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Conference Paper

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Publication date:
2002

Permanent link:
https://doi.org/10.3929/ethz-a-010090926

SOLERO: SOLAR-POWERED EXPLORATION ROVER

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ABSTRACT

A mobile robot is the most suited element to bring scientific instruments to a specific site in order to examine geology, mineralogy or exobiology on extraterrestrial planets. In contrast with the Mars Pathfinder mission, the actual need for mobility increases in terms of range and duration. In this respect, redesigning specific aspects of the past rover concepts, in particular the development of most suitable all terrain performances, autonomous navigation and a power management concept is appropriate. This paper presents some preliminary 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 has the objective to develop a system design for a regional exploration rover including breadboarding for demonstration of locomotion capabilities, payload accommodation, power provision, and control. In this paper we will focus on the locomotion and the energy management.

INTRODUCTION AND MOTIVATION

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 having a passive adaptation in rough terrain [4]. The motivation of SOLERO is to take full advantage of this structure in order to develop a planetary exploration platform adapted to actual mission requirement for Mars. To perform a Martian mission, not only the structure is important but also the navigation system as parts of an overall rover system. Particularly in rough terrain, navigation is a complex task, which requires the rover to be considered as a whole system. This task is currently investigated in the EPFL lab [5] but it is not the main purpose of this paper. We will focus on which contribution can have a "Shrimp" structure to reduce the complexity of the controller, the mass budget and the reduction of power consumption.

The first advantage of the Shrimp structure is the all terrain locomotion. This allows moving on Martian environment, like mountains, which are not reachable with actual rovers and landers. The second advantage is, except for the wheel motors, no additional actuators or complex control is required for locomotion. This leads to the global power consumption and total mass being lower than an active solution. This allows SOLERO to use mainly local energy sources to generate the electrical power for locomotion, communication and scientific operation, while operating on near sun planets. Energy storage is only needed for contingency situations.

Figure 1: Comparison between Pathfinder and the Shrimp structure

INNOVATIVE LOCOMOTION CONCEPT

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 [1]. 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 radius and an excellent adaptation to all sorts of terrains Fig 2.

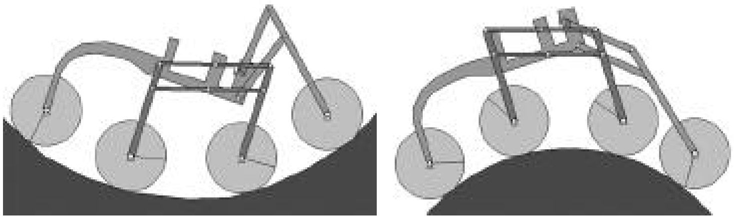


Figure 2: Suspension concept of the SHRIMP

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 Fig. 3, the front wheel has an instantaneous centre of rotation situated under the wheel axis, which makes it possible to get on an obstacle [1].

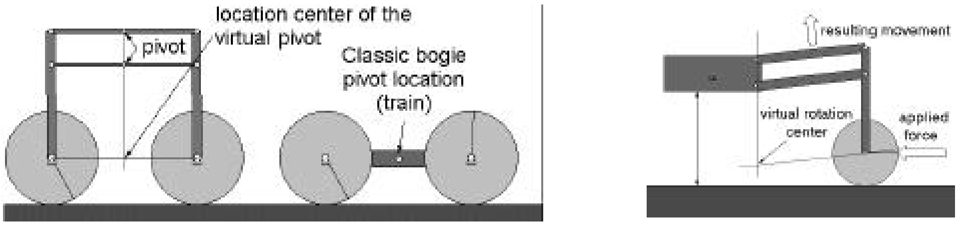


Figure 3: Concept of virtual rotation center for the front fork and the bogies

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 Fig. 3. The steering of the rover is realized by synchronizing the rotation of the front and rear wheel and the speed difference of the bogie wheels. An irreversible steering mechanism will be developed. This allows keeping the position of the front and back wheel without any additional power consumption, which permits minimal energy consumption for precise maneuvers and even turning on the spot with minimum slip.

STRUCTURE OPTIMIZATION PROCESS

The SOLERO mechanical structure is an optimization of the Shrimp-III prototype [4]. A homogeneous 1.4 scale factor was applied to Shrimp-III to have a structure with the desired size for payload and solar panel accommodation [2]. Using this new structure, we performed an optimization process with the help of a 2D physical model, validated with the real breadboard. This new structure was modelled in a 2D simulation program considering an Earth and Martian environment with a step obstacle. The structure was optimised, using a parameter variation process.

