72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021.


IAC-21-A3.4A.8

# Wheeled locomotion in milli-gravity: A technology experiment for the MMX Rover.

**Fabian Buse[a]*, Stefan Barthelmes[a], Maxime Chalon[a], Viktor Langofer[a], Wieland Bertleff[a], Roy Lichtenheldt[a], Juliane Skibbe[a], Markus Bihler[a], Roman Holderried[a], Josef Reill[a], Bernhard Vodermayer[a], Leon Stubbig[a], Jean Bertrand[b], Simon Tardivel[b], Pierre Vernazza[c], Naomi Murdoc[d], Stephan Ulamec[a], Patrick Michel[e]**

[a] *German Aerospace Center (DLR), Germany, firstname.lastname@dlr.de*
[b] *Centre National d'études spatiales (CNES), France, firstname.lastname@cnes.fr*
[c] *Laboratoire d'Astrophysique de Marseille, France*
[d] *ISAE-Supaero University of Toulouse, France*
[e] *University of Nice-Sophia Antipolis, CNRS, Observatoire de la Cote d'Azur, France*
* Corresponding Author

**Abstract**

For the Martian Moons eXploration (MMX) mission of the Japan Aerospace Exploration Agency (JAXA), the French Centre National d' Études Spatiales (CNES) and the German Aerospace Center (DLR) jointly develop a wheeled exploration rover. This paper will discuss the planned analysis of wheeled locomotion of the MMX Rover. The focus will be on the expected challenges, the methods how to overcome them and the plans on how to achieve a better understanding of wheeled locomotion in a milli-g environment by performing and analysing a set of driving activities on Phobos.

**Keywords:** Rover, Phobos, MMX, planetary exploration, locomotion

**Acronyms/Abbreviations**

Martian Moons eXploration (MMX), Soil Contact Model (SCM), Discrete Element Method (DEM), Rover Simulation Toolkit (RST), Onboard Computer (OBC).

## 1. Introduction

For the Martian Moons eXploration (MMX) mission of the Japan Aerospace Exploration Agency (JAXA) [1,2], the French Centre National d'Études Spatiales (CNES) and the German Aerospace Center (DLR) jointly develop a wheeled exploration rover. The rover will be the first system to perform wheeled locomotion in a milli-g environment. This, in combination with the uncertainties regarding environmental conditions, leads to many challenges in the design. The locomotion system of the rover, developed at DLR-Robotics and Mechatronics Center (RMC) needs to safely operate on the surface of Phobos. It is comprised of four symmetrical leg-wheel assemblies with individually driven joints, allowing each leg to be stored compactly on the side of the rover during transit. On Phobos, the legs can be unfolded allowing the rover to drive [3]. The operation on Phobos starts with an initial uprighting sequence where the rover needs to be orientated from a random initial orientation onto its belly. This up-righting sequence takes place just after the rover has been released from the spacecraft, descended to the surface and came to rest after a number of bounces. As the rover is up-right it will stand on its four legs and point itself towards the sun by adjusting its chassis orientation with its legs. Once this is completed and the battery is fully charged again, an initial checkout procedure of the system will begin. Afterwards, the main operation will start. This will include the first drives as well as measurements by the Rover's instruments, RAX a Raman spectrometer and MiniRad a thermal mapper as well as the rover's two sets of cameras, two cameras for navigation (NavCams) and two cameras observing the wheel-surface interactions (WheelCams) [4,5]. The wheel cameras are mounted on the rover's belly and allow for a detailed analysis of the wheel-regolith interaction. During the first drives, all assumptions, tools and methods, that were used to develop and now help to drive the rover, will need to be validated. All mechanical, electrical and control aspects of the rovers locomotion system were tested in experiments and simulations before, but with limited knowledge, especially on the behaviour of regolith. A better understanding of these aspects on Phobos is key for a successful mission.

