# SOLERO: SOLAR-POWERED EXPLORATION ROVER

**S.Michaud(1), A. Schneider(2), R.Bertrand(2), P.Lamon(1), R.Siegwart(1), A. Schiele(3)**

[1]*Autonomous Systems Lab,*
*Swiss Federal Institute of Technology, Lausanne (EPFL)*
*CH-1015 Lausanne*
stephane.michaud@epfl.ch

[2]*von Hoerner & Sulger GmbH,*
*D-68723 Schwetzingen, Germany.*
bertrand@vh-s.de

*European Space Agency*
*Automation & Robotics Section (TOS-MMA)*
*P.O. Box 299, 2200 AG Noordwijk, The Netherlands*
Andre.Schiele@esa.int



## ABSTRACT

A mobile robot is the most suited element to transport scientific instruments to diverse scientifically interesting sites on extraterrestrial planets. Instruments to examine geology, mineralogy or exobiology can be easily deployed. Since the Mars Pathfinder mission, new missions for in-situ planetary exploration demand for increased mobility on planetary surfaces. This can be seen at the example of the US Mars Exploration Rover missions, or at the example of ESA's EXOMARS mission, which is about to enter the definition phase.

In this respect, redesigning specific aspects of past rover concepts is appropriate; this is in particular the development of the most suitable all terrain performances, autonomous navigation and a power management concept. This abstract on-hand presents the results of a new rover concept study, carried out jointly by Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, and von Hoerner & Sulger GmbH (vH&S), Germany, under contract of the European Space Agency (ESA). Labeled SOLERO ("Solar-Powered Exploration Rover") this activity had the objective to bring forth a complete rover system using a predefined locomotion concept. As a model Mission, a Mission to the surface of Mars was chosen, aiming at the in-situ analysis of Martian geochemistry and mineralogy. Therefore it was necessary to accommodate a suite of miniaturized payload instruments inside the Rover, scaling the rover system and the instruments to a size suitable for accommodation, and to provide the required resources for operation (power, communications, control, thermal control).

## INTRODUCTION AND METHODOLOGY

The SOLERO activity was carried out in four steps:

1. The requirements for a mini-rover in the 10 kg-class, applicable for a geo-science mission, have been determined and compiled in a requirements document.

2. A conceptual system design for a SOLERO flight model was carried out, addressing all subsystems.

3. A breadboard model was designed, developed and manufactured, which is to demonstrate the locomotion capabilities, the feasibility of the configuration in total and, in particular, the autonomous power provision.

4. Finally, extensive laboratory and field tests have been carried out in order to verify critical system performance numbers through the existing breadboard design.

## INNOVATIVE LOCOMOTION CONCEPT

The Autonomous System Lab at EPFL developed an off-road rover called Shrimp [6], which shows good climbing abilities without any specific active control. This performance is due to the innovative mechanical design, which allows the use of a passive adaptation in rough terrain. The motivation of SOLERO is to take full advantage of this structure in order to develop a planetary exploration platform adapted to actual mission requirements for Mars.

Locomotion in rough terrain requires innovative locomotion principles. Various designs have been proposed using legs (walking machines) or other active means to climb over obstacles. However, these concepts are mechanically very complex and require sophisticated active control for locomotion. The "Shrimp" structure is much simpler, thanks to its passive mechanical design. It has one wheel mounted on a fork in the front, one wheel in the rear and two bogies on each side. The parallel architecture of the bogies and the spring suspended fork provide a high ground clearance while keeping all 6 motorized wheels in ground-contact at any time. This ensures excellent climbing capabilities over obstacles three times higher then the wheel diameter and an excellent adaptation to all sorts of terrains (Figure 1).

