European Moon Rover System (EMRS)

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Abstract

ESA's program "European Moon Rover System (EMRS)" is the first iteration of a European mobile robotic platform expected to operate on the Moon surface by 2030. Its goal is to provide a common locomotion element able to host and service a variety of payloads across different mission scenarios, from exploration of polar regions, to surface assets manipulation and regolith excavation. The Division Exploration and Science of Thales Alenia Space Italia S.p.A. (TAS-I) – prime contractor of pre-phase A – completed a preliminary cycle of conceptual design and full-scale functional prototyping. The presence of a functional prototype, so early in terms of program phases, is deemed as a positive evolution of model philosophy approach in the public European space sector, opening the door for early de-risking activities and fostering hands-on activities of European technicians and engineers in the sector of space robotics. The following paper exhibits the main findings of the activity, while highlighting the technological challenges of the prototyping and future opportunities for the program.

Keywords

Space and planetary robotics, Lunar exploration, Lunar rover

1. Introduction

The European Moon Rover System (EMRS) is a competitive Pre-Phase A program launched by the European Space Agency and assigned to TAS-I at the end of 2021.

The objective of the activity is twofold:

- Investigate a multi-use robotic mobility system for the Moon surface to be launched aboard the ESA Argonaut lander in 2030.
- Build and test a full-scale functional prototype to demonstrate locomotion capabilities and prove architectural hypotheses.

ESA challenged the industry by requiring that both activities should have been completed in 9 months' time, providing the occasion to integrate short-time design cycles in order to rapidly converge on a reference design and start production of the breadboard.

Additional challenge lies in the EMRS concept itself: to design a common platform containing all the necessary sub-systems to operate and support its payloads, capable to withstand different lunar environment, from Lunar South Pole to equatorial far side. The advantage of such system – granting a certain amount of re-engineering from mission to mission – is the abatement of re-qualification costs and a standard platform to foster and channel the efforts of payload designers.

Although the brief deadline, a meticulous mission and functional analyses – backed by TAS-I heritage on planetary exploration missions such as ExoMars and Mars Sample - have enabled the convergence toward an ambitious yet reliable EMRS design, shown in Figure 1.

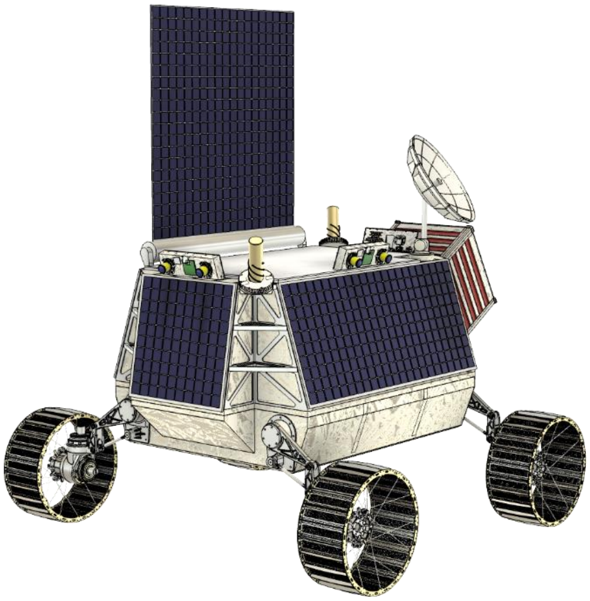


Figure 1: EMRS Polar Explorer Configuration

The baseline design of the EMRS consists of a locomotion platform that provides capability to carry and support different payloads with high level of reconfigurability (battery size, avionics, etc.), as shown in Figure 2.

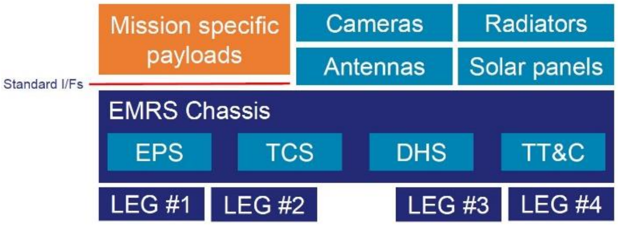


Figure 2: EMRS Conceptual Architecture

The locomotion consists of a 4-wheeled vehicle, where each wheel is drivable, steerable and integrated on a hybrid active/passive suspension system that can be independently controlled.

This design confers to the whole vehicle the ability to tilt, roll and change vertical excursion from the surface by utilizing the minimum number of actuations. A thorough description of EMRS locomotion capabilities is reported in chapter 4.

The chassis is hollow in the centre to provide support to a wide range of payloads that need to interact with the surface.