The goal of the locomotion experiments is to confirm, validate and adapt the assumptions, tools and methods used to develop, design and operate the rover. A second objective is to gain a more comprehensive understanding of the aspects that are critical for operating a wheeled system in milli-g. The final step will be to give a summary and evaluation on the viability of a wheeled system moving under milli-g conditions.

## 2. Challenges of wheeled locomotion in milli-g on Phobos

Operating a wheeled locomotion system on Phobos and its development poses a set of challenges [6]. These can be divided into two main groups. The first one is linked to the limited knowledge of the environment on Phobos, especially the exact composition, size distribution and behaviour of regolith. Although there exist images from orbiters passed by Phobos, as well spectral and thermal analysis of the surface, there is no direct information on the scale of a rover. With the available data, the regolith's behaviour cannot be accurately predicted. This especially poses the risk of being entrapped in soft soils and even at gentle slopes or ripples. The second set of challenges is related to known environmental conditions. In regards to locomotion mainly to the low gravity. With an effective gravity that is between 0.003 $ms^{-2}$ and 0.007 $ms^{-2}$, depending on the exact landing site, the gravity on Phobos is roughly 1/2000 of the gravity on Earth, 1/750 of Mars or 1/250 of the Moon. Note that the Moon is the body with the lowest gravity where a wheeled system has been operated up to the present day. An intuitive approach to understand the difficulty of moving in such environment is to consider how time scales with gravity. With the classic free-fall equation, we can derive an equivalence of motion between Earth and Phobos, by scaling the durations involved by a ratio of $\sqrt{g_{Earth}/g_{Phobos}} \sim 50$: falling from 1m height takes 0.5 s on Earth, but would take about 25 s on Phobos. Speed can be scaled in the same fashion. Robotic rovers, e.g. Yutu-2 or Perseverance, usually move at speeds of approximately 5 cm/s; translated to the very low gravity of Phobos it means we would expect the same types of motion for a rover moving about 50 times slower, so around 1 mm/s. The low gravity also results in manoeuvres, that are not of concern in other missions, becoming relevant for a rover on Phobos and in general errors in quasi static assumptions usually used, become much more relevant. For example, acceleration for a Martian rover is not critical, on Phobos even an acceleration and velocity, acceptable on Mars, may lead to wheels of the rover losing contact and the whole rover flipping on its back. The same is of course true for deceleration, turning as well as general operations. If traction on a single wheel gets too high, uncontrolled rover movements are possible. Furthermore, the torques required to safely overcome friction in mechanisms are often more than sufficient to overcome any torque resulting from gravity.

## 3. Mission and tool overview

### *3.1. Core locomotion activities*

During the operational phase of the rover on Phobos, the locomotion system is mainly used in three different activities: up-righting, alignment and driving. Up-righting is the first activity, where the rover needs to be oriented onto its belly from a random initial orientation. This autonomous phase unfolds and refolds the rover's legs to tumble the rover onto its belly once on its belly the rover moves its legs to stand up. In alignment mode, mainly used to point the rover towards the sun or align cameras or scientific instruments, the rover body's orientation and height above the ground is changed by coordinated moves of both legs and wheels, without inducing any translational motion. Sun pointing and thus alignment is expected to be executed after most activities to allow the rover to optimally charge its battery. Both, up-righting and alignment, are well defined procedures that do not allow any variation. Thus, there is no room for experiments within these actions. Therefore, the telemetry data will be downlinked to reconstruct and evaluate the rover's motion.

In contrast, regular driving activities need to be actively commanded from Earth and allow for exploration within limits. Basic driving commands like forward, backward, skid steering and point turns need to be tested early on to allow for a robust suite of actions to be available later on. Optimal driving velocity, acceleration strategy or other deviations from the baseline parameters will be explored in simulation before, but need to be confirmed on Phobos early on. The same is true for more complex driving modes like inching, where a coordinated movement of legs and wheels is used to improve the rover's traction. For more details see [5]. Additionally, the rover is able to autonomously navigate. This will allow to extend its operational range [6].

