MOBILITY ON THE SURFACE OF PHOBOS FOR THE MMX ROVER - SIMULATION-AIDED MOVEMENT PLANNING

Fabian Buse[1], Julien Baroukh[2], Stefan Barthelmes[1], Jean Bertrand[2], Tim Bodenmüller[1], Maxime Chalon[1], Sandra Lagabarre[2], Naomi Murdoch[3], Juliane Skibbe[1], Michal Smisek[1], Simon Tardivel[2], Mallikarjuna Vayugundla[1], and Pierre Vernazza[4]

[1]*German Aerospace Center (DLR), Germany, firstname.lastname@dlr.de*
[2]*Centre National d'Études Spatiales (CNES), France, firstname.lastname@cnes.fr*
[3]*ISAE-SUPAERO, France, firstname.lastname@isae-supaero.fr*
[4]*Laboratoire d'Astrophysique de Marseille, France, firstname.lastname@lam.fr*

ABSTRACT

The MMX Rover, recently named IDEFIX, will be the first wheeled robotic system to be operated in a milli-g environment. The mobility in this environment, particularly in combination with the interrupted communication schedule and the activation of on-board autonomous functions such as attitude control requires efficient planning. The Mobility Group within the MMX Rovers Team is tasked with proposing optimal solutions to move the rover safely and efficiently to its destination so that it may achieve its scientific goals. These movements combine various commands to the locomotion system and to the navigation systems developed by both institutions. In the mission's early phase, these actions will rely heavily on manual driving commands to the locomotion system until the rover behavior and environment assumptions are confirmed. Planning safe and efficient rover movements is a multi-step process. This paper focuses on the challenges and limitations in sequencing movements for a Rover on Phobos in the context of the MMX Mission. The context in which this process takes place is described in terms of available data and operational constraints.

Key words: MMX; Robotics; Mobility; Operations; milli-g; Locomotion; Terramechanics.

1. INTRODUCTION

The MMX Mission to the Martian Sphere led by the Japan Aerospace Exploration Agency (JAXA) will explore the origins of the Martian moons[5]. The launch is planned for 2024. The main spacecraft, which will land on the larger of the two moons, Phobos, will also carry a small rover, recently named IDEFIX, jointly developed by the Centre National d'Études Spatiales and the German Aerospace Center (DLR). This rover of about $25\,\mathrm{kg}$ will be dropped from a height of about $40\,\mathrm{m}$ onto the surface of Phobos. After coming to rest on the surface, it will perform an autonomous uprighting and start its primary mission to explore its surroundings. IDEFIX has two navigation cameras (NavCams) at the front, two cameras pointing at one front and one rear wheel (WheelCams), and two scientific instruments, "RAX" and "miniRad" [7, 13]. RAX is a Raman spectrometer positioned at the belly of the rover, enabling it to identify the material composition of the surface [10]. The miniRad instrument is an infrared radiometer positioned next to the rover's navigation cameras, providing precise measurements of the temperature of the surface [4]. Figure 1 shows the IDEFIX rover during integration with a fully assembled chassis and locomotion system but without the solar generator. This rover will be the first wheeled system to operate in a milli-g environment. This novelty, in combination with the operational constraints resulting from communication, makes efficient mobility planning key. With a robust methodology to plan and evaluate movements, the rover's exploration range will be expanded.

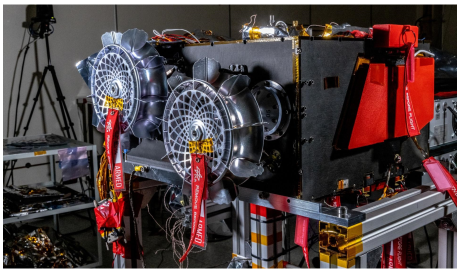

Figure 1. Rover during AIT in Toulouse at CNES, image CNES/DLR

This paper will first outline the challenges of operating a rover in milli-g and the aforementioned operational constraints. Then, the different scenarios relevant to rover mobility will be presented. The scenario overview is followed by a summary of the rover's tools for sensing and acting on Phobos. Next, organizational structure, called Mobility Group, is introduced. This group will aid in Rover mobility planning, Finally, an introduction to simulation tools will be given.

