SAMPLE FETCHING ROVER - LIGHTWEIGHT ROVER CONCEPTS FOR MARS SAMPLE RETURN

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ABSTRACT

As ESA and NASA are planning the Mars Sample Return (MSR) Programme, the 2018 ExoMars-MAX-C mission is being considered as the sample acquisition element in the overall MSR architecture. The MSR mission therefore requires a lightweight mobile platform dedicated to the collection of the sample cache, before returning it safely to the Mars Ascent Vehicle. Such a Sample Fetching Rover (SFR) concept is unlike any other past and current rover missions as it must traverse 15km over a 180-sols mission to retrieve a sample cache deposited by a previous mission and return it to the mars ascent vehicle. In addition, the mass allocation for the rover is currently aiming at a target of 60kg.

This paper presents the challenges involved in the design and operation of the rover element, and especially the impact at system level of a lightweight design solution.

1. INTRODUCTION

As part of the Mars Sample Return programme, the Sample Fetching Rover mission will be significantly different to other past and current rover missions due to the inherent challenging requirements called for by the mission:

- The rover must traverse 15km over the course of a 180-sol nominal mission (~120 soks actual traverse), leading to a challenging minimum average rover speed of 120m/sol across a variety of terrains while locating, navigating to, and retrieving the sample cache.
- The platform must be as light as practicable with a target of 60kg – (a fifth of the ExoMars rover ~300kg)
- Its primary objective is to retrieve a sample cache.

This paper is based on an ESA funded study that started in late 2010 and is due to complete with a preliminary rover design in Sept 2011. It addresses the unique challenges of the SFR concept, and therefore requires a thorough investigation of rover technologies, maximising the heritage developed for ExoMars [1], the MoonNEXT lightweight rover study [2], while looking beyond at innovative solutions.

2. THE MSR ARCHITECTURE

The goal of the MSR campaign is to return a number of samples of Martian soils to Earth to be analysed in minute detail. The MSR mission concept has received significant interest from the international community for the past decade and its architecture has seen a number of evolutions since its initial conception. The latest (2010) plans as drafted by ESA/NASA currently assume the following three missions:

- **2018** – A joint ESA/NASA Mars Exploration Mission, delivering MAX-C and ExoMars to the surface of Mars. MAX-C will prepare a cache - nominally 0.8 kg (max 1.2kg), diameter 75 mm (max 95mm), height 75 mm - to be retrieved and delivered to the Mars Ascent Vehicle (MAV) by a single-purpose fetching rover.
- **2022** – MSR Orbiter mission. Orbiter to act as a telecommunications relay, provide critical event coverage during the MAV Lander descent and ascent and also capture the orbiting sample and return it to Earth.
- **2024** – MSR Lander Mission. Consists of the single-purpose fetching rover and the MAV.

![Figure 1- NASA MSR lander preliminary concept](image)
MSR Lander and would carry the SFR. The rover would therefore egress from MPL, travel to the cache, acquire the cache from the Martian surface and then deliver it to the MAV itself. The MSR Lander and MPL are assumed to be delivered in September 2025. The MAV launch and orbital sample capture six months later is maintained regardless of whether SFR is deployed alongside the MAV or landed separately with MPL.

3. ROVER OPERATIONAL SCENARIO

The nominal surface mission is limited to 180 sols, including post landing checkout, egress, rover commissioning. Over the course of the mission, additional time allocations must be considered to identify the sample cache location, approach and pick it up. Finally the return operations to the MAV must be factored in.

The total time available for the 15km traverse is therefore a maximum of 125 sols. This includes an operational contingency allocation of 25 sols to factor in effects such as adverse weather conditions (i.e. dust storm), reduced power generation/mobility (dust, sand trap), but also the operational impact of evolving from a cautious direct-drive mode in the first days onto a more autonomous drive. The resulting rover speed has therefore to achieve a minimum of 120m/sol.

It is worth noting that the NASA SFR mission baseline foresees to fulfil the cache return operations within 3 months or 90 sol. This would lead to a speed of about 166m/sol. Considering the current assumption of a landing approximately 3 months before the global dust season, maximising the traverse speed would be beneficial for the overall mission concept as high optical depth would impair the mobility of the platform and its return to the MAV, affecting the timeline of the overall MSR mission.

