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A ROVER FOR THE JAXA MMX MISSION TO PHOBOS

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The Martian Moons eXploration (MMX) is a mission by the Japan Aerospace Exploration Agency, JAXA, to the Martian moons Phobos and Deimos. It will primarily investigate the origin of this moon by bringing samples back from Phobos to Earth and deliver a small (about 25 kg) Rover to the surface.

The Rover is a contribution by the Centre National d'Etudes Spatiales (CNES) and the German Aerospace Center (DLR). Its currently considered scientific payload consists of a thermal mapper (miniRAD), a Raman spectrometer (RAX) a stereo pair of cameras looking forward (NavCAM) and two cameras looking at the interface wheel-surface (WheelCAM) and consequent Phobos' regolith mechanical properties. The cameras will serve for both, technological and scientific needs.

The MMX rover will be delivered from an altitude of <100 m and start uprighting and deploying wheels and a solar generator after having come to rest on the surface. It is planned to operate for three months on Phobos and provide unprecedented science while moving for a few meters to hundreds of meters. MMX will be launched in September 2024 and inserted into Mars orbit in 2025, the Rover delivery and operations are planned for 2026-2027.

I. INTRODUCTION

The MMX Rover is a contribution by the Centre National d'Etudes Spatiales (CNES) and the German Aerospace Center (DLR) to the Mars Moon Explorer (MMX), a mission by the Japan Aerospace Exploration Agency, JAXA, to the Martian Moons Phobos and Deimos [1,2]. It will be delivered to the surface of Phobos to perform in-situ science but also to serve as a scout, preparing the landing of the main spacecraft. The

MMX Rover will deliver information on the regolith (geometrical and mechanical) properties by high resolution imaging of the interface of the wheels with the surface. Even movies are foreseen.

Phobos exploration with spacecraft goes back to the 1970s, when Mariner 9 took the first images of the Martian moons. Since then several spacecraft have taken images (or spectral data) of Phobos, from orbit or from the Martian surface, respectively [3]. The Origin of both Phobos and Deimos, however, are still not clear [4]. Two possible scenarios are currently discussed among the science community: asteroid capture [5] or formation after a major impact on Mars [6-8]. The MMX Mission targets to solve this puzzle by measuring in great details the properties of Phobos through measurements from orbit and on the surface and by returning samples to Earth.

Despite three attempts (Phobos 1 and 2 in 1988 and Phobos-Grunt in 2011, all were lost before arrival at Phobos) and several mission studies [e.g. 9-13], there has been no dedicated mission to the Martian moons, yet.

II. SCIENTIFIC OBJECTIVES

The Scientific Objectives of the MMX Rover are defined in line with those of the overall MMX Mission, however, complementing the science which can be performed with the instruments onboard the main spacecraft or the samples returned.

The data provided by the rover thanks to its instrument suit (see below) are of high interest for the communities interested in the regolith dynamics in the low gravity environment of Phobos, in surface processes and in the geological history of Phobos, in the composition of Phobos and in its thermal properties. This data set obtained in-situ is of high value for the interpretation of data obtained remotely by the spacecraft by adding ground truth, and to provide a geological context to the samples that will be returned to Earth in order to clarify the origin and history of Phobos.

The Rover will perform:

- Regolith science (e.g. dynamics, mechanical properties like surface strength, cohesion, adhesion; geometrical properties like grain size distribution, porosity)
- Close-up and high resolution imaging of the surface terrain
- Measurements of the mineralogical composition of the surface material (by Raman spectroscopy)
- Determination of the thermal properties of the surface material (surface temperature, thermal capacity, thermal conductivity)

This will allow determination of the heterogeneity of the surface material and thus will also help defining the landing and sampling strategy.

Characterization of the regolith properties shall considerably reduce the risk of the landing (and sampling) of the main spacecraft, as the touch-down strategy can be adapted accordingly.

III. INSTRUMENTS

The Rover design allows the accommodation of four PI (Principal Investigator) instruments, which are:

- NavCAMs
- WheelCAMs
- Raman Spectrometer – RAX and
- miniRAD

During phase A also a gravimeter (GRASSE), provided by the Royal Observatory of Belgium as well as a lightweight ground penetrating radar (GRAMM) to be provided by the Technical University Dresden together with the University Tokyo have been studied. However, the current limitations regarding mass and volume led to a removal of those instruments from the baseline configuration.

