Flying Solo and Solar to Mars

Global Design of a Solar Autonomous Airplane for Sustainable Flight

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The *Sky-Sailor* project aims to build an ultralightweight solar autonomous airplane capable of continuous flight over days and nights. It is intended to be used as a demonstrator of a Mars exploration airplane. In this article, we present the work done by the Autonomous Systems Lab of Ecole Polytechnique Federale de Lausanne (EPFL) on the global design of the airplane. A first prototype was built and tested with success. Furthermore, the realization of a lightweight control and navigation system is presented and discussed.

Introduction

The realization of a solar-powered microairplane capable of continuous flight during many days is a key challenge in the field of unmanned aerial robotics. Equipped with solar cells covering its wings, it retrieves energy from the sun in order to power its propulsion system, supply the control electronics, and charge the battery with the surplus of energy. During the night, the only energy available comes from the battery, which discharges slowly until the next morning when a new cycle starts.

Thus, an important value is the ratio between the power obtained from the solar panels and stored in the battery and the total power consumption of the airplane. It directly determines the autonomy that should be sufficiently high to survive one night and even includes a margin that could compensate for the lack of sun in cloudy weather.

Many elements must be taken into account for the design of such a system and finding the optimal concept is not trivial. In fact, in such a multidisciplinary problem, a choice that improves a certain characteristic often has important influence on the choice of other parts and can lead to a global reduction in performance.

Framework of the Sky-Sailor *Project*

The *Sky-Sailor* project was started within the framework of a feasibility study for the European Space Agency's Startiger (Space Technology Advancements by Resourceful, Targeted and Innovative Groups of Experts and Researchers) technology program. Whereas the exploration of Mars, so far, has been carried out by orbiters and rovers, there is a gap in the exploration of large areas close to the surface; this can be filled by aerial robots that serve as scientific platforms. In fact, they would combine the advantages of high-resolution imagery close to the ground, extensive coverage capability, and a freely selectable path.

The project began at the end of 2003, with a final target of studying the feasibility of a solar-powered airplane that would fly in the atmosphere of Mars and perform scientific measurements or exploration tasks for weeks or even months. This system should not only be autonomous in terms of control and navigation but also in terms of energy.

Goal of the Project

The goal of the proposed project is to develop a fully functional demonstrator that will be tested on Earth. Thus, the main objective of the *Sky-Sailor* project is the global design and the optimization of a solar airplane for continuous flight. The principal tasks of the project are to:

- identify and study the model of the different parts required on the airplane
- provide a general methodology for the design of a solar UAV depending on the scale and the payload

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- build a demonstrator within the range of some meters and validate the design phase
- develop a dedicated control and navigation system for this task in which a high priority is put on consumed energy
- demonstrate and evaluate continuous flight on Earth.

Overview of Existing Solar UAVs

The first solar airplanes were miniature models built by hobbyists in the mid-1970s. Even with low-efficiency solar cells and very limited battery technology, the most famous (F. Militky, H. Bruss, and V. Kupcik [1]) achieved flights lasting more than 4 h. Those airplanes required, of course, ideal sun conditions to fly and were remotely piloted. In 1979, the first manned flight took place with the *Gossamer Penguin*, developped by Astroflight.

Since then, the domain of the solar airplane was developed in both directions. In the manned category are *Solar Challenger*, *Icaré*, and, currently, *Solar Impulse* [19], which should achieve an around-the-world flight in 2009. For unmanned solar-powered aircraft, the most famous are *Pathfinder*, *Centurion*, *Helios*, and *Sunrise I*. The first three, all built by Aerovironment [17], have wingspans of 30, 63, and 75 m, respectively; for the last one, this value is only 9.6 m.

Although *Helios* established an altitude record of almost 30,000 m, none of those aircraft proved the feasibility of continuous flight. This stage was reached last year by *Solong*, a 4.75-m wingspan, radio-controlled (RC) plane built by AC Propulsion [18]. It landed in California on 3 June 2005 after 48 h and 16 min of flight, using only solar energy and ascending thermal streams.

Compared to these projects, *Sky-Sailor* aims to achieve continuous flight with solar energy only, onboard navigation, and reduced size and weight.

In the following section, we will talk about the design method and the global layout of the airplane. Then, "First Prototype of Sky-Sailor" and "Control and Navigation System" will approach the realization of the first prototype, i.e, the mechanical structure and the solar generator, and the control and navigation system, respectively. Finally, we will reveal the results of the first experiments and describe the ongoing work.

Airplane Design

We will present in this section, without going into too much detail, some basic principles of airplane physics in order to get an initial idea of the feasibility of a flight on Earth and Mars and see the scaling effects. Thereafter, we will enter into more detail, mentioning all the elements of the airplane.