4. ROVER SYSTEM DESIGN DRIVERS

Considering that most past rovers have only covered a fraction of this distance in the same amount of time (MER covered ~15km in ~7 years), this will drastically drive the design of the platform and its mobility system. Mobility is used here as a consolidated term for the locomotion system in addition to the GNC system to emphasise and recognise the interleaved nature of these two systems. I.e. a more capable locomotion system will traverse over larger rocks, decreasing the need to avoid them and therefore decreasing the complexity of the GNC system. In addition, the environmental conditions will play an important part in the design such as the season and optical depth (OD), surface and terrain condition and temperature.

In the frame of this particular mission, these requirements and constraints amount to 3 main operational factors that will affect the design of the rover (as shown below in Figure 2), namely:

- Factors relating to path length – that will drive the distance the Rover has to travel to reach the target e.g. Path planning performance, knowledge accuracy, locomotion system gradeability and obstacle negotiation…
- Factors relating to speed along the path – that will dictate the average speed of the Rover while travelling to the target e.g. slippage, navigation processing time, distances between stops…
- Factors relating to the time available – that will determine the time available to the Rover to reach the target e.g. available energy, system overheating, obstacle abundance…

![Figure 2 - SFR Design Driver, Dependencies, and Ultimate Impact on Mass](image_url)
These factors will then directly or indirectly drive the design of the mobility and power subsystems, the primary contributor to the overall rover mass which will in turn affect the design of the other systems on the rover. If the locomotion system is made more robust and capable to relieve the GNC system, the overall system will suffer from a mass penalty. Alternatively, if mass is critical, a smaller locomotion system with a highly capable GNC system could be made to offload the complexity to software, a “mass-free” system by definition (but by no mean risk-free either). A successful design will target the right balance between these two systems as part of the design of the overall rover platform.

Finally, the time available to reach the target is dependent upon the available energy and power, and is intimately linked to a number of environmental factors, subsystem design and operation. The landing in September 2025 at Ls133 only provides about ~40sols before the global dust season. The increase in the atmosphere optical depth will drastically affect the power generation of the rover and its ability to achieve its daily target distance.

5. DESIGN PHILOSOPHIES FOR A LIGHTWEIGHT ROVER

As shown in the following Figure 3, the mass distribution of a typical rover is concentrated on the locomotion, power system and structure. In the first instance, it is therefore of benefit to target these three areas to minimise the overall rover mass.

5.1. Stripped-out

This approach removes any mass that is not essential for the achievement of the major goals of the mission. To this end, the identification of the rover’s key goals is critical. Each element of the rover is then pared down to its minimum required functionality/performance whilst still ensuring that the original mission goals are maintained with sufficient risk mitigation. As a result, sub-system functionality must be distinguished from sub-system redundancy i.e. sub-systems can be descope and performance traded to achieve a lower mass solution, but component redundancy must be maintained.

5.2. Ready-to-go-approach

This approach seeks to remove any deployments or mechanisms that are not essential. As such, the design would implement fixed solar arrays, fixed mast, no wheel deployment and so on. This approach removes rover complexity and reduces risk during the commissioning phase. The gain from removing mechanisms must be carefully traded against the impact on performance and the reciprocal effects on the system design. For example, a rover with a fixed solar panel may have a smaller total array size due to the constraints imposed by the lander. The shortcoming in energy available will lead to the system travelling shorter distances each day as the rover is unable to support a longer drive. Furthermore, there is a danger that the risk and complexity associated with the egress is transferred to the lander resulting in a sub-optimal rover-lander configuration.

5.3. Locomotion System Optimisation

The design is driven by the optimisation of the locomotion system to ensure that mobility is central to the rover design and performance. To achieve the low mass and long transverse requirement set for SFR, the rover may use an evolution of the current technologies used on ExoMars or a novel configuration (with an associated risk and development cost).

5.4. 24/7 Drive

A perpetual power supply allows locomotion at any time during the Martian day and potentially night (with the necessary illumination). This is achieved with a power system that is not constrained by the availability of solar flux as seen in all the rovers relying on solar panels. To satisfy the perpetual power supply a Radioisotope Heater Unit (RHU)-powered Stirling Cycle Generator could be used. A RHU would provide a constant source of power and allow the SFR to traverse with a high duty cycle. The use of a Radioisotope Thermoelectric Generator (RTG) would lead to a more
compact rover, free from the constant trade of energy between the solar array and battery. Unfortunately, the low energy density of the foreseen RTG options based on Americium would lead to rather large RTG solutions for such a small rover. The 24/7 design approach is therefore not considered further for this particular design.