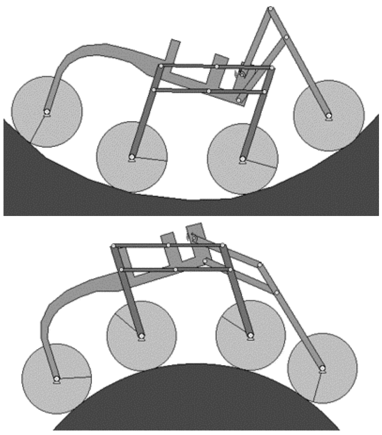

Figure 1 Suspension concept of the SHRIMP

The front fork has two functions: its spring suspension guarantees optimal ground contact of all wheels at any time and its particular parallel mechanism produces a passive elevation of the front wheel if an obstacle is encountered. As shown in Figure 2, the front wheel has an instantaneous centre of rotation situated under the wheel axis, which makes it possible to get on an obstacle [1].

The bogies provide the lateral stability. To ensure similarly good ground clearance and climbing capabilities, their virtual centre of rotation is set to the height of the wheel axis using the parallel configuration shown on Figure 2. The steering of the rover is realized by synchronizing the steering angle of the front and rear wheel and the speed difference of the bogie wheels. An irreversible steering mechanism will be used. This allows keeping the position of the front and back wheel without any additional power consumption, which results in minimal energy consumption for precise maneuvers and even turning on the spot with minimum slip.

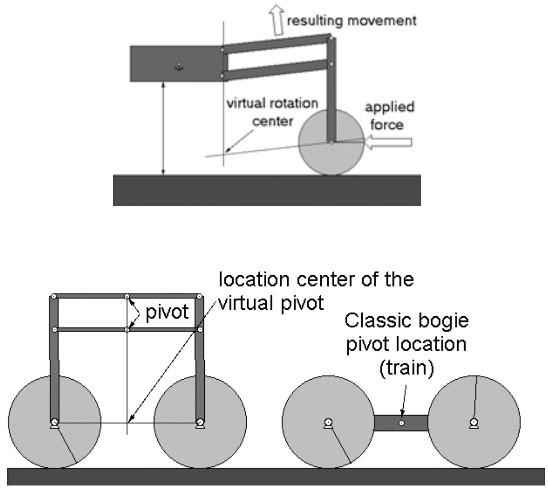


Figure 2 Concept of virtual rotation center for the front fork and the bogies

The first advantage of the Shrimp structure is the all terrain locomotion capability. This allows moving in harsh Martian environments, such as mountains or river valleys, which are not reachable with actual planetary rovers and landers. The second advantage is that, except for the wheel motors, no additional actuators or complex control is required for locomotion. This leads to the overall reduction of power consumption and mass, as compared to active locomotion systems.

## PRESENTATION OF THE FLIGHT MODEL CONCEPT

When defining a complete rover system flight concept, a variety of system elements must be considered, defined and adjusted in an iterative and heuristic process. For SOLERO, the most driving aspects for the system design have been:

Rover operation and control: the Rover must be able to carry out operations autonomously for a duration of at least one day. This implies the capability to autonomously solve the problems of rover localization, path planning, and trajectory execution.

Power provision, storage and control: the system was supposed to work without or with only a minimum of electrical storage. As a consequence the diurnal power profile is driving the operational capabilities of the

rover, i.e. driving, payload operation, tele-communication sessions, hibernation.
Further subsystems need of course to be assessed for the complete system concept; they however do not have a strong driving influence on the design process.

**Payload instruments**

As model payload, a set of three instruments has been selected like in the NANOKHOD Micro-rover:

| | |
|---|---|
| APXS<br>Alpha Proton X-ray Spectrometer | Ø52 x 90 [mm]<br>weight: ca. 400 [g] |
| MIMOS II<br>Mößbauer-Spectrometer | 90 x 40 x 50 [mm]<br>weight: ca. 400 [g] |
| MIROCAM<br>miniaturized camera | 20 x 40 x 40 [mm]<br>weight: ca. 200 [g] |
| **Total Mass:** | **1.25 [kg]** |

