MMX Rover Locomotion Subsystem - Development and Testing towards the Flight Model

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Wheeled rovers have been successfully used as mobile landers on Mars and Moon and more such missions are in the planning. For the Martian Moon eXploration (MMX) mission of the Japan Aerospace Exploration Agency (JAXA), such a wheeled rover will be used on the Marsian Moon Phobos. This is the first rover that will be used under such low gravity, called milli-g, which imposes many challenges to the design of the locomotion subsystem (LSS). The LSS is used for unfolding, standing up, driving, aligning and lowering the rover on Phobos. It is a entirely new developed highly-integrated mechatronic system that is specifically designed for Phobos. Since the Phase A concept of the LSS, which was presented two years ago [1], a lot of testing, optimization and design improvements have been done. Following the tight mission schedule, the LSS qualification and flight models (QM and FM) assembly has started in Summer 2021. In this work, the final FM design is presented together with selected test and optimization results that led to the final state. More specifically, advances in the mechanics, electronics, thermal, sensor, firmware and software design are presented. The LSS QM and FM will undergo a comprehensive qualification and acceptance testing campaign, respectively, in the first half of 2022 before the FM will be integrated into the rover.

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***Abstract*—Wheeled rovers have been successfully used as mobile landers on Mars and Moon and more such missions are in the planning. For the Martian Moon eXploration (MMX) mission of the Japan Aerospace Exploration Agency (JAXA), such a wheeled rover will be used on the Marsian Moon Phobos. This is the first rover that will be used under such low gravity, called milli-g, which imposes many challenges to the design of the locomotion subsystem (LSS). The LSS is used for unfolding, standing up, driving, aligning and lowering the rover on Phobos. It is a entirely new developed highly-integrated mechatronic system that is specifically designed for Phobos.**

Since the Phase A concept of the LSS, which was presented two years ago [1], a lot of testing, optimization and design improvements have been done. Following the tight mission schedule, the LSS qualification and flight models (QM and FM) assembly has started in Summer 2021. In this work, the final FM design is presented together with selected test and optimization results that led to the final state. More specifically, advances in the mechanics, electronics, thermal, sensor, firmware and software design are presented.

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1. Introduction to the MMX mission and the MMX rover

The Martian Moon eXploration (MMX) mission of the Japan Aerospace eXploration Agency (JAXA) is a sample-return mission to the Martian Moons Phobos and Deimos which is scheduled for launch in 2024. A four-wheeled 20kg rover is jointly developed by the French Centre National d'Études Spatiales (CNES) and the German Aerospace Center (DLR). The goals of this rover are manifold (the order does not reflect any prioritization):

- It shall scout the surface of Phobos to de-risk the landing of the main JAXA spacecraft. The impact acceleration is measured and images are taken to learn about the surface properties.
- It shall drive on Phobos to demonstrate wheeled locomotion in milli-gravity [2].
- It shall analyze the surface and regolith behavior by capturing images of the surroundings with its NavCam as well as the wheel-soil interaction with its WheelCams [3].
- It shall measure the mineralogical composition of the surface material with its Raman spectrometer [3].
- It shall determine the thermal properties of the surface material with its miniRAD instrument [3].
- It shall demonstrate autonomous navigation from CNES [4] and DLR [5].

The rover will be separated from the JAXA spacecraft in 2027 by dropping it from a height of about 50m above the Phobos surface. After the impact, the rover needs to unfold its legs/wheels to stand up and deploy its solar arrays before it is ready for operations as in figure 1. More information about the overall rover concept and its subsystems can be found in [4, 6], about the science objectives in [3].

As the first wheeled robot to drive in milli-gravity and in the harsh environment of Phobos, the MMX Rover's locomotion subsystem (LSS) plays a key role for achieving the mission goals. At the same time, the volume and mass allocation as well as the mechanical and thermal environment greatly restricts the design space. The requirements necessitate the design of a highly integrated, highly specialized LSS and the evolution of the environment information required numerous adaptions since the first prototype.

This paper summarizes the major design updates of the mechatronic LSS since its prototype (PT) design, which was presented in [1]. Both, the PT and an updated engineering model (EM) have been thoroughly tested. A second EM iteration (EM2) was built to solve some last design problems and the qualification model (QM) as well as the flight model (FM) will be almost identical to the EM2. This work presents the EM2 / FM design. All models have been and will be built at the DLR Robotic and Mechatronic Center (DLR-RMC) in Oberpfaffenhofen close to Munich.

Section 2 gives an overview of the full LSS with all its subassemblies and domains. In section 3, the mechanical updates are presented with a focus on the drive train and the Hold Down and Release Mechanisms (HDRM). The electronics design is detailed in section 4, where special attention is put on EMC and radiation tests. section 5 describes changes to the potentiometer design and other updates of the sensor suite of the LSS. Since the thermal environment has changed drastically, the thermal analysis as well as optimizations of the thermal design were made, see section 6. Firmware and software developments are presented in section 7 and are focused on new software components and the motor controller within the firmware.

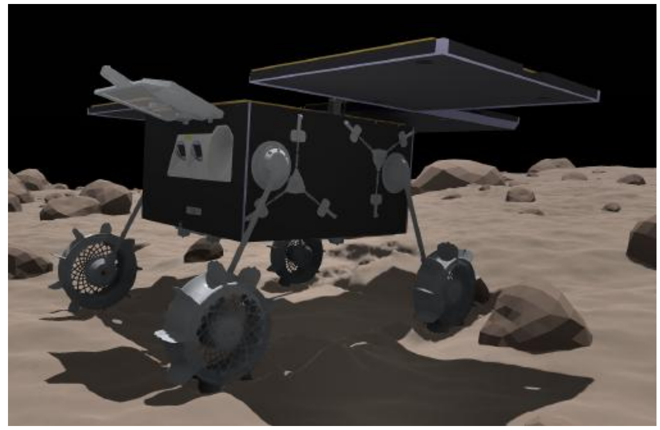


Figure 1: Simulation view of the full rover in drive configuration. The LSS components outside the chassis, i.e. the external shoulder side, the legs, wheels and HDRM, can be seen.