III.I NavCAM

The NavCAMs will be used for autonomous navigation but also to image the landscape and place some constraints on the level of heterogeneity of the regolith both in terms of composition and space weathering alteration with a higher spatial resolution with respect to the orbiter. Figure 1 shows a schematic view of the stereo pair of cameras, Figures 2 and 4 the position aboard the rover.

They will thereby provide context information for the remaining rover instruments.

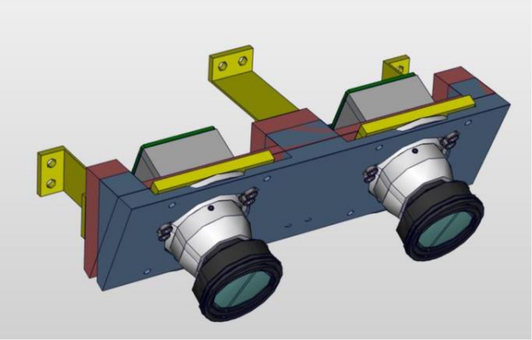

Fig. 1: Schematic view of NavCAM.

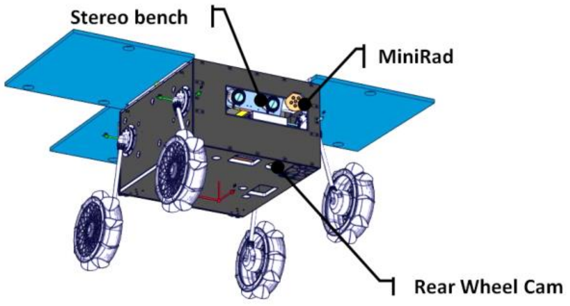

Figure 2: Rover in fully deployed configurations with positions of MiniRad, rear WheelCAM and NavCAM stereo bench

III.II WheelCAM

There will be two identical WheelCams on the rover (Figures 3 and 4). These panchromatic cameras have a 2048 x 2048 pixel resolution and a spatial resolution of approximately 35µm at the center of the image. The WheelCAMs will be used to image the wheels and their interaction with the regolith. By observing the properties of the regolith compaction and flow around the wheels it will be possible to characterise the mechanical properties of the regolith itself. In addition, the WheelCAMs spatial resolution will be sufficient to characterise the size distribution of regolith particles and their angularity. Such information is not only important for understanding the surface properties of Phobos and how regolith behaves in a low gravity environment, but this knowledge about the surface will also lower the risk of the MMX mission.

The CMOS camera sensor for the WheelCAMs, as well as the NavCAMs has been developed by 3DPLUS under CNES contract [14].

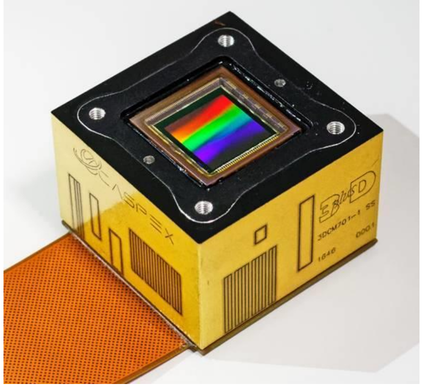

Figure 3: Image sensor of a WheelCAM (CASPEX module) [14].

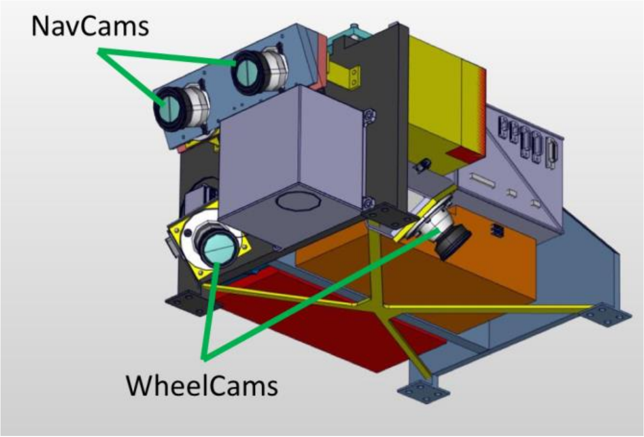

Figure 4: Camera emplacement. Schematic showing the respective locations and viewing angles of the NavCAMs and WheelCAMs.