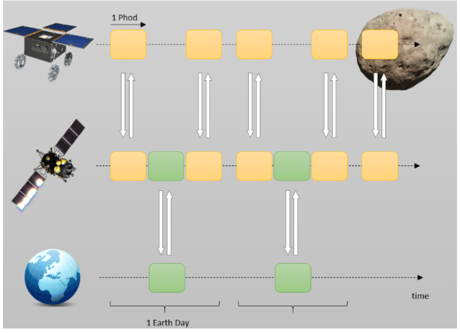

Figure 2. Simplified representation of the communication schedule

2. MOBILITY OF IDEFIX ON PHOBOS

After the rover has successfully landed, uprighted, and deployed on Phobos, phases with active mobility of the rover will start. Those will be divided into three main phases. First, a phase with cautious manual driving in which the general functionality of the locomotion system will be established and assumptions to the rover's behavior will be confirmed. Driving will mainly consist of single or very short chains of commands to the locomotion system with confirmation of the resulting movement in ground loops. During this phase, mobility rules already set on Earth based on analysis and simulation will be confirmed or adapted if required. Following this, a phase of more active driving is planned to follow. In this phase, the mobility rules confirmed before will be used to move the rover manually, if possible, in larger increments. During this phase, it will be possible to maneuver the rover into a specific position on the surface that is particularly interesting to the scientific instruments. This phase will be followed by a phase where the two autonomous navigation software available to the rover will be applied to further extend the exploration range during a single day on Phobos. A very similar evolution in the type of operation can be observed in the reports from the Perseverance rover [15].

Due to the limitations in power and mass, it is impossible to accommodate an antenna on the rover powerful enough to communicate directly with Earth. As a result, data is relayed in both directions by the MMX probe, and indirect-only communications are established: on 2 out of 3 Phobos days (Phod) (approx. 1/3rd of an Earth day), communication is established between the rover and the MMX spacecraft, followed by one communication between the spacecraft and Earth. This communication scheme is depicted in Figure 2. Consequently, the time between sending a command to the rover and displaying the results in the rover's telemetry on Earth is very long. On the other hand, the rover's nominal mission is relatively short: only 100 days are planned. It is, therefore, particularly important to plan carefully on the ground any action on the rover to avoid wasting time as much as possible.

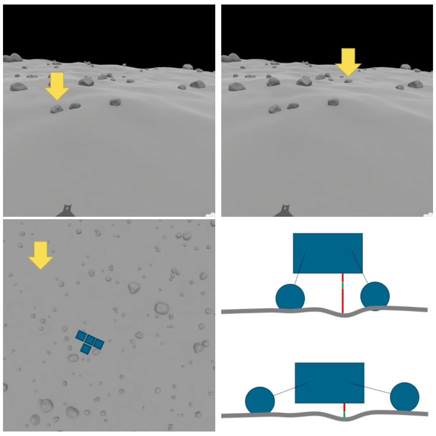

Figure 3. Four of the relevant planning scenarios.

The mobility operations of IDEFIX can be separated into various scenarios. Of course, these planning scenarios cannot cover all situations encountered during the rover's operational phase on Phobos. Nevertheless, they are a means to discuss the procedures, methods, and tools required to perform mobility on Phobos.

The simplest scenario, see top left in Figure 3, is the approach of a target within view of the navigational cameras that is close enough to perform the approach in a single drive session. It is expected that the goal is not only to position the rover at that target but also to place it there in a specific orientation, for example, to align the cameras rigidly mounted to the chassis towards the target or allow for optimal battery charging. This scenario can be seen as a key building block in the complex scenarios.