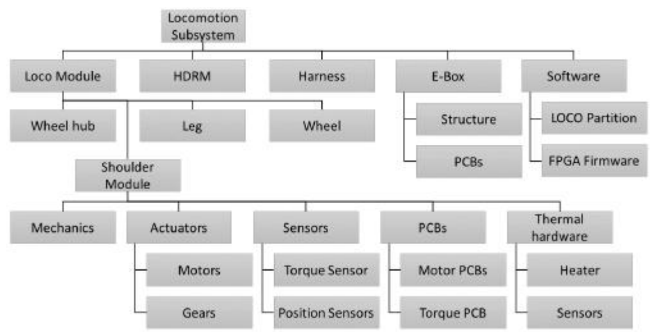


Figure 2: Product tree of the LSS.

2. Overview of the LSS

The LSS needs to meet several high-level functional requirements: Prior to driving on Phobos, the four wheeled legs need to be unfolded from the cruise position and the rover needs to stand up on its wheels on the correct side (so-called *uprighting*). Subsequently, it needs to point its solar array towards the sun to maximize the power generation. To investigate the regolith behavior and the locomotion performance in milli-gravity, as well as to re-locate the rover to areas of interest, the LSS needs to provide driving functionality including skid steering and point turning. For the on-board Raman spectrometer, the rover needs to lower its body to adjust the ground distance. A total driving distance of about 100 m and a mission duration of about three earth months is envisioned.

Components of the LSS

The outside parts of the LSS can be seen in figure 1. Figure 2 shows a tree structure of all main components of the LSS. It consists of four *Loco modules*, see figure 3 (bottom), which include the shoulders, the leg and the wheel. The shoulder itself, see figure 3 (top), is a highly integrated module that houses two motors - one for the wheel and one to rotate the leg -, two angular position sensors, one torque sensor, electronics, thermal hardware, accelerometer and several temperature sensors. For launch, cruise and the drop on Phobos, a hold-down and release mechanism (*HDRM*, see figure 11) is used to lock the legs and wheels to the chassis sides. In the inner compartment of the rover, the locomotion *E-box*, see figure 15, contains all motor drivers, the converters for reading the analog sensors and an FPGA to control the LSS. This E-box is controlled by the Loco *Software*, which is a C-code partition that runs within the hypervisor framework of the Rover's on-board computer. Last but not least, the 8 motors, 4 sensor connectors, 4 cruise heater connectors and 4 HDRMs are connected with 20 *harnesses* to the locomotion E-box, the main connector to the spacecarft and the power conversion and distribution unit (PCDU) of the rover.

3. Mechanics

Since the mechanical design of *Phase A*, described in [1], several adaptions were made for the final mechanical design to rectify the investigated problems during an intensive testing campaign. Vibration, impact and operation loads, as well as thermal stress and contamination by regolith were applied to the LSS within multiple particular tests.

In the following, different tests with their resulting design modifications are described.

Impact tests

The impact loads were applied to the LSS in two dedicated tests. The primary was performed with a full rover model (*Phase A prototype*) at DLR Bremen, as shown in figure 4. After several impacts from different orientations and on different targets, such as the ones shown in figures 4b and 4c, the functionality and robustness of the LSS was confirmed for the drivetrain and the HDRM concept. However, when the release was performed, the HDRM pillars (see figures 6b and 11), which are supporting the rim of the wheel during

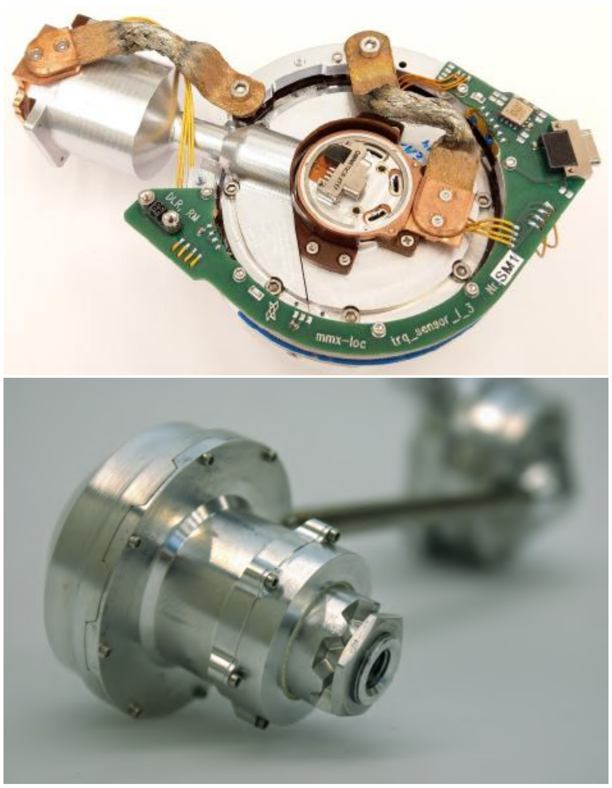
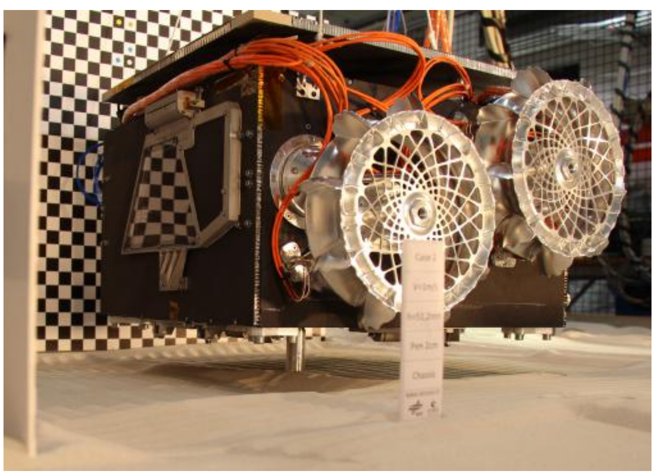
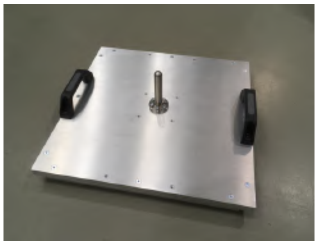


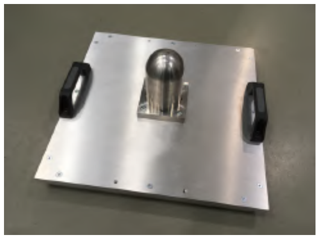
Figure 3: The shoulder module (top) and the full locomotion module, consisting of shoulder, leg and wheelhub (wheel not mounted) (bottom)



(a) The full rover mockup is dropped onto a target.