5.5. Day Rover Approach

The Day rover approach relies on a paradigm opposite to the 24/7 method where solar panels alone are used. In its simplest form, no battery is used to save mass. As a result there are no night-time operations and the rover has to rely on the solar array to provide power. The solar flux availability defines the period of operation of the system. The major savings are derived from the lack of battery and the need to support the battery during the night. Without a battery, the body can be made smaller and potentially not as thermally controlled and with less harnessing. The lack of a battery however limits the operation of the rover to day-time impacting performance if communication windows can only be established during the night-time.

5.6. Cold Skeleton

This approach aims at minimising the structure and the mass necessary to accommodate the equipment. In its simplest form, the rover body is replaced by a bare frame chassis onto which are mounted all the sub-systems. Equipment must survive the harsh Mars thermal environment without the protection of a rover body. This approach therefore calls for the development of low-temperature electronics and mechanisms or will require localised small enclosure and heating (e.g. battery). However, the structural mass of a “bathtub” configuration as used for ExoMars provides a good stiffness and strength for a relatively low mass. A careful trade would therefore be required. Evolving this approach, the use of lower temperature systems would already relax the complexity of the thermal design (simpler and lower mass) or simplify the operation of the rover (e.g. remove the need of a power hungry locomotion system warm up at dawn).

5.7. SFR Implementation

Although a number of design approaches are available, the SFR Mission Requirements provide a number of constraints that limits the scope of the trade-space. As such, photovoltaic systems are prescribed for SFR as well as the support for night-time communication. As a result, the 24/7 drive approach, which relies on a constant power source such as an RTG and the day rover approach, which doesn’t support energy storage (and hence night-time communications) cannot be used here. Instead, the design focus must be placed on implementing the remaining strategies and incorporating the design philosophies into sub-system design. In addition, the strategies presented here are not mutually exclusive and may be combined to deliver the most efficient design. As such, a rover design may implement a ready-to-go approach by removing deployment mechanisms in addition to implementing a cold skeleton approaching by implementing cold electronics and minimising the chassis size.

6. SFR MOBILITY SYSTEM

The rover mobility system will be critical to the success of the SFR mission. As a cache acquisition rover, the performance of the mobility will heavily draw upon both the locomotion system and the GNC capabilities while providing design and operational options so far unavailable to past and current rovers.

6.1. Operational and Functional requirements

The SFR rover must cover a minimum of 15km in 125sols. The terrain is anticipated to be more benign than that of ExoMars. However, due to the importance of getting the cache from the Max-C rover, it will be necessary to investigate the capability of the SFR rover in the same environment as Max-C and Exomars in case Max-C cannot find a suitable location to drop the cache. As such, the SFR locomotion system must be able to negotiate slope of at least 20deg and obstacles of at least 15cm. In addition as the main driver for the sizing of the power system, it should be sized to be compatible with the power that the rover can generate as it operates in favourable illumination conditions (e.g. 10.00 to 14.00 LST) with an optical depth of 1. Similarly, the GNC and any vision-based system must be capable to reliably cope with such optical depths.

6.2. Design drivers

The selection of the rover locomotion and suspension system is the major driver for the rest of the rover such as sub-systems accommodation or power requirements and generation. The current mission requirements target specifically wheeled locomotion systems. As discussed in section 4, the locomotion system is critical to achieve the key mission requirements in terms of traverse distance in the allocated time. In addition, the terrain topography and physical properties play a critical role in the design and performance of the locomotion system:

- The soil properties will affects the rover slope gradeability, power requirements, grousers size, number of wheels.
- The size of the rocks and boulders will influence the design of the suspension system, the wheel size, and power requirements.
• The distribution of these rocks and the size of the rover will dictate the mean free path of the rover that will influence to an extent some of its navigation requirements.

• Finally, the slope will dictate the minimum gradeability of the locomotion system, the static stability of the rover and its power requirements.