TAS-I sub-contracted the manufacturing and assembly of the breadboard to Space Application Services NV/SA (Belgium); the activities were completed in August 2023 with the hand-over of the hardware, and will proceed with testing and software development, culminating in a final demo in Q4 2023.

TAS-I Robotics and Mechatronics group can rely on its own analogue terrain called RoXY (Rover eXploration facilitY) – Figure 3; initially conceived as a Martian yard, RoXY spans 400 m^2 and it presents heterogeneous terrain characteristics that aim at challenging a robot locomotion and navigation capabilities.

Figure 3: TAS-I RoXY Facility

2. Mission Scenarios

The European Space Agency initially identified three representative mission scenarios that EMRS shall be able to fulfil:

- Polar Explorer is the first mission, planned for 2030, it aims at performing scientific prospecting in the Lunar South Pole. Among all missions, it poses the greatest technological and operational challenges: some of the requirements include fully independent night survival, extended operability in permanently

shaded regions and autonomous navigation between regions of interest.
- Astrophysics Lunar Observatory (ALO) foresees EMRS to operate on the lunar far side at near-equatorial regions (e.g. Tsiolkovsky Crater) in order to carry and deploy a series of antennas for creating a radio observatory. Challenges include the initial distance between landing site and deployment site, up to a few kilometres, but also the positioning accuracy of each antenna (0,5 m on x/y axes, 1° orientation on z axis).
- Collection and processing of in-loco resources (ISRU) differs slightly from the first two mission scenarios and while it might pose looser requirements with respect to scientific prospecting and antennas deployment, it raises the attention on elements such as mechanisms seal, operability under variable load scenarios (e.g. batches of more than 150 kg of fine regolith) and robust excavation tools.

3. Functional Analysis

After an initial detailing of mission requirements and high level system functions, the most compelling matter was the selection of a suspension and steering architecture that could encompass the so heterogeneous mission profiles: historically, planetary mobile robots are designed to fulfil a limited set of tasks in an unstructured environment, thus their locomotion apparatus is optimized to support exactly those tasks. Modern rovers such as NASA Curiosity (NASA JPL - LS-2013-01-007E-JPL — JPL 400-1516E, s.d.) and ESA ExoMars (Patel, 2010) share a similar passive suspension system that enables them to slowly traverse rough terrain while maintaining the chassis relatively tangent to the gravity vector, although its asset is fixed. On the other hand, rovers such as the NASA Lunar Roving Vehicle (NASA, 1972) and the Soviet Lunokhod (Gromov, 2003) implemented suspensions more similar to automotive designs in order to meet higher speeds and mass variability during mission profile.

EMRS suspension design choices were led by three factors:

- EMRS is meant to host a wide variety of payloads – many of which shall physically interact with lunar surface – across different missions without the possibility to adapt and requalify the suspension subsystem, thus the entire drivetrain.
- EMRS shall be able to descend and climb out of South Pole steep craters and PSRs; reference craters such as Shackleton (89.9° S 0.0° E) and the Shoemaker (88.1° S 44.9° E) present radial slopes up to 25/30° following ideal traverse for sunlight and direct-to-Earth visibility.
- Even though different wheel design can be envisaged in order to meet changing terramechanics properties, it was deemed crucial to fit EMRS suspension system with sufficient degrees of freedom such that the rover could avoid or escape loose soil traps, or high slippage conditions. This point is exacerbated by the lack of precise regolith characterization, especially in the polar regions.
- Matching the requirement of a fully autonomous navigation with the performances of what will be likely employed as on-board avionics (considering also the computational penalty of perhaps using laser-based vision systems), TAS-I has estimated an average obtainable speed of 5 to 10 cm/s, with peaks of 15 cm/s or more for teleoperations. Speed limitation actually factors in – among other things – thermal stability of highly reduced drive actuators, rock distributions and illumination condition for safe traverse in case laser-based systems are not utilizable.

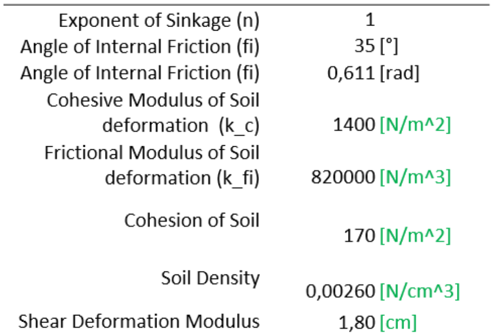
A qualitative interpolation of the aforementioned constraints and functions led us to consider a suspension system that can actively vary the rover’s asset (roll, pitch, elevation), be it to facilitate surface-interacting payloads design (no need for dedicated lowering or tilting mechanisms), or compensating for slopes and terrain asperities while navigating. Furthermore, the capability of tilting and rolling the rover’s body enhances static stability in high slopes conditions and facilitates the descend and exit from craters.