Table 1 SOLERO Model Payload

**SOLERO Flight Concept**

| | |
|---|---|
| Overall Dimension<br>Launch configuration | ca. 880 x 600 x 400 [mm]<br>ca. 860 x 600 x 300 [mm] |
| Total Mass | 10 [kg] |
| Solar Power | 16W worst case daily peak power |
| Mean Power | 8W for locomotion |
| Navigation | Autonomous Navigation up to 1km distance by 3D obstacle recognition and negotiation |
| Telemetry | Close to the Beagle 2 design |
| Locomotion Speed: | 0.02m/s, 220m in 4 hours |

Table 2 Key data of the SOLERO Flight Concept

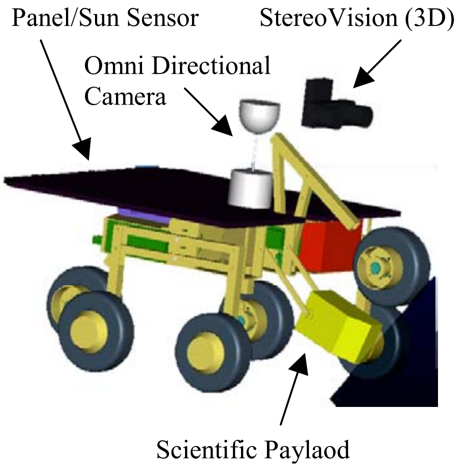


Figure 3 SOLERO conceptional flight model

**MISSION PHASES FOR SOLERO**

The planned mission for SOLERO on Mars can be decomposed in three phases:

- A travel phase, to reach an area of interest with a maximal range of 1 km. This will be ensured by the autonomous navigation system, which is currently being developed at EPFL.
- Secondly, a more precise approaching phase, in which the Rover will move to a specific target with a minimal accuracy of ±10cm.
- Finally, in the scientific instrument operation phase motion is performed by the two degrees of freedom payload cab to position the scientific instruments to a sample surface and the instruments are operated.

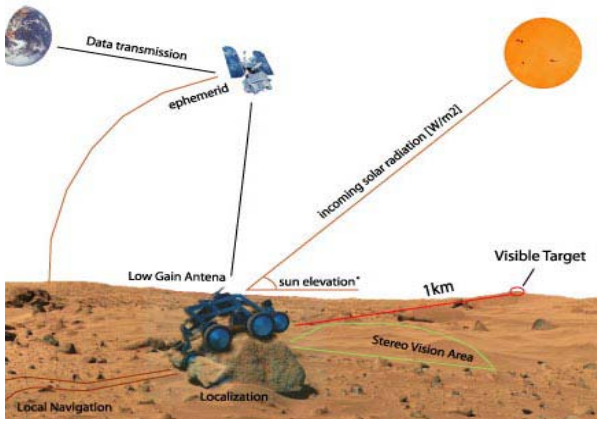


Figure 4 Overview of the control strategy on Mars

**ELECTRICAL POWER GENERATION**

The power management is determined by the limited availability of electrical energy provided by the solar array. The electrical power will be generated by a solar array with a total area of 0.3m². The power output of this solar array is expected to deliver a minimum of 15W daily peak power for a latitude of +20 degrees during Martian spring and summer seasons. With this power budget the power distribution over a typical Martian day can be calculated as shown in Figure 5. This calculation is based on an estimated total efficiency of 15% for the solar array and dust deposition of the solar panel after 100 days.

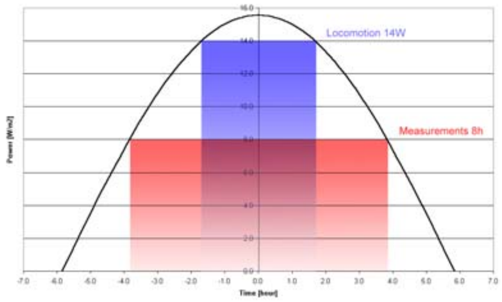


Figure 5 Power distribution for a typical Martian day

The SOLERO can move on rough terrain during the four hours around noon with a positive energy balance or perform the scientific measurement during about 8 hours per day.