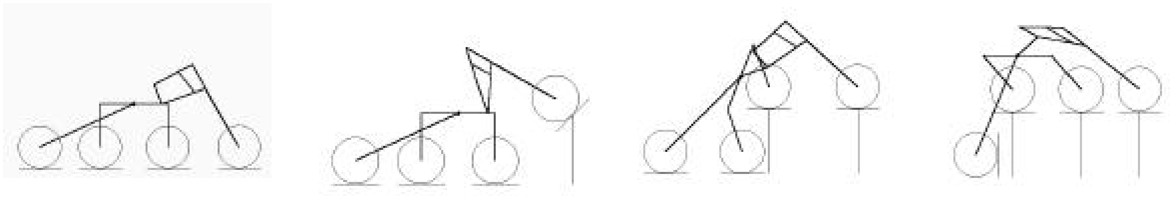


Figure 4: Movement decomposition for a step obstacle

The results outputs from the 2D model are the minimal friction coefficient m and the torques M of each wheel needed to move when the rover is on a determined position. Twelve key positions to get over a step were used to understand the influence of each internal parameter, e.g. the wheel radius, to the climbing abilities. These studies lead to an optimization process that minimized both m and M. This optimization of the structure was difficult to do because each parameter is linked to the others and all combinations can’t be tested. But, with some fine-tuning, the maximal needed torque for the SOLERO has been reduced from 2.2 Nm to 1.6 Nm for a step climbing. However, to move on a steep slope (>30°), the needed torque is 2 Nm and can’t be reduced by changing the geometry. The optimization must be done in parallel with other investigation like the motor controller and the spring design.

PRESENTATION OF THE FLIGHT MODEL

The SOLERO flight model doesn’t need any lander for communication. With a total mass of about 10 kg (6 kg for the structure) it can perform a scientific mission with its payload cab of 1kg. The envelope size is 730x600x390mm (without the camera mast) and the overall rover will stand in a 600x600x500mm box in a launch configuration.

MARS MISSION CONCEPT FOR A SOLERO FLIGHT MODEL

The planned mission for SOLERO on Mars can be decomposed in three phases: A travel phase (phase A), to reach an area of interest with a maximal range of 1 km. This is done with a dedicated autonomous navigation system, which is currently being developed at our lab. Secondly, a more precise approach, to move to a specific target with a minimal accuracy of ±10cm (phase B). The maximal range must be a couple of meters when the target is visible from actual rover position. Finally the scientific instrument operation phase (phase C) performs movements with two degrees of freedom of a 170x95x100mm payload cab (Fig 5).

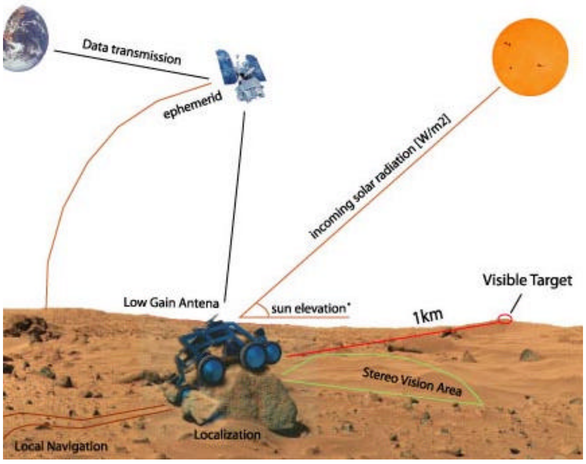


Figure 5: Overview of the control strategy on Mars

ELECTRIC POWER GENERATION

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 like the diagram showed in Figure 7. This calculation is based on an estimated total efficiency of 15% for the solar array.