Being it an active suspension system with totally independent modules, even the slightest terrain asperity would need to be compensated; that has been considered unfeasible from a computational and power consumption standpoints, thus the insertion of a passive compliance element within each module’s kinematic chain.

4. EMRS high-level design

Once identified requirements and functions, EMRS design has proceed based on the following approach:

- Terramechanics analyses based on revised regolith properties (Figure 4) enabled the decision of number of wheels and wheel design
- Steering design based on desired locomotion modes and wheel design
- Suspension design based on maximum vertical and lateral compensation.
- Chassis design based on worst case configuration needs: the objective was to guarantee that all basic sub-systems – mission independent – could be hosted within the main chassis unit.



Exponent of Sinkage (n)	1
Angle of Internal Friction (fi)	35 [°]
Angle of Internal Friction (fi)	0,611 [rad]
Cohesive Modulus of Soil deformation (k_c)	1400 [N/m^2]
Frictional Modulus of Soil deformation (k_fi)	820000 [N/m^3]
Cohesion of Soil	170 [N/m^2]
Soil Density	0,00260 [N/cm^3]
Shear Deformation Modulus	1,80 [cm]

Figure 4: Regolith properties

In its current study configuration, EMRS has a footprint of roughly 2m x 2m and a variable deck height ranging between 0,3 and 0,4 m of active displacement (rover’s chassis in contact with surface at its lowest elevation). In its heaviest configuration – Polar Explorer – it reaches 600 kg, while the sole locomotion platform (structures, TCS, EPS, TT&C, Avionics) standing around 300 kg.

Once again taking the Polar Explorer mission as an example, a power budget of 500 W has been allocated for traversing during the day, 270 W for stationary operations within PSRs, and 42 W for night survival. Worst case battery capacity has been estimated at around 30 kWh, mainly driven by night survival and PSR prolonged operations.

4.1 Wheel and steering design

Terramechanics analyses focused on granting EMRS Polar Explorer (worst case) the maximum climbing capability in very loose regolith conditions by leveraging rigid metallic wheels; the choice was determined as flexible wheels would most likely suffer from extreme lunar thermal cycles, they tend to negatively affect odometry, and they would inject additional complexity in the qualification campaign.

The selected wheel presents the following properties: 500 mm diameter, 250 mm width, 24 grousers with an height of 5 cm.

EMRS can safely traverse 20° slopes with maximum slippage of 60% at a speed of 5 cm/s and maximum sinkage of 2÷3 cm. In this configuration, each drive actuator is required to provide 36 Nm of output torque; the figure can rise up to 70 Nm in case of temporary load imbalances. Drive actuator foresees a brushless DC motor coupled with one planetary stage and one harmonic drive.

Having such cumbersome wheels prohibits from implementing an implicit steering: the mounting bracket would result inadequately bulky, and the steering torque would quickly rise as a result of higher sinkage. TAS-I ream resorted to an explicit architecture, thus the wheel is laterally offsetted with respect to the steering actuator axis: this solution presents pros and cons. One clear advantage is that the steering manoeuvre could be obtained by simply unlocking the steering actuator and utilizing the drive actuator to “drive around” the steering axis; on the other hand, a more complex and robust control strategy must be implement in order to coordinate steer and drive while navigating.

In terms of capabilities, EMRS differentiates from the majority of planetary exploration vehicles as it is capable of performing all drive modes reported in figure 5; while modes (b) and (d) are considered the standard locomotion modes, crabbing (e) is particularly helpful in polar regions, as it enables the rover to move while increasing the exposure of fixed lateral solar panels towards the sun; similarly, it allows for precise Cartesian movements while operating in excavation or deployment operations. Point turn (f) around the geometric centre or a point that lies on the x/y axes turns out immensely helpful for scientific prospecting, for example by circumnavigating a rock while keeping an instrument precisely pointed towards it.

