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Optimizing Cold Resistance: The Thermal Design of the MMX Rover IDEFIX's Locomotion Subsystem for the Martian Moon Phobos

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The Martian Moon eXploration (MMX) mission, led by the Japan Aerospace Exploration Agency (JAXA) is set to launch in 2026. Its objectives are to conduct the first sample-return of the moon Phobos and collect further scientific data by observing the moon Deimos. The main goal is to understand the origin of both Martian moons. Within this mission, the MMX rover IDEFIX, a collaborative development of the French Centre National d'Études Spatiales (CNES) and the German Aerospace Center (DLR), is designated to serve as a mobile scout and explore the surface of Phobos. It will perform on-site scientific measurements using various on-board instruments and contribute data for JAXA's sample collecting task. The Locomotion Subsystem (LSS) of the MMX rover, developed, built, and qualified by DLR's Robotics and Mechatronics Center (RMC), holds a pivotal role in achieving the rovers' objectives. To ensure the resilience of the LSS under demanding conditions, especially the harsh environment during the cruise phase and the extremely low temperatures of Phobos surface during the night, a comprehensive thermal design was developed. This paper offers an examination of DLR RMC's design for addressing the thermal demands of the LSS in various mission phases.

Nomenclature

α	=	Solar absorptivity
ε	=	Infrared emissivity
dT	=	Temperature difference
i_H	=	Gear ratio of harmonic drive
i_M	=	Gear ratio of motor unit
i_P	=	Gear ratio of planetary gear
p_I	=	Preload increase
p_L	=	Preload loss
p_N	=	Nominal preload
T_{WO}	=	Operation torque of the wheel drivetrain
T_{WF}	=	Friction torque of the wheel drivetrain
x_C	=	Clearance distance of bearing contacts
v_W	=	Wheel velocity

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CNES = Centre National d'Études Spatiales (French National Space Agency)
DLR = Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
FM = Flight Model
FS = Flight Spare
HDRM = Hold-Down-Release-Mechanism
JAXA = Japan Aerospace Exploration Agency
LSS = Locomotion Subsystem
MASCOT = Mobile Asteroid Surface Scout
MMX = Martian Moons eXploration Mission
MECSS = Mechanical-Electrical-Communication-and-Separation-System
MLI = Multi-Layer-Insulation
OBC = On-Board Computer
PCB = Printed Circuit Board
PDCU = Power Distribution and Control Unit
QM = Qualification Model
RMC = Robotics and Mechatronics Center
SEM = Service Modul
TBT = Thermal Balance Test
TCS = Thermal Control System
TCT = Thermal Cycling Test
TRP = Temperature Reference Point

I. Introduction

THE Martian Moons eXploration (MMX) mission, spearheaded by the Japanese Aerospace Exploration Agency (JAXA), is a pioneering mission to the Martian moons Phobos and Deimos. The main objectives include the return of a sample from Phobos and further scientific observations of Deimos to improve the understanding of the origin of both moons. The MMX spacecraft is scheduled to land on Phobos to collect a soil sample and subsequently launch one of its modules back to Earth.[1]

After the expected launch in 2026 and a journey of about one year to the Mars orbit, the spacecraft will approach Phobos for thorough investigation. In late 2028 or early 2029, during the initial rehearsal of the approach sequence, a small rover will be deployed from an altitude of approximately 50 meters above the ground.

The 25 kg rover named IDEFIX is a joint effort between the Centre National d'Études Spatiales (CNES) and the German Aerospace Center (DLR).[2,3] Its primary objective is to serve JAXA as mobile scout to characterize the properties of the ground surface prior to the spacecraft's landing. During its operational lifetime (about 100 Earth days), IDEFIX will demonstrate wheeled locomotion in milli-gravity for the first time in history. Autonomous navigation algorithms serve as both a tool to cover longer distances and a technology experiment.[4] On the scientific side, the rover is equipped with instruments to investigate the material composition and thermal properties of the Phobos ground. In Ref. 5, the scientific objectives and instruments are described in more detail.

The Locomotion Subsystem (LSS) of the MMX rover, developed by DLR's Robotics and Mechatronics Center (RMC), is crucial for achieving the objectives of the rover mission.[6] IDEFIX must endure the harsh environments during the cruise phase and the Phobos phase, due to the extremely low temperatures on the surface at night. To ensure durability in these conditions, a comprehensive thermal design was implemented for the LSS. This includes broad strategies, such as employing a Heater Zone design with double-layered heat foils and thermal straps, alongside advanced isolation interface designs to protect sensitive mechatronic components, as well as considerations regarding the thermal expansion for the mechatronic drivetrains.

This paper provides an extensive description of DLR RMC's approach to meet the thermal requirements of the LSS across the mission phases and is structured into different sections. Section II offers an brief overview of IDEFIX and describes the LSS, including its components, functionalities and major tasks during the Phobos mission. Section III elaborates on the specific thermal environments of the mission, covering both the cruise and the Phobos mission phase. Section IV details all thermal design aspects of the LSS, covering the strategies, methods and considerations utilized to ensure its functionality and resilience throughout the mission. Section V presents the thermal design performance across the thermal qualification, acceptance and balance tests. Finally, Section VI summarizes the paper with a conclusion.

II. IDEFIX

Figure 1 illustrates a simulated view of IDEFIX. The structural basis is the chassis box, constructed from carbon-aluminum-honeycomb sandwich plates. It is equipped with multiple inserts designed for attaching various subsystems, such as the navigation camera NavCAM, radiometer MiniRAD, Front Shutter, and the rover's antenna.[5]

External solar panels are present on the rover's top surface, capturing sunlight to generate electrical power for recharging IDEFIX's battery, thereby ensuring sustained operation throughout the Phobos mission phase.

The exterior components of the LSS are the Locomotion Shoulder Module, mounted on the chassis side plates, the Locomotion Wheel Drivetrains, and the Hold-Down-Release-Mechanism (HDRM).

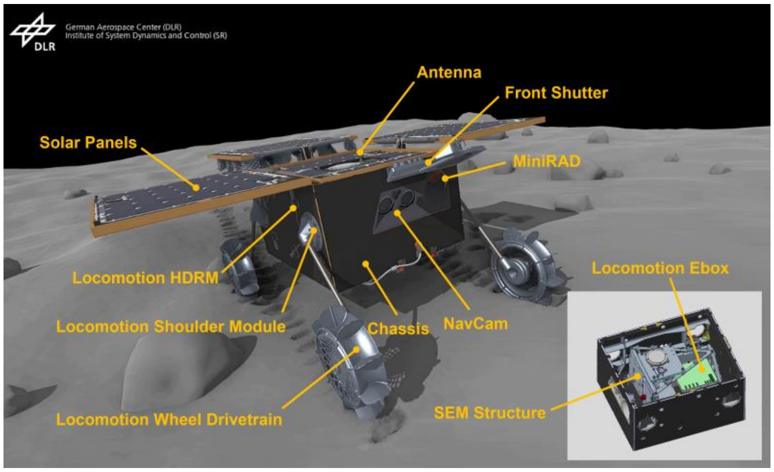

Figure 1. Simulated view of the IDEFIX rover[7]

Inside IDEFIX is the so-called Service Module (SEM) which is thermally wrapped with Multi-Layer-Insulation (MLI) and thereby the warmest compartment of the rover. The SEM consists of a lightweight aluminum structure used for mounting essential electronics, including the On-Board Computer (OBC), the Power Distribution and Control Unit (PDCU), the battery, as well as the Locomotion E-Box and other subsystems' E-Boxes.

