storage will be necessary before seeing such aerial robotic platforms capable of year-around operation at high altitude.

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