DRIVING IN MILLI-G: THE FLIGHT MODEL OF THE MMX ROVER LOCOMOTION SUBSYSTEM AND ITS INTEGRATION & TESTING IN THE ROVER

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ABSTRACT

IDEFIX is a 25 kg four-wheeled rover that will explore the surface of the Martian Moon Phobos in 2027. The rover is jointly developed by the German Aerospace Center (DLR) and the Centre National d'Études Spatiales (CNES) and will be brought to Phobos within the Japan Aerospace Exploration Agency's (JAXA) Martian Moon eXploration (MMX) mission. Being the world's first wheeled system to drive in milli-gravity, IDEFIX's locomotion deserves special attention.

This paper gives an overview of the locomotion subsystem (LSS) of the rover, which is entirely developed and built by the Robotics and Mechatronics Center of DLR (DLR-RMC). A representative LSS, mounted on an IDEFIX prototype, is shown in Figure 1. The LSS is tailored to the needs for the IDEFIX rover and the most important, sizing challenges and functional requirements are summarized. It is then shown how the final flight model (FM) design answers to these requirements. The assembly, integration and testing (AIT) with respect to the LSS consists of several steps of integration and testing at different facilities as well as a comprehensive test sequence once the rover is mostly integrated. Since the LSS is an important, interconnected and the functionally most complex subsystem of the rover, some functionalities could only be tested once the LSS was integrated into IDEFIX. These AIT aspects are therefore summarized in this paper as well.

Key words: Exploration; Phobos; Mars; Rover; Locomotion.

1. INTRODUCTION

The Japanese MMX mission is designed around the goal to return a sample from the Martian Moon Phobos. IDEFIX therein has the role of a surface scout, which means that JAXA is especially interested in the mechanical properties of the Phobos surface. Therefore, IDEFIX shall record the accelerations during the impact on the surface and take images of its surroundings.

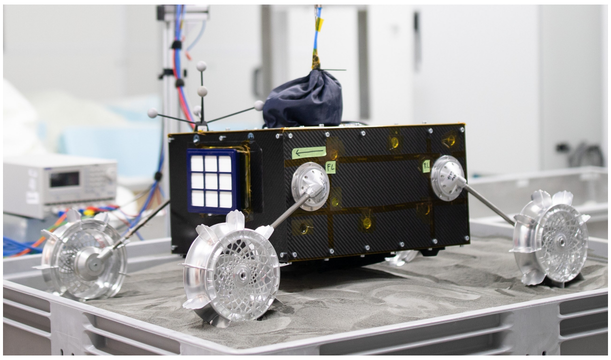

Figure 1. The IDEFIX prototype with representative LSS in the DLR-RMC testbed.

However, IDEFIX has several more scientific and technological mission goals (see also [9]):

- Locomotion science: Perform first drive in milli-gravity and learn how the interaction of rovers with the ground work in such low gravity.
- Regolith science: Analyze the behavior of the ground material itself by manipulating it with the rover wheels and filming it with dedicated downward cameras.
- Mineralogical composition: Raman spectroscopy to determine the elements of the Phobos surface with the RAX instrument.
- Thermal properties: Determine e.g. temperature, temperature gradient and emissivity with the miniRAD instrument.
- Navigation experiment: Perform autonomous navigation in Phobos environment.

IDEFIX will be shipped to Japan in November 2023 to be integrated into and tested in the main spacecraft. The launch is planned for September 2024 and the travel to Phobos takes about 2.5 years. Around February 2027, IDEFIX will be separated from the spacecraft in a height of about $50\,\mathrm{m}$ above the Phobos surface and reach the surface in a free fall. After some expected but uncontrolled bouncing, IDEFIX stands up onto its four wheels, which are mounted at the end of 360° rotatable legs. Only then can the solar arrays be safely deployed and the battery can be recharged. To do so more efficiently, the whole rover body is oriented such that the solar arrays point in an optimal angle to the sun. This entire first sequence is referred to as *Separation-Landing-Uprighting-Deployment* and will need to be executed completely autonomously. The need for autonomy stems from the communication round-trip time: IDEFIX itself does not have enough power to communicate to the Earth directly but uses the JAXA spacecraft as a relay. The latter, however, only communicates to the Earth or the Rover in an alternating pattern of a couple of Phobos days in each direction. This results in a communication round-trip time of 1-2 Earth days, which prohibits any ground interaction with the rover before it can recharge its battery.