Simplified Views on the Power Requirement for Leveled Flight

Sky-Sailor will mainly achieve leveled flight and avoid abrupt maneuvers that would result in a loss of energy. For this type of flight, a rough estimation of the aerodynamics can be represented with the following equations where the lift force is equal to the weight of the airplane:

$$\begin{cases} F_L = m \cdot g = C_L \frac{\rho}{2} S v^2 \\ F_D = C_D \frac{\rho}{2} S v^2 \\ P_{\text{level}} = F_D \cdot v. \end{cases} \tag{1}$$

Here, C_L and C_D are, respectively, the lift and drag coefficients, ρ the air density, S the wing area, v the flight speed, and m the mass. If we combine those equations, one can express the power for leveled flight independently of the airspeed.

$$P_{level} = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{(m \cdot g)^3}{S}} \sqrt{\frac{2}{\rho}}. \tag{2}$$

If we further assume that the airplane mass is proportional to wing area

$$m = k_{\text{mass}} \cdot S = k_{\text{mass}} \cdot \frac{L^2}{A_R}, \tag{3}$$

we obtain

$$P_{\text{level}} = \frac{C_D}{C_L^{3/2}} \sqrt{(k_{\text{mass}} \cdot g)^3} \sqrt{\frac{2}{\rho}} \cdot S. \tag{4}$$

Furthermore, the electrical power generated by a solar panel is also roughly proportional to the wing surface

$$P_{\text{solar}} = k_{\text{solar}} \cdot S. \tag{5}$$

Equations (4) and (5) tell us that the feasibility of a solar-powered glider in a first-order estimation does not depend on the size of the airplane or the flying speed, if we assume that the airplane mass scales quadratically with the reference length. This means that efforts must be concentrated mainly on two sides: the optimization of the airfoil to obtain a low ratio $C_D/C_L^{3/2}$ and the materials and manufacturing processes for the realization of a very lightweight wing structure.

Flight Conditions on Mars

Despite its low gravitational acceleration of only 3.72 m/s^2, our neighbor planet is much less favorable for flying than Earth because of its atmosphere density, which is around 80 times lower. Through (4), one can calculate that the energy required for leveled flight on Mars will be $\sqrt{g^{*3}/\rho^*} = 2.21$ times higher than on Earth for the same lift and drag coefficient. In order to reduce the power consumption, efforts must be concentrated on aerodynamics (C_L, C_D) and weight (m).

Moreover, as Mars is approximately 1.5 times more distant from the sun than Earth, the incident solar energy available at its orbital radius is 590 W/m^2, whereas on Earth the amount is 1,000 W/m^2 at the surface (AM1.5) [13].

Concerning wind and dust storms, direct observations of winds on Mars are extremely rare [5]. However, winds have been inferred from a variety of secondary effects and observations. As with Earth's environment, the wind speeds on Mars are highly variable with the time of year and location. At the *Viking* landing sites, the wind speeds were in the range of 2–7 m/s. These measurements were, however, taken within the boundary layer near the surface. Above the boundary layer, it is estimated that the wind speeds can approach 50 m/s [6].

In terms of temperature, the average value is much lower than on Earth. Although at certain times of the year and locations the temperature will rise above freezing, most of the time temperatures are well below the freezing point of water.

Similarities Laws for Earth Demonstration

For feasibility demonstration on Earth, with the objective to validate the concept of a Martian airplane, flight and energy conditions similar to a flight on Mars must be reached. If we consider a target altitude of 1,500 m on our neighbor planet, a consistent choice of flight altitude, listed in Table 1, will allow us to validate continuous flight (power similitude, speed similitude) and the aerodynamics at low Reynold's numbers. It is also planned to achieve wind tunnel tests with a scaled model.

Table 1. Corresponding altitudes for flight similitude.

	Altitude on Earth (m)	Altitude on Mars (m)
Speed similitude	13,500	1,500
Power similitude	17,530	1,500
Re similitude	34,710	1,500

Basic Layout for Continuous Flight

The design of an airplane, especially a solar-powered glider, includes the necessity of taking into account a large number of parameters in order to reach the final target, which is the maximum autonomy for a given payload. In this kind of problem, the optimization is not trivial because a modification of one part of the system often has one or many consequences on the choice of the others.

In this section, the layout of the entire airplane is investigated. This is done by finding the power balance as a function of the airplane size. By combining the airplane mass models with the basic aerodynamic model for leveled flight (4), one finds the condition for feasibility of continuous flight at different atmospheric densities and selects optimal solutions. Once the airplane size is chosen, more thorough estimations result in the proposed layout.

Figure 1 presents a schematic of the main parameters of the parts constituting the airplane and playing a role in its final characteristics and performances in terms of autonomy and payload. The left side contains the masses of all the parts, giving the total airplane mass. This value allows the calculation of the required mechanical power, according to the aerodynamics characteristics of the wing, and finally the electrical power of the motor that will give (after adding the power for control and communication) the total power consumption. This will set the requirements in terms of propulsion unit, batteries, and solar cells.

In this schematic, one can identify:

- **fixed parameters**: They are the requirements or the inputs of the optimization, here, for example, the mass of embedded payload and the desired autonomy.