(b) Small target

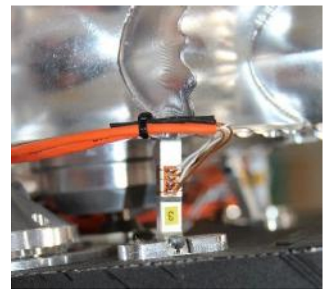


(c) Large target

Figure 4: The droptest setup. Courtesy of: DLR Bremen, LAMA, MMX.

Figure 5: The standoff, which supports the wheel to the side, was broken during the drop test.

(a) Local damage of the wheel spoke structure without impact on functionality.



(b) Pillars of Phase A prototype during Droptest equipped with strain gauges.

Figure 6: The LSS in the droptest.

vibration at launch and impact on Phobos, were not retracting due to a too weak motorization. To cope with that problem, the motorization of the pillars was increased to 2.5 N m, which is a multiple of the original value.

The secondary test was conducted with a standalone locomotion module (EM, see figure 3) at DLR Oberpfaffenhofen. At this point, the loads were extended due to changed parameters and the higher motorization of the pillars had been implemented. Three structural weaknesses were discovered: The teethed adapter of the leg, the standoffs of the pillars (see figure 5) and the base part of the pillar housing were plastically deformed. However, the functionality of the overall drivetrain was intact, i.e. the HDRM was able to release completely and wheels and shoulders were working nominally. As a result of this second test, the material selection was changed in the final mechanical design to provide a reinforcement for the corresponding interfaces.

Vibration test

The vibrational test case was conducted at IABG, Ottobrunn on a *Unholtz Dickie R16C-3* electrodynamic shaker. Two configurations (EM, figure 7) were tested to investigate the natural frequency shift. The first (baseline) configuration consists of a full locomotion subsystem unit and a complete HDRM unit with pillars (as shown in Figure 11). In this configuration, the wheel is fixed at four points during flight: in the wheel axis, where the Hold Down and Release Component (HDRC) is placed, and at three equally distributed points on the rim of the wheel through the pillars, which has the effect of increasing the overall stiffness of the system. The second configuration is missing the pillars, such that the

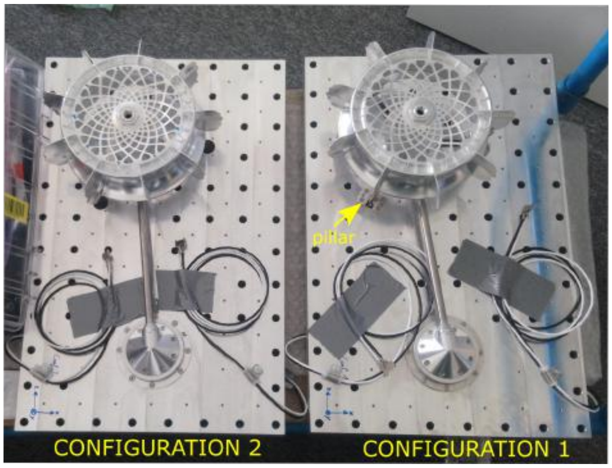


Figure 7: Configuration 1 (with pillars) and 2 (without pillars) for shaker test

wheel is only fixed in the wheel axis to the HDRC, making the system less complex, but also less stiff.

Both configurations passed the test without major damage, only some parts related to the wipers of the potentiometer sensors were affected by the test. Even though they had been structurally intact, safe operation of the potentiometers would not be guaranteed throughout the mission. These findings led to a design and material change of potentiometer carrier parts and wipers for the final design. The first (baseline) configuration was found to satisfy the required natural frequencies, whereas the second configuration of the vibrational test showed natural frequencies below 200 Hz. The missing pillars allow the leg and wheel to react to lower modes. This point is deemed critical by the system engineers due to similar frequency modes of the rover chassis. The release of the HDRM failed for the first configuration due to a known design error at the basement of the pillars, which is also resolved in the final design.

All these improvements will be verified in the structural model (SM) of the rover and later in the qualification and acceptance testing.

Sealing test

Although there is a large uncertainty about the surface of Phobos, it is likely to be at least partly of fine regolith. Therefore, the LSS must block regolith particles down to a size of 40 µm from reaching the inside of the rover or impairing the LSS functionality. Since the shoulders are a direct interface between the exterior and interior of the rover, this joint is protected by two serial sealings. The first is a labyrinth seal to stop the larger grains of sand and the second one, a lip seal made of PTFE, protects the inside against the powdery dirt and dust. The wheel has a PTFE sealing as well but this is not described in more detail here.

A *dust break-in test* was performed at the DLR Oberpfaffenhofen to test the described sealing system. The sand was mixed from olivine, calcium carbonate and coarse lava grains to achieve a particle size range of 40 µm - 6 mm.

While the sand trickled onto the hardware, see figure 8, the motor was turned first 2.5 min clock wise and then 2.5 min counter clockwise. This was repeated four times. Note

Figure 8: Setup of the dust break-in test: The external part of the shoulder sticks out of the protective blue foil and is covered with sand.

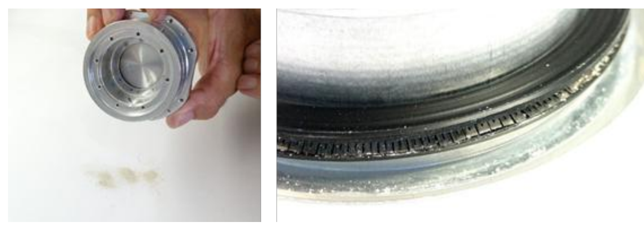


Figure 9: Inspection of the hardware after the dust break-in test. A small number of particles reached the outside of the PTFE seal.

that this is a rather extreme scenario since it represents 30 rotations of the shoulder while being constantly covered in sand.

After disassembling the hardware, a small amount of fine sand trickled out of the labyrinth seal, see figure 9, left. Only a very small number of particles reached and were blocked by the PTFE seal, see figure 9, right. No notable sand particles were found inside the shoulder module, which demonstrates the good functionality of the sealing concept.