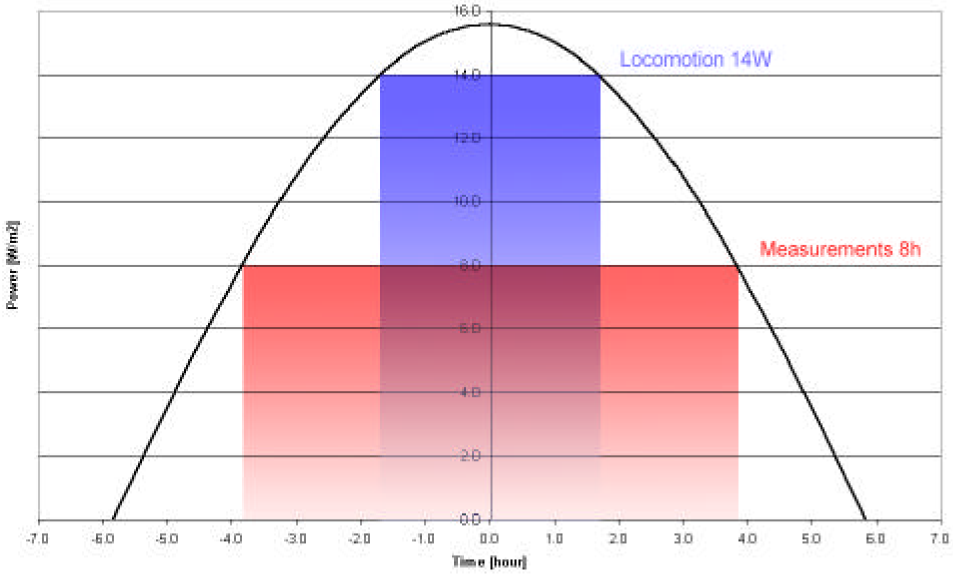


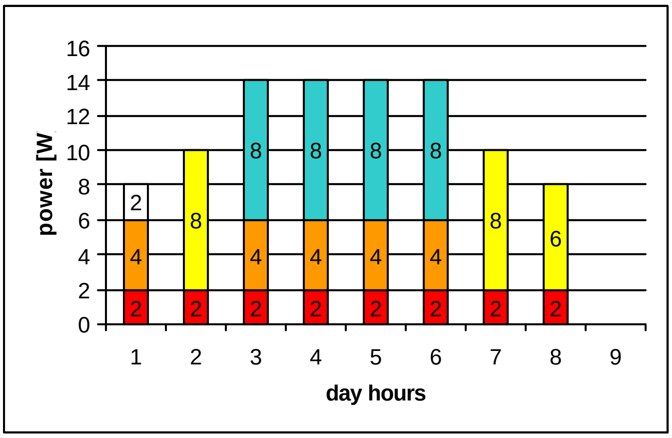
Figure 6: Solar array output power during a Martian day

A first candidate for the solar cell selection is the *10LiTHI-ETA® 3* cell developed for the ROSETTA mission by RWE Solar GmbH Germany [13]. This cell is especially developed for LILT (Low Intensity Low Temperature) applications, where high efficiency for low intensity and low temperatures is essential. This is also the case for Mars surface missions, where low temperatures have to be handled. A further feature of this cell type is, that its spectral response does prettily match the solar spectrum on the Martian surface, as well as the capability to convert even high diffuse light fractions to electrical energy.

POWER BUDGET AND MANAGEMENT

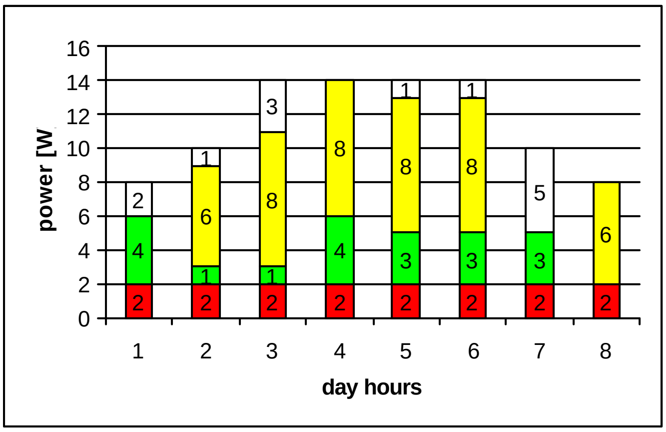
The daily power distribution determines the possible SOLERO Power Budget and Management for each of the three phases A,B and C:

	Power budget	**Mean [W]**	**Max [W]**	**Duration [time]**
🟥	Global controller minimal need	2	2	all daylight
🟧	Control system	4	4	4 hours/day
🟦	Path execution (motors + servos)	8	30	4 hours/day
🟨	Communication power	6-8	15	according to orbiter
🟩	Payload + Positioning	2.5-4	4	8 hours/day
⬜	Overpower	-	-	-



PHASE A & B

1 SOLERO self localization
2 Communication possibilities
3 Phase A or B
4 Phase A or B
5 Phase A or B
6 Phase A or B
7 Communication possibilities
8 Communication possibilities



PHASE C

1 Payload positioning
2 APXS and Communication
3 APXS and Communication
4 Payload positioning and communication possibilities
5 MIMOS II and Communication
6 MIMOS II and Communication
7 MIMOS II and MIROCAM
8 Communication possibilities

Figure 7: Power management for phase A,B and C without energy storage

ELECTRIC POWER STORAGE

The power demand for locomotion is illustrated more detailed in Table 1.