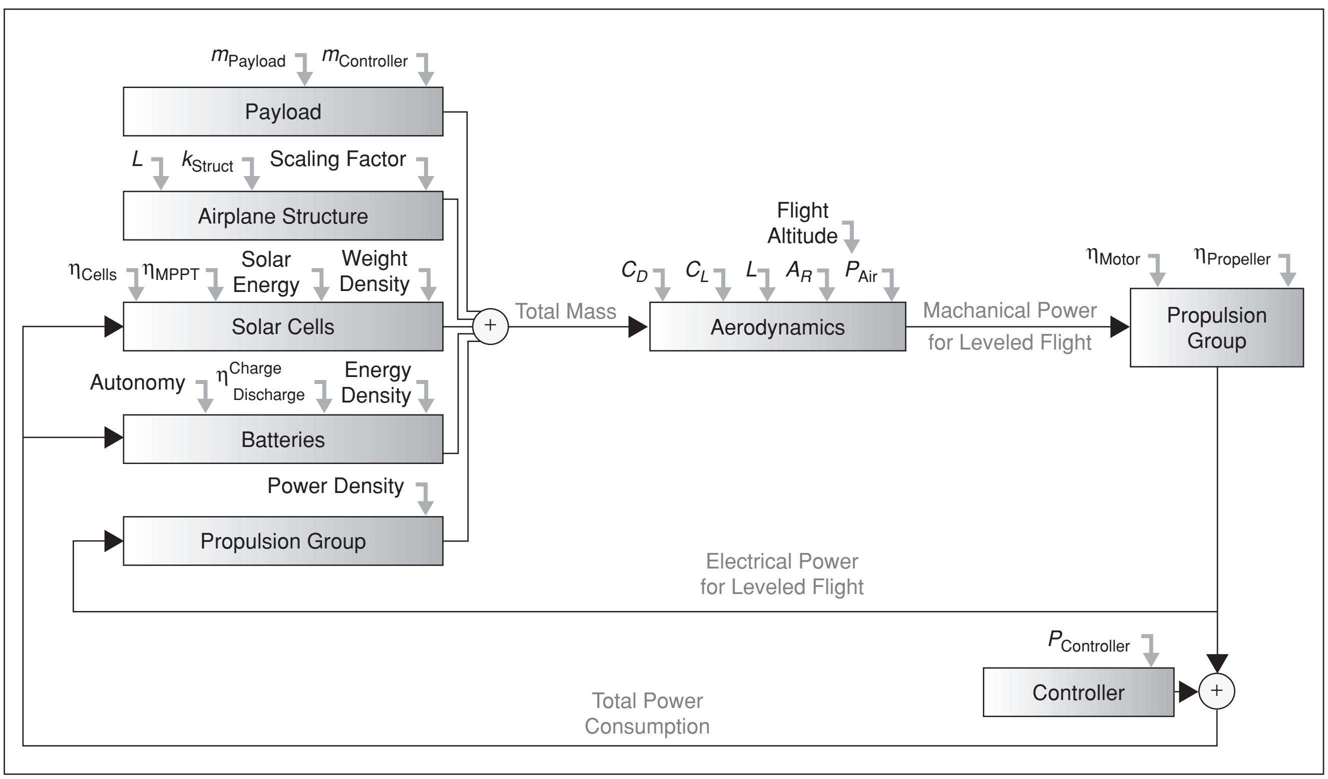

__Figure 1.__ The parts constituting the airplane and their relations for energetic balance.

- **local optimum parameters**: Some parts have one predominant parameter, which makes the choice quite obvious; for example, the battery where the power density-to-weight ratio must be as high as possible. Other parts need a tradeoff between many of their characteristics, the best example being the choice of solar cells. In fact, high-efficiency cells will provide, compared to thin-film cells, a higher power, but they will also constitute an additional weight that must be supported, even during the night when they are useless. Moreover, due to their important thickness and poor flexibility, their integration on the wing will also be a problem. The selected cells will thus need to combine these properties in the best way.
- **global optimum parameters**: They are the parameters describing the general shape of the airplane, i.e, the wingspan and the aspect ratio.

Results

Figure 2 shows the feasibility of continuous solar-powered flight for an exponential coefficient for the scaling of the structural mass of 2.3 and 3 respectively. One can see that the wing size has an optimum of around 3.5–4.0 m if we assume cubic scaling of the structural mass. This result indicates that the feasibility does not become more realistic for big airplanes because additional wing weight becomes a disadvantage.

One important constraint is the volume of the shell in which the airplane would be folded during its travel to Mars. It represents a cylinder of 1 m in diameter by 0.4 m high. According to these constraints, the proposed wingspan is around 3.0 m, which enables a double folding of the wings.

It is interesting to note that the weight of the batteries represents around 50% of the total mass of a small glider. The energy density of the batteries is therefore a dominant value concerning feasibility. Today, batteries reach around 200 Wh/kg, and it is expected that this value will double within the next five years.

Thus, one can see that the feasibility of continuous flight is now possible on our planet at low altitude. Of course, it still depends on the season and the geographical position. However, with higher energy needs and lower sun irradiance, having an airplane fly in the atmosphere of Mars within a decade is a dream that can only come true with important improvements in battery technology.

First Prototype of *Sky-Sailor*

According to the optimal dimension calculated with the algorithm depicted in the previous section, a first prototype of *Sky-Sailor* was realized during the beginning of 2005 (Figure 3).