Thermal tests

The thermal and operational conditions, which were given by preceding simulations, were reflected in multiple tests. The phase A prototype and EM actuators (consists of the motor and two gear stages, see figure 10) of the LSS were tested as standalone units. Tests were performed in a climate/thermal vacuum chamber (TVAC) at DLR Oberpfaffenhofen and as integrated units in the complete drivetrain (EM, see figure 3) in the TVAC at DLR Bremen. The actuators alone and integrated in LSS were exposed to low temperatures down to −180 °C non-operational storage temperature. Within functional tests after the thermal tests, no degradation of mechanical or electrical components was investigated. Further, a performance test was conducted in the TVAC at DLR Bremen to investigate the characteristics of the drivetrains at lower temperatures. The drivetrains were exposed from 20 °C down to −80 °C at different speeds and applied loads

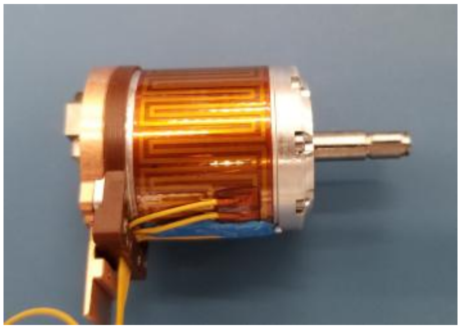


Figure 10: One actuator unit consists of the motor, two gear stages and a backshell with three hall sensors. The whole actuator is wrapped with a double-layer heat foil, see section 6.

Figure 11: HDRM unit (EM) in released state consisting of three pillars and central cone interface during Structural Model integration

from 0 to 4 N m. It was found that the drivetrain is working reliable with six step commutation down to its operational limit of −40 °C. As expected, there was a deterioration of the performance in the drivetrain observable below this allowed operational temperature. Lower temperatures lead to higher friction in the grease (Braycote 601EF) of the gearbox and the hall sensors, which are used for the position control of the motors (see section 7), reach their operational limit for correct switching. A few actuator units were succesfully tested outside the specified operational temperature between −40 °C and −80 °C by applying a *feed-forward mode*, which does not require the hall sensor measurements. This contingency mode worked well with the few tested units in the complete load range at low and medium speed at a cost of increasing the power consumption by multiple times.

Summary for the drive train

Going through the test campaign, the motorization of the drivetrains was always checked before and after a particular test. Neither vibration, impact, contamination or thermal stress led to a degradation of the LSS. Within the allowed temperature range, the required motor torques were achieved. Only below the minimium operational temperature of −40 °C, deterioration of the performance was observed. Several design weaknesses were found in the Phase A prototype and few last ones in the EM during the test campaign, which are considered and rectified in the final design of LSS. The improvements consist mainly of enhanced material selection, reduction of mass, modifications in design to respect thermal budget, see also section 6, and to increase the LSS reliability.

Wheel developments

The expected regolith surface of Phobos has been defined in more detail and the wheel design was optimized and refined for its use on Phobos. Only few details are known about the upper Phobos regolith layer at the scale relevant to rover driving, leaving a range of possible surfaces from coarse grained regolith dispersed with larger rocks to powdery soft soils. Out of this possible range of surface conditions, soft soil with little cohesion has been identified as the most challenging one, as it entails the danger of permanent entrapment due to high sinkage. Testing wheels in these conditions in lab experiments is complicated due to the effects of gravity on bulk granular materials, which are a topic of active research and cannot be replicated on Earth.

Thus, a simulation-based optimization study was conducted to improve wheel performance on challenging soils in Phobos gravity [7]. The simulation method of choice was the Discrete Element Method (DEM) as implemented in the *partsival* simulation software [8]. It enables large simulation campaigns by efficiently running simulations on GPUs. Soil parameters were chosen with worst-case assumptions to challenge the wheel design. The shape of the wheel is parametrized in terms of grouser height (at constant outer wheel diameter), grouser number, grouser curvature and rim curvature. These optimization parameters were chosen based on experience and previous wheel design studies [9–11]. The optimization conducts single wheel experiments driving forward and reverse on flat and sloped grounds and optimizes for traction, i.e. minimum slip. In comparison to the breadboard wheel [1], the optimized wheel shape, as shown in figure 12, has larger, straight grousers while keeping the inward curved rim. The optimal grouser number reduced from 9 to 7.

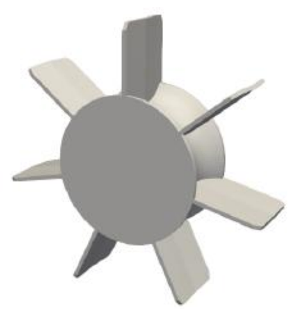


Figure 12: Traction-optimized wheel shape for Phobos [7]

Additional simulations were run for the wheel in a forced side slip scenario, as is the case during point turn manoeuvres. The knowledge gained from these simulations led to rounded shape and a reduction of the outer rim diameter, which lowers soil resistance when the wheel is pushed outwards. As the wheel hub is hollow, soil resistance is already lower for the other two wheels that are pushed inwards during the point turn.

The optimized shape was implemented in a new mechanical design for the FM wheel. This design had to consider more requirements than optimized traction, i.e. mechanical strength, manufacturability and the HDRM interface. Thus, functional integration had to be performed to meet mechanical requirements with the lowest mass possible. Therefore, the spoke structure is an outcome of topology optimization using FEM. Finally, the grouser number was kept at nine to keep the strong grouser base at the HDRM pillar interface. Following the optimization trends for nine grousers, the grouser height is increased less than the optimization suggests. The grouser shape has kept a slight curvature to increase their strength and stiffness. Other wheel features such as the shape of the grouser tips, the spoke structure and the side struts were adopted from the breadboard wheel as they increase the design's structural strength and traction on harder surfaces and obstacles. This balance between traction and structural features as well as the use of a high strength aluminum alloy were the key points to keep the wheel's mass as low as 190 g. The FM wheel design is shown in Figure 13.

Figure 13: The FM wheel design.