### *3.2. Available telemetry data*

The locomotion subsystem has eight identical 12bits ADCs with eight channels each. This results in a total of 64 analogue values being measured. The majority of the measured values are covering voltages, currents and temperatures. They are used to monitor the health of the system.

A measurement of the joint torques using a custom developed sensor and a redundant position sensing based on two potentiometers is available in each of the four shoulders joints. Those are used to calculate the attitude of the rover with respect to the ground and detect collisions, e.g. with rocks. One tri-axial accelerometer is placed in each shoulder, recording at a sampling rate of 2kHz during the descent and impact on Phobos. The recorded data will reveal information on the surface properties and is among the first scientific data to be transmitted from the surface of Phobos.

Two single-axis gyroscopes are placed in the rover's body and can serve as "tip-over" detection during the autonomous up-righting phase of the rover.

Each motor has a sum current measurement at a rate of 40kHz, synchronized with the PWM generation, used to detect motor anomalies. The rest of the channels are read at 2kHz. Several channels are directly monitored by the FPGA on motor control board and can be used to trigger alarms. In particular, the motor currents can be monitored. Since the communication frequency with the OBC is slower than the ADC sampling rate, the FPGA processes the data stream to provide a minimum, maximum and average.

In total this provides:

a) Two single axis gyroscopes
b) A set of four tri-axial accelerometers
c) One torque sensor per leg
d) Two potentiometers per leg, providing an absolute position
e) A Hall sensor on each motor, providing accurate relative measurements.
f) Current and temperature measurements per motor

In addition to this telemetry provided by the locomotion system, the rover's camera systems, the two navigation-cameras at the front of the rover, as well as the two wheel-cameras mounted on the rover's belly looking at the wheels, will provide contextual information on the environment [4]. High resolution images of the rover's operational area from the orbiter can further help with terrain and environment reconstruction.

### 3.3. Simulation tools

Due to large differences between the Phobos and Earth environments, it is almost impossible to perform laboratory experiments to design, develop and validate robotic operations. Thus, simulations are critical for many of the mission's robotic aspects.

#### *3.3.1. Full system simulation*

To support the development of the rover, a full system simulation suite has been developed. This suite consists of a multi physics simulation of the rover itself built with the DLR Rover Simulation Toolkit [10].

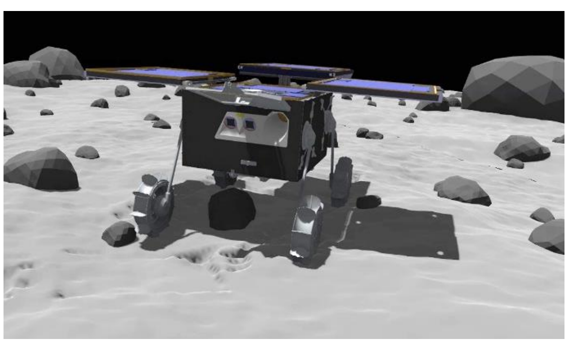

Fig. 1 Visualization of the MMX Rover simulation

In addition to an accurate representation of the rover itself, including error models for both sensors and actuators, an adequate model of the environment is required. This environment model, especially considering regolith and rocks, not only needs to be geometrically representative but also physically behave similarly. Special tools have been developed to procedurally generate environments based on parametric descriptions with the current environment assumptions. For a more detailed description see [11]. The simulator is designed to accurately reproduce the full system's behaviour with a reasonable computational effort. This means that, especially when it comes the ground interaction, a contact model that is able to depict deformations is key, thus the Soil Contact Model is used [12]. With this setup, the simulator is able to quickly compare the system behaviour under various environmental conditions. During the development, this has been used to cope with the high uncertainty in many environmental parameters.

#### *3.3.2. Single wheel simulations*

Single wheel simulations are performed to design and assess the performance of the wheel. In order to allow both precise and yet sufficiently fast calculations the GPU-driven particle simulation framework "Sir partsival" [13] is used. An example single wheel simulation is shown in Fig. 2.