III.III RAX

RAX (Raman spectrometer for MMX) is a compact, low-mass Raman instrument with a volume of approximately 81x98x125 mm³ and a mass of less than 1.4 kg developed by DLR, INTA/UVA and JAXA/UTOPS/Rikkyo. It will perform Raman spectroscopic measurements to identify the mineralogy of the Phobos surface. The RAX data will support the characterization of a potential landing site for the MMX spacecraft and the selection of samples for their return to Earth. The RAX measurements will be compared with Raman measurements obtained from the RLS instrument during the ExoMars 2020 mission, to provide evidence for the Martian or non-Martian origin of the surface minerals of Phobos. Furthermore, RAX measurements will be compared with Raman measurements performed in Earth laboratories on the returned samples for better interpretation of the data acquired. Figure 5 shows a schematic of the spectrometer module.

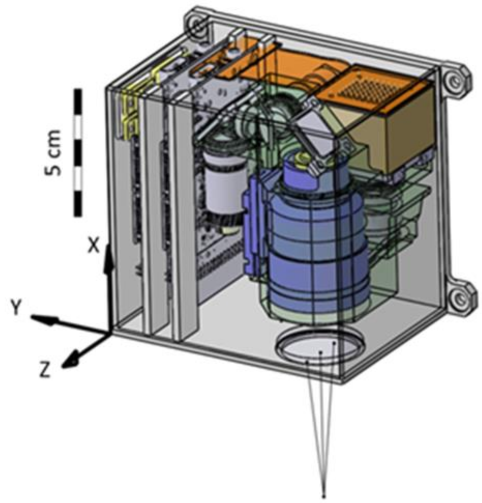

Figure 5: RAX spectrometer module (RSM)

III.IV miniRAD

The miniRAD instrument will investigate the surface temperature and surface thermo-physical properties of Phobos by measuring the radiative flux emitted in the thermal infrared wavelength range. miniRad will use thermopile sensors to measure flux in 6 wavelength bands and obtain information on regolith [15,16] and boulder [17] thermo-physical properties. The instrument will thus directly address or contribute to addressing fundamental MMX science objectives and provide a basic picture of surface processes on airless small body. Furthermore, miniRAD will help to characterize the space environment and the surface features of Phobos, thus enabling a comparison with asteroids. The instrument has strong heritage from the MASCOT radiometer MARA [18].

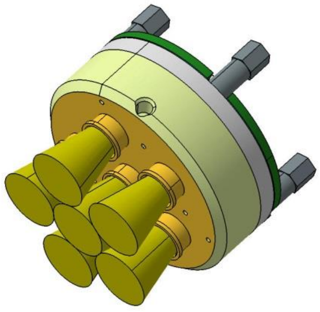

Figure 6: Conceptual design of the miniRAD sensor head showing the fields of view of the six individual infrared channels. The instrument's field of view will overlap that of the rover's navigation stereo cameras.

IV. SYSTEM OVERVIEW

The overall Rover system consists of 2 ground segments (one in Germany and one in France) and the flight hardware. The communication between the Rover ground segment and the flight segment is linked via the JAXA MMX mission (JAXA ground segment, ground stations and MMX main spacecraft).

The MMX Rover flight system consists of the Mechanical Support System (MECSS) which provides interface (mechanical fixation, electrical link…) between the Rover and the main spacecraft and allows the release and the ejection of the Rover. The RF communication hardware (antenna and RF electronic box) aboard the spacecraft is also part of the Rover flight hardware.

The Rover itself has an internal module referred to as Service Module (SEM), thermally insulated from the outside and supporting the electronics, batteries, attitude sensor and instruments. The service module is embedded into the chassis (outside walls) which support the locomotion system and solar generator.