The structural design of the FM wheel was tested and confirmed during shaker, thermal and drop testing. Traction tests were performed on olivine sand using an LSS prototype, which showed good driving performance and confirmed an improvement in traction over the breadboard wheel, also under Earth-g. Additional DEM simulations of the FM wheel design in Phobos-g were run for the optimization scenarios and new simulations were conducted for the soil deemed most likely in the ERD (which shows cohesion), again confirming the FM's improved performance. Overall, the FM performs 42% better than the breadboard wheel (based on the weighted travel distance in the flat, reverse and slope single wheel simulations [7]).

4. Electronics

Overview

Figure 14 shows an overview of the locomotion subsystem electronics.

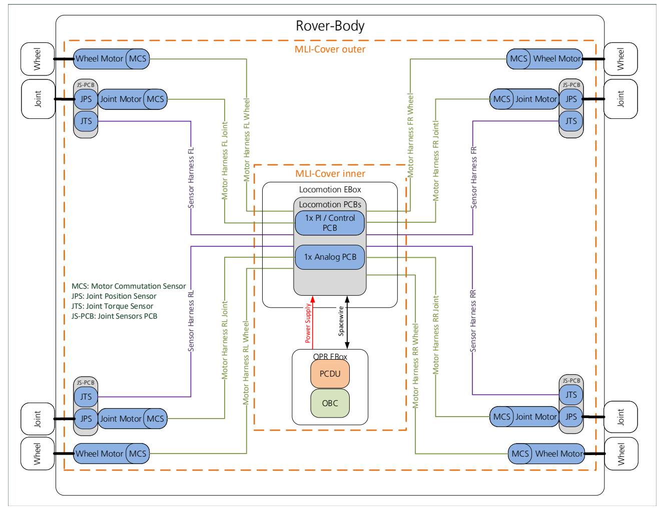


Figure 14: Overview LSS Electronics

Figure 15: The Loco E-Box

The main task of the central locomotion electronics box (E-Box) is to control the eight wheel and joint motors and to collect the sensor data. These are motor currents, joint positions, joint torques, accelerations, rotation rates as well as temperatures and voltages for housekeeping purposes. Due to the extreme temperatures in the vicinity of the rover, as many electronic components as possible are housed in the central E-Box in the tempered inner part of the rover. Only the motors and some sensors are located in the peripheral area of the rover, where they have to withstand significantly lower temperatures.

The E-Box is supplied with power from the rover's central power control and distribution unit (PCDU). The data interface is a SpaceWire link, via which the E-Box communicates with the on board computer (OBC) of the rover. The movements of the motors are commanded and the measured sensor values are sent to the OBC via this interface. The central element of the E-Box is a radiation-hard FPGA. The FPGA controls the power inverters for the motors, collects the sensor values via Analog Digital Converters (ADCs) and communicates with the OBC. Details on this have already been presented in [1].

Compared to the concept presented in the aforementioned publication, the topology of the locomotion electronics has been optimized to save space and weight. A backplane to connect several printed circuit boards (PCBs) is no longer used. The FM E-Box only consists of two PCBs, one on top of the other, which are connected via a board-to-board connector. The FPGA and the SpaceWire communication interface as well as the power inverter for all eight motors are integrated on one circuit board. On the second PCB there are power input filters and analog sensor interfaces. Both PCBs are in a common aluminum housing, which is used for mechanical support, electrical shielding and heat dissipation at the same time. Thereby, the entire electronics is accommodated in a space-saving manner in the space available in the temperature-controlled inner part of the rover. At the same time, care was taken to ensure that the mass of the electronics was kept as low as possible thanks to this integrated topology. Compared to the concept presented in [1], two rotation rate sensors were also integrated into the E-Box to provide supporting information for the autonomous uprighting process of the rover.

The motors and sensors in the peripheral area of the rover are connected to the E-Box via cables. These cables have been optimized with regard to the technical requirements of current rating, operating temperature resistancy, insulation voltage and weight.

EMC, ESD

The electronic design is optimized in terms of reliability, electro-magnetic compatibility (EMC) and performance. A proper operation of the LSS in case of an electrostatic discharge (ESD) of the residual charge on the rover during the impact on Phobs is ensured by design and optimized by simulation. With up to eight motors driven by a three phase pulse width modulated (PWM) signal at the same time, the electromagnetic emissions of the cables and motors could lead to a faulty operation of the rover. These emissions are reduced and optimized to ensure a safe operation of the rover system by the comprehensive shielding and grounding concept.

A custom tailored EMC specification and test environment based on the ECSS-E-ST-20-07C is developed to ensure the auto-compatibility of all rover subsystems during the complete mission. Multiple pre-compliance tests of the locomotion subsystem were performed during the hardware development and commissioning. The electronic design is optimized based on the results of these tests and the effectiveness of the system shielding and the grounding concept was also checked and verified by this. Potential sources of electromagnetic interference were identified and could therefore be taken into taken into account in an early design stage.

Testing

The rover must survive in extreme low temperatures on the surface of Phobos. Therefore, multiple thermal test campaigns on component level were conducted. Especially the hall effect sensors which are located on the backside of the motors are exposed to very low temperatures due to the fact that the motors are located outside of the heated cabinet of the rover and the heating of the drives was set to an absolute minimum in order to save energy.

The used hall effect sensors from Infineon (TLE4945, [12]) are Commercial off-the-shelf (COTS) parts. These parts are rated down to $-40\,^{\circ}\mathrm{C}$ storage and operational temperature which is not sufficient for this mission. Therefore, thermal cycling tests between $-130\,^{\circ}\mathrm{C}$ and $-60\,^{\circ}\mathrm{C}$ storage temperature were conducted. Additionally, the operational behavior down to $-70\,^{\circ}\mathrm{C}$ was insvestigated with functional tests. After this thermal cycling test campaign, hundred percent of the cycled sensors were functional tested and then a subset of them was analyzed by polished micrograph section and X-rays in order to find mechanical defects of the parts. The other used COTS parts are located inside the heated cabinet of the rover, therefore, no additional temperature tests on component level were conducted.

Although the expected radiation level is rather low during this mission, for all used COTS parts at least TID (Total Ionizing Dose) tests were performed at the Helmholtz Zentrum Berlin Wannsee (HZB, [13])). These COTS parts are: An automotive rated brushless DC motor controller from Texas Instruments (DRV 8332, [14]), a 3-Axis Accelerometer from ADI (ADXL356-EP, [15]) which is suitable for military applications and finally, a precision gyroscope from Silicon Sensing (CRM200, [16]).

