# SKY-SAILOR Design of an autonomous solar powered martian airplane

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# DESIGN OF AN AUTONOMOUS SOLAR POWERED MARTIAN AIRPLANE

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## ABSTRACT

*For more than two decades, Mars has been of great interest for scientific exploration, using orbiting spacecrafts or landers. Orbiters like "Mars Express" cover large areas and give images of the surface with a resolution limited to several meters. Rovers missions, like "Pathfinder" or "MER", offer the ability to maneuver to scientifically interesting sites, perform analysis of soil and rock composition, but are limited in range to the immediate surroundings of the landing site. There is a strategic gap for systems that would combine high-resolution imagery and extensive coverage. This gap can be addressed by micro-airplanes that will give more accurate images than satellites, thanks to their proximity to the ground (about 0.5 to 2 km) and cover much larger areas than rovers without being limited by terrain roughness. This paper presents a feasibility study and the first design of a very lightweight solar powered airplane for Mars exploration. Called **Sky-Sailor,** it was investigated in an ESA definition study within the framework of the Startiger technology program.*

## INTRODUCTION AND MOTIVATION

The enabling technology for the realization of a solar powered micro-airplane with continuous flight capabilities on Mars is available today or in the near future. In fact, significant progress has been made recently in the critical fields for such a project that are: Efficiency, weight and flexibility of solar cells, power to weight ratio of batteries, miniaturization of MEMS and CMOS sensors, performance of single board computers, etc. However, major interdisciplinary effort is necessary in order to optimize and integrate concepts and technology to a fully functional system. Therefore, a strong collaboration of specialists from the fields of autonomous systems design, aerodynamics, solar cells, micro-sensors, light-weight structures, energy storage and much more is needed.

The Autonomous Systems Lab (ASL) at EPFL is already very active in the field of VTOL (Vertical Take-Off and Landing) indoor flying robots (OS4 project), ultra-light airplanes (Celine, 10 [g]) and bio-inspired vision-based flying robots (Blimps, F2). With the Sky-Sailor project, the ASL enters the new field of outdoor flying robots. The goal of the project is to develop and test on Earth a prototype of solar powered micro-glider that will be fully autonomous in navigation and power generation and thus validate the feasibility of a Mars dedicated version.

## OTHER PLANETARY UAV PROJECTS AND ORIGINALITY OF SKY-SAILOR

The idea to explore the red planet using UAV (Unmanned Aerial Vehicle) is not very recent and had given rise to many projects. In the 1970's, the earliest one was the Mini-Sniffer, a 6.7 [m] wingspan and hydrazine powered airplane, designed, built and flown by NASA [1]. Since this time, considerable improvements, in particular in propulsion concepts, energy storage and materials, have led us to more advanced Martian UAV proposals; the most famous are ARES (Aerial Regional-scale Environmental Survey) from NASA Langley Research Center [2] and the AME (Airplane for Mars Exploration) from NASA Ames Research Center [3]. Several other planetary UAV projects with a large variety of concepts are in study, like inflatable wings glider [4], special helicopters [5,6], lighter than air balloons [7], flapping insect robots [8], etc.

ARES and AME can embed an important payload for scientific operations but they are quite heavy and have a short autonomy (Table 1). On the opposite, Sky-Sailor will be limited to lightweight sensors and scientific instruments, but its coverage possibilities and autonomy will allow it to achieve very long period missions.

Table 1. Comparison table of Martian UAV projects

|  |  | ARES, NASA Langley | AME, NASA Ames | Sky-Sailor |
|---|---|---|---|---|
| Wingspan | [m] | 6.4 | 12.4 | 3.2 |
| Weight | [kg] | 100-150 | 204 | 2.5 |
| Payload | [kg] | n.a | 25 | 0.5 |
| Speed | [m/s] | 140 | 110 | 30-40 |
| Propulsion |  | Rocket pulse | Electrical motor, fuel cell | Electrical motor, Li-Po batteries |
| Endurance | [h / km] | 1.5 / 850 | 8.8 / 3500 | Continuous long-term, mainly depending on battery life cycle and dust deposition on solar panels |

**FLIGHT CONDITIONS IN MARS ENVIRONMENT**

As aerodynamics is a major challenge and the Martian environmental conditions are totally different as on Earth, flight feasibility on the red planet has first to be studied.