The overall mass of the Rover Flight System (incl. the units on the main S/C) is 29.1 kg. (see Table 1 for a mass breakdown). The payload, including the cameras has an overall mass of about 2.6 kg. Figure 7 shows the Rover, attached to the MECSS, wheels and solar generator folded, as in launch/cruise configuration. Figure 8 shows the rover assembly.

	Mass [kg]
Electronics (incl. OBC, battery …)	4.7
Attitude sensor	1.1
Service module, SEM (structure, harness…)	3.8
Cameras (all cameras, bench…)	1.0
RAX	1.5
miniRad	0.3
Chassis (structure, shutters, harness…)	4.4
Mobility (motors, legs, wheels)	5.6
Solar array	3.4
∑ Rover	25.8
MECSS	2.3
RF hardware on main spacecraft	1.0
∑	**29.1**

Table 1: Mass breakdown of MMX Rover

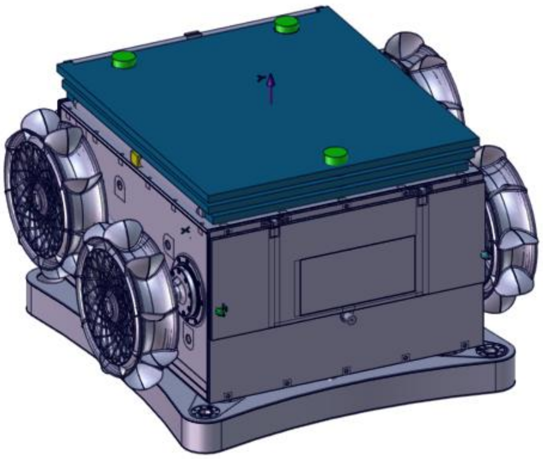

Figure 7: MMX Rover in launch configuration

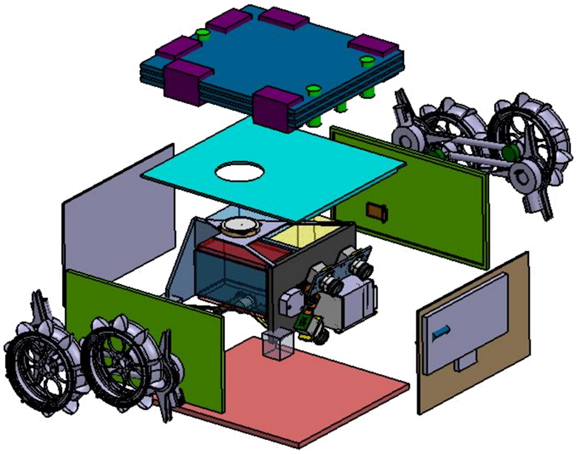

Figure 8: Exploded view of Rover assembly, showing Service Module, chassis, locomotion system and solar generator.

IV.I Structure

The two rover system primary structures, Chassis and MECSS, feature a carbon fibre-reinforced plastic (CFRP) sandwich designs.

The MECSS is a single sandwich plate design with a 30 mm aluminium honeycomb core and 1.5 mm CFRP face sheets. Next to providing an interface to the MMX S/C, the four corners are part of an integrated rover bearing concept (see Fig. 9). This combines the interface to the MMX main spacecraft and the rover bearing as well as the Hold-Down and Release Mechanism (HDRM) in one integral insert. Thus, the rover is clamped right at its four bearings, which are aligned concentrically to the four HDRM frangibolts. Further the MECSS features a Push-Off Mechanism that is based on the MASCOT design [19]. After releasing the HDRM, the Push-Off mechanism will stabilize the rover and provide it with the required separation energy.

Similarly to the MECSS, the Rover Chassis has two structural main interfaces, one towards the MECSS and the other towards the Service Module. During launch the chassis must remain secured on the MECSS and also support the Service Module. Once separated from the MECSS and the MMX spacecraft, respectively, the Rover chassis must sustain the landing impact on Phobos surface keeping its structural integrity. Thus, the chassis features an integral base element and separable panels closing the base element. Additionally, there are titanium flanges next to each locomotion unit, which are part of the base element and redirect loads into the removable front and rear panel. A top panel, which also supports the solar generator, is closing the chassis. Except for the top frame and the locomotion interface flanges, all parts are sandwich plates (5 mm aluminium honeycomb core and 0.5 mm CFRP face sheets on each side). Only the chassis bottom plate, which includes the main interface with the SEM and the MECSS, as well as three shutters and the umbilical, is a sandwich plate including a 10 mm aluminium honeycomb core and 1 mm face sheets.