The structure of the airplane is made of balsa wood, carbon fiber, and other composite materials that confer excellent rigidity for minimum weight. The wing is composed of a D-Box containing the main spar to which the numerous ribs are attached. The manufacturing process is currently still very long, and one future goal is to simplify it in order to be able to build new models in a short period of time.

A total of 216 RWE-S32 solar cells cover the wing on an area of 0.512 m^2. With a thickness of 130 μm, these silicon cells offer very high flexibility for their integration on the curved wing. Thanks to their efficiency of 17%, more than 80 W can be retrieved under good sun conditions at noon

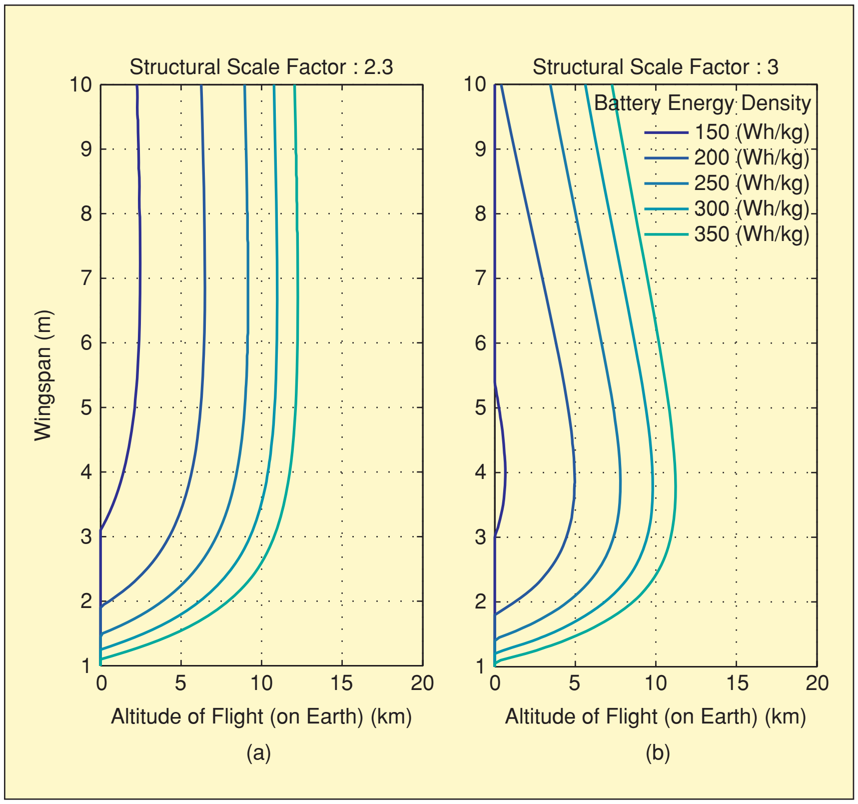

Figure 2. The wingspan as a function of flight altitude and battery energy density for continuous flight.

Figure 3. Sky-Sailor *v.1.*

(AM1.5). As depicted in Figure 4(a), the cells are encapsulated using a mechanically favorable symmetrical laminate combined with a fiberglass-reinforced plastic coating. Thus, we obtain three flexible solar modules that can be very easily integrated on the airplane and connected to the power circuit.

Three MPPTs (maximum power point trackers), basically dc/dc converters with variable and adjustable gain, ensure the use of the solar panels at their maximum efficiency. At a frequency of 50 Hz, they monitor the voltage and current between the solar panels and the battery and adapt the gain to reach the maximum efficiency. The last version weighs only 7.55 g for a maximum power of 40 W and reaches 97% efficiency [Figure 4(b)].

The energy is stored in a lithium-ion polymer battery that has a nominal voltage of 29.6 V, a capacity of 7,200 mAh, and a weight of 1,150 g. The charging process is controlled safely by the MPPT, which reduces, for example, the charge current when the battery is full, in order to avoid an overcharge that could result in the damage of the battery.

The propulsion group is composed of an RE-29 Maxon dc motor, an 8.1:1 gearbox, and a carbon-fiber propeller. The first prototype has a resulting total weight—including motors, propeller, solar cells, batteries, and controller—of less than 2.6 kg. The most important part of this weight is the battery, which represents 45% of the total mass. Figure 5 shows an overview of all the components and their location on the airplane.

The required electrical power for leveled flight of *Sky-Sailor* is around 16.25 W.