One step up from this simple scenario is planning the traverse to a target beyond the range of a single driving session, shown in the top right in Figure 3. Beyond the need to plan the individual trips, this now also needs consideration of the intermediate positions. These parking positions must allow for sufficient battery charging and potential communication. Further, with this longer distance, the number of potential paths expands. In the context of the previously mentioned communication constraints, this scenario also results in the need for a quick evaluation of a go no-go decision of the second drive path. The short timespan on Earth between receiving telemetry and sending new commands will not allow extensive replanning.

Further extending the driving scenario, the approach of targets beyond the rover cameras' visual range, shown in the bottom left in Figure 3, needs planning in images provided by the orbiter. This planning will require knowledge of the rover's position within the large-scale map generated from orbiter data. When executed without autonomous navigation, such a driving scenario is realized into multiple smaller scenarios of the previous categories. In both cases, the execution will require high-level path planning on Earth within the large-scale map.

The final scenario shown in the bottom right in Figure 3

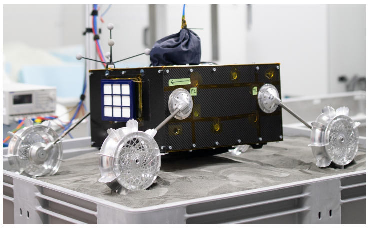

Figure 4. QM parts of the locomotion system integrated with a mock up chassis during combined locomotion RAX experiments in the Terramechanics Robotics Locomotion Lab at DLR.

is not immediately related to driving. In this scenario, the goal is to position the rover's chassis such that the RAX laser can focus and perform a measurement. Precisely controlling the distance between the chassis and the surface requires exact knowledge of the absolute position of the rover on top of a patch of soil that is not anymore in view of the rover's cameras. Even though the wheel cameras are positioned at the belly of the rover, their field of view does not cover the exact measurement position of the laser.

3. THE ROVER MOBILITY TOOLS

3.1. Locomotion System

The locomotion sub-system, shown during experiments in Figure 4, can be divided into three major components: The locomotion modules, the locomotion ebox, and the locomotion software [1, 11]. The locomotion modules combine the shoulder modules holding the two motors, one for the leg and one for the wheels, with the legs and wheels. The leg and wheel can be driven independently. The wheels cannot be steered. The ebox holds most of the electronics for realizing the analog to digital conversion of sensors, inverters to power the motors, and an FPGA for motor control and low-level monitoring. The locomotion software translates high-level commands received from Earth or other rover software and converts them into trajectories for each of the motors, which are then executed by the ebox [12].

The locomotion system provides five types of movements relevant to mobility:

The **drive** mode allows for conventional driving. As no steering is available, this mode relies on skid steering for turning. A delta position, delta orientation, and max wheel rate defines the command. Straights, curves and point turns can be implemented by setting these three parameters. No onboard slip compensation is implemented. This mode allows the chaining of multiple commands; thus, a new command can be started before the previous command has finished. This smooth transitioning allows connecting different commands without stopping the wheels between the different movement sections. No constraints to the leg angles are defined for driving, although a nominal driving position exists.

The **alignment** mode allows the orientation of the rover chassis with respect to an assumed flat surface. It is defined by the rover normal and height with respect to an assumed flat contact plane. This mode is designed to align the solar arrays in a specific direction for optimal charging. This mode is further used to move the chassis in the desired height for RAX measurements or to align cameras.

The **inching** mode is a unique movement mode for rough terrain. Similar movement techniques have been studied before by Moreland [8] and a related variant is also available to the ExoMars Rover [9]. In this mode, the fore and aft wheels are moved forward alternatingly so that an inch-worm-like movement originates. The moving pair of wheels is rotated with speed to achieve $0\,\%$ slip. This movement requires actuation of all four legs and wheels and is thus less efficient, but promises improved hill climbing capabilities or safer crossing of particular soft regolith.

The final two modes **passthrough** and **uprighting** allow manually giving commands to a subset of all legs and wheels. The uprighting mode differs from passthrough, as in this mode, the wheel rotation is coupled to the leg rotation. Beyond the uprighting phase, these modes are not planned to be required, but they can be utilized to perform custom yet-to-be-planned movements. Like the drive mode, these modes can be chained to construct complex, smooth movements if required.