In terms of driving, the mission itself consists of straight and curve driving as well as point turns. Wheel cameras allow to take images and video clips of the wheel interaction with the regolith, which will be taken during drive sessions. For the Raman spectrometer onboard IDEFIX, the LSS needs to lower the rover body to allow proper focus. Ultimately, IDEFIX will make a daily check if the orientation towards the sun is still sufficiently good and the LSS – together with a CNES algorithm – re-aligns the rover body in case it is not.

2. MAIN CHALLENGES AND REQUIREMENTS

Phobos's gravity ranges between 1/1500 to 1/3000 of Earth's gravity, whereas wheeled exploration rovers were so far only successfully deployed on the Earth Moon ($\sim 1/6g$) and Mars ($\sim 1/3g$). Besides challenges associated with the gravity, the temperature range over a Phobos day-night-cycle are extreme as well. This section first details the challenges associated with the extreme environment and MMX Rover mission in Section 2.1 before summarizing the main functional requirements in Section 2.2.

2.1. Challenges

The most prominent challenges are associated with low gravity. Four aspects are especially relevant for the locomotion system.

First is the system's unintuitive behavior, even at low speeds, when moving. As the inertia stays constant, but weight and thus traction forces derived from weight are scaled with gravity, even low speeds can cause effects usually only associated with high velocities. Even low acceleration can easily cause the rover to flip, caused by too high acceleration of the wheels or legs of the rover or by collisions with the environment. This effect leads to strict limitations in maximum velocity and maximum acceleration.

Second, when compared to the dry regolith under Earth gravity, the low gravity is changing the dominant effects in ground interactions. Indeed, on Earth, the main contribution to the reaction force is friction, which depends on a normal force usually stemming from gravity, whereas cohesion usually plays a minor role. On the contrary, on Phobos, with roughly 1/2000 of Earth gravity, the friction component significantly decreases in magnitude, while cohesion is predominantly unaffected. This results in a dramatic increase of the contribution of the cohesion effects.

Third and of particular interest for the design and selection of components is the detrimental relation between friction in the drive trains and the expected loads required to operate the rover. On Earth, Mars, or the Moon, forces required to move the rover usually exceed shoulder friction. On Phobos, these friction components supersede the external forces by a significant amount. This ratio makes it nearly impossible to design passive suspensions suitable for Phobos.

Finally, experimental testing of system behavior on Earth is limited to component-level tests or is heavily limited. Sensible system designs for a Phobos environment are not built to withstand loads from Earth's gravity without support. Further, the points mentioned above will heavily change the system's behavior, limiting the significance of experiment results. This challenge results in the need for accurate simulation tools during the development and operation of such a system. For more details on simulations, see [4].

Besides the challenges associated with the low gravity, the thermal environment poses additional problems. The surface temperature on Phobos changes from about $-150\,^\circ\mathrm{C}$ to about $50\,^\circ\mathrm{C}$ within a day-night cycle. Besides the extremely cold absolute temperatures at night, this means a full temperature cycle of about $200\,\mathrm{K}$ within 7.6 hours, resulting in challenging gradients.

2.2. Main Functional Requirements

In Section 1, the overall mission objectives and rover movements were already introduced. For the LSS, these high-level requirements result in several functional and performance requirements. Not all requirements can be listed here but some important functional and performance requirements are presented to enhance the understanding for the system:

- Drive $100\,\mathrm{m}$: Although the minimum mission goal is much less, the LSS shall be designed to drive at least $100\,\mathrm{m}$
- Allow Uprighting: The LSS shall provide the uprighting functionality.