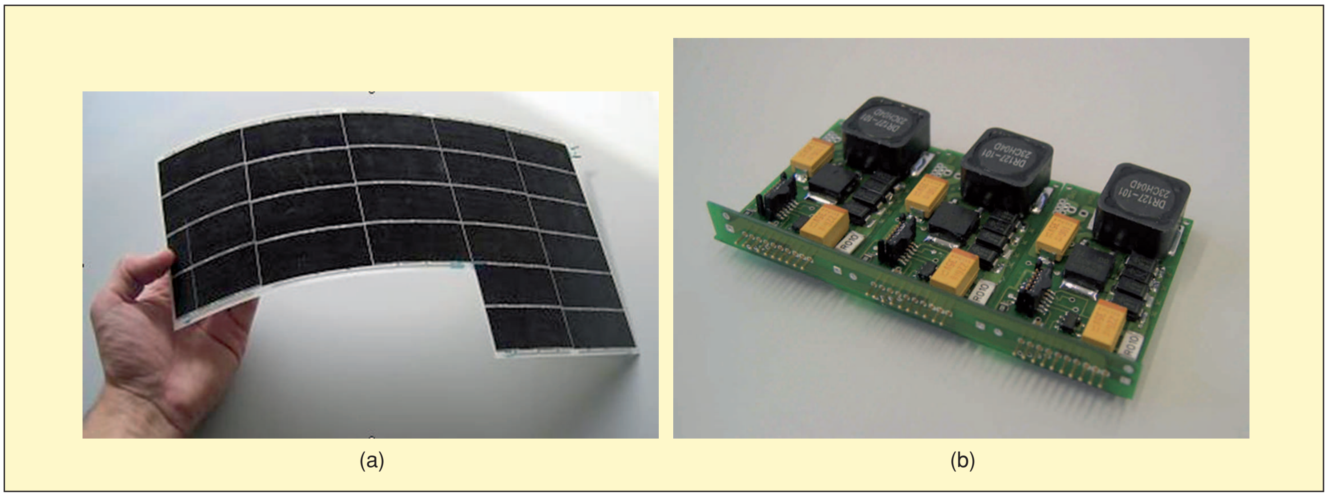

Figure 4. *Parts of the solar generator: (a) the flexible solar panel and (b) the three MPPTs.*

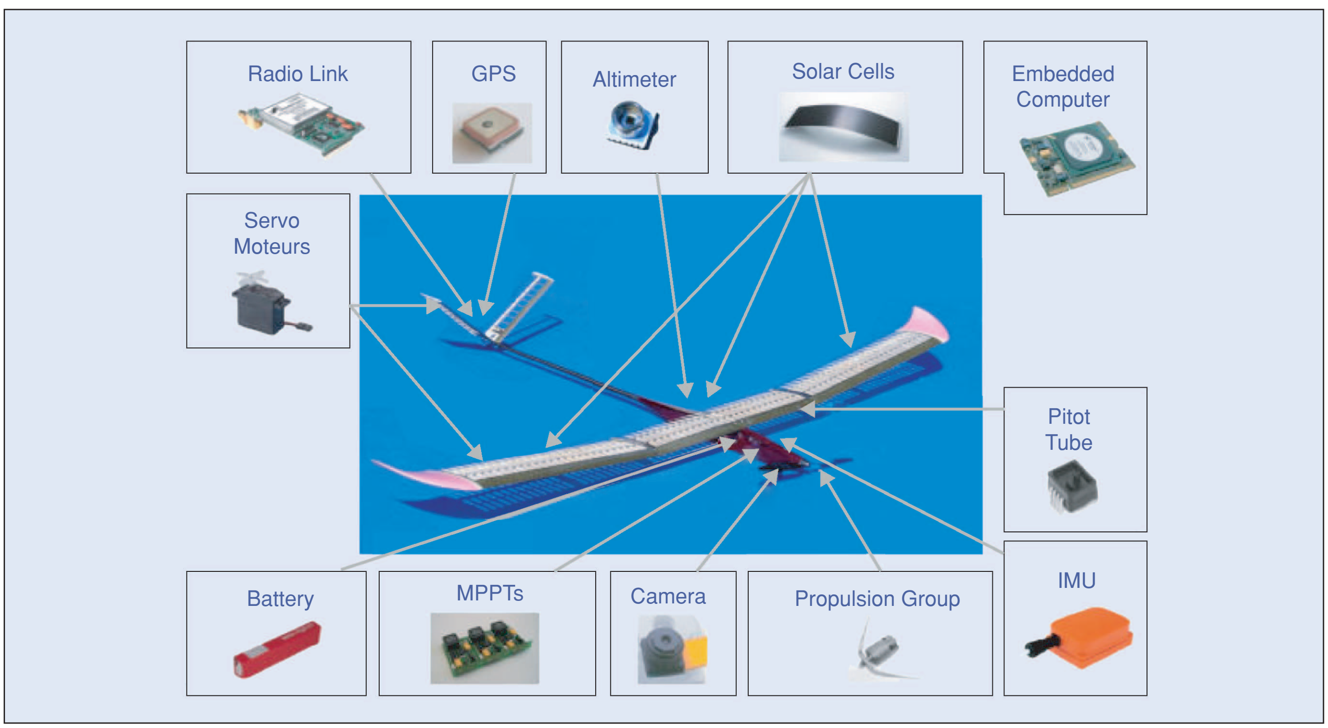

Figure 5. *Location of the various components of* Sky-Sailor.

Control and Navigation System

In order to meet the strong weight and power constraints, the control system must be realized, especially for this particular application. For this reason, we started to build a dedicated control and navigation system while, in parallel, flight tests were achieved with a commercial product.