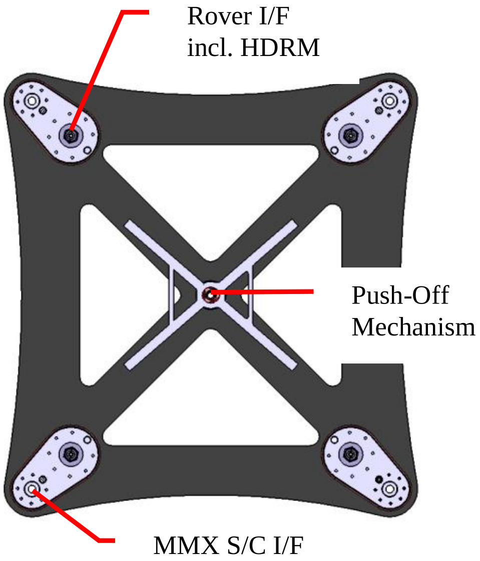

Figure 9: Top view of the MECSS with central Push-Off Mechanism. In the four corners a combined interface to the MMX S/C and the Rover Chassis, respectively, including the HDRM.

IV.II Thermal Concept

The thermal control of the MMX Rover is quite challenging due to the cold environment of Phobos and the low level of electrical power available for rover operations and control. In addition, some internal equipment temperature requirements are difficult to reach.

Power dissipated by the units inside the service module has to be kept inside as much as possible to reduce the need of additional heating power. Consequently, all the thermal leaks between the internal module, the chassis and the environment have to be minimized.

During cruise, the Rover will be heated by the orbiter via an umbilical to power cruise heaters and read out thermal sensors for regulation.

On the surface of Phobos the operational modes have to be chosen carefully to keep the instruments and electronics within the thermal limits and minimize the required heating power.

Thermal and power requirements limit the latitudes on Phobos, where the Rover can be operated.

IV.III Power System

The MMX Rover power architecture is composed of 3 deployable solar panels and one fixed on the top panel of the rover, one rechargeable battery and one power conversion and distribution unit (PCDU). A particularity for this rover is a connection with MMX spacecraft umbilical via MECSS equipment. This will enable the rover to be powered by the spacecraft during cruise phase. The umbilical and its separation connector pair are based on technologies already used on PHILAE and developed further for MASCOT [19].

Power management on board during the operation phase on Phobos is critical because the solar flux is limited. To guarantee a positive power budget, the Rover shall point the solar panels toward the Sun, using the locomotion subsystem while stationary.

IV.IV Locomotion Concept

The technology for locomotion on the surface of Phobos is one of the major endeavors of the MMX rover. As the rover is very compact and light weight, the locomotion concept is based on four wheels only. No additional steering actuators are used. The rover features four legs to bring itself into nominal orientation from any initial position after landing phase. The sequence of positioning the four legs to the ground depends on the achievement of nominal orientation and needs to be selected autonomously. To increase flexibility on that, the upper joint is able to perform one full rotation. Figure 10 shows the main module of the locomotion system, one leg of the rover.

The wheels have been designed in order to maximize the likelihood of success even in case of very soft soil thanks to advanced particle simulations.

The drive train is designed to fulfill three purposes:

- execute the self-righting moves required to bring the rover in an upward position after landing,
- drive the rover to a location on the surface of Phobos,
- orient the body of the rover in order to maximize the performance of the science instruments and to maximize the energy flux on the panels.

The actuators and sensors for the four wheels and legs are all placed inside the rover, to provide a more advantageous thermal configuration at the cost of a more complex mechanical design. The actuators are three phase brushless motor, with a nominal six-step commutation mode and a stepper mode commutation in case of sensor error. The leg position is measured redundantly with two potentiometer technology, a classical resistive track with grabber and a foil potentiometer. Finally, a very sensitive joint torque sensor is used as a safety mechanism to detect extraordinary torques applied to the legs, most likely indicating a large rock or an unexpected wheel sinkage.