Despite its low gravitational acceleration of only 3.72 [m/s$^2$], our neighbor planet is much less favorable for flying because of its atmosphere density, which is around 80 times lower (Table 2). Based on the basic equations, we present here a rough estimation of the aerodynamics. For an airplane, lift and drag forces are:

$$F_L = C_L \frac{\rho}{2} S\, v^2 \tag{1}$$

$$F_D = C_D \frac{\rho}{2} S\, v^2 \tag{2}$$

where $\rho$ is air density, $S$ wing area, $v$ flight speed and $C_L$ and $C_D$ the lift and drag coefficients. The required power for leveled flight is then, using (1) and then substituting (3) in (4):

$$P_{level} = F_D \cdot v = C_D \frac{\rho}{2} S\, v^3 \tag{3}$$

$$F_L = m\, g = C_L \frac{\rho}{2} S\, v^2 \tag{4}$$

$$P_{level} = \frac{C_D}{C_L^{3/2}} \sqrt{\frac{(m \cdot g)^3}{S}} \sqrt{\frac{2}{\rho}} \tag{5}$$

If we assume that the airplane mass $m$ is proportional to wing area $S$, we get

$$P_{level} = \frac{C_D}{C_L^{3/2}} \sqrt{(k_{mass} \cdot g)^3} \sqrt{\frac{2}{\rho}} \cdot S \quad \text{with} \quad m = k_{mass} \cdot S \tag{6}$$

Table 2. Comparison table of important flight parameters

|  |  | Earth | Mars |
|---|---|---|---|
| Air composition | [m/s$^2$] | 78% $N_2$, 21% $O_2$, 1% Ar | 95.3% $CO_2$, 2.7% $N_2$, 1.6% Ar, 0.13% $O_2$ |
| $g$ gravitational acc. | [m/s$^2$] | 9.81 | 3.72 |
| $\rho$ density of fluid (air) | [kg/m$^3$] | 1.225 | 0.015 |
| $\mu$ viscosity | [kg/m·s] | $1.8 \cdot 10^{-5}$ | $1.2 \cdot 10^{-5}$ |
| Sideral rotation periode | [hour] | 23.9344 | 24.6229 |
| Solar mean radiance | [W/m$^2$] | 1367 | 589 |
| Temperature (min/mean/max) | [°C] | -76/+15/+59 | -143/-63/+27 |

This rough estimation shows us, considering that the solar power is proportional to the surface of the wing, that the feasibility of a solar-powered glider does in a first order estimation not depend on the size of the airplane or the flying speed. It is interesting to notice that for the same aerodynamics and the same surface, a flight on Mars will need $(g'^3/\rho')^{1/2} = 2.1$ times more power than on Earth. In order to reduce this power, efforts have to be concentrated on the aerodynamics ($C_L$, $C_D$) and the weight ($m$). The Reynolds number is a very important characteristic for the airfoil selection and performance. It is defined as:

$$Re = \frac{\rho L_P v}{\mu} \tag{7}$$

with flight speed $v$ and wind cord $L_p$. On Mars, the $Re$ number is very low, which increases the difficulty of flight because the boundary layer is much less capable of handling an adverse pressure gradient without separation and the maximum lift capability is restricted.

In order to demonstrate the feasibility of continuous solar powered flight on Mars, we have to define similar flight conditions for experiments on Earth. Mars airplane validation can then be achieved on our planet with a consistent choice of flight altitudes, listed in Table 3, to prove the feasibility of continuous flight (*power similitude, speed similitude*) and the aerodynamics at low Re numbers (*similar Re or flight speed*). It is also planned to use special wind tunnel tests with scaled model.