6.3. Locomotion System Options

Before performing detailed performance analysis of a selected few concepts, some 20 locomotion concepts have been investigated covering a wide spectrum of 4, 5 and 6 wheels configurations. These were preliminary down-selected based on a number of first order criteria such as mass, number of actuated joint, TRL, level of redundancy, mechanical simplicity, stowage and deployment volume required, static stability or internal volume. The down-selected options included three 6-wheels and three 4-wheel concepts as presented in the following Table 1:

• The 6-wheel concepts include the NASA rocker-bogie, and two versions of the ExoMars 3-bogies concept.

• The 4-wheel configurations comprise two concepts based on 2 bogies and a differential, either geared or by means of a mechanical link. Alternatively an Extra-Large Width/Wheel (XLW) concept is introduced with a single transverse rear bogie, rigidly mounted front struts and larger wheels (400mm) to investigate the possibility of providing a large footprint (~1.8m x 1.8m).

In addition, a number of wheel concepts were investigated from the flexible ExoMars wheel to the rigid Lunokhod mesh-spokes wheel (as shown Figure 4). In term of mass, the spoked wheels are lighter for a given diameter, yet, the flexible wheel have potentially greater performance compared to rigid wheel as they behave like wheels of a greater diameter, providing a greater contact patch area. However, for a given mass, it may be possible to provide a spoked wheel with a greater diameter, potentially mitigating the benefit of the flexible wheel. Further analysis will be necessary at subsystem and system level to select the best wheel concept for SFR.

| Table 1 - Representative Configurations for a Selected Number of Suspension Concepts |
|---------------------------------|------------------|------------------|
| **Options**                     | **Stowed (1x1x0.7m)** | **Deployed**     |
| - **Heritage - 6WD 3-Bogies**   | ![Image](image1.png) | ![Image](image2.png) |
| - **Alternative - 4WD – 2bogies + Differential** | ![Image](image3.png) | ![Image](image4.png) |
| - **Radical - 4WD – XLW (Extra large Width/Wheels)** | ![Image](image5.png) | ![Image](image6.png) |
Following further detailing of these locomotion concepts, the promising configurations exhibit a mass between 16kg (4WD XLW) and 20kg (3-bogies 6x6x4) inclusive of maturity and system margins. However, the mass saving between a 4 and 6 Wheel configurations must be put into perspective of heritage (4WD will need an entirely new development) and mission risk (6WD may provide additional redundancy should a wheel fail). As such, the baseline SFR locomotion configuration is currently based on an evolution of the 3-bogie concept, leaving open the actual level of actuation built-into the system, from a 6x6x6 (6 wheels, 6 drive, 6 steer) down to 6x4x4 (6 wheels, 4 drive, 4 steer).

This activity showed that with a rover of this size (~60kg), the locomotion system can adopt a reasonably large footprint for a mass between a quarter and a third of the ExoMars locomotion system mass (~60kg). While this helps bring the platform mass down, only a careful trade with operational constraints (e.g. impact of removal of actuated joints) and specific subsystem optimisation will allow to bring this mass down further.

6.4. Guidance Navigation and Control System

The second aspect of the mobility is the GNC system. In broad terms, it is responsible to perform 4 critical functions:

- **Localisation**: Determination of the Rover position and attitude.
- **Navigation** (including path planning): Determination of a navigable, safe and optimal path from the Rover current location to a predefined target.
- **Control**: Safe and optimal control of the Rover along the selected path.
- **Autonomy**: Reduces non-essential Ground commands and improves the mission return depending on the level of autonomy implemented in the On-Board Software, but increases software complexity.

Where the Localisation and Control aspects are anticipated to be an evolution of current and forthcoming designs, the navigation aspects present new options unavailable thus far to past and current rover missions and can be implemented in a number of ways.

The Stop-Go approach is currently being used to some extent on the MER and is planned for ExoMars. It requires stopping to image the way ahead with a steady camera and process the data to derive a safe path. It requires heavy processing, but provides a careful path planning and dead-reckoning. However, it holds up the progress of the traverse due to the on-board processing power limitations. New developments such as the ESA SPARTAN study however, promises to improve these operational bottlenecks.

The Continuous Drive implements a somewhat simpler scheme by only providing the rover with a traverse vector (direction and distance). The rover then sets off in the target direction and avoids obstacles along the way. This approach can be time, and therefore power inefficient as the navigation seeks a path continuously through obstacles, however for terrains with fewer obstacle, this can provide quick traverses.