For the 3-Axis Accelerometer ADXL356-EP, a proton test was conducted at the HZB additionally. Finally, the radiation performance of the TI DRV8332 was characterized by means of a proton test (performed at the HZB) and a heavy ion test. The heavy ion test was conducted at the radiation effects facility in Jyvaskyla (RADEF, [17]).

Test results: The hall effect sensors survived the temperature cycling tests without any broken device. Furthermore, the operational limit was found below $-40°C$ but with degraded performance, which was confirmed again in the actuator tests that were described in section 3. During the TID tests no failure or malfunction was measured for any of the tested parts. Due to needs of other projects, where the hall effect sensor and the brushless motor controller are used, the applied dose for this parts was 645 Gy(Si) (TLE4945) resp. 550 Gy(Si) (DRV8332). For the ADXL356-EP a total dose of 293 Gy(Si) was applied and for the gyroscope only 167 Gy(Si), which exceeds the needs of the MMX mission by factors.

Similar to the TID tests, during the proton tests no failure was measured. The applied fluence was $2.0 \cdot 10^{10}$ protons per square centimeter, the used energies were below 68 MeV per proton. Finally, during the heavy ion test of the DRV8332, Nitrogen, Krypton and Xenon ions were used. The applied fluence was $1.0 \cdot 10^{10}$ ions per square centimeter. A detailed description of the DRV test campaigns could be found at [18].

5. SENSORS

Advances on rotational sensors

The MMX LSS utilizes a set of potentiometer sensors to assess the angular position of each locomotion joint. This capability is required during all mission phases, e.g. during the uprighting after impact and deployment as well as for the process of sun-pointing to increase the amount of engery collected by the solar arrays. On top of that, the measurement of the joint angle will be used when the joint position is adjusted during driving or in case of a power down phase that requires a re-initialization of the joint positions.

Regarding the safety concept, a diverse approach has been chosen that leads to the implementation of two different potentiometer technologies in each shoulder module. The first potentiometer is a scratch wiper based type on FR4 substrate including support components, that have been modified to match the environmental requirements. The second potentiometer consists of a 0.5 mm thick sandwich of polyimide sheets and is activated by pressing on the sensor surface. The geometries of both sensors have been intensively optimized to fit in the small inner compartment of the shoulder unit. The sensors are backed-up by the mentioned hall sensor, that is integrated by the FPGA and stored on and re-stored from a non-volatile memory of the OBC by the locomotion software.

One of the big challenges regarding the rotational poten-

Figure 16: FR4-based (left) and Polyimide-based rotational Sensor (right)

tiometer sensors are the cold temperatures during the mission. The sensors are located in the cold area of the shoulder module, i.e. thermally insulated from the heated motors and shoulder electronics. The temperature of the sensors, however, conincides very well with structural parts of the locomotion Shoulder module on which the temperature is measured with temperature sensors. To this end, temperature coefficents for both potentiometers can be taken into account.

Support parts for both potentiometer sensors comprise specially designed wipers and wiper carriers. Initially, ULTEM 1000 was selected for the prototype and EM LSS due to suitable properties for space applications. However, as mentioned in section 3, these parts have shown structural weakness during vibrational tests, related to their small size and delicate geometry. In detail, the vibrations lead to the formation of cracks in the wiper carrier of the FR4-based potentiometer around the mechanical connection points. Furthermore, the wiper of the Polyimide-based potentiometer showed increased wear at the contact point. Even though further operation may have been possible, which basically shows the robustness of the concept, a change of materials and slight changes in the design have been performed to solve the issues. The wiper carrier for the FR4-based potentiometer was split into two parts: A TECASINT insulator for the wiper is connected to the structure by an aluminum carrier with the geometry of the former wiper carrier in order to match the integration options of the original setup. The size of the complete structure is kept equal. The wiper for the Polyimide-based potentiometer kept its original geometry while its material was changed to polished high-grade steel and its mechanical connection to rivetting.

At the moment, tests with the new parts are ongoing whereas main activities aim at validation for environmental requirements and the optimization of joint angle assessment from the acquired potentiomenter signals under various thermal conditions.

Torque sensor

The torque sensor is a special design for the requirements of the MMX rover mission. Goal of this development was the compromise between robustness and precision. Robustness because of the rover's impact on Phobos after its drop out of the spacecraft. Precision because of the milli-g environment and the related very low measurement signal.

The torque sensors, based on the strain gauge technology, was chosen because of its robust and reliable technology which has already been used on several space missions, e.g. in the Robotics Component Verification on ISS (ROKVISS) project [19]. Due to the harsh environmental conditions on Phobos, special attention was paid to the torque sensor development and test. For example, for the current EM and the following

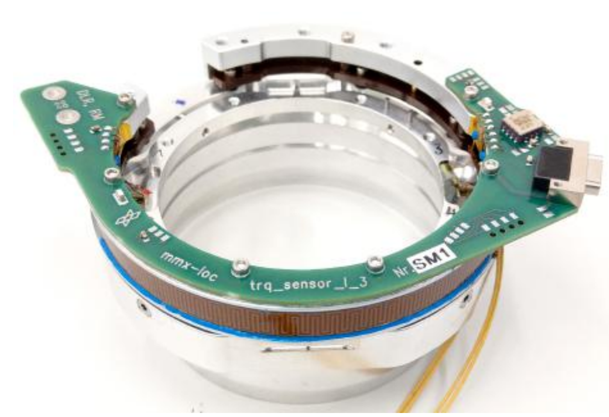


Figure 17: Torque-Sensor with PCB and heater

FM, a thermal structure with a heating foil was implemented between PCB and sensor mechanic. This was done to prevent the sensor electronics against the extremely low temperature to which the hardware is exposed because of the proximity to the outer wall (down to less than -100°C).

Due to the low gravity on phobos (milli-g environment), special care must be taken for the accuracy of the sensor calibration. In order to obtain this high measurement accuracy, each torque sensor is calibrated with the help of a tensile testing machine. The mechanical end stops which are included in every torque sensor are foreseen to protect the sensor mechanics especially during the impact of the landing phase.