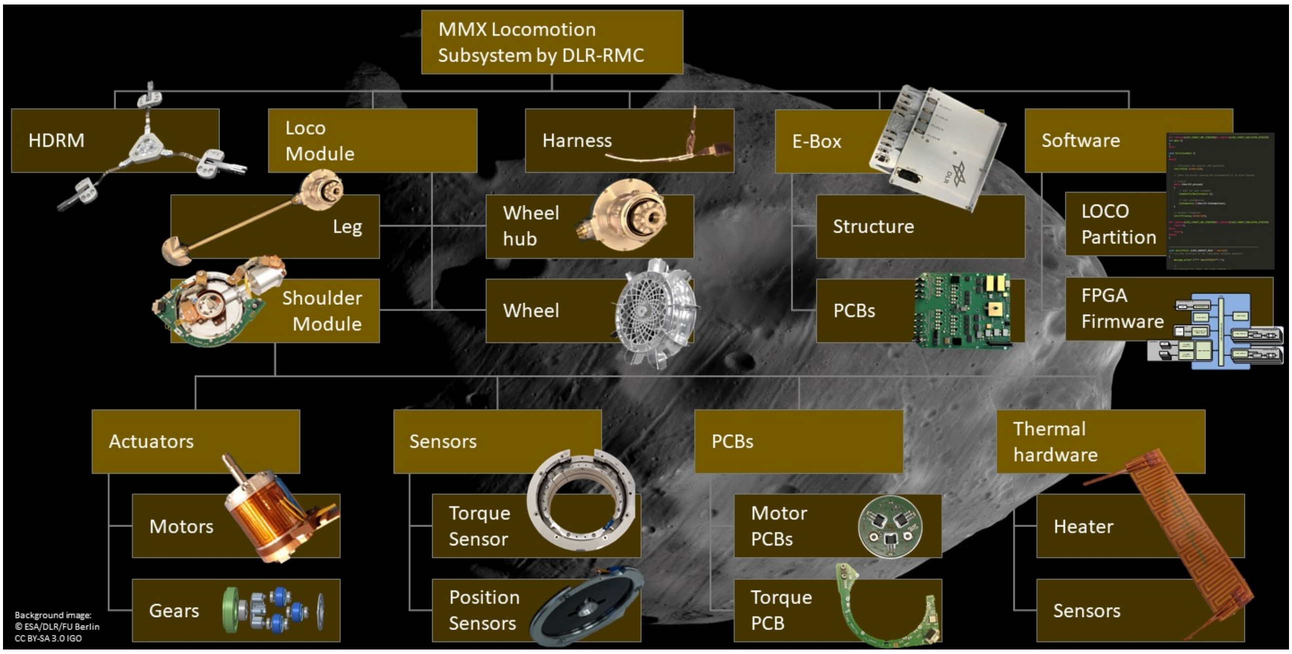

Figure 2. Components of the locomotion subsystem (from [2])

- Provide a rover pose information: The LSS shall know and communicate the pose based on its current leg angles to other subsystems onboard the rover.
- Alter the rover body orientation and height: The LSS shall allow to change the rover body orientation (for sun-pointing) and height (for increasing stability and for the RAX instrument positioning).

3. THE FLIGHT MODEL

As shown in Figure 2, the LSS consists of five main parts. Mounted on the IDEFIX's chassis side plates (see Figure 3) are the locomotion modules, consisting themselves of shoulder, leg and wheel, as well as the hold-down-and-release-mechanisms (HDRMs). The locomotion E-Box is located in the thermally isolated inner compartment of the rover together with electronics of other subsystems and the main power conversion and distribution unit (PCDU) and on-board computer (OBC). Harnesses connect the locomotion shoulders to the locomotion E-Box, the OBC, the PCDU as well as to the umbilical connector that connects IDEFIX to the JAXA spacecraft. Ultimately, a custom firmware is flashed to the field programmable gate array (FPGA) inside the locomotion E-Box to provide high-frequency motor control, current surveillance as well as sensor reading and communication to the OBC. On the OBC, a locomotion software partition provides kinematic control functions, fault detection isolation and recovery (FDIR), monitoring and telecommand processing and telemetry packetizing.

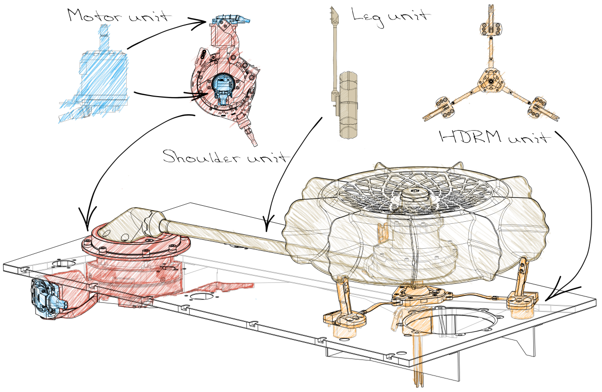

Figure 3. Overview of the locomotion module and HDRM assembly on a chassis side panel (from [7]).

