HOPPING ROBOT FOR PLANETARY EXPLORATION

Erick Dupuis, Steeve Montminy, Pierre Allard

Canadian Space Agency, Space Technologies
6767 route de l’Aéroport, St-Hubert (Qc), J3Y 8Y9, Canada
Email:firstname.lastname@space.gc.ca

ABSTRACT

The Canadian Space Agency is investigating technologies for lowering the cost of planetary exploration missions through miniaturization of landed platforms. One of the consequences of miniaturization is that traditional locomotion schemes such as wheels are not appropriate any more. To a small rover, even the very small obstacles become insurmountable. Alternate locomotion schemes must then be investigated to overcome this problem and enable miniaturized missions. Another consequence of miniaturization is that electric energy obtained through solar panels becomes very scarce.

In light of these constraints, a hopping robot for Mars exploration is being designed and prototyped. A mock-up of the robot was built in 2004 to demonstrate the feasibility of conducting useful science in such a small package. The peculiarity of the CSA design is that it uses diurnal temperature variations to accumulate the mechanical energy necessary for hopping. The hopping mechanism is based on a novel cylindrical scissor mechanism. This paper presents the results of a trade study on miniaturisation of Mars landers, introduces the main requirements to be met by such a system and describes the concept of operation of the hopping robot addressing some of the key issues with planetary landed missions of this size.

1 INTRODUCTION

The last decade has seen a revolution in the miniaturization of satellites for Low Earth Orbit (LEO) applications. The advent of small satellites and micro-satellites has changed drastically the cost models associated with space operations. The cost of micro-satellites in LEO has historically been orders of magnitude lower than that of traditional spacecraft. Organizations with modest budgets can now afford to develop and launch their own spacecraft.

A similar revolution in space exploration could have a dramatic impact on the affordability of exploration and on the kind of science that can be conducted on the surface of other planets. In addition, the availability of micro-spacecraft for planetary landed missions would open the door to the conduct of network science missions that require large geographic coverage and simultaneous measurements over large areas.

Finally, the low cost associated with such missions would allow redundant spacecrafts to be sent thus increasing the chances of success in two ways. First, this provides resilience through redundancy: each lander is going through a different Entry Descent and Landing (EDL) sequence. Second it increases the probability of scientific breakthrough by allowing the same set of instruments to examine different sites on the planet.

2 MINIATURISATION TRADE STUDY

A trade study was conducted to assess the benefits of conducting small landed Mars exploration missions. The trade-off has clearly demonstrated that there are advantages to miniaturizing landed planetary exploration missions. Data from past programs and current programs shows that the ratio of scientific instrument mass to entry mass increases dramatically as entry mass decreases.

Figure 1 and Figure 2 demonstrate that, based on past missions and on current designs, the EDL systems for Martian landers scale in a quasi-linear fashion over the full range from large missions such as the MER rovers to the small DeepSpace2 impactors. A linear regression was performed on the overall mission data set as well as on the reduced subset of missions under 120kg. In each case, a regression index superior to 0.93 was obtained (superior to 0.99 over the entire data set). The only exception to this linear progression is the Beagle2 lander, which was subject to failure upon Mars entry.
Figure 1 – Landed Mission Scalability

Figure 2 - Landed Mission Scalability (Light Class Missions)

Figure 3 clearly shows that lighter missions have historically carried a much larger proportion of their entry mass as scientific payload. This is explained that larger platforms have typically provided much more functionality than small platforms. For example, the MER rovers, although carrying a smaller mass fraction of scientific instruments, did provide mobility, which has proven critical to the success of their mission.
An exponential curve was fitted to the data and shows extremely good match with the data. The only two exceptions are Beagle2 and Mars Polar Lander, which were both extremely aggressive missions from a mass and cost perspective and which have both failed to survive EDL.

![Figure 3 - Ratio of Instrument Mass Versus Lander Mass](image)

This analysis indicates that there is merit to the application of the micro-satellite philosophy to landed planetary exploration missions. Without claiming that the linear and exponential regression will hold all the way to the end of the spectrum, there is ample evidence leading to the conclusion that the payload mass fraction is typically higher for lighter missions and that the analysis seems to scale over a large spectrum of lander entry mass.