Acceleration sensor

The MMX rover is dropped from the spacecraft to land on the Phobos surface in a "landing by impact" phase. This maneuver was tested in the DLR Landing and Mobility Test Facility (Bremen), through various drop tests with a full rover mockup. To simulate different surface cases, a sandy environment as well as test surfaces (targets) were used. For the drop tests, a special PCB for the torque sensor was designed to verify the torque- and position sensors as well as to select between two accelerometer sensor (ACC) ranges. The sensor ADXL 326 with range of $\pm$16g and the ADXL 377 ($\pm$200g) were used in the tests. Beside these sensors on the LSS hardware, a number of other sensors were installed on different locations on the rover mockup to verify the forces of the drop test and the associated impact limits. It turned out, that the large range of $\pm$200g was not needed, however, some cases exceeded the $\pm$16g range. Additionally, the low z-axis bandwidth of 550Hz as well as the expected low radiation resistance of both sensors, leads to the selection of the sensor ADXL356EP. This military used sensor has a range of about ±40g, a high bandwidth in all axes and even a higher operational temperature range.

6. Thermal design

Thermal design locomotion modules

The locomotion modules can be divided into two main thermal areas, the shoulder module and the leg structure including the wheel (see figure figure 3). The former is located inside the chassis and mechanically connected to the chassis side panels and contains the position- and torque sensors, as well as the actuators. With that design choice, temperature sensitive parts and components are shielded from the harsh environmental conditions of the different mission phases.

For externally exposed body surfaces of the shoulder module, different reflective coating options have been investigated to reduce the thermal radiative heat leakage into the cold environment. However, thermal analyses have shown that for the AL7075 parts, the coating Surtec650, which is used for the electronic grounding concept, provides sufficient properties already. For the structural connection between the locomotion shoulder module and the chassis panel, an optimization process has been conducted by means of part geometries and material selection. Therein, the thermal link was maximally decoupled, while simultaneously meeting the mechanical load requirements expected in the mission phases. Another significant thermal design choice is located inside the shoulder module. Equally to the chassis connection, the two actuators and the torque sensor electronics are thermally isolated from the remaining shoulder components, in order to reduce the heating power required for the survival and operational temperature setpoints.

Three individual double-layer heat foils are used for each locomotion shoulder module. The respective layers of the heat foils provide the heater resistance for the independent heater control lines of the spacecraft (during the cruise phase) and the rover (for the Phobos mission phase). They are positioned directly on the housing of the actuators and on the torque thermal ring where the torque PCB is attached (see figure figure 17). In addition to providing the available surface area for the heat foil, the torque thermal ring is also used to increase the heat capacity of the torque PCB, which significantly improves the temperature controllability for this area. Since only a limited number of temperature sensors are available for the heater control lines, an individual control of each heat foil area is not feasible. Therefore, the thermal design is optimized by the usage of thermal straps, as shown in figure figure 3, to couple the heating areas of each shoulder. Furthermore, the heat foil outputs are thermally adjusted. This results in a heating zone which can be controlled with one temperature sensor. The leg structure and the wheel consist exclusively of mechanical components. The material Ti6Al4V is used for the leg parts. Due to the low thermal conductivity it is used to further isolate the shoulder modules from the wheel, which touches the cold surface of Phobos.

Thermal design Ebox

The locomotion E-box is located inside the service module of the rover. The thermal environment of the service module is isolated from the external environment and maintained for several instruments. Therefore, the locomotion E-box does not have active thermal control elements and the temperature is passively maintained. As described in section 4, the locomotion E-box contains two PCBs, and one of the PCBs carries the motor controllers DRV 8332, which are the largest heat dissipating elements in the locomotion E-box. They are mounted on the PCB, but in the meantime they are attached to the aluminum housing of the locomotion E-box as well, in order to efficiently remove heat from the motor controllers. Between the housing and the motor controllers, a silicon based thermal gap pad is implemented in order to ensure the thermal connection over the interface. The external surface of the locomotion E-box has Surtec650 coating with low emissivity. Therefore, the major portion of the generated heat inside the locomotion E-box is transferred to the mechanical interface by conduction.

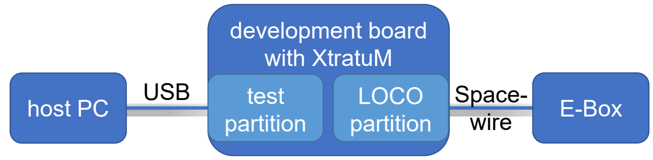


Figure 18: The test setup for the full communication chain.

7. Firmware & software

Architecture

The OBC of the MMX rover is provided with the hypervisor XtratuM, which divides the overall rover software into more manageable pieces. Certain subsystems have their own partition, receiving commands from and sending telemetry to a command and control partition (CCSW), that is developed by CNES. Thus, also the LSS has its own partition on the OBC, which is the only interface to control and supervise the LSS. The OBC and the LLS are connected via a SpaceWire Link.

The main improvements of the software compared to Phase A are the implementation of additionally required features and testing on a flight-similar setup. In the following, the development of the locomotion partition is described in more detail followed by an overview of the E-Box firmware development and motor control aspects.

Software

After the development of the required locomotion control algorithms in MATLAB [20], these algorithms were implemented with some improvements in the target language C. A test driven development was followed such that all functions and subfunctions in the control algorithms module are already unitary tested. To form the required partition for the MMX rover's on-board computer, the software was extended by several features:

- a statemachine which is managing the functions that the software executes
- an event generator that is controlling the state machine based on notifications that can be issued by all parts of the locomotion software
- the inter-partition communication to receive telecommands from other on-board partitions and send housekeeping data in the desired format
- the spacewire communication to send telecommands to the E-Box and receive housekeeping data
- monitoring of the sensor values of the E-Box and fault recovery when required.

All these features were tested within the test setup shown in figure 18. In this setup, the OBC is replaced with a development board featuring hardware similar to the actual MMX rover OBC and is connected to the E-Box via SpaceWire. The CCSW partition is replaced by a testing partition that sends and receives telecommands and telemetry in the same designated format. The hypervisor running on this development board is scheduling the locomotion partition as required for 5ms in a frequency of 10 Hz. With this test setup, the inter-partition communication as well as the spacewire communication from and to the locomotion partition could be verified.