During the cruise phase, IDEFIX is positioned on the bottom side of the MMX spacecraft, between four landing legs, via the Mechanical-Electrical-Communication-and-Separation-System (MECSS). This subsystem features a carbon-fiber frame secured to the spacecraft, which holds the rover in place during the launch and cruise phase using a Hold-Down-and-Release-Component. Upon release, a push-out mechanism located in the center of the MECSS pushes IDEFIX away from the spacecraft.

A. Locomotion Subsystem

1. Components of the Locomotion Subsystem

Figure 2 shows an overview of the components within the LSS.

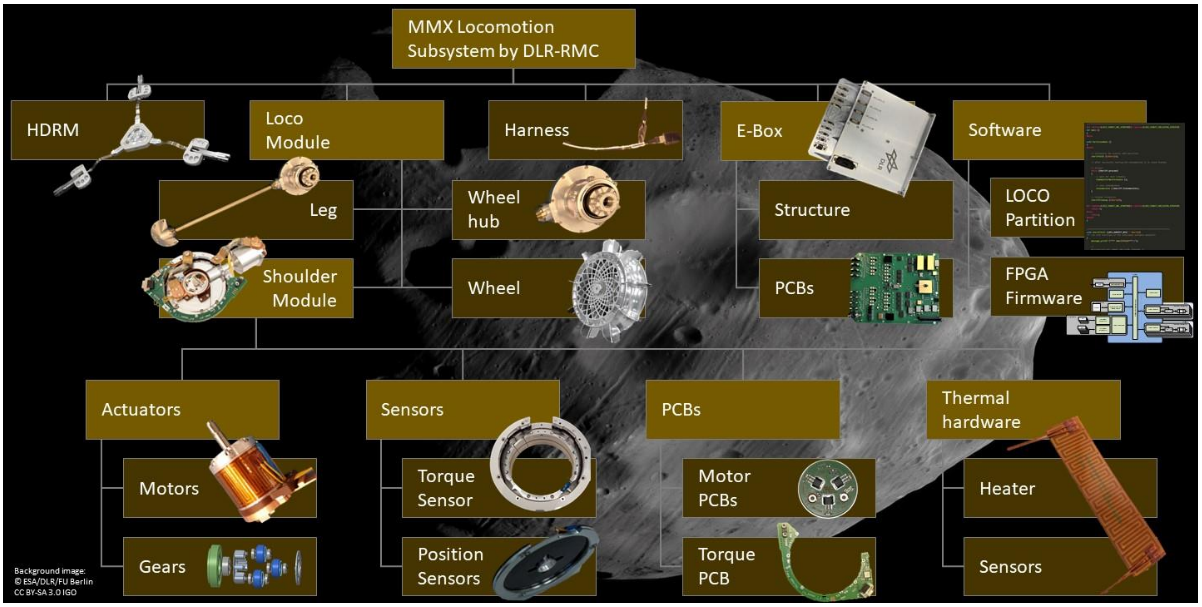

Figure 2. Components overview of the Locomotion Subsystem[9]

The central component is the Locomotion E-Box, serving as the control and data acquisition unit. Connected to the OBC and the PDCU, it executes motor movements and provides data readouts of all Locomotion Modules.

The Locomotion Shoulder Module houses all drivetrain-related mechatronics, most of which are located inside the rover. Each module is equipped with two motor units: one is responsible for moving the shoulder (and therefore the legs) and the other for driving the wheel. Additionally, each module is equipped with torque and position sensors, providing data utilized by the navigation and control algorithms.[10]

The Locomotion Shoulder Modules also contain thermal hardware, including heaters and temperature sensors, to facilitate the corresponding thermal control systems (TCS).

The HDRM, mounted on the rover's chassis panel, plays a pivotal role in safeguarding the LSS against external loads, such as vibration during launch and impact during the landing on Phobos.

2. Mission Tasks

The primary mission tasks, depicted in Figure 3, are outlined as follows:

Uprighting: After the release of IDEFIX at a distance of about 50 m and its ballistic landing on Phobos, the exact orientation of the rover is uncertain. The LSS is tasked to unfold from its stored configuration by releasing the HDRMs and moving the shoulders, positioning the rover to stand on its wheels.

Multi-physics simulations have demonstrated that IDEFIX can be up righted from any side across a wide range of different Phobos soil types.[7]

Sun pointing: After the rover has been repositioned on its wheels, it is tilted towards the Sun by a kinematically controlled movement of the LSS legs and wheels, aided by a sun sensor and an iterative algorithm.

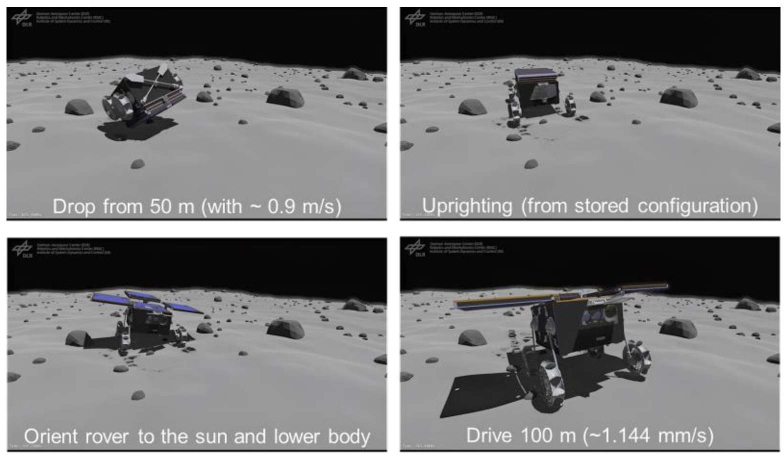

Figure 3. MMX Mission tasks of the LSS

Body lowering: In preparation for scientific measurements conducted by the Raman spectrometer,[5] the rover body is lowered to ensure the optics of the instrument are in focus. This adjustment is accomplished through coordinated movements of the LSS legs and wheels, similar to the sun positioning process.

Driving: For the relocation on the ground surface of Phobos, the LSS enables the rover to drive straight, in curves via skid-steering as well as perform point turns. The LSS is expected to move the rover over a total distance of at least 100 meters.

Inching locomotion: In scenarios where IDEFIX encounters particularly soft soil areas, potentially with slopes, a special sequence is implemented to enhance the traction for forward or backward driving. In this movement, the legs and wheels move together, causing the rover body to crawl. To achieve this, the front/rear wheel pairs rotate alternately while the other ones remains still. Meanwhile, slight leg movements cause the rover body to move up and down, resembling an inchworm. Furthermore, the LSS control software prevents collisions between the Locomotion Modules and other parts of IDEFIX.[10,11]

III. Thermal Environments

The LSS is exposed to harsh thermal environments throughout different mission phases, and its TCS was designed to ensure the survival and operability under these conditions. In the following subsections, the expected characteristics of the LSS thermal environment during the cruise phase and Phobos phase are described.

A. Cruise Phase

During the cruise phase, IDEFIX is mounted on the instrument panel of the MMX spacecraft, which is nominally oriented in the opposite direction of the Sun. For some limited periods during the Earth departure and the Phobos orbiting phase, IDEFIX is illuminated by the Sun. However, those hot environments are not expected to be critical for the LSS. Thus, the main interest in the cruise environment is the cold case, where IDEFIX is under shadow.

Meanwhile, IDEFIX radiatively exchanges heat with nearby instruments and the structure of the MMX spacecraft. On the LSS level thermal study, those radiative effects from the different sources are represented by the equivalent sink temperature.