This control and navigation system is based on an X-board single board computer running a reduced distribution of Linux based on Debian. It has a clock frequency of 266 MHz, 128 MB of RAM, and the same amount of Flash memory. The standard USB, RS232, and I^2C interfaces are available, which makes the interface to the sensors easier and, thus, the development time shorter.

Figure 6 gives a schematic overview of the autopilot system with all the sensors needed for autonomous flight. As the aircraft is intended to fly for long periods and, thus, spend the minimum amount of power, the criteria of mass and electric consumption had a rather dominant influence on the choice of the sensors. Moreover, in order to reduce development time, digital output models were preferred to analog ones.

The attitude and angle rates of the airplane are given by the MTX, a low-cost inertial measurement unit (IMU) from X-sens that is perfectly suitable for our application [4]. Its DSP achieves sensor data fusion on board, reducing the computational cost on the central processor of the autopilot, and sends the data at a maximum frequency of up to 512 Hz through the RS232 or USB interface.

An ultralow-power NB1042AP GPS from Nemerix, supporting WAAS/EGNOS correction, provides a very accurate position estimation (2-m precision 95% of the time) for only 60 mW and 10 g.

Table 2. Weight distribution on Sky-Sailor V.1.

Part	Weight (g)
Fuselage (including tail unit, motor, gearbox, propeller, controller RC-receiver)	469
BEC	17
LiPo Battery	1,150
Central part of the wing	306
Right part of the wing	253
Left part of the wing	250
Winglets	44
3 MPPTs	23.3
Autopilot, radio modem, antennas, servo board	80
Diverse cable	3
Total	2,595.3

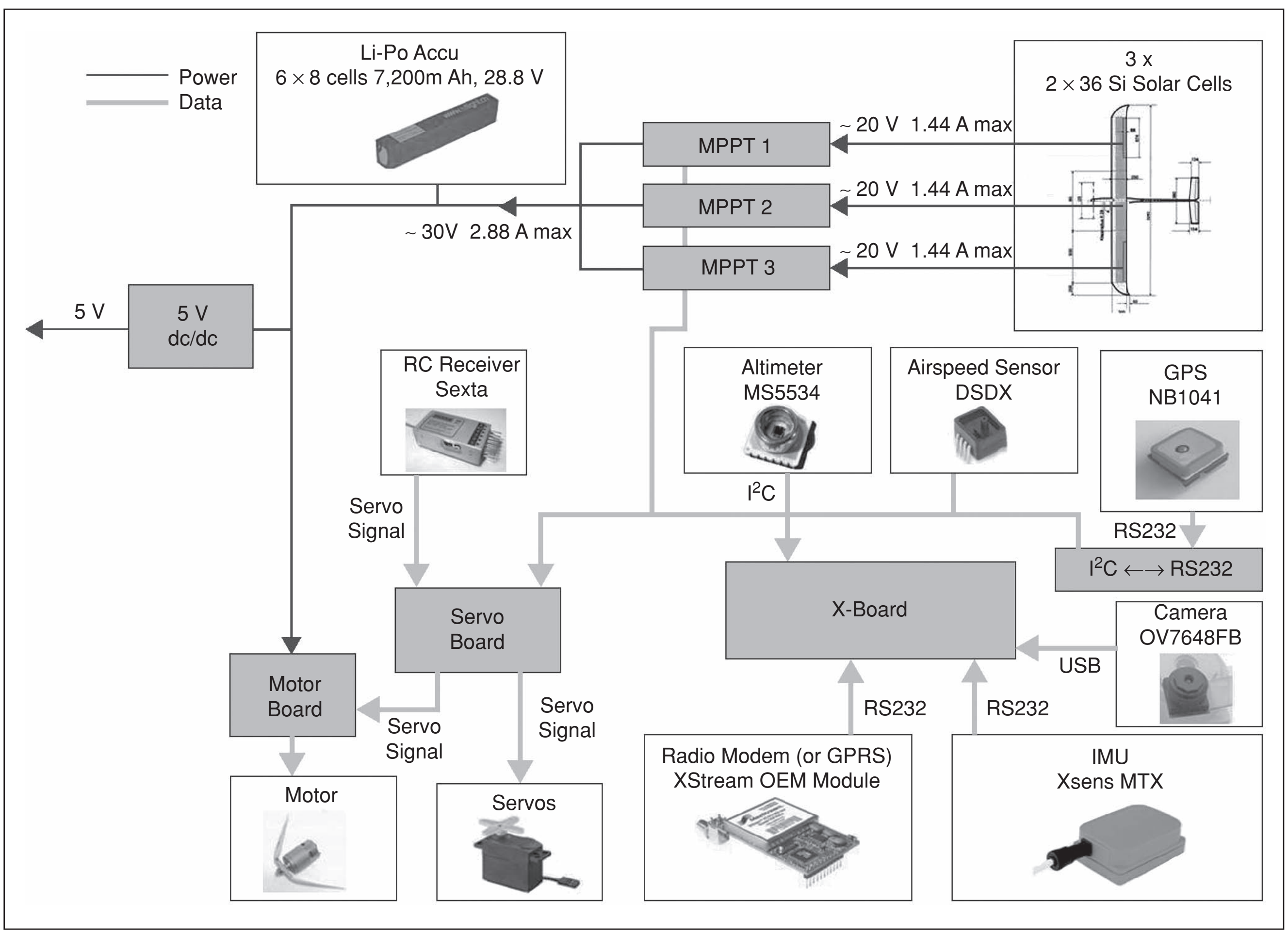

__Figure 6.__ The schematic of the control and navigation system

Two digital output pressure sensors are used for altitude (absolute pressure) and airspeed (differential pressure) measurements. This sensor is connected to a Pitot tube fixed at the leading edge of the wing.