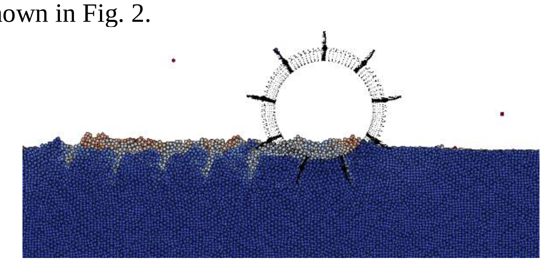

Fig. 2 Simulation of a single wheel on cohesive soil

This tool allows for several hundreds of thousands of particles to be simulated for long driving periods of about a minute for the MMX mission. Given this performance advantage, it was also possible to optimize the wheel for its challenging task in potentially extremely soft soil. Another advantage of "Sir partsival" and other DEM approaches over other types of soil simulations methods is that soil parameters are defined on a particle level, which means that gravity may be changed as a parameter, with the soil behaviour automatically adapting to the changed gravitational acceleration.

Given the knowledge of the usage of particle simulations from InSight, the analysis of mission data will be an already known task in DEM [14]. These analyses will help to verify the decisions and model used for the wheel development.

## 4. Experiment goals and procedures

The goal of the locomotion experiments performed with the rover can be divided into two categories. First, improve, validate or confirm the methods, tools and assumptions used in the rover's development. Second, evaluate the viability of a wheeled system in these conditions and provide valuable lessons learned for future missions in similar conditions.

Many of the actions performed by the rover in its nominal operations can be classified as experiments when viewed from the point of locomotion. In the initial phase, the small movements during the locomotion checkout will give first data. Later driving actions can be tailored to give more focused answers to certain questions while still fulfilling the mission's needs to move the rover to its desired position.

### *4.1. Rover pose estimation*

From the sensors listed in section 3.2, it is currently planned to use only the hall sensors and potentiometers for on-board rover pose estimation. At that, the orientation of the rover and the driven distance are calculated by direct kinematics algorithms, where a constant slip is assumed. Furthermore, this rover wheel odometry, combined with visual odometry, is used on-board by the navigation subsystem to detect wheel slip [9].

The other sensors' telemetry data are used to reconstruct and estimate the rover's pose and motions on ground. For example, by comparing the reconstructed motion with movements reconstructed manually from images, the viability of the tested methods can be evaluated. The sensor data collected during this mission can be used to develop more advanced rover pose estimation methods for future missions. Investigations will tell if different or more accurate sensors are required. Algorithms for future on-board sensor fusion can then be developed and tested based on the collected mission data.

The WheelCam images will also provide an independent verification of the rover's velocity and thus of the wheel slip [4]. The results will be compared with the locomotion system data.

### *4.2. Evaluation of wheel design and simulation methods*

Using the telemetry data, the wheels' performance will be assessed and a soil equivalent of Phobos' regolith will be built in DEM. With these data, we will analyse and validate the wheel features, as well as the optimization and development processes. Thus, the mission data will be an important building block for future wheeled rover missions in milli-g environment.

### *4.3. Rover control methods*

In the rover control, particularly the impact of the gravity on locomotion will be analysed.

The rover is currently feed-forward commanded, where the standard driving is implemented via skid steering due to the lack of steering actuators. The performance in Earth gravity and in Phobos gravity will be compared. In particular, it is expected that the sinkage and lateral resistance of the wheels and thereby the lateral slip in curve driving and point turning differ.

Besides the standard driving, an inching locomotion algorithm is implemented [8]. The resulting slip and thus performance between these two locomotion modes can be compared. It is expected that the slip of the inching locomotion will be lower, as it was shown in tests under Earth gravity. However, the extent of the improvement will be compared between the tests under Earth gravity and Phobos gravity.

The results of these studies can help to develop more advanced control algorithms in the future for similar rovers with an active chassis. As an example, the legs could be controlled according to the shoulder torque. It was shown in a preliminary study that an impedance controller can be designed for a smoother movement of the rover on uneven terrain. Although the translational velocity of the rover is very low, its dynamics are still tricky to predict as was described in Section 2. Another example is the use of gyroscopes in a more advanced controller to enhance the dynamic stability and prevent e.g. wheelies.