3.1. Locomotion Module

As depicted in Figure 3, the locomotion shoulder unit, leg, wheel and HDRM are mounted together to the chassis side panel. The HDRM is described in more detail in Section 3.2, whereas the other components of this assembly are described here. Note that each side panel carries a front and a rear unit and not only the one depicted in Figure 3 for readability.

Wheel design From the outside, the wheel is the most prominent part of the LSS. The wheel shape is optimized in discrete element simulation (DEM) for good traction even on softest soils, which leads to the large grousers and concave rim surface that can be seen in Figure 3.

Purely optimizing the traction would have lead to even larger grousers (see [8]) but would have compromised stability and robustness. An optimization of the mass with a finite element model (FEM) yields the meshed spoke structure that connects the wheel rim with its hub. Following side-slip tests and DEM simulation, the wheel rim curvature was furthermore designed asymmetrically to reduce the side-slip resistance of the leading wheels during a point turn.

Drive trains Due to the temperatures on Phobos ranging down to about $-150\,^\circ\mathrm{C}$, the wheel motor was not designed into the wheel hub. The drive torque is rather applied to the wheel via a crown gear in the wheel hub, a drive shaft inside the leg and a bevel gear in the shoulder module. The wheel motor unit itself is in the center of the shoulder module and consists of stator, rotor, two gear stages, several bearings, a sealing and a backshell for commutation. To be resilient to very low temperatures, the bearings as well as the first gear stage – a planetary gear with ratio 1:5 – are dry-running. Possible cold-welding issues are prevented by using only dissimilar materials: The bearings are made of silver-coated stainless steel rings with ceramic balls and a polyimide snap cage. In the planetary gear stainless steel and self-lubricating polyimide are used for the sun / ring gear and the planets, respectively. For achieving the high reduction ratio that is needed for the slow movements on Phobos, a harmonic drive gear with a reduction of 1:100 completes the motor unit. The latter gear is lubricated and thus limits the minimum temperature to $-80\,^\circ\mathrm{C}$. Heat foils are wrapped around the motor housing to stay within the required operational and non-operational temperature environment. In combination with the large temperature variation, the different thermal expansion coefficients of the used materials require soft-preloaded bearing arrangements. Altogether, the motor unit weighs about $80\,\mathrm{g}$ and has a diameter of $27\,\mathrm{mm}$. For rotating the leg, an identical motor unit is used together with another crown gear. This shoulder motor can be seen in Figure 3 as the motor unit that sticks out of the otherwise round shoulder module. The total resulting gear ratio for both drivetrains – wheel and leg – is 1:2227 and allows to achieve the required output torques of $0.5\,\mathrm{N\,m}$ for the wheel and $1.5\,\mathrm{N\,m}$ for the leg plus margins and friction.

Leg position In the commutation backshell, three Hall effect sensors are assembled and the backshell is rotationally aligned to the rotor during a calibration process. The Hall signals are used in the FPGA to get a relative position encoder, which is mainly used for an efficient feedback control of the motors (see [1]). Apart from this function, the encoder-values are communicated to the OBC and the locomotion software constantly computes the current leg angle from the relative encoder value and an offset from previous operation. This offset is constantly updated in the non-volatile memory of the OBC. Although this combination is almost equivalent to an absolute position sensor, another truly absolute position sensor is implemented in the shoulder. Two different potentiometer technologies were developed and integrated all the way into the qualification model of the LSS (see [1]): A polyimide foil sandwich based potentiometer and a scratch wiper based on FR4 substrate potentiometer. During the qualification campaign, the foil potentiometer has, however, shown problems with low temperatures and was thus passivated. A dedicated monitoring and FDIR strategy is implemented in the locomotion software to combine the encoder-based with the potentiometer-based leg angle value.