Moreover, a CCD camera is installed under the fuselage and allows the aircraft to have an imagery of the flown-over ground. Therefore, it could fly in circle over a predefined target of interest or follow a coast or a canyon. One direction of research is, therefore, autonomous navigation based on vision, using, for example, simultaneous localization and mapping (SLAM) techniques [8] [9].

The commands given to the actuators, i.e the servos and the motor, are sent on the I^2C bus to the servoboard that transforms them into a servo motor pulse position modulation (PPM) signal. This board can also receive the command of a standard RC-receiver, which allows a human pilot on the ground to take control of the airplane in case of a problem or simply for takeoff and landing.

During the development phase of the controller, the tuning of parameters, or every test phase in general, it is very important for safety reasons to be able to pilot the airplane manually after a critical event. Numerous causes, from the instability of a controller to a bug that reboots or completely stops the main processor, could be the origin of a critical problem. It is therefore necessary to decouple at the maximum the path through which the manual and automatic orders are given to the servos. In addition to the two control modes, manual and automatic, a third mode that combines the orders coming from the autopilot and the ground operator is implemented. The functionality is particularly useful during the development phases of the controller. For example, the operator has the possibility of tuning the control parameters of the ailerons while controlling the throttle, the rudder, and the elevation by himself. During a second step, he configures the autopilot system to control one more degree of freedom and so on, allowing the development of the controller in a progressive manner.

Ground Control Station

A ground control station (GCS) was also developed in the form of a graphical user interface (GUI) for interaction with the airplane during a flight (Figure 7). It allows the user the following functionalities:

- monitor the state of the airplane during the flight and give a fast visual feedback to the operator. The user can select the point of view and zoom in or out in the three-dimensional (3-D) environment. The interface includes a board of virtual instruments for speed, altitude, heading, and attitude as well as solar power, battery voltage, or communication signal strength.
- edit parameters of the controller that is running on board the airplane. The user can save or load a file containing those parameters directly on the airplane.
- edit flight plans or give other high-level orders for the navigation of the solar UAV, for example by adding and moving waypoints on the map. Here, too, the flight plans should be saved or loaded easily.

This bidirectional communication between the GCS and the autopilot system is done using a radio modem that acts as a RS232 cable. With a range of 10 km, data can be transmitted at a baudrate of 9,600 b/s (bits per second).

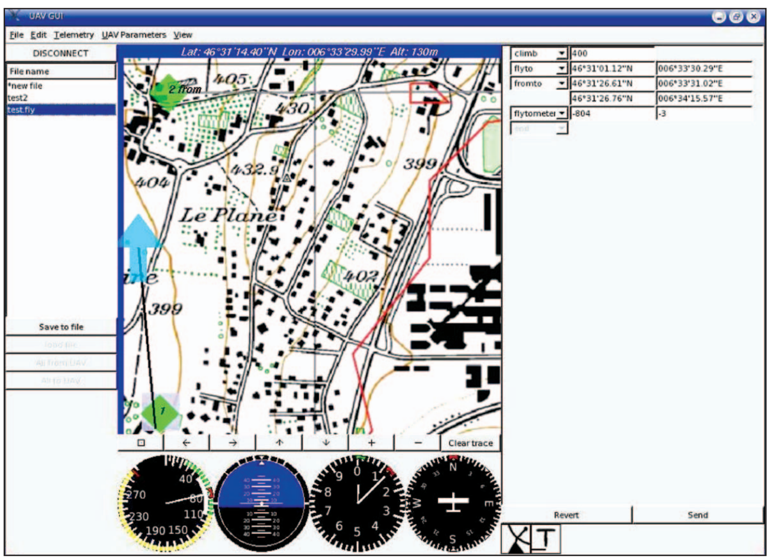

Figure 7. The graphical user interface for the interaction with the airplane during a flight.

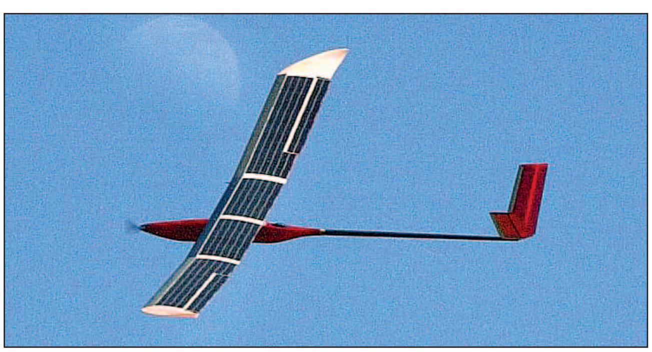

Figure 8. Sky-Sailor *in the air, flying with solar energy.*

Experiments and Results

The flight tests with the first prototype of *Sky-Sailor* were achieved both manually with an RC-transmitter and autonomously with the commercial autopilot (Figure 8). They showed very good characteristics in terms of aerodynamic capabilities. The airplane is passively stable with a neutral position of its servo motors and can thus recover from a critical position that could occur in case of turbulence or perturbation.