	Earth	**Mars**[1]	**Explication**
Normal condition	6W	6W	<10° slope, soft rotation
Hard condition	12W	8.5W	20° slope, hard rotation
Special case 1	15W-30s	9.5W	>20° slope
Special case 2	22W-10s	~12W	obstacle climbing
Special case 3	30W-5s	30W	obstacle climbing

Table 1: Solero locomotion power estimation

For special locomotion tasks, especially for obstacle climbing, the power demand can exceed the available solar power even when assuming the maximum power peak at Martian noon. Because these tasks are essential features of this rover concept, an exclusion of these tasks cannot be taken into account. To be able to overcome a lack of power for a short time period, an implementation of a power storage has entered into the design. The examination of various possibilities for power storage has finally lead to two preferred candidates: super-capacitor and lithium ion accumulator. The super-capacitor has an excellent cycle life and perfect handling conditions, but suffers from a low energy density. The lithium ion accumulator has contrary properties: low cycle life, difficult handling conditions, but excellent energy density. Most super-capacitors have –40°C as lowest operating and storage temperature, while most lithium ion accumulators need higher temperatures. A special design of the lithium ion technology is needed to extend the temperature range to –40°C, but tests showed, that this is possible. The poor cycle life of the lithium ion accumulator can be extended by nearly factor 10, when reducing the depth of discharge (DOD) from 100% to ca. 10% - 20%, but nevertheless, the cycle energy is still higher than the cycle energy of a super-capacitor of the same weight. The rest of 80% - 90% of the energy capacity is available for emergency situations.

As a conclusion, the first candidate for the energy storage will be the lithium ion accumulator with following properties:

- High energy density
- Low DOD of 10% - 20% for standard cycles
- DOD of 100% for emergency situations
- Special cell design needed for low temperature capability
- Difficult charging process

The exact behaviour has to be determined by extensive tests, which are needed for a final selection of the lithium ion technology. The super-capacitor will be the backup solution.

Regardless of the final selection between the two candidates, a strong thermal constraint has to be obeyed: the storage temperature of the energy storage must not fall below –40°C. So a careful thermal design is necessary. This will be obtained by a passive design.

STATE OF THE ART AND FUTURE WORK

Navigating autonomously in a rough and unknown environment is not a solved problem. Since many years researchers have been working in this field but a lot of effort has still to be done. Since SOLERO is able to tackle with very rough terrain the problem is even more complicated.

The most important task, which the robot must fulfil is to keep track of its own position: e.g. tasks like path planning need good position estimation in order to work well. For rough terrain this task is much harder and requires the

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[1] Locomotion energy can be decomposed in two parts: $F_{Frott} \cdot d + mgh$. The energy need for a flat terrain move is the same (normal condition), but slope and obstacles climbing (mgh) have a difference of a 0.38 factor (g_{Mars} / g_{Earth}).

estimation of six degrees of freedom. 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 points sets produced by stereovision can be found in [7] and [8]. An extension of shape-from-motion to omni directional cameras is presented in [9]. Because of the camera's wide field of view and lack of degenerate motions, this method is more likely to produce robust motion estimates. The fusion of both inertial and visual cues can improve the motion estimation [10][11].

The methods presented above generally assume small displacements and angular changes between two acquisitions (feature tracking) and therefore limit their application to smooth environments and/or slow speeds. In order to improve the robustness of the position tracking for SOLERO one has to fuse the data from different types of sensors, e.g. inertial, visual, lasers and wheel encoders. For this reason we will fuse the motion information provided by the IMU, the stereovision system, the omnicam, and the odometry (see Fig. 5). Until now, most of the applications integrate only two sensors e.g. inertial and standard vision, inertial and stereovision, or odometry and vision.

The energy consumption is a big issue for SOLERO. This aspect must be taken into account at every level of the system. Not only must the robot choose a secure path but also consider the energy need for its execution. So it is important to optimize the mechanical structure and the trajectory controller for the locomotion. The passive design of Shrimp allows the rover to move smoothly across the obstacles and therefore limits the energy needs. Furthermore, a good balance of the torques and speeds between the wheels is essential for optimizing the robot's motion [12]. This reduces the wheel slippage, the overall energy consumption and even increases the robot's climbing performances.

Some tests have already been carried out on the Shrimp-III at the ASL. Nevertheless, this platform doesn't allow to carry all the sensors we planned to use. Therefore, a SOLERO breadboard is currently manufactured to test the system in a Mars like surface-environment.

CONCLUSION

The Shrimp, this original combination of wheeled locomotion and passive adaptation helps to reduce power consumption. This structure offers better efficiency compared to active design such as legged rovers, whilst not suffering sensible reduction of climbing abilities. This allows to use exclusively solar cells for the rover operation and locomotion in flat terrain. However, 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 14W on Mars, during the four hours around noon. The 1kg scientific payload needs less that 8W power and can be used during a maximal time of eight hours during daylight. However, limited power storage capacities will be used in specific cases like a shadow motion operation, transmission and hard obstacle climbing.

The reduction of power consumption for locomotion allowed this rover to be small, light and operational during more then 100 sols (Martian days). The total mass is only 10kg and its locomotion performance, in comparison with actual rovers, leads SOLERO to become the perfect candidate for long-range missions on near-sun planets.

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