Since there are four Locomotion Modules mounted on the different sides of the rover chassis, the thermal radiative environments are not exactly the same for each module. Therefore, radiative sink temperatures are calculated for each module on the rover system level thermal study, and applied to the detailed thermal study of the LSS. In the cold case, the equivalent sink temperature of the Locomotion Module reaches approximately −120 °C, and the conductive interface at the rover chassis becomes approximately −70 °C. In this environment, the thermal design of the LSS has to be able to keep temperature-sensitive components, such as the motors and the torque sensor electronics above the non-operational temperature. Since the LSS must be switched on regularly during the cruise phase to perform health check operations, its thermal design has a capability to heat up the Locomotion Module temperatures to the operational level as well.

B. Phobos Phase

For the Phobos mission phase, the thermal environment of IDEFIX is mainly driven by the Phobos day-night cycle with a period of 7.65 hours. On Phobos, the LSS temperature is radiatively influenced by multiple sources, such as solar flux, reflected solar flux from the Phobos surface, and infrared fluxes from the Phobos surface and the rover chassis. Similar to the cruise phase, the LSS level thermal study is performed based on the radiative sink temperatures which are calculated by the rover system level thermal study.

During the Phobos operation, LSS parts, which are exposed to the external environment, are expected to be partially covered by the Phobos dust. As the Phobos dust has high emissivity and absorptivity, the dust should increase the incoming and outgoing heat flux, which could result in more extreme temperatures of the LSS. For the evaluation, 50% dust coverage is assumed as the baseline, and the corresponding radiative sink temperatures and optical properties are applied.[12]

In terms of thermal conductivity, the Locomotion Module interacts with the rover chassis and the Phobos soil. The conductive heat exchange between the Locomotion Module and the Phobos soil is not considered in the subsystem thermal study, but the effect is mitigated by the isolation design of the wheel area, where the Phobos soil has direct contact. The radiative sink temperature of Locomotion Module varies approximately between −135 °C and 20 °C, and the chassis conductive interface temperature varies approximately between −95 °C and 0 °C, during one Phobos day.

These changes in the surrounding temperature imply that the major challenge for the LSS during the Phobos phase is to survive the cold environment of the night. Nominally, the temperatures of the sensitive components shall be maintained above their non-operational temperatures by the rover heaters. However, because of the limited electrical power budget of the rover, there is a possibility that the heater threshold is lowered causing the temperature-sensitive components to reach a minimum temperature of -75 °C, which is significantly colder than the non-operational condition during the cruise phase. For the LSS operation of the Phobos phase, the temperatures have to be increased to the operational level. This pre-heating operation is expected to be performed in the early phase of the Phobos day, when the surrounding temperatures start increasing by the sunlight.

IV. The Thermal Design of the Locomotion Subsystem

The following subsections provide a detailed thermal design description of the LSS. For this purpose, it is segmented into the following distinct areas: the Locomotion Drivetrains, the Locomotion Shoulder Module, the Locomotion E-Box and the HDRM. This division reflects the physical arrangement of the LSS. Despite being interconnected via mechanical and/or electrical contact, their positions within IDEFIX vary considerably, influencing individual design decisions.

For instance, the Locomotion Drivetrains and HDRMs are tailored to endure cold environmental conditions and additional external factors, such as the direct contact with the surface of the Martian moon Phobos. Conversely, the thermal design for other components has been optimized for interior placement within the rover. Specifically, the inner part of the Locomotion Shoulder Module, which houses critical electronic components, such as the torque and position sensors. Another example is the Locomotion E-Box, which is situated at the center of the rover as part of the SEM, entirely enveloped by MLI to protect temperature-sensitive electronic components and the rover's battery from cold environments and to prevent heat leakage.

The materials of the LSS were chosen based on load conditions, weight minimization, thermal properties, and considerations of the interfaces to other components. Two situations were distinguished: components with relative movement to each other and static components. A dissimilar material approach was generally followed for parts moving in relation to each other in order to prevent cold welding at contact points.[8] Additionally, the selection process was influenced by factors such as the heating budget, leading to the choice of materials based on their thermal conductivity.

In order to reduce radiative heat transfer with the surroundings and to meet the critical requirements of the electromagnetic compatibility grounding concept, Surtec650 was selected as surface coating for all aluminum parts of the LSS. This decision was influenced by its low infrared emissivity $\varepsilon = 0.02$ and solar absorptivity $\alpha = 0.2$, as per conducted measurements, along with its capability to prevent surface oxidization, ensuring a high electrical conductivity across interconnected parts.

A. Locomotion Drivetrains

The Locomotion Drivetrains can be differentiated based on their following kinematic functions: The Wheel Drivetrain, illustrated in Figure 4, facilitates the rover's movement across the surface of Phobos. The Shoulder Drivetrain (see Figure 5) allows the angular adjustment of the Locomotion legs against the body of IDEFIX.[8]

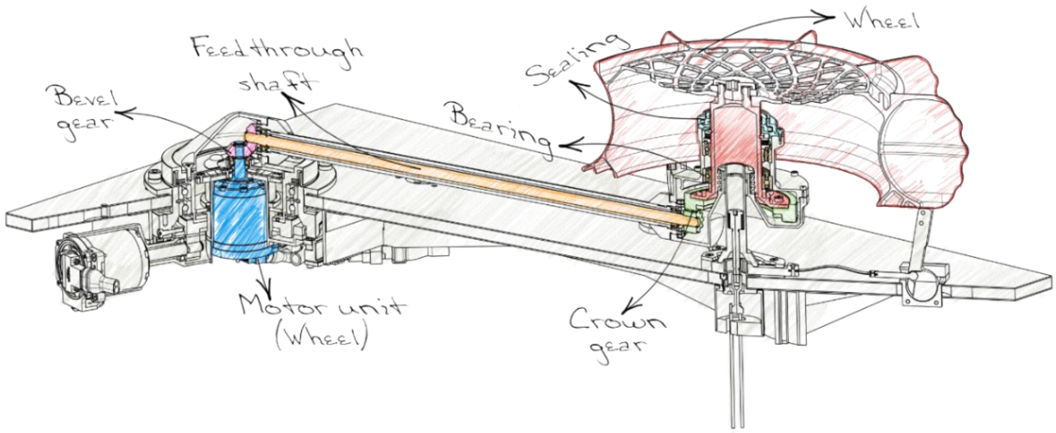

Figure 4. Cutview of the Wheel Drivetrain

One notable design feature is implemented in the Locomotion Wheel Drivetrain, where titanium 3.7164 (Ti-6Al-4V) is utilized for both the feedthrough shaft and the surrounding tube (see Figure 4). While primarily selected for mechanical load and weight considerations, this material offers advantages for the thermal design. Its low thermal conductivity effectively isolates the Locomotion Shoulder Module from the cold soil of Phobos.

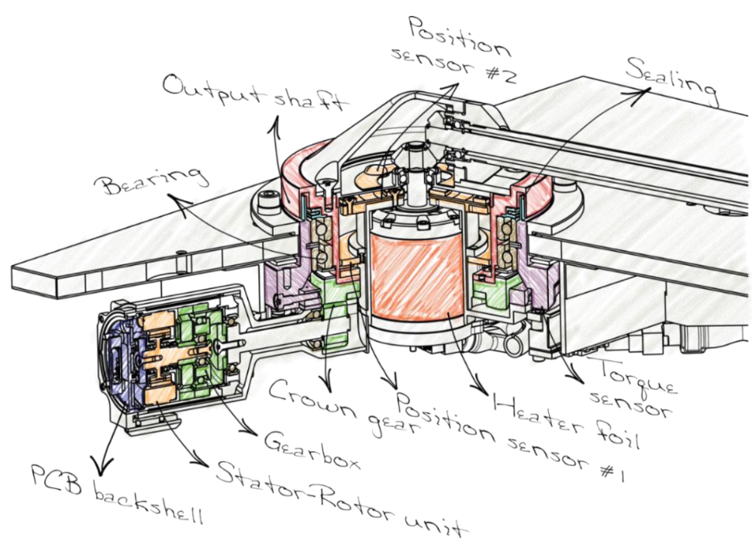

Figure 5. Cutview of the Shoulder Drivetrain

Both drivetrains share the commonality that their motor units were placed within the Locomotion Shoulder Module as part of the Heater Zone. The selection of lubricants, the design of gears, bearings, and preload forces are similar for both drivetrains, allowing their description to be consolidated in the following subsections 1 to 4.