The findings of the MMX rover on Phobos will show to what extent more complex estimation and control algorithms can improve roving in milli-gravity.

### *4.4. Rover system simulation*

Due to the heavy use of simulation both in the rover development and operation, the validation of these tools is essential. By using the data available, especially the NavCam and WheelCam images to reconstruct the environment and the locomotion telemetry to reconstruct the rover's behaviour it will be possible to analyse the accuracy of the simulations. It is planned to apply optimization techniques to find the best match between observed and simulated behaviour and find the optimal parameters to describe the environment. With the resulting improved simulation setup, experiments, like testing additional strategies for locomotion can be performed in simulation without additional risk to the rover on Phobos. Although, any additional simulation will still be limited to previously observed behaviour.

### *4.5. Sensor performance*

The MMX rover will apply a set of two different potentiometer based rotary sensors in each joint. In contrast to using redundant components, a diverse approach has been followed to minimize draw backs of each sensor technology. While a lot of effort has been put into optimization of sensors, support components, materials and integration techniques, this concept will be intensively validated with respect to environmental properties, especially with respect to temperature effects on the sensors and the full signal chain.

The main challenge that will arise in the project, is the lack of direct heating by the available motor heaters which renders direct temperature control for the sensors impossible. Hence, testing setups rely heavily on prior thermal simulations and thermal balance testing as well as careful design of the tests and the used setup components. During the mission, position sensor values will be cross-correlated between the joints on the same rover sides with respect to their temperature, as a mostly equal temperature distribution on the rover sides is assumed. Furthermore, the position will also be cross-referenced to the digital encoder value that can be created by the motor controller. In sum, a high accuracy rotational information can be produced despite challenging environmental properties.

The mechanical parts of the torque sensors have been designed to survive the drop out from the spacecraft as well as the event of the hard impact on Phobos, whereas damage to the mechanics must be prevented. This increase of the mechanical robustness of course leads to a reduced sensitivity of the sensor measuring system. The reduction of sensitivity however, is not critical for the operation since the torque system was primarily designed to monitor the up-righting process where much bigger signals are to be expected in contrast to the signals acquired during driving. The process of up-righting, which is the first rover activity on Phobos, will probably generate the highest usable signal outputs of the torque sensors. Therefore, this process is the most interesting and exploitable part to validate the sensor performance and to observe relatively quick changes of the sensor signals. During this step, an automatic emergency stop in case of a jammed wheel would be possible to be implemented.

### *4.6. Hardware design and sizing assumptions*

In the design of the locomotion hardware, many design decisions had to be taken based on environmental conditions like assumptions regarding the regolith behaviour and different load cases (vibration during start, impact on Phobos, thermal stress during different mission phases, etc.). With data provided by especially the torque sensors during uprighting, it will be possible to verify and adapt the assumptions regarding the regolith behaviour. These especially concern the expected loads on the shoulders of the locomotion system. Further, with the motor, temperature and position sensors, the change of performance of the hardware, for example observed in the torque or current required to move the legs, will give an indication to the robustness of the hardware against expected load cases, dust contamination and the challenging thermal environment.

### *4.7. Motor, joint design and control methods*

The locomotion subsystem is using eight brushless DC motors with Hall effect position sensors. With respect to the limited computational resources, simple yet fail-safe motor controller algorithms have been implemented on a FPGA for each one of the motors.

Six-step commutation based on the hall sensor signals was chosen for its simplicity, which still ensures suitable operating behaviour of the drives due to the high gear ratio of the transmissions. The motor control strategy is based on a closed-loop position controller providing a means to control the motor speed in an open-loop manner. This allows driving operation at very low motor speeds, which are required in milli-g environments.