Table 3. Altitudes required for flight similitude

|  | Earth | Mars |
|---|---|---|
| Speed similitude | 13'500 [m] | |
| Power similitude | 17'530 [m] | 1500 [m] |
| Re number similitude | 34'710 [m] | |

## SKY-SAILOR DEMONSTRATOR V1.1 DESIGN

The key constraints on the airplane design in terms of weight and dimensions are the required capacity to embed 0.5 [kg] scientific payload and the ability to be stowed in a cylinder of 1 [m] diameter and 0.4 [m] height. According to those requirements, Sky-Sailor version 1 was designed. It has a wingspan of 3.2 [m] and a total weight of around 2.5 [kg]. The wing has winglets to its extremities, in order to prevent vortex around wing tip, which decreases lift at the tip, and a V-Tail ends the fuselage. Based on aerodynamics studies, the power required for a low altitude flight on Earth is around 13.2 [W].
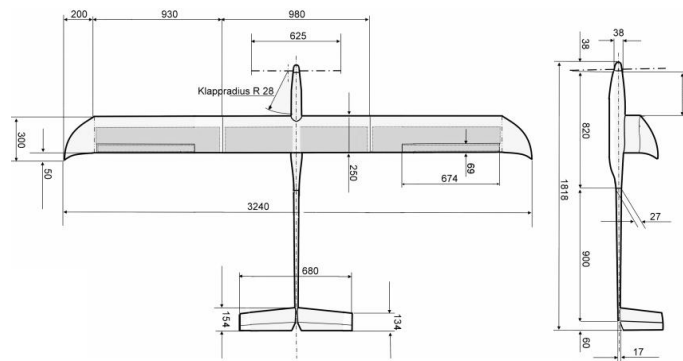


Fig. 1. Sky-Sailor demonstrator v1.1

**POWER MANAGEMENT**

Another major challenge is the power management that has to ensure continuous flight by day and night. During the day, the Sky-Sailor will have to retrieve solar energy for continuous leveled flight, but also for scientific measurements, navigation and control electronics and battery charging for night flight. This chapter presents all main issues of power management, from solar cells to the motor and the propeller.

**Solar power**

At noon, the solar power on Mars is estimated at **430 [W/m²]** during spring and summer at latitude lower than 20°N. For the same condition on Earth, we assume **950 [W/m²]** during a sunny day. According to the variable position of the sun in the sky, the solar power function can be approximated by a cosine (Fig. 2) and the mean power on 24 hours is estimated with:

$$P_{mean\_Earth} = \frac{1}{\pi} P_{peak\_Earth} = 302 \ [\text{W/m}^2] \tag{8}$$

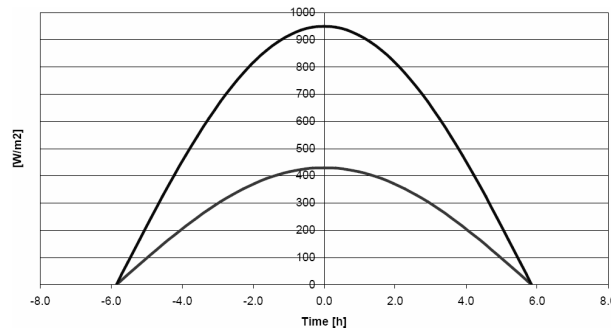$$P_{mean\_Mars} = \frac{1}{\pi} P_{peak\_Mars} = 137 \ [\text{W/m}^2] \tag{9}$$


Fig. 2. Day solar power on Earth and Mars

**Solar cells and MPPT**

To retrieve this energy, solar cells cover the wing (around 0.512 [m²] for the 3.2 m wingspan airplane). In terms of efficiency, the better choice would have led us to GaAs Triple Junction cells with efficiencies of 27-28 [%]. However, those cells have a mass density of around 90 [mg/cm²]. As weight has a major impact on the required power for leveled flight, the better choice is silicon cells (e.g. RWE-32 cells) that reach 16-18 [%] efficiency with only 32 [mg/cm²]. Furthermore, the flexibility of those thin cells will also be an advantage for their integration on the wing.