Firmware

During the development of the firmware for the E-Box FPGA, particular attention had to be paid to FPGA resources and development time. With eight motor controllers and a large number of sensor data registers, close to 95% of the FPGA's resources are utilized. Therefore, several firmware submodules are used in a multiplexed fashion to conserve resources. Additionally, with the E-Box going through its development iterations, the firmware had to be adapted to cover for new and removed functionalities. The Wishbone On-Chip bus [21], connecting firmware modules, combined with SpaceWire Remote Memory Access Protocol (RMAP) [22, 23] allow to reuse and adapt previous developments easily. Accessing the E-Box firmware in a memory mapped manner reduces the effort to update software to new firmware versions. Additionally, experiments like the rover drop test required different functionality. Here, an extension board for the breadboard LSS electronics was used to record acceleration data. For motor control development, motor currents were recorded by the same firmware modules in a different configuration. The same modules or updated versions of those were successively integrated into the E-Box firmware.

Motor Control

The motor controllers implemented on the E-Box FPGA have been significantly improved during the development process in terms of robustness and functionality. While keeping the firmware architecture as simple as possible to maximize ressource effectiveness, various operation modes allows it for the LSS software to operate the motor controllers in a toolbox manner. This design philosophy was chosen to achieve a high degree of flexibility and because, unlike the LSS software on the OBC, the FPGA firmware cannot be updated during flight.

The nominal Six-Step mode makes use of the hall sensor signals to efficiently commutate the motors and to calculate the positional information of the drive as a feedback signal to the position controller. To account for the harsh environment in which the drives are intended to operate, an additional "feed-forward" fallback mode has been implemented. Therefore, at the cost of energy efficiency and with no means of closed-loop position control, it is possible to continue the drive operation even if the positional feedback system fails. The "pattern" mode, c.f. figure 19, was designed to support the functional safety features of the LSS software, such as algorithms for health check and stuck recovery. The motor controller moves the motor according to a predefined, hard-coded pattern without requiring any interaction with the LSS software during the movement. The advantage of this mode is that the rate of the commanded movements can be chosen arbitrarily, regardless of the restrictions imposed by the communication cycle rate. Since the actual position value of the drive is recorded at certain key points, no further synchronization mechanism with the software is required to obtain a result vector from which a pass/fail criterion for the algorithm can be derived.

Simulation

For the rover's design, prior knowledge and analysis of the rover's behavior on Phobos is needed. To provide this knowledge, a rover simulation has been developed. A detailed description of the full system topics and the simulator design itself can be found in [24]. One of the analysis that have been performed for the LSS design is the search for the maximum save acceleration of the motors. Although the joint design provides an upper limited due to friction, inertia and

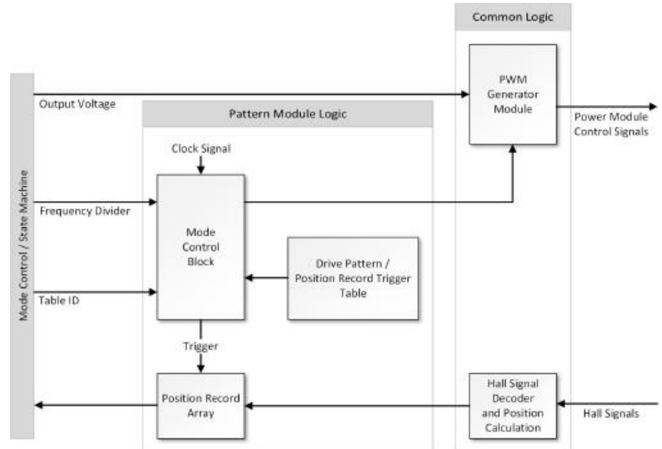


Figure 19: "Pattern" mode design architecture.

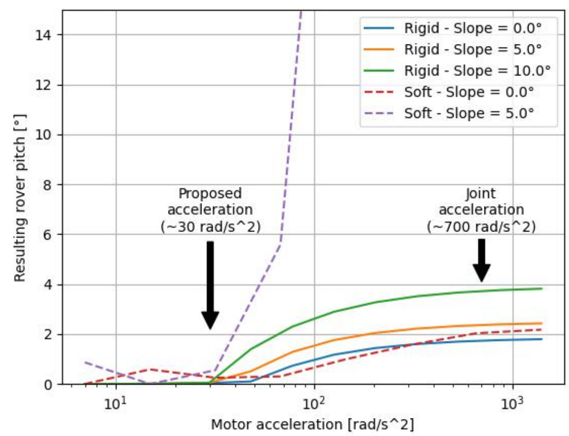


Figure 20: Rover pitch plotted versus the motor acceleration for different slopes on soft and rigid terrain.

power limits, it was required to determine if this is sufficient or if more restrictive limits have to be implemented in the software. To provide this answer, a simple experiment was designed in simulation, where the rover accelerates to its nominal driving velocity while being positioned on different slopes within the expected range for Phobos. The simulations were performed on an idealized flat surface as well as on soft deformable terrain. For each of theses cases the resulting rover pitch from acceleration at different accelerations rates is shown in Fig. 20. The results show, independently of terrain and slope, that a critical acceleration of around $30\,\mathrm{rad\,s^{-2}}$ exists. As this acceleration is well below the joint acceleration, an additional limit in software is recommended to ensure safe operation on Phobos.

8. Conclusion

The LSS for the MMX rover is a complex, mechatronic system that is an entirely new and custom development at the DLR-RMC. From the start of the developement in 2018 over the phase A concept, that has been presented in 2020 [1], the team has now reached the final FM design. Tremendous testing, analysis and optimization campaigns have been performed and led to numerous design changes in several iterations. The most important ones were described in this paper and an overview of the final FM design was given.

During the writing of this paper in Autumn 2021, the production of the qualification and flight model of the LSS is ongoing and the qualification and acceptance test campaigns will be finished before Summer 2022. The MMX spacecraft will be launched in 2024 and the rover is scheduled to land on Phobos early 2027. The LSS will then be a central part of the mission timeline on Phobos from the uprighting all the way to exploring the vicinity of the landing site. As part of the mission, the locomotion science experiment [2] will provide new knowledge and findings on all aspects of the LSS and the first locomotion in milli-G.

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