Finally, a hybrid method can be envisaged. Unlike many of the past and current missions, a wealth of high resolution imagery data will be potentially available to the mission. The location of the cache, and the landing area for the SFR and MSR lander, will have been mapped out in detail. Currently, the HiRise imager provides up to 30cm/pixel ground resolution. By using multiple images of the same location, it should be possible to detect 30cm rocks or possibly smaller features. Shapes-from-shading techniques may also be used to further enhance the generation of accurate terrain and obstacle maps. Based on the Golombok rock model, a 30 cm diameter rock can be translated to a rock height of 15cm, the current target for the SFR locomotion. Using this data, the Ground will be able to plan long traverses and upload to the rover the relevant high res 2D or 3D maps. The onboard autonomous navigation can then use structure-from-motion and hazard avoidance techniques to follow the path given by the Ground. Should an unexpected situation arise such as the detection of loose soil, local path re-planning (either based on Stop-Go approach or using the high res maps) can take place to complete the traverse.

7. POWER SYSTEM

The power system must provide the rover with sufficient energy to support the system needs and meet peak power demand to fulfil the main mission objectives. As discussed earlier, solar generation is baselined for SFR due to high TRL and lower cost compared to alternative options. While the system must be sized to maximise the driving time and survival at
high optical depth, it must nevertheless be easy to stow, deploy and be mass efficient to limit its impact on the overall rover configuration.

The preliminary assessment of the energy requirements over the course of the mission shows that the rover would require an array of about 1.5m$^2$ to provide an average driving time of 4 hours per sol. A number of panel configurations have been proposed as shown in Table 1 to accommodate such an array while minimising the impact on the rover and the lander. For example the configuration shown on the 6WD gives a large overhang and no power generation when stowed. On the other hand, both panel configurations showed for the 4WD provide power when stowed and balance the weight of the panel around the centre of mass of the rover. The panel hinges could be actuated or be made to passively deploy when the HDRMs are released.

It is anticipated that the current configuration will evolve as the energy budget is detailed further. In addition, it may be possible to limit or decrease the size of the solar panel. On the one hand, the current cell assumption are reasonably conservative and do not account for the latest cell technology development anticipated for 2015. On the other hand, the implementation of an electro-dynamic screen could allow the removal of dust from the panel and restore its power generation capabilities back to 90% of its original level. This technique would limit the increase in panel size that must be factored in to account for dust degradation effects, but has currently a low TRL.

For the power regulation, three options were considered, keeping in mind the low mass of the platform:

- **Maximum Peak Power Tracking (MPPT):** The array load is dynamically altered to ensure maximum power transfer from the array to the system. However the rover arrays will be subject to local temperature variations caused by shadowing or dust deposition. Due to the complexity and associated mass associated with the local regulation of the voltage, it is not anticipated that this solution will be investigated further.

- **Direct Energy Transfer (DET):** The system operates at a fixed voltage throughout its life, typically a diode drop above the bus voltage. ExoMars rover originally baselined a DET system to reduce complexity, mass and avoid using a MPPT system, which has not yet been demonstrated on Mars.

- **Maximum Power Point Prediction (MPPP):** This approach attempts to benefit from the MPPT implementation with a lower associated cost. Sensors are used here to determine the temperature of the arrays. Empirical estimates are then used to track the voltage of the array and maximise the power output. MPPP is currently being investigated for ExoMars to provide a simplified version of MPPT, while maximising the array capability compared to the DET approach.

Finally, the battery is sized to provide night-time communication capability and complement if need be the locomotion energy requirements. Pending on the actual scheme, a battery mass between 1 and 1.7kg is used based on ABSL 18650F batteries. Overall, the preliminary mass allocated to the power subsystem is around 13.5 kg including margins.

8. **ON-BOARD DATA HANDLING**

The OBDH system must handle the flow of on-board data for the SFR, providing the typical functional performance found on interplanetary rovers. The unique aspect of the SFR design compared to most conventional rovers is its sole purpose of acquiring the sample cache. Traverse and navigation functions create the greatest loads on the OBDH subsystem so the removal of the science payload will do little to reduce the OBDH loading for the SFR design, except perhaps for some memory storage capacity.