1. Lubrication

The selection of lubrication is influenced by various mechanical, chemical and environmental factors, including but not limited to cold welding, corrosion, friction, and temperature variations. Dry lubrication is particularly favored for several functional parts. For example, certain gear components like the planetary gears within the motor units and the crown gears are constructed from TECASINT 2391, a polyimide with 15% MoS_2. This composition facilitates self-lubrication with the stainless-steel counterparts of the respective gearboxes. Moreover, utilizing polyimide-based materials for gears offers the additional advantage of maintaining resilience to cryogenic temperatures without becoming brittle.

For most bearings, raceways coated with silver have been chosen. This decision accounts for a higher friction compared to lubricated bearings within moderate temperature ranges, but ensures a more constant level of friction over a broad temperature range, especially for the cold temperatures expected in the mission.[8] An exception to these design decisions is the harmonic drive used in the motor units, where Fomblin Z25 is utilized for the wave generator bearing and Braycote 602EF for the gearing. This selection was based on prior experience with the lubrication of similar motor units on other space missions, particularly on the mobility mechanism of the Mobile Asteroid Surface Scout (MASCOT) in the Hayabusa-II mission,[13] and the ROKVISS technology experiment on the ISS.[14]

2. Gear Design

The gear design of the drivetrains integrates various factors. For instance, due to Phobos' milli-gravity, IDEFIX's velocity must be deliberately limited to ensure continuous physical contact between the locomotion wheels and the ground during maneuvers, thus preventing the rover from flipping over. Multi-physics simulations have indicated that a maximum wheel velocity of approximately $v_W \approx 1\ \text{mm/s}$ is recommended.[4]

Additionally, the potential range of ground surface properties and environmental factors at landing sites must be considered, notably for the drivetrain torques. This includes, but is not limited to, overcoming friction, especially in cold temperatures, and scenarios where the wheels are in full contact with cohesive soil. In such instances, a sufficient torque is vital to mobilize the wheel grousers within the soil for forward movement. Studies suggest a worst-case operational torque of $T_{WO} = 0.5$ Nm, plus a friction torque of $T_{WF} = 0.33$ Nm for the wheel drivetrain. During the qualification test of the wheel drivetrain, along with a qualification margin of a factor of 3, a total torque of 2.5 Nm has been qualified.[8]

Furthermore, the gear design is also essential for the on-board measuring devices, which demand accurate data collection and precise adjustments of the rover's orientation and location.

To ensure efficient motor operations aligned with the needs, a high transmission ratio has been implemented for both drivetrains. By combining a planetary gear (ratio $i_P = 1:5$) in series with a harmonic drive (ratio $i_H = 1:100$) within the motor unit, a ratio of $i_M = 1:500$ could be achieved at the output shaft.

It was crucial to position the harmonic drive in warmer regions of the drivetrain due to the lubrication with Braycote 602EF, which has a minimum operational temperature limit of -80 °C according to the datasheet. However, considering that the harmonic drive is placed inside the motor unit, whose electronic components have a higher temperature sensitivity, the actual minimum operational temperature is warmer. Consequently, the use of Braycote 602EF does not compromise the drivetrain's operational limits. To reach the necessary temperatures, the motor units are strategically placed in the Heater Zone of the Locomotion Shoulder Module (see subsection 6).

In order to achieve both the high transmission and avoid stiction caused by solidifying grease, a correspondingly small diameter is employed for the sun gear of the planetary gearing compared to the effective radius of the friction forces in the harmonic drive.[8]

3. Bearings

The bearings were selected on the basis of various load case analyses. In addition to vibration, impact, and operational loads, thermal factors, particularly thermal expansion, played a significant role in the considerations. The worst-case scenarios of the non-operational and operational state were selected and subsequently used to dimension the bearings. In general, all drivetrain bearings are installed with play fits in housings and on shafts. A soft preloaded configuration is incorporated, where an additional spring part maintains the preload on the bearing arrangement. The following example demonstrates the design decisions made for the shoulder bearings. As illustrated in Figure 6, the Locomotion

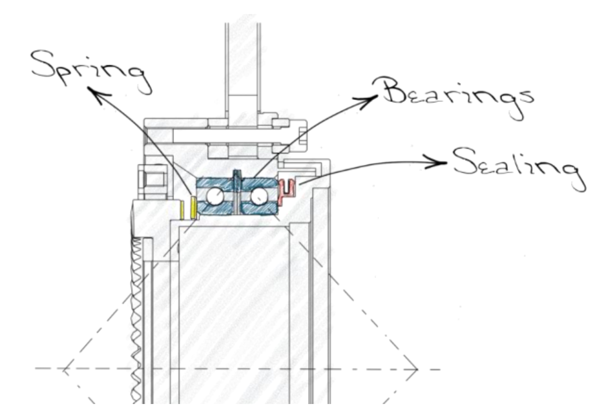

Figure 6. Shoulder bearing arrangement (preloaded)

Shoulder Module features a soft preloaded bearing setup consisting of a shaft, housing, two angular contact bearings, and a wave spring to maintain the preload.

Deep-temperature-resistant stainless steel (1.4108) is used for the bearing rings, while the balls are made of Si_3N_4. Aluminum 3.456 (EN AW-7075) is selected for the shaft and housing due to mass considerations. This design results in different thermal expansion coefficients, for which the mechanical stress must be taken into account.

In cases where a press fit occurs at low temperatures, the contact pressure is evaluated to ensure that material limits are maintained. Due to the complexity of the surrounding geometry, this assessment is conducted using numerical simulation. For the bearing in Figure 6, this situation occurs at the interface between the housing and the outer ring of the bearing. At -80 °C (worst-case scenario), a press fit with a clearance of $x_C = -0.083$ mm is calculated at this interface on the diameter. Conversely, the interface at the shaft has more play, and the preloading will be maintained by the wave spring.

4. Preload forces in screwed connections

Thermal loads also induce a change of preload forces in screwed connections. Similar to the bearing design, the screwed connections were also analyzed under thermal worst-case scenarios. For example, the fastening of the Locomotion Shoulder Module to the rover's chassis panel requires a certain rigidity due to the expected loads during the mission, while also providing a high thermal resistance. The latter is essential, as the chassis panel of IDEFIX reaches very low temperatures during the mission.

In order to fulfill both requirements, titanium 3.7164 (Ti-6Al-4V) screws where used at this location, as they provide sufficient strength for the expected mechanical loads and have low thermal conductivity. A maximum temperature difference of $dT = -80$ °C is anticipated, resulting in a preload loss of $p_L = -246$ N from the nominal preload of $p_N = 2436$ N (at 20 °C) in combination with the chassis structure and is acceptable for the expected loads during the mission.

B. Locomotion Shoulder Module

The design of the Locomotion Shoulder Module can be divided into two thermal regions: the Shoulder-Chassis interface and the Heater Zone (see Figure 7). The Shoulder-Chassis interface represents the mechanical contact area between the Locomotion Shoulder Module and the rover chassis, while the Heater Zone contains all temperature-sensitive electronic components.