The motion controller electronics is divided into three PCBs. Two of them include the power inverter electronics for providing the motor phase voltages. One PCB is going to measure the sensor signals, ensure communications link to OBC via SpaceWire and compute the control algorithms for all eight actuators.

The MMX Rover is equipped with all the software and hardware needed to perform autonomous navigation to overcome the limitations of receiving telemetry and sending commands between Phobos and Earth, leading to a drastic reduction of effective speed by “manual” operations. The rover can create digital elevation maps, traversability maps and detect obstacles. Therefore, once it is confirmed that the rover can drive on the surface, combined with its path planning and scheduling software, the rover will be able to safely navigate on the surface of Phobos, covering much greater distances and collecting more scientific data. One of the important activities on ground will be the modeling of the ground properties based on the collected data in order to drive faster and more efficiently. Autonomous driving is a prerequisite in the design of roving vehicles to explore celestial bodies even more distant than Mars.

Figure 10: Locomotion system. The image shows one leg including the wheel and the actuators

IV.V Communication

The RF system for the Rover – main spacecraft communication link will be managed on Rover and spacecraft side by the rover system.

On board the main spacecraft an S-Band communication system with a patch antenna will communicate with the Rover (see Fig. 11).

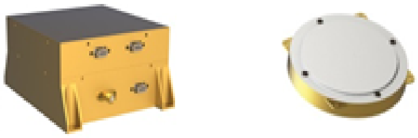

Figure 11: RF communication on the spacecraft : RF S-Band and patch antenna

This communications subsystem allows communication up to 100 km, which covers all mission phase of the Rover while the MMX spacecraft is in visibility of the Rover.

The data rate for the telecommand is 32 kbit/s whereas the data rate for the telemetry can go up to 512 kbit/s.

V. OPERATIONS CONCEPT

The MMX Rover will be commanded via the MMX main spacecraft, operated at JAXA. All TMTC will be linked via the main spacecraft as relay. During cruise, the rover is connected to MMX via an umbilical, after separation an S-band RF system will be used.

The Rover itself will be operated from two control centers, at CNES Toulouse and at DLR/MUSC in Cologne, respectively.

Operations will be divided into several mission phases:

- Launch and Cruise (incl. commissioning, health checks)
- Separation-Landing-Upright-Deployment (SLUD) phase (from separation from the main spacecraft, to descent, bouncing-phase to the quasi-autonomous up-righting and solar generator deployment)
- Phobos commissioning phase, to check the functionality of the Rover, its subsystems and payload.
- Phobos Operational (Driving & Science) Phase with a life-time of >100 days (including previous commissioning phase) on the surface of Phobos. During this phase different locomotion modes (including automated) will be tested and instruments will perform measurements at different locations on Phobos´ surface.
- End of Mission phase (finally passivating the Rover).

Figure 12 shows the Rover with its solar generator deployed as it would be in the Phobos operational phase on the surface of Phobos.

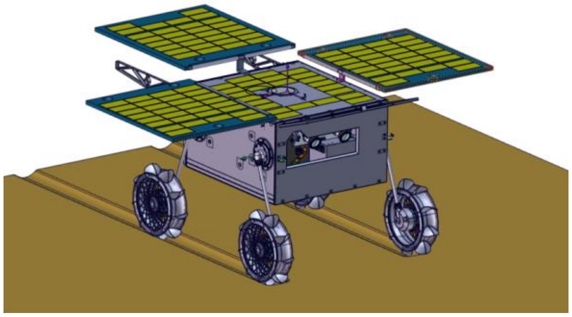

Figure 12: MMX Rover with deployed wheels and solar panels in on-surface configuration

VI. CONCLUSIONS AND OUTLOOK

The Rover is currently in its phase B and will go through development and qualification in the coming years. The logic of development of the Rover is based on a protoflight approach. The Rover AIT shall start in 2022 and the Flight Model will be delivered to JAXA in early 2023. The MMX mission is to be launched in 2024.

Rover operations are currently foreseen for at least 100 days, in 2026. It is currently planned, that MMX will leave Mars orbit to return to Earth in 2028 [2].

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