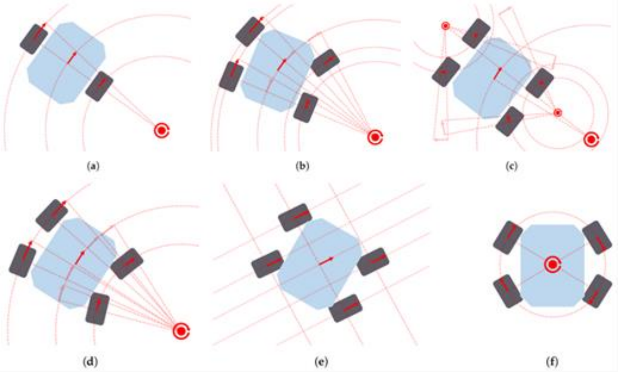


Figure 5: Locomotion modes: (a) Differential Drive, (b) Ackermann, (c) Skid Steering, (d) Double Ackermann, (e) Crabbing or pure translation, (f) Point Turn or pure rotation

4.1 Suspension

As already mentioned, EMRS features four independent locomotion modules (“*legs*”); each module has three degrees of freedom (shoulder, steering, drive), and the vertical movement of the whole leg is enabled by a parallel pantograph directly linked to the output of the shoulder.

In order to measure the load on each leg, thus providing the control algorithm input data to correlate with IMU readings for traction and asset control, EMRS integrates in each shoulder actuator an elastic element in series, attached to one end to the carcass of the vehicle (fixed end), and on the other to the oscillating stator of the actuator.

This series is called Series Elastic Actuator (SEA) (Lee, 2017), and it allows the spring to deflect passively by varying the load received from the other end of the kinematic chain (e.g. Figure 6).

By correlating the elastic constant of the spring to its deflection and the kinematic of the leg, it is possible to obtain the reaction load acting on the wheel.

Ad-hoc design and calibration of the spring element can also create the conditions for using the SEA as a suspension itself, furthermore given that the locomotion dynamics are generally slow and some energy is lost in bearings and friction, it is possible not to implement a damper in the chain.

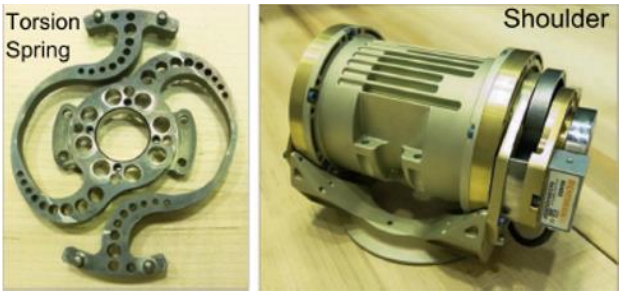


Figure 6: Left: torsion spring developed by NASA for humanoid robot Valkyrie; Right: SEA Actuator mounting the torsion spring in series to the output

Figure 7 shows EMRS actively varying its height from the surface by 40 cm, while Figure 8 shows how EMRS can compensate up to 15° both laterally and longitudinally.

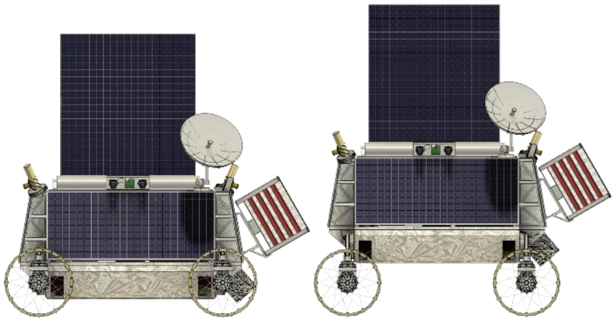


Figure 7: Suspension active vertical excursion

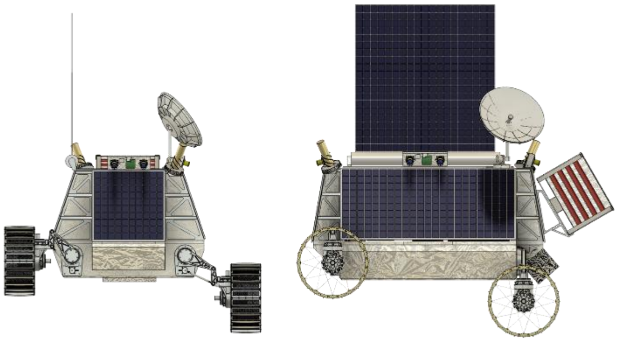


Figure 8: Lateral and Longitudinal compensation: ~15°

5. Prototype AIT activities

EMRS prototype consists of an aluminium extrudes structure upon which custom aluminium and steel machined parts and COTS components are installed. It implements all locomotion functionalities of the study model, but it does not feature autonomous navigation or perception of any kind, as it was deemed unnecessary for this stage of development.

Figure 10 displays the first ground test of the breadboard: the current configuration weighs 250 kg and it can support around 100 kg of additional payload, it does not implement an on-board battery for mass and convenience reasons and it momentarily mounts standard motorcycle tires for budget and time constraints. The rover has shown rock overcoming capabilities up to 30 cm while passively granting compliance of the other wheels; software development is proceeding in order to enable active compensation and traction distribution. Drive actuators can grant traction at maximum load up to 20° slopes.