It is important to note that, despite the Shoulder Drivetrain's integral location in the Locomotion Shoulder Module, this segmentation focuses on stationary components, which maintain their static position relative to the rover.

Given the rover's exposure to cold environments during mission phases, significant efforts have been taken to minimize the thermal contacts between the Locomotion Shoulder Module regions and the rover chassis. These optimizations aim to reduce heat leakage from the interior of the rover to the exterior, thereby decreasing required heater power and improving energy efficiency. This is particularly important during the Phobos mission phase, where dependence on battery power is crucial.

Throughout the optimization process it was necessary to ensure that the requirements regarding mechanical stability for the interfaces between the regions were met across different mission phases, including launch and ballistic landing on Phobos. This serves as limiting factor for the optimization of the thermal design, which determines how far it can be exhausted. For instance, the reduction of contact surface areas is constrained by the mechanical load and stress characteristics of the interface materials.

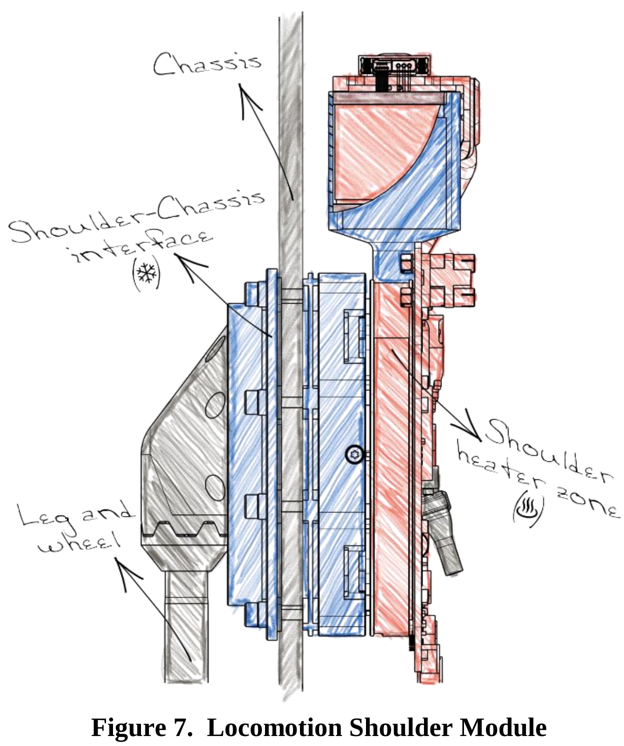

Figure 7. Locomotion Shoulder Module

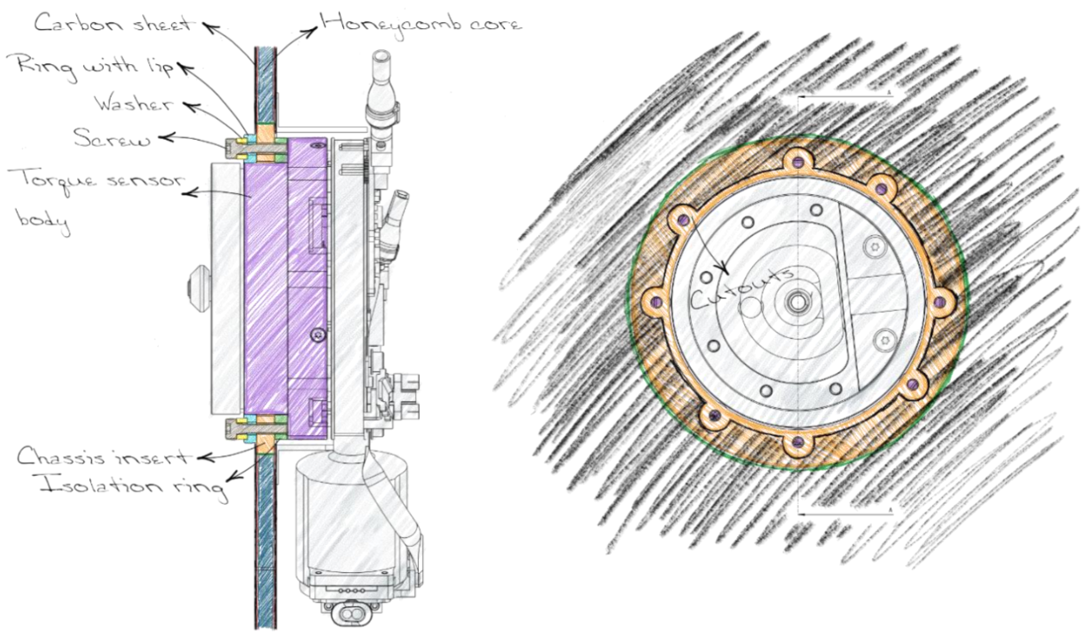

Figure 8. Shoulder-Chassis interface overview

5. Shoulder-Chassis interface

Figure 8 illustrates the Shoulder-Chassis interface. The rover chassis panel consists primarily of an aluminum honeycomb core sandwiched between layers of carbon sheets. Dedicated inserts are used in threaded connection areas. To minimize the thermal contact at the interface area for the Locomotion Shoulder Modules, two thermal design improvements have been implemented. Firstly, the carbon sheets and the aluminum core were cut out at the interface areas. Secondly, chassis inserts made of carbon-fiber PEEK (CF-PEEK) are glued into the rover chassis panel to serve as mounting surfaces. Due to CF-PEEK's low thermal conductivity (measured with 0.54 W/mK out-of-plane and approx. 2.6 W/mK in-plane), these steps effectively decrease the thermal contact conductance compared to a direct connection of the rover chassis panel.

The Locomotion Shoulder Module is fixed between both sides of the chassis panel via eight M3 screw connections, each directly inserted into the torque sensor body. A ring-shaped flange is utilized on the outside, featuring a lip design to create a sealed contact with the cut-outs of the carbon sheets. This effectively prevents dust particles from entering the rover's interior, which is particularly important during the Phobos landing maneuver.

Since the torque sensor body is made of aluminum 3.4365 (EN-AW-7075), the same material has also been selected for the ring flange. This design decision effectively reduces mechanical stress and changes in preload forces for the screw connections due to thermal expansion effects across the expected temperature range during the mission.

Considering that the ring flange is also exposed to cold external environments, isolation washers are strategically placed underneath the screw heads. Crafted from TECASINT 2011, a polyimide material, these washers leverage its attributes, including low thermal conductivity (0.22 W/mK as per datasheet) and, as mentioned earlier, resilience to low temperatures.

The same material is also utilized for the isolation ring which is placed between the PEEK insert and the torque sensor body on the interface contact on the inside. Combined with the selection of titanium 3.7164 (Ti-6Al-4V) for the screws, these design choices enhance the overall thermal isolation on the interface.

6. Heater Zone

The Heater Zone (see Figure 9) is a dedicated region designed to protect critical mechatronic components within the Locomotion Shoulder Module and to further reduce heat leakage between the rover's interior and the external environment. Components within this zone utilize parts from TECASINT 2011 as isolated interfaces to the bodies of the Shoulder-Chassis interface.