In order to get the highest amount of energy from the solar cells, a so called **Maximum Power Point Tracker (MPPT)** is required. A MPPT is basically a DC/DC converter with variable and adjustable gain. It contains electronics that will monitor the current and the voltage of the cells and battery. By changing the gain, it will ensure the best use of the solar cells energy.

A total of 216 solar cells will be installed on the demonstrator plane. They will be divided in 3 modules connected in parallel, each of them composed of 2 series of 36 cells. The cells will be encapsulated using a mechanically favorable symmetrical laminate combined with a fiber glass reinforced plastic coating. This encapsulation is non-reflective. Thus, we will obtain a flexible arrangement easily integrable on the plane and connectable to the power circuit. At maximum sun conditions, the available power will be 28 [W] for each module, which makes a total of 84 [W].

**Battery**

Battery selection is the most critical issue for an autonomous solar powered aircraft because it represents the most important part of the total weight. After having compared all energy storage technologies available today, Lithium-Ion-Polymer batteries have been selected for Sky-Sailor project, because it represents currently the best energy/mass ratio that is commercially available.

The batteries are mainly used during the night flight, when the solar power is below the power requirement for a leveled flight. As the total effective night duration is 13.2 hours, we can calculate the needed capacity:

$$Battery\ Capacity = 13.2\,[\text{h}] \cdot 13.2\,[\text{W}] = 174.2\,[\text{Wh}] \tag{10}$$

Finally, including a margin of 20 [%], our battery is composed of eight E-tec1200 cells in series, six in parallel, which lead to a capacity of 207.36 [Wh] with 7200 [mAh] at 28.8 [V] and a total weight of 1.2 [kg].


**Motor, gear and propeller group**

Based on the required power on the propeller shaft, several iterations have been made in order to select the best motor for our application. Both the DC and DC Brushless (BLDC) technologies were considered. Finally, a MAXON DC, RE-MAX 29 (161g) was selected. The motor is well suited for long-term operation thanks to its graphite brushes and the selected optimal operating point, far from the short-term operation. A gear with a reduction ratio of 7.28:1 is connected to the motor.

The propeller is composed of two 60 [cm] diameter blades with a Goe795 profile. The calculated specifications of the propeller, at high altitude on Earth for speed similitude with Mars, are listed in Table 4.

Table 4. High altitude propeller specifications

| Propeller speed | 1114 [rpm] |
|---|---|
| Plane speed | 7.6 [m/s] |
| Power | 8.98 [W] |
| Thrust | 0.88 [N] |
| Efficiency | 74.2 [%] |


**NAVIGATION**

Autonomous localization and control of flying devices has been proven to be feasible on Earth. Rockets controllers and autopilot for planes are two amongst many available examples. On Earth, such systems usually use inertial measurement units, altimeters and GPS for localization and vehicle stabilization. During the last decade, such sensors have been miniaturized and their accuracy has been improved. This technology opens a large range of applications and therefore can be integrated in small flying devices.

For planetary exploration, the GPS is not available and many problems arise for long-range missions. The use of proprioceptive sensors is not sufficient because they lead to unbounded error propagation. The position information must be completed with exteroceptive sensors such as range sensors and vision. In our application, vision will be used to track a predefined targets or contours, and localize the airplane in relation with the skyline.