Primary methods to reduce OBDH mass whilst maintaining performance include:

- Produce low mass variants of the ExoMars solutions
- Use new lower mass/power equipments
- Improve implementation efficiencies through innovative configurations / architectures

To provide a starting reference point, the ExoMars OBC design is used here. It has a projected mass of ~3.9kg and estimated power consumption (during traverse) in the region of 20W. Ways must be found to achieve a similar level of performance and functionality in order to achieve the minimum mass and power consumption. Two simplified OBDH configurations can be proposed to see how they affect critical aspects of the rover design such as power and mass.

The first is based on variations of the ExoMars design seeking to benefit from the heritage and high TRLs that ExoMars equipments will provide. The implementation would be based on a modified ExoMars OBC without a TM/TC processing module and science package interface as one is not currently required for the SFR design. By increasing the level of integration, reducing the board count, replacing the LEON implementation (2 LEON main processors plus 2 LEON co-processors) with two dual-core LEON boards the board’s mass can be reduced to approximately 1.8kg though the power consumption will remain to around 20W on full loading.

The second option considers a more radical approach which removes the centralised OBC and distributes the
processing loads. Recent developments by the Swedish Company, AAC Microtec have produced the Motion Control Chip which aims at providing an energy and mass efficient design for the control of mechanism electric motors. The basic design of MCC-SC10 incorporates a LEON3 processor that offers a great deal of flexibility and processing power in an efficient and compact form. This has been proposed for the ExoMars mission to control wheel drive and steering motors as well as pan and tilt and other mechanisms.

The MCC design modularises three areas of functionality – the MCC-C (Computer processing) the MCC-M&D (Main and Drive interfaces) and the MCC-PSU (Power Supply Unit). Based on the baseline locomotion configuration and the implementation of this OBDH approach, the configuration comprises 5 MCC units with LEON cores (5W nominal power), but no central OBC. This design seeks to reduce the mass and power consumption of the OBDH by distributing the processing loads to the LEON Cores within the 5 MCC units situated throughout the Rover. The resulting mass is therefore shared with the locomotion system and the additional mass for mass memory, SpaceWire and miscellaneous hardware would be limited (<0.5kg). The use of SpaceWire technology should result in a responsive system capable of providing the low latency required for critical rover on-board processes and operations and also able to cope with the high bandwidth traffic associated with image data passed from the imaging equipment to on-board mass storage and between mass storage and the transceiver for relay to Ground.

This approach would have significant implications for the design and implementation of software and many decisions on how best to do this are required e.g. how to best distribute processes around the LEON cores. A benefit of such distributed systems is that the function and operation of each processor can be monitored, checked and handled in the event of anomalies by the other processors. Recovery should be swift with so many monitoring assets and resources to which the anomalous processes can be transferred and run.

The implementation of any system has an optimum cost/volume efficiency e.g. a larger build may be simpler but will incur a mass penalty related to efficient use of materials (the functional density is low). If made smaller than the optimum size, the costs of squeezing greater functionality into a smaller area increase and the costs of integration will tend to dominate. The main drivers of the mission will determine where on this scale an implementation sits.

9. CONCLUSION

The SFR mission concept is unlike any other past or current rover mission as it focuses solely on a long and rapid traverse to retrieve the sample cache deposited on the Martian surface. To facilitate the mission architecture, a lightweight rover (with a target of 60kg) would be highly desirable. Although extremely constraining, this opens up the possibility of investigating the fundamental challenges in designing a capable mobile platform for such a small mass. Mobility is critical to the mission and although the platform is lighter, it must be compatible with an environment similar to that of ExoMars and Max-C. The resulting locomotion configuration therefore builds upon Exomars heritage, while leaving open the potential to implement innovative designs and solutions at system and sub-system level.

To date, the mass of the preliminary rover concepts range from 73 to 78kg including maturity and systems margins. It is anticipated that in the next preliminary design phase, additional mass saving options will be investigated to save mass in the three main subsystems, i.e. locomotion, power and structure, while exploring mass saving options in the collateral systems such as the thermal system, OBDH, communication and harness.

While the SFR mission concept is looking at a mission some 14 years away, this study has the potential to have a wider ranging impact by investigating lightweight subsystems solutions resulting in lighter rover configurations. Whether based on heritage or requiring future development, these will provide future missions with a selection of alternative implementations and an overall better understanding of rover platform sizing.

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11. REFERENCES