Torque sensor Each shoulder is also equipped with a strain gauge based torque sensor with a measurement range of $\pm 2\,\mathrm{N\,m}$. The technology has heritage from other space missions and is also described in more detail in [1]. For IDEFIX, the sensor is integrated in the sealed shoulder, which leads to a considerable friction. Therefore, accurate torque measurements down to the gravitational forces on Phobos are not feasible. For their intended purpose of a blockage detection, the achieved accuracy is, however, sufficient (see also [3]).

Accelerometer One three-axis accelerometer is mounted on each of the four shoulder PCBs. Based on impact tests with a prototype of the rover, the sensor ADXL356EP with a measurement range of $\pm 40\,\mathrm{g}$ was selected. The sensor was successfully radiation tested to confirm its suitability for the mission. Since the communication frequency to the OBC of 10Hz is not enough to accurately measure the impact, a non-volatile magnetoresistive random-access memory (MRAM) is added to the LSS E-Box. With the capacity of 128Mbit, a recording of the whole free-fall, impact, and most of the bouncing on Phobos can be achieved in a frequency of 1kHz.

Thermal hardware Naturally, the outer LSS components are exposed to the cold environment during the cruise phase and on Phobos. A low-emissivity coating is applied on the aluminum parts and selected components are made from Titanium or TECASINT 2011, which both feature a relatively low thermal conductivity. However, the passive thermal design of the LSS is not enough to protect the electronics of the shoulder module from the extreme cold on Phobos. Therefore, the zones to be heated – the electronics of both motors as well as the main shoulder PCB with all the other electronic components and the connectors – are connected with thermal straps. One dual-layer heat foil is wrapped around each of the motors as well as around an aluminum body that is connected to the shoulder PCB. Together with two temperature sensors, the heat foils are used for two independent heating circuits. One is connected to the spacecraft for heating during the cruise phase and the other one to the IDEFIX's PCDU for heating on Phobos.

Figure 4. LSS E-Box

3.2. HDRM

Each HDRM consists of a central part, which contains the separation nut itself and a cup-cone interface to the wheel hub. Three pillars provide support to the wheel rim to prevent oscillations of the wheel as well as for a possible first impact on Phobos with the wheel. The pillars are held in their upright position by wave springs that connect the pillars to the central part of the HDRM. As long as the HDRM is locked, the cup-cone of the wheel hub also holds the pillars upright and the whell rim is pressed with a pre-load onto the pillars. When released, the wheel hub lifts from the cup-cone interface, giving free the sliders that hold the pillars. Pre-loaded rotational springs consequently flip the pillars flat onto the chassis.

3.3. E-Box

The E-Box shown in Figure 4 is the control center of the LSS. It records the sensor data, controls the actuators and communicates with the OBC. These different tasks are carried out internally by two circuit boards, the *Power inverter + control* (pi_ctrl) PCB and the *Analog* PCB. A detailed view of the functionality of each board is shown in Figure 5 and Figure 6. The two boards are connected via a board-to-board connector and the pi_ctrl PCB interfaces with the OBC for communication, while the analog PCB interfaces with the PCDU for power.

Power inverter + control board Figure 5 shows a detailed view of the power inverter and control PCB of the LSS. A FPGA is used as central control and processing unit, while a SpaceWire interface with standard LVDS physical layer connects to the OBC for communication functionality. While all other required voltages are supplied to the E-Box by the PCDU, the FPGA core supply voltage is generated directly on the pi_ctrl board. A reset controller supervises the FPGA supply voltages. Eight separate 3-phase motor drivers are located on the board. They generate the phase voltages to operate the BLDC motors that are described in Section 3.1. The non-regulated bus (NRB) of the rover, which is directly connected to battery power, is used to power the motors. The 3-phase output of each power inverter is filtered with a LC-filter for reducing the electro-magnetic interference produced by the power inverter. The motors of all four shoulders are connected with shielded cables to the pi_ctrl board. As power consumption is critical, separate switches are integrated for the power lines for wheels and legs to be able to switch off the power inverters and motor commutation sensors if e.g. the motors actuating the leg are not used. The board provides a single shunt current measurement for each power inverter, to supervise the motor currents and detect overcurrent conditions. The analog conditioned signals of the motor current measurement are digitized by ADCs. Two gyroscopes on the board provide information e.g. to support impact trajectory reconstruction. Temperature sensors at the FPGA and the power inverters provide the board temperatures for housekeeping purposes and overheating prevention.