For the first flight tests, we will evaluate the aerodynamics design and validate the preliminary concepts, using a commercially available autopilot. In parallel, we develop our own guidance, navigation and control system, which will be based on a X-board single board computer. The sensors that will be used are two pressure sensors for altitude and speed measurements (Pitot tube), a VGA miniature camera, a X-Sens Inertial Measurement Unit (IMU) and a GPS that will be used in the beginning to get position information relative to a target location. Our final goal is to get rid of GPS and use vision only. In term of control, we will use classical approach, like proportional-integral-derivative (PID) command, but also modern approach, like optimal control. Only high-level commands, like waypoints, will be sent to the controller board. Communication between the plane and the ground will be assured by a 30 [km] range serial radio modem allowing an over-the-air baud rate of 19.2 [kbps].
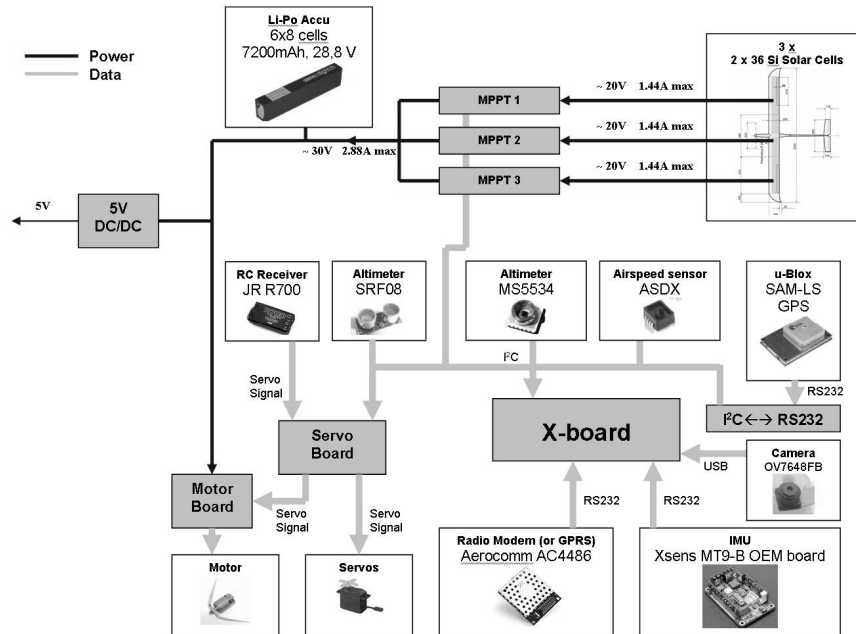
Fig. 3. Systems overview of Sky-Sailor Demonstrator

## MARS MISSION CONCEPT

### Mission phases

Sky-Sailor would be carried to Mars in a small aeroshell that would be attached to a carrier spacecraft. Upon reaching the red planet, the aeroshell would be released for direct entry into the Martian atmosphere. From this point, the operations could be decomposed in different phases:

During **phase 1**, the Micro Airplane is stowed, together with its deployment means in a cylindrical volume of 1 [m] in diameter and 0.40 [m] in height. After the ballistic entry of the aeroshell, the supersonic deployment of a decelerator parachute would reduce the speed [1]. Stowage possibilities and deployment means, using springs or only aerodynamic forces [3], will be investigated and tested.
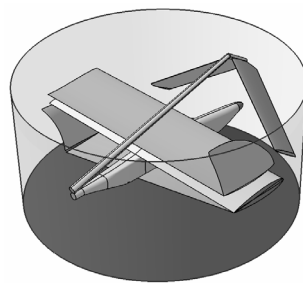


Fig. 4. Example of stowage possibility

**Phase 2** corresponds to the subsonic release of Sky-Sailor during the atmospheric entry of the aeroshell traveling at speed in the range of 30 to 60 [m/s]. It should be deployed at high altitude and will need self-stabilization to initiate the flight. The airplane shall then reach the desired flight altitude of 1.5 [km].