Figure 9 shows EMRS in its stowed configuration: vertical translation is performed by aligning the wheels parallel to the pantograph and coordinating the shoulder and drive actuators, as rubber tires would generate high lateral friction; this limitation will be surpassed with usage of representative rigid wheels with straight grousers, so that vertical adjustments can be performed during nominal navigation without the need to stop.

A partially completed upper cover (visible in Figure 9 and 10) is temporarily applied to protect the electronics from direct sun, and once finished it will be helpful for configuration activities.

Figure 9: EMRS BB - Stowed Configuration

Figure 10: EMRS BB locomotion tests - 30 cm rock overcoming

Figure 11 and Figure 12 partially show the prototype leg configuration: the SEA is obtained through the installation of two parallel traction springs, fixed on one side to a reconfigurable rigid anchor, and on the other to the oscillating actuator stator. The rotation of the stator is directly correlated to the spring elongation (considered purely linear for simplicity) and transmitted through a reduction to an absolute encoder. By correlating the encoder reading with the physical properties of the springs and the actuators configuration, it is possible to precisely obtain the wheel load.

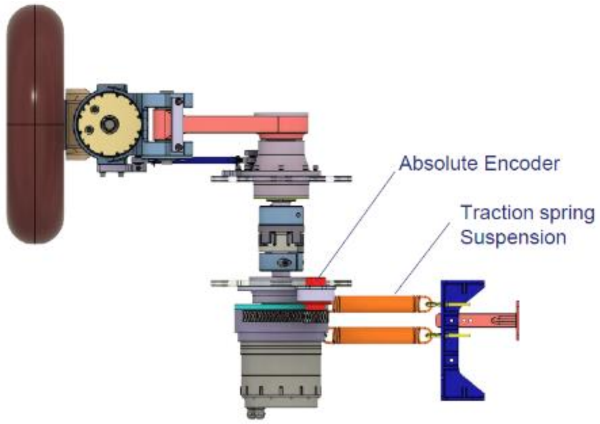


Figure 11: EMRS Breadboard Shoulder Assembly - top view

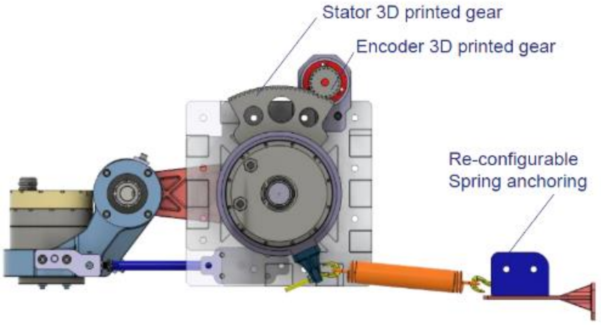


Figure 12: EMRS Breadboard Shoulder Assembly - front view

6. Future design iterations and conclusions

EMRS experience – study and prototype – is a concrete first step towards a long term European robotic presence on the Lunar surface; its design choices, functionalities and rationales are well rooted into the international context and draws best practices from past and recent missions, enabling a more dynamic and courageous programmatic approach.

Given the short timeframe of development and manufacturing, some design aspects are optimizable and represent a unique learning opportunity: a set of metallic wheels (Figure 13) is being studied in order to be fitted on the breadboard as soon as Q4 2023; custom-made Series Elastic Actuators (including motor and reductions) would also represent a great step forward in terms of representation. Last but not least, fitting EMRS breadboard with perception systems and developing an autonomous mapping and navigation algorithm would represent a remarkable improvement, supported by the expertise of TAS-I Robotics team in the field of planetary mobile exploration.

The author and the whole TAS-I EMRS team believes that the current breadboard activity is a solid foundation for an iterative and organic design process, developing early engineering models also in favour of payload designers and testing features directly on the ground on a representative platform.

Figure 13: EMRS BB - Rigid Metallic Wheel prototype

Acknowledgments

Although this work represents just a tiny first step in the horizon of an end-to-end Lunar exploration mission, the outcome reflects the effort and dedication that have been expressed by the industrial and agency teams.

Special thanks go to Space Application Services team and their proactivity and care in tackling some challenges during the assembly of the EMRS prototype.

In conclusion, ESA’s approach of early prototyping has already started to bear fruit: the hands-on work has fostered industrial collaboration and the creation of a development platform that has the potential to act as a catalyst for the upcoming efforts of European Lunar mobility and utilization.

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