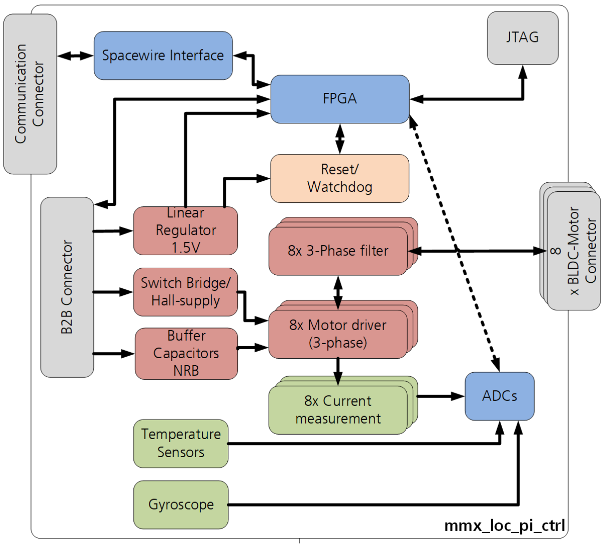

Figure 5. Block diagram of the pi_ctrl PCB

Analog board The block diagram of the analog PCB is shown in Figure 6. The analog circuitry for reading the shoulder torque and position sensors and the accelerometers is connected to the control board via the board-to-board connector. The four sensor PCBs of the shoulders are connected via shielded 25-pin cables. The board provides ADC functionality where the conditioned analog signals of the sensors are digitized. For electro-magnet compatibility, all power input lines from the PCDU are filtered on the analog PCB. The NRB input is filtered

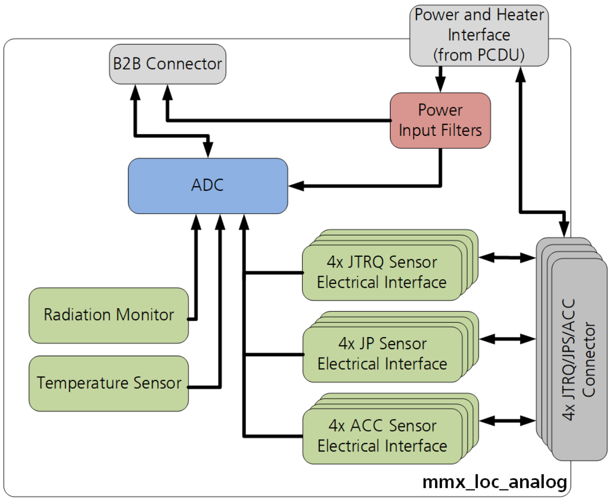

Figure 6. Block diagram Locomotion Analog PCB

with a PI-Filter and fed to the pi_ctrl-board via the board-to-board connector, where the buffer capacitors for the motor drivers are placed. The other power lines (12V, 5V, 3.3V) are filtered with a LC-filter. Temperature sensor information for the shoulder heating on Phobos is routed from the shoulders to the OBC trough the sensor harness. In the opposite direction, heater power from the PCDU is distributed to the shoulders. For housekeeping purposes, a radiation monitor and a temperature sensor is placed on the analog PCB. To save power, the supply of the accelerometers and the radiation monitor can be switched off when these sensors are not used.

3.4. Firm- and Software

The FPGA provides a SpaceWire Remote Memory Access Protocol (RMAP) Core to interface with the OBC, which allows a memory mapped access on the locomotion electronics. The tasks of the FPGA are split into several modules: A control module can switch on and off several components of the LSS (see Section 3.3. The motor controller generates pulse-width modulation (PWM) pattern to reach a certain commanded position. The baseline for this is a six-step commutation with a feed forward mode as fallback solution. The sensor data module processes all data from the ADCs and performs basic data processing like calculating average and minimum/maximum values of the 40 kHz data that are sent to the OBC in 10 Hz. Finally, one firmware module serves to record the accelerometer data during impact of the rover onto Phobos into the MRAM (see Section 3.1 and reading it out at a later point in the mission.