## ELECTRIC POWER NEED

| | Earth [W] | Mars [W] |
|---|---|---|
| Flat hard terrain | 3.5 | 3.5 |
| Flat sandy terrain | 12 | <8 |
| Mean Slope<15° | 32 | <15 |
| Peak power | 55 | ~30 |

Table 3 SOLERO locomotion power estimation

The power demand of the SOLERO flight concept on the Martian surface has been estimated, and the results are illustrated in Table 3. The estimation is based on typical power data of the SOLERO breadboard model on earth, from which the values for Mars are derived. The difference between Earth and Mars is of two types:

First, the Earth values are the results from SOLERO Breadboard with over dimensioned motors (to support the breadboard mass of 13 kg).

Secondly, the gravity changes the required power values to move on rough terrain and slopes in a non-linear way. The Martian power estimation is given with the help of the SOLERO simulator. However, this simulator doesn't take into account the ground type, thus further investigations have to be done to confirm these values.

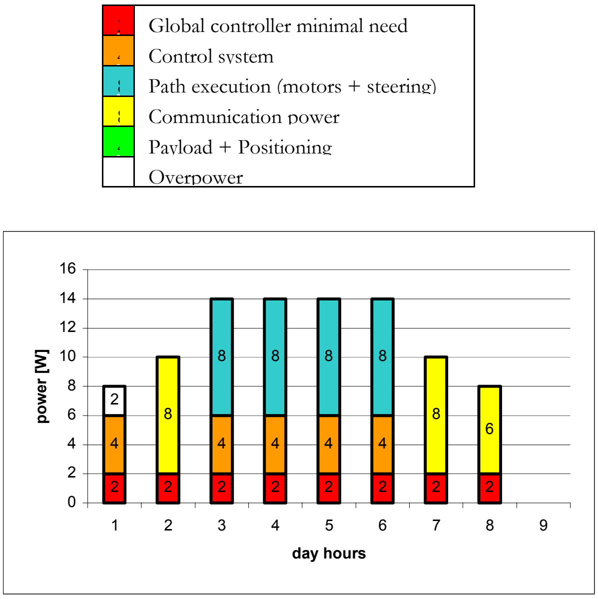


Figure 6 Typical daily power management

In conclusion, the dimensioning of the solar panel does not cover peak power demands as they occur for the period of climbing over hard obstacles, for slopes over 15° and during data transfer phases. Additionally the sun angle of the solar panel can change dramatically during climbing maneuvers, so that the power generated by the solar panel can momentarily break down. This means, that an energy storage is needed to cover peak power demands as well as power breakdowns.

## ENERGY SYSTEM DESIGN FOR FLIGHT CONCEPT

| | |
|---|---|
| Solar cells | 0.3 [m²]<br>300 [g] |
| Peak power output | 15W min., 20W type. |
| Cell type | 10LiTHI-ETA®3 (cell type of ROSETTA spacecraft) from RWE Solar GmbH / Germany |
| Li-ion Energy storage | 76 x 52 x 26 [mm]<br>mass 222 [g]<br>capacity 97 [kJ] |

Table 4 Energy system design

The cells for the solar panel have to be carefully selected for the harsh Martian environmental conditions. These are in particular the very low

temperatures (down to –100°C) and the spectral density of the sunlight on Martian surface. Considering this, low bandgap cells with LILT capability (Low Intensity, Low Temperature) offer the best solution.
The energy storage with the best mass/capacity ratio is the lithium ion accumulator. A good alternative is the super-capacitor, though its mass/capacity ratio is much worse, but it convinces by its excellent reliability and handling simplicity. Both technologies have their lowest (non operating) temperature limit at –40°C, under which an irreversible process will destroy the storage cells.

## SOLERO BREADBOARD DESIGN

An important directive within the SOLERO activity was the design and production of two breadboard models. SOLERO-B was specified to be representative for a prospective flight concept system with respect to size, locomotion capabilities and power provision. The second, SOLERO-N, was specified to be representative with respect to localization, navigation and autonomy capabilities.