3 MICRO-ROBOT REQUIREMENTS

In response to the conclusions of the miniaturisation study, the Canadian Space Agency is currently investigating the feasibility of building micro-landers of 1-2 kg to perform scientific measurements on the surface of Mars.

A set of requirements has been developed for such platforms in cooperation with selected members of the planetary science community. The main set of requirements imposed on the platform is that it should be capable of transporting a scientific payload on the surface of Mars. The micro-lander is expected to receive commands and transfer its telemetry through an orbital relay of the same class as the current family of Mars orbiters (e.g. Odyssey, Mars Express).

The total landed mass should not exceed 2 kg and an allocation of 250g is made for the science payload. Examples of instruments to be carried by such platforms include a microscopic imager, a panoramic imager, a meteorological sensor suite and magnetic field sensors. The micro-landed platform is expected to provide continuous operation for a period of 150 sols with a design goal of one Martian year (668 sols).

Several challenges must be overcome to enable such missions to be successful. One of the most important challenges to be faced by such a mission is its survival to large swings in the Martian thermal environment. The diurnal temperature cycle on Mars can range between –125 Celsius at its coldest and +25 Celsius at the hottest time of the day. Given the small size of lander being considered, active thermal control is almost impossible. The lander must therefore be able to survive such temperature variations.

Another important challenge for micro-landed platforms is the scarcity of electric power. For simplicity reasons, it is preferable to rely on photovoltaic arrays for electric energy generation. However, the solar panels on such platforms are, by necessity, small and provide very low levels of power and energy. A large portion of the electric energy is required for communications to send scientific data back to a relay station (possibly in orbit). For
robustness, it is therefore preferable to avoid any dependence on electric power for functions related to survival such as thermal control, environmental protection and mobility away from permanently shadowed regions.

Finally, the last challenge on such a scale is mobility. To a robot whose size is on the order of a decimetre, almost every pebble is an insurmountable obstacle. One potential solution to mobility at such a scale is hopping. Hopping as a mobility scheme for planetary exploration is not novel. Such concepts were proposed as far back as the late 1960’s [3][4]. Recently, hopping has been investigated for Mars exploration [1][2] and for the exploration of asteroids [5].

The purpose of introducing mobility on such platforms is to increase the diversity of the scientific data. In particular, the microscopic images obtained while looking under the robot’s footprint. The robot is not expected to be capable of jumping accurately to a given target destination. The requirements imposed on the hopping mechanism are that each jump should be at least 0.75 meter high to be able to clear most obstacles on the surface. The robot should be capable to travelling the equivalent of 3 meters per sol with at most one hop per day. The heading accuracy should be on the order of 45 degrees.

4 CONCEPTUAL DESIGN

To maintain the priority on low cost borrowed from the micro-satellite philosophy, the main assumption underlying the design and operations concept of the micro-hopping robot is simplicity. Therefore, trade-offs performed in the design of the platform generally favour simplicity over performance.

The geometry of the micro-hopping robot is based on a regular tetrahedron. This geometric configuration has been selected because the hopping robot can land in any orientation at the end of a jump. A regular tetrahedron provides robustness to recover from landing on any of its faces. Three of the faces are petals that open to roll the robot to its vertical configuration. The interior of the petals is covered with photovoltaic cells to provide. The fourth face is used to locate the hopping mechanism that will provide locomotion. Such a configuration has been proven on the Pathfinder and Mars Exploration Rover missions to provide the ability of the lander to right itself up after the completion of the landing sequence. Figure 4 shows the hopping robot in its open configuration after the opening of the petals.

![Figure 4 - Micro-Hopping Robot in Open Configuration](image)

To enhance robustness, it was decided to avoid dependence on electric power for the opening/closing of the petals and for the locomotion. A Shape-Memory Alloy mechanism is therefore used to drive the petals and to charge a mechanical accumulator storing the energy for jumping.

A typical day of surface operations therefore starts with the hopping robot righting itself up as the petals open under the influence of the warming temperature (see Figure 5). At the same time, the shape-memory alloy drive cranks the spring that will be used to deliver the impulse for the robot to jump. As the petals open, the solar cells get exposed to the sun and start loading an accumulator.