The software, called LOCO-SW hereafter, is part of the on-board computer (OBC) and serves as connection from the LSS hardware to the other subsystems and to ground. Thus, it has software interfaces to the other partitions on the OBC on the one side and the SpaceWire [5] connection to the E-Box (see Section 3.3) on the other side. The software is collecting the data received via the SpaceWire connection and forwarding it in a defined protocol as housekeeping data to be send to ground. Additionally, this data is monitored on-board to detect faults, identify them and recover them so that the LSS can continue operating even in the case of e.g. a disfunctional actuator or sensor as far as possible. Other than the hard- and firmware, the software can be updated even after launch of the rover. It is therefore still under development and testing by writing of this paper.

4. SYSTEM INTEGRATION AND TESTING

The assembly, integration and testing (AIT) of the LSS into the full rover is done in three main tracks. In Toulouse at CNES, the LSS E-Box is mounted into the so-called service module of the rover after incoming inspection, safe-to-mate and stand-alone test. This inner compartment of IDEFIX is mechanically damped and thermally controlled and houses most of the electronics. With ground support equipment (GSE) to mimic the motors and sensors as well as a test laptop and SpaceWire USB bridge, the nominal functionality of the FM E-Box was subsequently tested. The second track is performed in Bremen at DLR. There, the locomotion modules, including shoulders, legs, wheels and HDRMs are integrated into the chassis structure. Analogously to the integration of the E-Box, an engineering model E-Box, a test laptop and a SpaceWire USB bridge are used to test the LSS modules after integration. Finally, the pre-assembled chassis, including the LSS modules, are shipped to Toulouse for the final integration step. The service module is mechanically integrated into the pre-assembled chassis and subsequently, all electrical connections are made and secured after ensuring again that it is safe to mate. Since the flight hardware is now finally connected, no LSS GSE is needed anymore, and the test to confirm successful integration is instead performed through telecommands (TCs) and the actual OBC. The LOCO-SW is therefore integrated in the overall on-board software and tested at DLR-RMC in Oberpfaffenhofen.

TCs are sent and telemetry is received by a tool based on the ISIS [6] ground operation system, which is used in the mission later. The most important check is the one for a constantly stable SpaceWire connection between the OBC and the E-Box. After that, the complete state of the system is monitored by a health check procedure. A passive health check is first switching on and off all of its components sequentially and then all together. This validates that all elements of the LSS can be powered individually and together. An active health check performs micro-movements on the motors: Each motor moves a few increments, so that these motions are visible with the hall effect sensors but marginal at the output, i.e. the leg and wheel. The active health check thereby allows to confirm the functionality of the motors and hall effect sensors even in the locked cruise configuration. The health check procedure was repeated regularly during AIT, allowing us to keep a history of the system across the full test campaigns (see [3] for more information). This proved particularly useful when cross-checking the behavior of the qualification model and acceptance model.

After full integration, the LSS HDRMs were unlocked to perform different tests with larger movements of the legs and wheels. First, a "sign" test validated the harnessing and interaction of all software components by testing that all legs and wheels move in the desired direction. Thereafter, two procedures similar to mission scenarios were tested: The very first and most important is the uprighting movement, where the rover shall get from its fold-up cruise position to a position where the solar arrays can be unfolded. The second scenario is the heliotrope sequence where the rover orients the chassis such that the solar panels' angle to the sun is optimized. In both activities, the LOCO-SW receives its commands from another software partition which calculates these commands onboard. Finally, large movements of $>360^\circ$ of the legs and wheels are also performed, similar to the full functional tests that were performed during the subsystem acceptance campaign [2]. The data collected was used to confirm good health and no degradation of the full drive train and of the position and torque sensors.

All AIT tests were completed successfully, and the data demonstrated full functionality of the flight model of the LSS.

5. CONCLUSION

In this paper, we have shown a brief overview of the locomotion subsystem of the IDEFIX mission within the MMX mission. After a summary of main challenges and requirements, the FM design of mechanics, electronics and software was presented. By the writing of this paper, the AIT activities in Germany and France are almost completed. A summary of what has been done as well as of the results was provided.

IDEFIX will be shipped to JAXA in November 2023 and the spacecraft with the rover on-board will be launched in September 2024. In February 2027, IDEFIX will perform the world-first landing on Phobos and the world-first driving in milli-gravity.

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