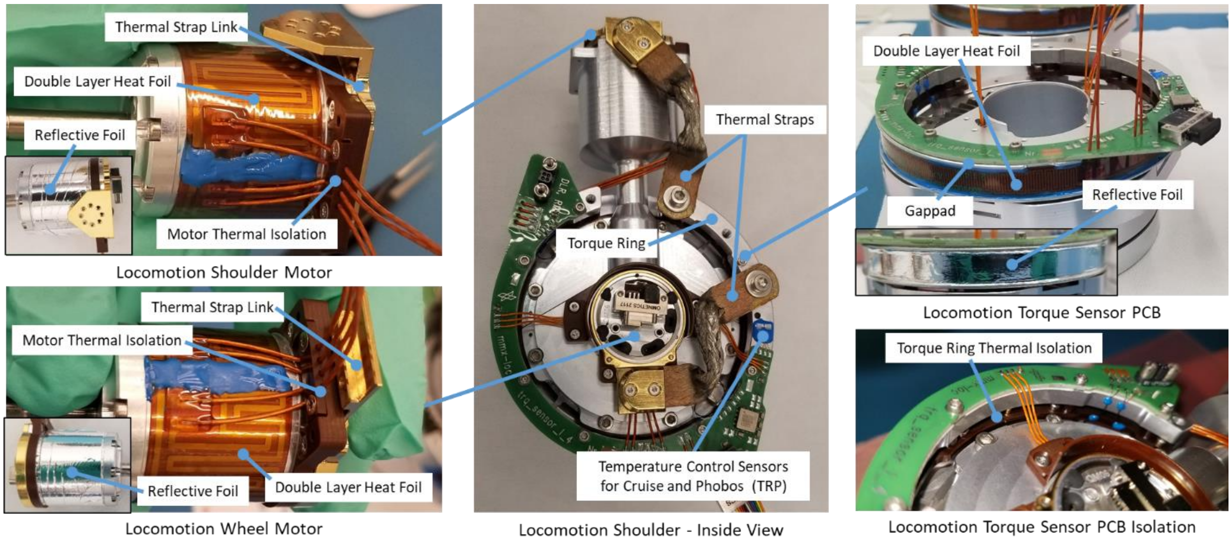

Figure 9. Heater Zone Overview

The primary temperature-sensitive elements are the motor units and the torque sensor printed circuit board (PCB), with their respective unit/part design temperature ranges detailed in Table 1.

Table 1. Heater Zone Unit/Part Temperature Range

Component	Min. non-operation	Min. operation	Max. operation	Max. non-operation
Motor unit	-55 °C	-40 °C	+90 °C	+90 °C
Torque sensor PCB	-55 °C	-55 °C	+125 °C	+125 °C

Three double-layered heat foils are mounted on the housing of both motor units and to the so-called torque ring, which provides a heat foil attachment area for the torque sensor PCB. The first layer of each heat foil is connected to the spacecraft's dedicated non-regulated bus heating line via MECSS, operating with a voltage range between 33 V and 50.2 V. This heating line is controlled by the MMX spacecraft's TCS, which is exclusively utilized during the mission's cruise phase. The second layer of each heat foil is internally connected to the rover's non-regulated bus used during the Phobos mission phase. These heating lines provide a voltage range between 11 V and 16.8 V. They are powered by the rover's battery via the PDCU and controlled by the OBC. The power characteristics of all heat foil layers are fine-tuned to ensure that the TCS effectively regulates the coldest spot of the Heater Zone, thus guaranteeing that all components stay within their specified temperature ranges.

Additionally, to minimize radiative heat exchange with the surroundings, a reflective single-layer insulation foil with a low infrared emissivity ε is applied to all heat foils, thereby improving heating efficiency.

The torque sensor PCB serves as electrical interface, establishing links between the heating lines and their respective heat foil layers, as well as the PT1000 temperature sensors to the corresponding TCS. While for the rover's TCS each Locomotion Module has its own dedicated heating line and PT1000 sensor, only one heating line is available for all Locomotion Module Heater Zones combined for the MMX spacecraft. Consequently, only two temperature sensors are utilized, with one serving as a backup. Due to pinning restrictions, the redundant sensor is positioned on another Locomotion Module. The sensors have been placed on the Locomotion Shoulder Modules that are expected to experience the lowest temperature during the cruise phase, based on system level thermal analysis results.

The torque ring serves as a thermal-mechanical node of the Heater Zone, facilitating the placement of the TCS temperature sensors, hence representing the temperature reference point (TRP) for each heating line. The corresponding thresholds for each heating line are listed in Table 2.

Table 2. TRP Heating Line Thresholds for TCS

TRP Heating Line Thresholds	Non-operation	Operation
Spacecraft	ON -27.0 °C / OFF -24.0 °C	ON -12.0 °C / OFF -9.0 °C
Rover	ON -47.0 °C / OFF -44.0 °C	ON -27.0 °C / OFF -24.0 °C

Additionally, the torque ring provides a mounting area for thermal straps made of braided copper. These thermal straps aim to balance the thermal behavior of all three heat foil areas, improving homogeneous temperature distributions and preventing steep temperature gradients during heating up and cooling down. Their mechanical design provides high rigidity, ensuring that they maintain their bent shape and thus prevent accidental contact with cold components outside the Heater Zone. The connections to the motor units are established through dedicated thermal strap link interfaces, also constructed from copper, which make direct contact with the motor housings. To address corrosion concerns and ensure low infrared emissivity ε, these strap link interfaces are coated with a layer of gold.

C. Locomotion E-Box

The design of the locomotion E-Box can be seen in Figure 10. It contains two PCBs: the E-Box Analog PCB and the E-Box Power Inverter and Control PCB. Each of them is mechanically attached to the E-Box housing using six M3 screw connections, along with a dedicated gap pad positioned at the interface area to enhance thermal contact. Their respective unit/part design temperature range is shown in Table 3.

Table 3. E-Box PCBs Unit/Part Temperature Range

Component	Min. non-operation	Min. operation	Max. operation	Max. non-operation
E-Box Analog PCB E-Box Power Inverter and Control PCB	-55 °C	-40 °C	+85 °C	+90 °C

The E-Box Analog PCB is responsible for managing the data readouts for all torque and position sensors of the Locomotion Modules, while also facilitating the connection of the heat foil layers and TCS temperature sensors to the rover's heating lines. The E-Box Power Inverter and Control PCB controls the motor units and is therefore linked to all motor stators, hall sensors, and additional 3K-NTC sensors for dedicated temperature measurement. In order to address the heat generated by the motor drivers during prolonged operation, they are additionally attached to the E-Box housing to distribute their heat. Thermal gap pads serve as interface material to compensate for placements tolerances and to enhance the thermal contact with the housing.

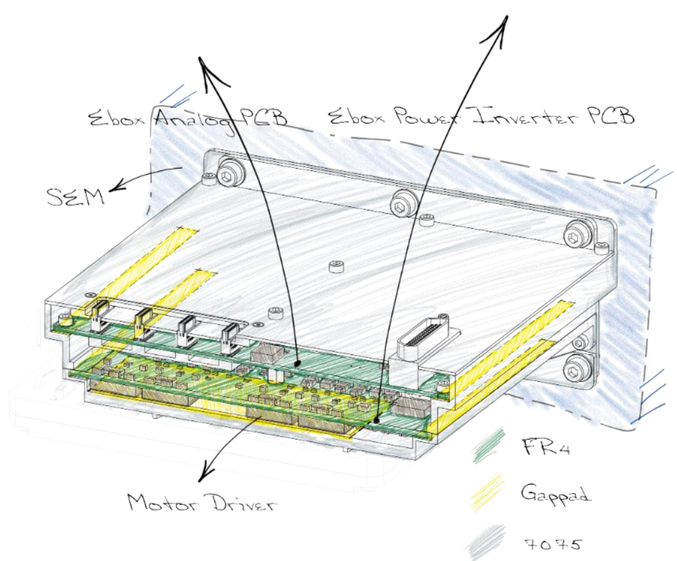

Figure 10. Locomotion E-Box Overview

Mechanically, the E-Box is attached to the SEM using six M3 steel screws. Electrically, the E-Box Analog PCB serves as the power interface to the Rover's PDCU, facilitating interconnection between the two E-Box PCBs. Due to the necessity for electrical grounding, the E-Box housing, is coated with Surtec650, which provides a low infrared emissivity ε, as previously mentioned. Given, that MLI covers the entirety of the SEM to shield against the cold mission environments, the primary method for heat transfer during operation is through thermal contact conductance via the SEM interface. The Locomotion E-Box does not need a dedicated active TCS, since it is kept within the required temperature range as part of the SEM's TCS.