3.2. Cameras

Both sets of cameras are based on a microcube CMV-4000 developed by CNES and 3DPLUS. For a detailed description of the cameras and their scientific applications, see [7]. At the front of the rover, two **navigation cameras** are the main contributor to information on the rover's environment. With a spatial resolution of about $1\,\mathrm{mm}$ at a distance of $1\,\mathrm{m}$, these cameras allow reconstruction of the surface topography. Localizing the rover in the digital terrain maps (DTMs) before and after a movement makes it possible to evaluate the rover's driving performance, especially information on the resulting slippage is of interest. At the belly of the rover and pointing one at the front-left- and rear-left-wheel, the **wheel cameras** allow an in-depth analysis of the wheel-regolith interaction. Based on the analysis of the observed interaction and resulting trenches, information about regolith parameters like the angle of repose, material cohesion and bearing capacities can be gained.

3.3. Rover Attitude Control System

The rover attitude control system, named SKA for ”Système für die Kontrolle of the Attitude” is designed to improve the battery charge by orienting the rover solar array towards a direction that optimizes the energy received over a whole Phod. The attitude control is based on Sun sensor measurements and locomotion commands to modify the rover height and orientation vector. The SKA sequence, named ”heliotrope sequence” is composed of a first movement to lower the rover into a theoretical stability area, followed by a loop of several movements to optimize the rover orientation [6]. The last step is to compute the rover’s three-axis attitude, used on-ground for mobility studies. The heliotrope sequence is performed autonomously each Phod at a given solar time close to noon. After that, the rover does not move, potentially for a few days, until the battery is sufficiently charged. It implies that the driving sessions take place in the morning. The interrupted communication schedule leads to a long duration to perform manual rover movements, and besides, the risk of burying the rover wheels in the regolith increases if too many movements are performed. It is, therefore, important that the planned rover movements stay compatible with the expected heliotrope sequence to optimize the global rover movements sequences.

3.4. Autonomous Navigation

DLR-RMC aims to provide a DLR Autonomous Navigation Experiment (DLR NAV), a demonstration and a technology validation of DLR semi-local autonomous navigation solution with the IDEFIX Rover. The main objective of this experiment is to demonstrate the benefits of on-board semi-local autonomous-navigation-functions for the operation of small rovers, where direct teleoperation is not possible, like in our case on the Phobos [14]. In detail, two possible benefits are investigated. First, DLR NAV should provide a safe motion interface to operations that still allows for optimally utilizing the limited mission time. On-Earth planning of rover motions requires visual feedback after every motion, decreasing the utilization of available mission time due to the high communication delays. The DLR NAV module allows for safe execution of more complex trajectories by tracking the rover motion and the environment. To achieve this, the driven distance is tracked, high wheel slip is detected and obstacles/slopes on the path are checked. Thus, more motion per mission day is possible, simultaneously minimizing the risk for the rover. As a second benefit, DLR NAV provides more detailed surface information of the rover surroundings for operations and scientists. A rolling elevation map that moves with the rover is generated from the sensor readings. This requires less bandwidth than sending back all camera images.

The modules of the navigation solution are shown in Figure 5. For more details on the algorithms and modules that make up the navigation pipeline, refer to [14]. Navigation Cameras are the primary sensors for both generating dense depth maps and estimating the rover movement as a visual odometry. Here, the computationally expensive depth map generation is implemented on an FPGA. Both information is used for building a representation of the Phobos environment in the form of digital elevation maps (DEMs) as well as obstacle maps (used for obstacle avoidance). In addition, wheel odometry is considered by the pose estimation module to estimate wheel slip. The Pose Estimation module uses the absolute orientation information provided by the SKA together with the visual odometry measurements to estimate the 6D pose of the rover as there is no Inertial Measurement Unit (IMU) on the rover.