On the side of the solar power generator, the MPPT adjusts the working point of the solar panels according to the load very efficiently and in less that 100 ms. The charge of the battery is safe because overcharge is avoided by limiting the current once the maximum voltage of 33.5 V is reached (Figure 9).

The power consumption, calculated theoretically during the design phase, was validated with in-flight measurements. An average electrical power of 16.25 W is used for leveled flight at a speed of 30 km/h. The power required for the climbing phase and the sink rate with the motor off was also validated by experiments.

The energy accumulated during the day is sufficient to power the airplane in leveled flight until the next morning, which proves the feasibility of continuous flight. The longest flight achieved in autonomous mode lasted 5 h, and a 24-h flight is planned next summer when the autopilot system will be ready to control the airplane safely during the night.

Ongoing and Future Work

The control and navigation system is currently in the test phase, and research is being conducted on the control technique for such an airplane. A simulation environment is also under development in order to evaluate the performance of the controller before testing it on the real airplane. Efforts will also be on the integration and miniaturization of the separated modules that currently compose the autopilot.

Concerning the structure of the airplane, the actual prototype was assembled and built manually, representing many hours of handwork. Improvements must be made on this side to reduce the time required for the building of one model. This would allow the fast development of new prototypes with different wingspans and shapes.

Potential Applications

Small- and high-endurance UAVs find uses in a lot of varied fields, civilian or military. The civil applications, leaving aside the military ones, could include coast or border surveillance, atmospherical and weather research and prediction, environmental, forestry, agricultural, and oceanic monitoring, imaging for the media and real-estate industries, and many of others. The civilian market was estimated at US$40.29 billion for the period 1999–2008 [14]. The great advantages of *Sky-Sailor* compared to other solutions undoubtedly would be its ability to remain airborne for a very long period, its low cost, and the simplicity with which it can be used and deployed without any ground infrastructure for the launch sequence.

Case Study: Forest-Fire Monitoring

A study of the United Nations on forest-fire statistics in the former USSR, North America, and Europe reports an average number of 225,000 forest fires per year between 1989 and 1998 in those region [15]. They destroyed annually more than 6.474 million hectares of wooded land. Canada spends approximately US$400 million for the extinction of 10,000 fires every year.

During a warm period with a high risk of forest fires, many *Sky-Sailors*, easily launched by hand, could efficiently monitor an extended surface (Figure 10), looking for a newly ignited fire with an appropriate detection system [7]. The immediate reporting of starting fires would allow rapid intervention and, thus, reduce the cost of such disasters, in terms of human and material losses.

Conclusions

In this article, we presented the work done in our lab on an unmanned solar airplane with the objective to fly continuously.

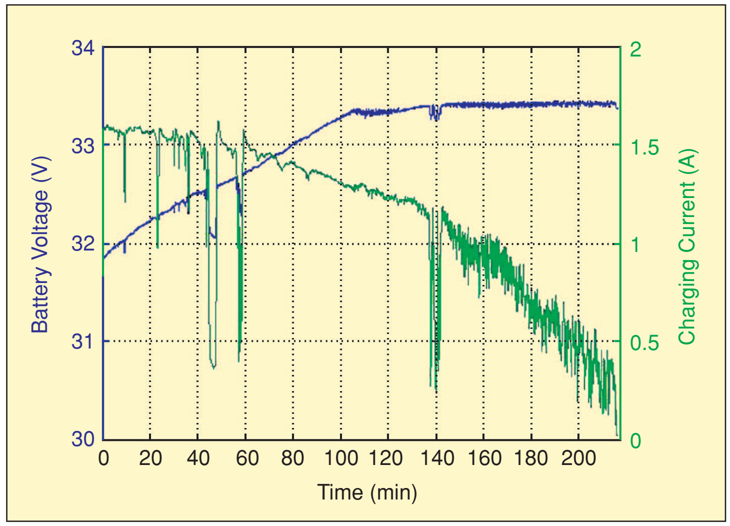

Figure 9. The battery charge with overcharge avoidance.

Figure 10. A futuristic view of Sky-Sailor *in the task of forest-fire detection*

We presented our design method and demonstrated that there is a global optimum in terms of the wingspan for such aircraft. A first prototype of *Sky-Sailor* was built, and it presents very good flight characteristics. We achieved an autonomous flight of 5 h with its energy only from the sun. The feasibility of continuous flight has been proved for Earth by tests and experiments where the power consumption and the solar charge of the battery were validated. On Mars, this dream will certainly come true in a decade.

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Keywords

Solar airplane, unmanned aerial vehicle, sustainable flight, solar powered UAV.

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