D. Hold-Down-Release-Mechanism (HDRM)

The HDRM (see Figure 11) was also designed using a dissimilar material approach, consistent with the design guidelines outlined in section IV. Tribologically optimized materials, such as TECASINT 2391, were selected for all moving parts, such as the pillar housing or the slider guide.

During launch, flight and touchdown on Phobos, the LSS is in a stowed configuration (see left side of Figure 11). At this state, the leg and wheel are constrained in their motion by the split cone interface and the pillars to prevent over stress of the structural integrity and the drivetrains. This results in a hyper static state and is compensated by the elastic spokes of the wheel, leading to a closed kinematic loop through the wheel rim, the wheel spokes, the wheel hub, the deployable part and the load carrying structure. Consequently, the system's overall stiffness is increased, providing improved resistance to vibration and impact loads, as required for this specific application.[8]

The deployable part in particular plays an important role in maintaining the preload of the HDRM. Due to the different materials between the surrounding structure and the central screw, there are various changes in length at temperature differences of $\mathrm{dT} \geq -120\ °\mathrm{C}$ during the mission phases. Due to the complexity, the preload loss was determined via numerical simulation with regard to the expected environmental temperatures. In the non-operational cold case ($\mathrm{dT} = -120\ °\mathrm{C}$) this results in a preload loss of $\mathrm{p_L} = -392$ N and in the hot case ($\mathrm{dT} = 47\ °\mathrm{C}$) in a preload increase of $\mathrm{p_I} = 77$ N from the nominal preload (at +20 °C) of $\mathrm{p_N} = 1100$ N. The range of the preload change does not affect the functionality of the LSS or the material stress limits and was taken into account during the qualification of the system.

Once the rover has landed on Phobos, the HDRMs are released by burning the fuse-wire of the separation nut via IDEFIX's PDCU. Multiple spring elements are used to retract the deployable parts and the pillars (see right side of Figure 11).

In addition to addressing preload considerations, potential sticking or clamping of the HDRM was also considered to ensure the robustness of the release mechanism. Extensive thermal testing, alongside numerical simulation, was performed. The functionality of the finalized design was successfully tested during the qualification and acceptance test campaign.

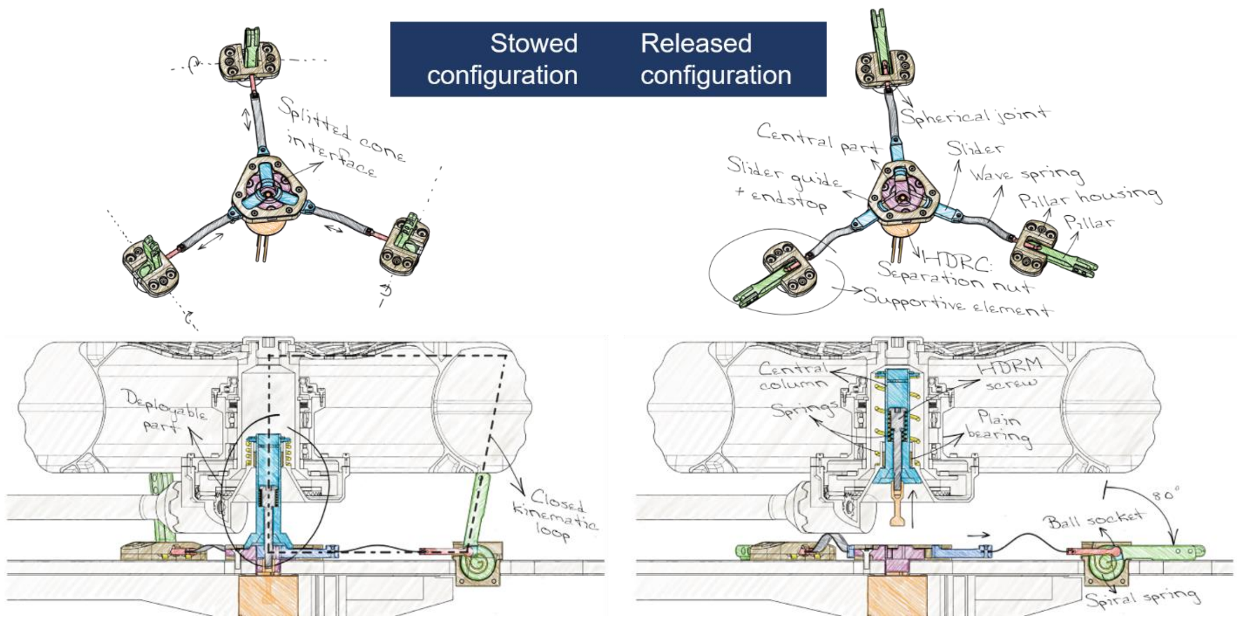

Figure 11. Components overview of Locomotion Subsystem HDRM

V. Thermal Design Verification

The thermal design of the LSS underwent verification through various individual thermal vacuum tests with combined functionality tests on component and subsystem level, starting from the early stages of the development phase. Of particular significance are the thermal cycling tests (TCT) during the qualification and acceptance test campaign, described in subsection B and the thermal balance test (TBT) outlined in subsection C.

A. Deep Temperature Test

During the development phase of the LSS, a series of individual component thermal tests were conducted,[15] including the so-called deep temperature test. This involved subjecting electronic parts, such as the position and torque sensors, as well as motor units, to temperatures of $\leq -140\ °\mathrm{C}$ in the thermal vacuum chamber. These temperatures exceed the non-operational ranges specified in the datasheets. The objective was to evaluate their resilience and determine whether they remained functional after returning to the operational range. Subsequently, visual inspections were conducted to ensure that no visible signs of damage or degradation were present. All components successfully passed the test, demonstrating the robustness of the Locomotion Module, even in scenarios where the heater threshold might need to be adjusted due to a limited electrical power budget during the Phobos night.

Moreover, this could also offer an advantage, as IDEFIX does not have component redundancy, allowing potential utilization of the LSS even in fault scenarios, such as the malfunction of heating lines or heat foils. However, in such non-nominal circumstances, it is important to acknowledge that the components of the Locomotion Module must attain the operational temperature ranges for safe operation. This could potentially limit the time frame during which IDEFIX can use the LSS, as it may need a longer waiting period to reach these conditions, for example, during Phobos day, when the environment and the rover is heating up.

B. Qualification and Acceptance Tests

In order to verify the finalized thermal design and the functionality under the required mission's temperature range of the LSS, TCTs were conducted on the qualification model (QM), flight model (FM) and flight spare (FS).[9]

Due to time constraints and the limited availability of test facilities, it was not feasible to test the entire LSS together. Instead, the tests were divided into two parts: one involving the Locomotion Modules in combination with the HDRMs, and the other focusing on the Locomotion E-Box. In general, vibration and shock testing preceded thermal cycling in the test sequences.

For the qualification TCTs of the Locomotion Modules with the HDRMs, a total of nine temperature cycles were applied on four QM modules. Table 4 outlines the temperature ranges for the front right (FR) and rear right (RR) Locomotion Module. It should be noted that the temperatures are not directly comparable to the ones stated in section III. They are based on worst-case thermal analyses conducted at system level including additional uncertainties and margins, and solely focusing on the Shoulder-Chassis interface (Chassis IF) and TRP of the Heater Zone.