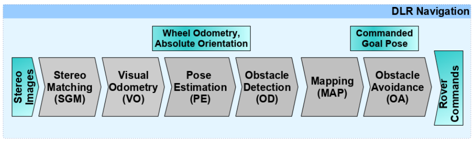

Figure 5. DLR Navigation Pipeline

Summarizing, DLR NAV is planning to provide the following features for the safe mobility of the rover:

- generation of a digital elevation map (DEM) and access as on-demand telemetry
- safety stop due to wheel slip detection
- safety stop due to obstacles in the path
- closed-loop autonomous commanding of the rover to be close to its actual commanded trajectory
- execution of an on-Earth planned trajectory as a set of goal points

CNES aims to provide IDEFIX with a full-fledged autonomous navigation software, whose core software is named ANAKIN (Autonomous Navigation Acquiring Knowledge from Image Nuances). It derives from the autonomous navigation software devised by CNES for the Exomars rover, which was extensively validated and tested with ESA’s rover fully representative hardware, on the ground in 2022.

With a single session of 1h of drive, even at $1\,\mathrm{mm/s}$, IDEFIX can cover more than 3m, hence likely beyond the exploitable horizon of the NavCams. Given the lengthy rover-ground-rover loop, the main purpose of ANAKIN is to provide mission control with the ability to drive the rover, safely, beyond the immediate view of its NavCams cameras. In the most favorable illumination and environment conditions, and with an appropriate autonomous navigation software, IDEFIX could drive on Phobos about $10\,\mathrm{m}$ per Earth day extending significantly what is achievable with ground in the loop. Contrary to most rovers, IDEFIX lacks an IMU. So, the software works purely on image-based information, hence its name. One additional piece of information is used, once-a-day at the start of a drive session: the 3 axis attitude measurement from the SKA subsystem to reset its internal orientation state.

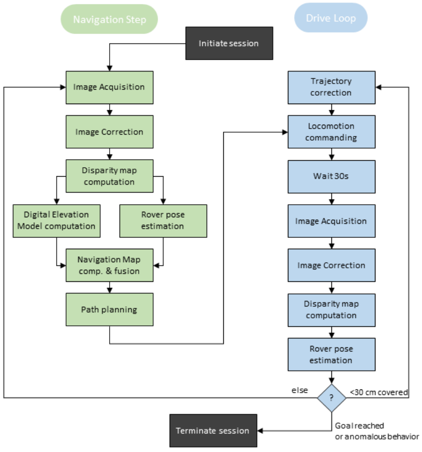

Figure 6. CNES Navigation Pipeline

ANAKIN onboard routines are implemented functionally as a single process that takes as input a list of waypoints and orientations, as well as associated tolerances, and attempts to reach them. The core sequencing of ANAKIN is made of two steps, as depicted in Figure 6. First, a navigation step computes a path to the waypoints or goal. Through stereo imaging techniques the 3d scene in front of the rover is reconstructed.

A navigation map is created and fused with the previous maps of earlier acquisitions. This map allows for the identification of a smooth path getting closer to the waypoint, such point is usually beyond the view of the rover. A loop of pose estimation and locomotion orders allow the rover to follow its prescribed path. Through 3d point tracking the rover estimates its pose, every 30s, and the deviation from the commands. Small deviations are expected and orders are then sent to locomotion to counter such errors. However,the deviation from the path is too large or if an unexpectedly large slip rate at the wheel interface is detected, ANAKIN may abort the session, judging that the observed behavior is too unpredictable to guarantee rover safety. Once the distance covered reaches about 30 cm, this drive loop exits back to a navigation step. Eventually, when the rover has reached a waypoint, within the associated tolerances, the drive loop updates the navigation objective to the next waypoint on the list. If there the final goal is reached, then the navigation session is terminated.

As a final note, the image correction process (SITH), which converts raw images to radiometrically corrected, debayered orthorectified, images usable for stereonavigation purposes, is also provided to DLR NAV.