![Figure 5 - Hopping Robot Righting Sequence](image)
As the electric power increases, the robot electronics powers up and starts taking sciences measurements of the surroundings. These could include a panoramic view of the landing area, microscopic imaging of the ground underneath the lander in both visible and UV light, and atmospheric temperature. The data acquired from the scientific instruments is stored in a non-volatile memory for eventual uplink to an orbital asset. The robot has the capability to store data for a few sols of operation while waiting for a communication window, which is appropriately synchronized with the robot’s power cycle.

As the Martian day draws to a close, the petals close, and the electronics shuts down. If the hopping mechanism has accumulated enough energy for a jump, the closing of the petals triggers the release of the impulse delivery mechanism. The robot executes a jump of a few meters in length and crash-lands back on the ground, protected by its closed petals. The next morning, as the petals open, the lander is automatically righted up and the cycle starts again.

5 PROTOTYPE DESCRIPTION

Several prototypes and mock-ups are currently under fabrication to validate the feasibility of the concepts being put forward by this design. A mock-up with functional electronics has already been fabricated to demonstrate the feasibility of packaging useful scientific payloads in such a small volume and mass allocation. (See Figure 6).

Figure 6 - Mock-up of the Micro-Hopping Robot

The sides of the mock-up are approximately 15 cm in length. It contains a Commercial-Off-The-Shelf MOTE processor and RF transmitter from Crossbow (See Figure 7). This electronics package allows the mock-up to receive commands from/send telemetry to a base computer located several meters away from it. This mock-up contains a sensor suite composed of a temperature sensor, a 2-axis accelerometer, a 2-axis magnetometer, a light sensor, a microscopic imager with controlled illumination and a panoramic imager.

Figure 7 - Crossbow MOTE Electronics

Figure 8 and Figure 9 show images obtained from the microscopic imager under white light and ultraviolet lighting conditions.

Figure 8 - Microscopic Image Obtained under White Lighting

Figure 9 - Microscopic Image Obtained under UV Light
Two generations of the impulse delivery mechanism have been produced so far to verify clearances and ensure proper deployment. The mechanism is based on a cylindrical scissor design as shown in Figure 10. The main advantages of this mechanism are that it folds into a compact disk in its closed configuration, it is suitable for the incorporation of a compact torsional spring for energy accumulation and winding mechanism. Furthermore, the scissor configuration provides more mechanical advantage to the spring at the end of the deployment, which is compatible with an optimal impulse-delivery for hopping. [1]

Figure 10 - Cylindrical Scissor Mechanism

Two more prototypes are currently under design. The first will contain all mechanical functions associated with the hopping mechanism: petal deployment, spring winding, steering and impulse delivery. This mechanism will be tested in the CSA’s Mars emulation terrain to verify the performance of the mechanism on a natural surface. The performance of the mechanism under Martian gravity can simply be extrapolated by multiplying by the ratio of Earth’s and Martian gravity. Tests have already been started to evaluate the work performed by shape-memory alloys under variations in temperature.

The second prototype will be used to verify the feasibility of building representative electronics using parts that are qualified for survival to extreme cold (down to -125 Celsius). The subsystems to be prototyped include the power subsystem and a representative communication subsystem capable of relaying telemetry at power levels equivalent to those expected on Mars.

7 CONCLUSION

This paper presented a concept for a micro-robotic landed Mars mission based on the same premises as the micro-satellite philosophy. A trade study was performed using the data from all landed Mars missions since Russia’s Mars96. The trade study indicates that generally, smaller missions have carried a larger portion of their mass as payload.

In response to this study, the CSA has been conducting R&D to develop technologies for 1-2 kg class micro robotic landers. The main challenges to be faced by such small systems include thermal regulation/cold survival, scarcity of electric power and mobility.

The proposed concept to address the requirements imposed on such a mission is a hopping robot using diurnal temperature variations and shape-memory alloys to provide the energy required for mobility.

Prototypes have been developed to demonstrate the viability of packaging scientifically useful payloads in such small mass and volume allocations and to investigate the feasibility of developing the impulse delivery mechanism. Additional prototypes are currently under development to validate the complete hopping mechanism and to investigate the feasibility of designing key electronic sub-systems using components rated for extreme cold survival.

7 REFERENCES