Each motor driver has a current measurement circuit that allows to detect malfunctions. However, given the low speed of the motors, the high friction of the gear boxes and the limited computation resources, the current measurements are not used in the control loop. An overcurrent protection is implemented in the motor driver to shut down the motor in case of too high currents.

Since the drives are exposed to harsh environmental conditions, alternative operation modes have been implemented. This includes a “feed forward” mode that allows the drives to be operated even if the positional feedback system fails. In addition, the locomotion subsystem provides methods for life and status analysis as well as for stuck recovery.

If any non-nominal situations occur, the validity of the recovery methods will be evaluated. Nevertheless, it is of course not foreseen to enforce any situation that would lead to the use of the fallback systems.

## 5. Conclusion

The MMX Rover mission to Phobos will be the first wheeled system driving in a milli-g environment. With the telemetry provided by its locomotion system in combination with camera images and the tools developed during the mission’s earlier phases, it is planned to evaluate the systems performance on Phobos and provide a summary on the viability of wheeled locomotion in milli-g.

**Acknowledgements**

The authors of this paper would like to thank all colleagues at JAXA, CNES, and DLR working on the MMX and MMX rover projects.

*List of references*

[1] Fujimoto, M., H. Miyamoto, and K. Kuramoto, JAXA's Martian Moons Exploration, MMX. European Planetary Science Congress. Vol. 11. 2017.

[2] Kuramoto, K., Kawakatsu, Y., Fujimoto, M., Araya, A., et al., Martian Moons Exploration MMX: Sample Return Mission to Phobos Elucidating Formation Processes of Habitable Planets. submitted to Earth, Planets and Space, 2021

[3] Barthelmes, Stefan, et.al., MMX Rover Locomotion System – Development and Testing towards the Flight Model 2022 IEEE Aerospace Conference. IEEE, 2022

[4] Michel, P., Ulamec, S., Böttger, U, Grott, M., Murdoch, N., Vernazza, P., et al., The MMX rover: performing in-situ surface investigations on Phobos, Earth, Planets and Space, in print, 2021

[5] Ulamec, Stephan, et al., A rover for the JAXA MMX Mission to Phobos., 70th International Astronautical Congress. International Astronautical Federation, 2019.

[6] Bertrand, Jean, et al., Roving on Phobos: Challenges of the MMX rover for Space Robotics., Proceedings of 15th Symposium on Advanced Space Technologies in Robotics and Automation. 2019

[7] Duxbury, Thomas C., et al., Spacecraft exploration of Phobos and Deimos., Planetary and Space Science 102 (2014): 9-17.

[8] Skibbe, Juliane, Stefan Barthelmes, and Fabian Buse., Locomotion Control Functions for the Active Chassis of the MMX Rover., 2021 IEEE Aerospace Conference (50100). IEEE, 2021.

[9] Vayugundla, Mallikarjuna, et al., The MMX Rover on Phobos: The Preliminary Design of the DLR Autonomous Navigation Experiment., 2021 IEEE Aerospace Conference (50100). IEEE, 2021.

[10] Hellerer, Matthias, Stefan Barthelmes, and Fabian Buse., The DLR rover simulation toolkit., (2017).

[11] Buse, Fabian, et al. MMX Rover Simulation - Robotic Simulations for Phobos Operations, 2022 IEEE Aerospace Conference. IEEE, 2022

[12] Buse, Fabian, Using superposition of local soil flow fields to improve soil deformation in the DLR Soil Contact Model – SCM, Proceedings of the 5th Joint International Conference on Multibody System Dynamics (IMSD) 2018

[13] Lichtenheldt, Roy, Shoko Ono, and Leon Stubbig, Large Scale Discrete Element Simulation Campaigns–Simulating Extraterrestrial Soils in Partsival., World Congress on Computational Mechanics (WCCM). 2021.

[14] Lichtenheldt, Roy, Bernd Schäfer, and Olaf Krömer,Hammering beneath the surface of Mars–Modeling and simulation of the impact-driven locomotion of the HP3-Mole by coupling enhanced multi-body dynamics and discrete element method (2014).