During **phase 3,** Sky-Sailor performs scientific operations, depending on the season between 45°N and 45°S from Martian equator, at a nominal height with a predefined path. It explores large areas and records atmospheric, ground and/or geological data that will be transmitted to Earth via a Mars orbiter. Dropping of small payload like micro-robots is also possible for ground interaction at specific location. Flying at a speed of 40 [m/s], the airplane can cover a distance of approximately 1700 [km] during a 12 [h] period. During the night, the vital goal is to remain airborne, using minimal energy from the battery.

At **phase 4,** the exploration mission will end when the airplane crashes normally due to the batteries life cycle and dust deposition on solar panels. However, a controlled crash-landing shall allow the mission to continue for some time with a ground interaction possibility.

If a failure occurs during **phase 3**, the airplane interrupts all scientific activities and tries to remain airborne until a communication link to Earth can be established, in order to troubleshoot the failure or modify the mission.

**STATUS OF THE PROJECT AND PROJECT PLANNING**

A major challenge is the design and construction of a structure that can embed the 0.5 [kg] payload and at the same time can be folded in a Ø 1 x 0.4 [m] cylinder. It must therefore combine lightweight and robustness. The original approach we chose to reach this goal is to team up with experts from various fields, from aerodynamic modeling up to lightweight model airplanes design. This allowed us to push the limits of the overall systems design, using latest findings in all key technologies. The starting point for the demonstrator design was the model airplane of Walter Engel that holds the world record for flight duration of over 15 hours with 1 kg of battery. The resulting Sky-Sailor version 1 has a structural weigh of only around 0.6 [kg] for a wingspan of 3.2 [m] and a wing surface of 0.776 [m$^2$] (see Fig. 5). The resulting total weight including motors, solar cells, batteries, controller and payload is around 2.5 [kg].
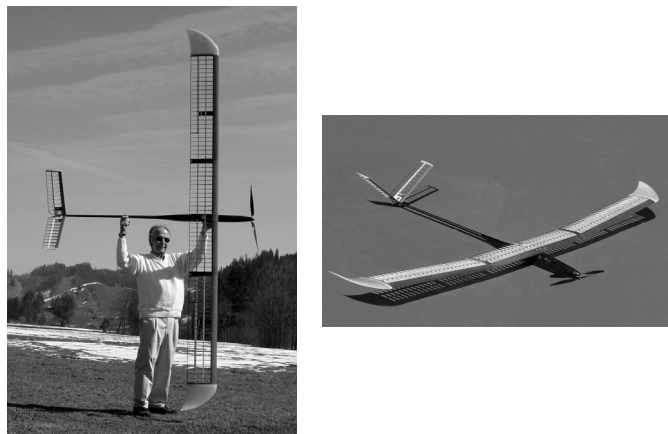


Fig. 5. First version of Sky-Sailor glider

The next steps of the project will be the integration of the solar panels and the MPPT's and the installation of an autopilot, in order to validate a non-stop autonomous flight during 24 [h]. This event is planned for summer 2005.

Simultaneously, aerodynamics will be optimized as much as possible for Mars condition. Experimental verification of aerodynamics for low Re numbers will be achieved with a scaled model in the wind tunnel.

**CONCLUSION**

We have described the preliminary study and the first design of a Mars Solar-Powered airplane. It shows that continuous flight on Mars should be feasible in the near future if the involved technologies are pushed to the limit and a strong integrated system engineering approach, applying on a highly interdisciplinary team, is taken.

Autonomous micro-airplane technology is still in the beginning. However, microtechnology is getting ready and we are convinced that in one or two decades, its will open new ways for planetary exploration and Earth observation.

Beyond the primary goal on exploring our neighbor planet, such micro-airplane have numerous other applications on Earth like inspection from the air (pipelines, …), low enforcement, traffic monitoring, telecommunication, forest fire fighting, environmental data retrieving over long period or rescue mission. Those are cases where, compared to manned mission in helicopter, the use of tens of autonomous micro-airplanes would be inexpensive and allow covering a much more important area in the same time.

**ACKNOLEDGEMENTS**

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