Functionality tests were performed before, after and also during the thermal cycling, and HDRM releases were performed partially before and at the 9th cycle. All functionality tests, including the HDRM releases successfully fulfilled the requirements. Further information can be found in Ref. 15.

Table 4. Qualification test temperature ranges for the FR/RR QM Locomotion module

	Chassis IF min	Chassis IF max	TRP min	TRP max
NOP	−125 °C	+85 °C	−80 °C	+85 °C
OP Phobos	−100 °C	+70 °C	−35 °C	+80 °C
OP Cruise	−125 °C	+70 °C	−35 °C	+70 °C

For the acceptance TCTs, four FM modules and two FS modules underwent six thermal cycles with the temperature ranges shown in Table 5, and the functionality tests were successfully performed.

Due to the differing temperature goals for the Chassis IF and the TRP of the Heater Zone in both tests, stemming from the isolated thermal design, additional heating of the Heater Zone was required. However, due to technical constraints, achieving this solely with the thermal vacuum facility was not feasible. To address this, the pre-existing LSS heat foils in the Heater Zone were utilized.

The Chassis IF temperature was regulated using a temperature-controlled plate together with a thermal shroud, while for the TRP in the Heater Zone, a custom-made heater controller was specifically designed and built for this tests, ensuring precise and individual temperature regulation.

Table 5. Acceptance test temperature ranges for the FM, FS Locomotion modules

	Chassis IF min	Chassis IF max	TRP min	TRP max
NOP	−120 °C	+80 °C	−55 °C	+80 °C
OP Phobos	−75 °C	+65 °C	−35 °C	+80 °C
OP Cruise	−120 °C	+65 °C	−35 °C	+65 °C

Subsequently, the Locomotion E-Box successfully went through the qualification and acceptance thermal cycling test as well. Eight thermal cycles were applied to the QM E-Box, and six thermal cycles were applied to the FM and FS E-Box. For each test, the related temperature ranges are summarized in Table 6.

Table 6. Qualification and acceptance test temperature ranges for the Locomotion E-Box

	Qualification		Acceptance	
	E-Box TRP min	E-Box TRP max	E-Box TRP min	E-Box TRP max
NOP	−50 °C	65 °C	−45 °C	60 °C
OP	−35 °C	65 °C	−35 °C	60 °C

C. Thermal Balance Test

Although the qualification and acceptance tests verified the functionality of the LSS under the required temperature ranges, certain thermal behaviors and control performances could not be characterized within these tests. Therefore, an additional thermal balance test with the following objectives was performed. Two QM Locomotion Modules were utilized for this purpose. First, a realistic heater control logic was applied for maintaining the LSS temperatures, and the resulting behavior was observed. Second, a constant heater power was applied to examine the temperature distribution over the Locomotion Module under the steady-state conditions. Third, each individual motor unit was powered with a constant input power to characterize the heat distribution.

The verification of the heater regulation and the characterization of steady-state heater operation were conducted under the cruise cold environment. To imitate the external radiative environment, the shroud of the thermal vacuum chamber was set to −130 °C. Additionally, a cold plate was set to −70 °C to establish reasonable boundary conditions for the rover chassis. During the heater regulation test, the Heater Zone was controlled in an on/off manner based on the measured TRP temperature. The applied voltage was 50.2 V, which corresponds to the maximum voltage supplied from the MMX spacecraft's heating line.

For the cruise phase survival condition, the heat foils of Heater Zone were activated at −27 °C and turned off at −24 °C. In the cruise operational condition, the heaters were turned on at −12 °C and deactivated at −9 °C, based on the expected heater control settings in flight (see Table 2). Subsequently, the heaters of the Heater Zone remained constantly activated with the applied voltage of 33 V, which is the minimum voltage supplied from the heating line of the MMX spacecraft.

Figure 12 illustrates the recorded temperatures of the rear left (RL) Locomotion Module. The lowest temperature was observed at the wheel part, which is fully exposed to the cold external environment and almost thermally isolated from the rest of the Locomotion Module. The Shoulder-Chassis interface temperature was maintained at approximately −70 °C by the conductive and radiative connection with the cold plate. Due to the isolation design at the Shoulder-Chassis interface, the temperature of the torque sensor body remained at a higher temperature than the chassis.

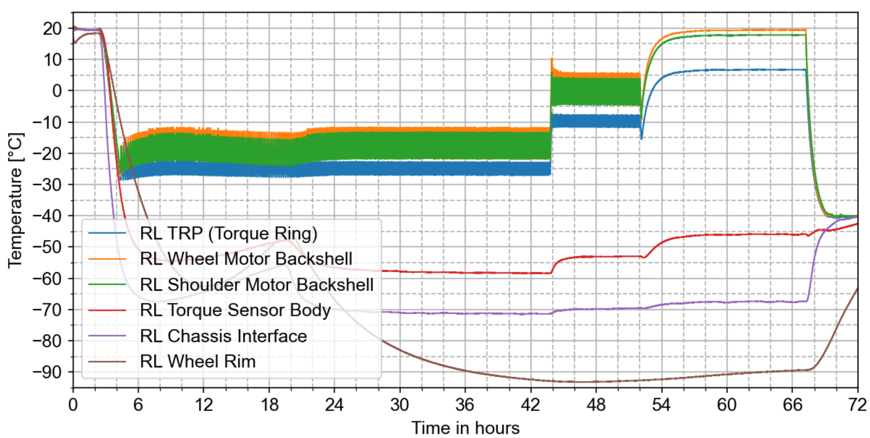

Figure 12. Locomotion module (RL) temperature during the TBT cruise case

Additionally, the isolation design implemented for the Heater Zone resulted in a significant temperature difference between the torque sensor body and the motors, as well as the torque sensor PCB. For both the cruise survival phase and operational phase, it was verified that they are kept on a sufficiently warm temperature level.

The test with constant heater power provided useful data for the thermal model correlation, and also demonstrated that the minimum voltage from the MMX spacecraft is sufficient to heat up the Locomotion Modules above the operational level in the cold cruise environment.

On the LSS level, the thermal model was developed by using the software Thermal Desktop, and the correlation was performed by manually adjusting the model parameters.

The investigation on the motor unit heat dissipation was performed under the simplified surrounding conditions. The shroud and cold plate temperatures were set to the uniform temperature level and only one motor was powered during each test case. Although these test cases do not correspond to a specific mission condition, the collected data supported improving the thermal model of the Locomotion Module.

VI. Conclusion

In this paper, the thermal design of the LSS was examined in-depth, providing insight into the strategies, methods, and considerations used to ensure its functionality and resilience throughout the mission. Both, the cruise and Phobos environments were considered during the development process. The qualification, acceptance, and thermal balance tests validated the performance of the TCS and verified that the thermal design complies with the harsh environmental requirements of the mission. Beyond these formally required tests, numerous additional thermal tests and studies, along with associated design iterations, contributed to the refinement of this finalized thermal design.

Despite thorough analysis and testing, some uncertainties remain regarding the mission's impact on IDEFIX's thermal system, such as the limited electrical power budget of IDEFIX's battery during Phobos' night. However, deep temperature non-operational tests demonstrated resilience to $\leq -140\ °C$.[15]

Another notable uncertainty for the LSS involves a potential change in the optical parameters of the Locomotion Shoulder Module's outer structure due to regolith accumulation during the landing maneuver.[12] Nonetheless, the Heater Zone of the Locomotion Shoulder Modules, in conjunction with its effective thermal isolation from other parts of the rover, ensures robustness against any deviations from the nominal case.

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