4. MOBILITY PLANNING

The Mobility Group within the wider IDEFIX operation team will focus on solving the challenges outlined in Section 2 while optimally utilizing the tools presented in Section 3. The overall task of this group is to aid in finding the optimal solution to a high-level mobility goal.

The input to the mobility planning phase is the target and the available telemetry. An environmental analysis is required and varies in scope based on the goal and type of movement scope. This analysis uses a reconstructed environment with the rover's absolute position and orientation, information about the sun's trajectory, and regolith type and composition estimations. The goal is to identify environmental constraints relevant to the given goal. These may be geometric or non-geometric obstacles. Typical examples of geometric obstacles would be rocks or slopes, while non-geometric would be areas of particular soft soil or shaded areas in which battery charging is limited.

Assuming no autonomous navigation is planned to be used, a path is manually planned in the local planning step. Based on the reconstructed environment and the analysis results, multiple paths through the environment to the target will be designed. The planning of these paths will consider previously set up movement rules. These rules may limit allowed velocity, acceleration, the smallest applicable turning radius, or the largest allowed point turn angle. A critical part of the first cautious driving steps will be to confirm or refine those movement rules.

In the next step, the movement generation, this path is then translated into commands that the locomotion system can execute. This translation will be performed based on a previously tested method. In this translation, effects like slip will be compensated. The translation will be performed for each of the planned paths.

The different command chains will be tested in simulation in the evaluation step. For each chain, a Monte-Carlo-style simulation will be performed. Environmental parameters, like regolith parameters and terrain geometry, will be varied with uncertainty bounds to identify potentially critical aspects. Various metrics, like the statistics on the expected slip or stability margin during the execution of the command chain, will be provided for each checked path.

In the filtering step, the results of the evaluation step will be used to select potential paths. This selection will be based on previously tested criteria. If no satisfactory solution is found, this step may lead to the need for replanning.

The output to the broader operations team will be a set of suggested paths, each with the necessary movement commands to execute and a synopsis of the path's characteristics. The operations teams will then further examine the suggested paths, considering topics such as thermal and energy consumption.

Once the mission is further advanced and more onboard navigation is used, the planning process will shift towards more parametrization of the navigation software and selecting navigation targets. The selection of what method, manual driving, guarded modes from the DLR MAV or the fully autonomous modes provided by both ANAKIN and DLR NAV, will become more critical.

5. MOBILITY EVALUATION IN SIMULATION

In the planning process outlined above, simulation plays a critical role. The simulation suite planned to be used is based on a set of simulators already applied throughout the mission [3]. The simulation setup is based around a Modelica model of the physical rover system, focused on the robotic aspects. The setup is modular so that appropriate levels of detail can be selected for all active components. A rigid setup for all components other than the locomotion system is used to set up the simulator for mobility analysis. To control the simulated joints, the actual flight software, combined with an accurate simulation of the motor control software on the FPGA, is used. An additional part of the software that emulates the remaining onboard computer (OBC) software is added so that the commands expected to be forwarded to the locomotion software can be defined in a Lua script. This setup allows for a precise translation between commands sent to the OBC and commands tested in simulation. Another component important in this setup is environment generation. Other than in the previously done simulation studies [3], no fully synthetic terrains can be used. Instead, the input terrain based on a height map must be used and, if needed, slightly modified to capture uncertainties. Finally, the regolith simulation, based on the SCM model [2], needs to capture the most significant uncertainty. As no measurements for the interaction of a rover with Phobos regolith exist, no validated exact prediction of the behavior is possible. Instead, multiple parameter sets covering various possible regolith behaviors will be used. With further progression of the mission, the results of previous drive sessions can be used to narrow down the applicable regolith parameters further.

6. CONCLUSION

The paper gave an overview of the mobility of the IDEFIX rover. The environment and operational constraints due to the communication in combination with the short mission duration create a unique challenge. This challenge needs to be solved by the Mobility Group, which will use an efficient on ground planning schedule to optimally utilize tools available on the rover. The developed, implementation and finalization of the outlined process has started and continue into the cruise phase.

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