Figure 7 SOLERO-B Breadboard

### Climbing abilities

A very flexible breadboard model could be delivered. It has a high functionality and excellent climbing abilities with its passive locomotion design.

<u>Maximal slope:</u>

Sandy terrain : 15°
Hard terrain like a rock : 30°
Stony terrain : 30°
Artificial ground : 35°

<u>Obstacles:</u>

Stone height for the fork : 215 mm
Stone height for the bogies: 280 mm
Stone edge : 90°
Stone height if edge > 90° : 75 mm
Hole depth (90°) : 400 mm

**Energy balance:**

With the field test data, it's possible to characterize the energy balance as follow:

$$Power_{OUT} = 12 + 0.23 \cdot Angle[°] + 1.33 \cdot Slope[°]$$
$$Power_{IN} = -30 \cdot \cos(Slope) \cdot \cos(Pitch)$$

With speed = 0.05 m/s in sandy terrain at 25[°C].

| **General specifications** | | **Unit** |
|---|---|---|
| Overall dimension<br>steering angle 90° | 876 x 605 x 390<br>821 x 605 x 390 | mm |
| Wheel size | Ø150 x 93 | mm |
| Ground Clearance | 215.5 | mm |
| Overcoming abilities | 230 | mm |
| Steering radius | 0 | mm |
| Lateral stability | >45 | ° |
| Max. speed | 0.5 | m/s |
| Motorization | 6 DC motors 12V gearing 128: 1 | |
| Steering | 2 DC motor 12V | |
| Batteries NiMH | 12 V / 3Ah | V Ah |
| Solar Panel | 30 | W |
| Electronic | 2.5 | W |
| Maximal motor power back wheel | 12V x 2 A<br>12V x 2.5 A | W |
| Power consumption | 5 to 55 | W |
| Structure total | 10500 | g |
| Solar Panel | 850 | g |
| Electronic total | 715 | g |
| Batteries | 615 | g |
| Total | 12.70 | kg |
| Payload | 1250 | g |

Table 5 SOLERO breadboard specifiaction

The SOLERO breadboard was able to accomplish all rover specific design goals like locomotion speed, payload accommodation, mass and power autonomy with a very simple low cost design. Considerable improvements concerning power efficiency, mass, climbing capability can be expected with intensified investments.

## NAVIGATION SYSTEM STATE OF THE ART AND FUTURE WORK

Keeping track of position is one of the most important tasks for an autonomous mobile robot. The estimation of the six degrees of freedom is critical when operating in an unknown and rough environment such as a foreign planetary surface. A lot of research on ego-motion using different kinds of sensors has been done. A computation of displacements by tracking pixels from one image frame to another and considering the corresponding 3D point-sets produced by stereovision camera can be found in [7] and [8]. An extension of shape-from-motion to omni directional cameras is presented in [9], to produce robust motion estimates. The fusion of both inertial and visual cues can improve the motion estimation [10][11].

The autonomous system lab (EPFL) is currently investigating methods for long-range position tracking in rough terrain. To fulfil this goal a probabilistic multi-sensor fusion using redundant information coming from different types of sensors will be used.

## CONCLUSION

SOLERO's innovative combination of wheeled locomotion and passive adaptation structure helps to reduce power consumption. This structure offers better efficiency compared to active designs such as legged rovers, while at least providing equal climbing abilities. This allows using exclusively solar cells for the rover operation and locomotion in flat terrain. Though, limited power storage capacities will be used in specific cases like a shadow motion operation, transmission and hard obstacle climbing.

The integrated solar power generation restricts the operation time and power to specific daytime. The electrical power provided by a solar panel of $0.3m^2$ is over 14 W on Mars, during the four hours around noon and the 1kg scientific payload needs less than 8W power and can be used during a maximal time of eight hours during daylight.

The reduction of power consumption for locomotion enables this rover to be small, light and operational during more then 100 Martian days. The total mass is near 10kg and its locomotion performance, in comparison with current rover designs, advances SOLERO to a perfect candidate for long-range missions on near-sun planets.



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