CONQUERING THE COLD: THERMAL TESTING OF MMX ROVER IDEFIX'S LOCOMOTION SUBSYSTEM FOR THE EXPLORATION ON PHOBOS

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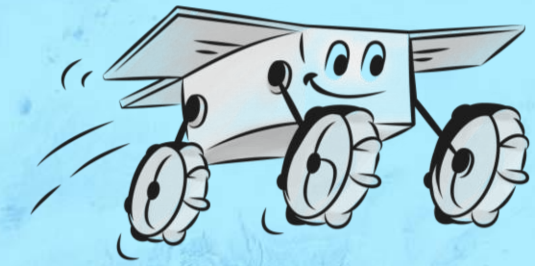

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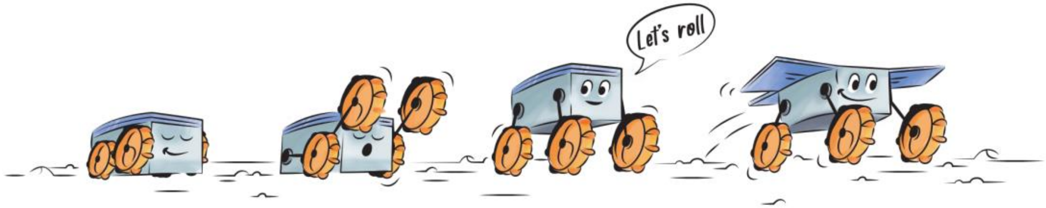
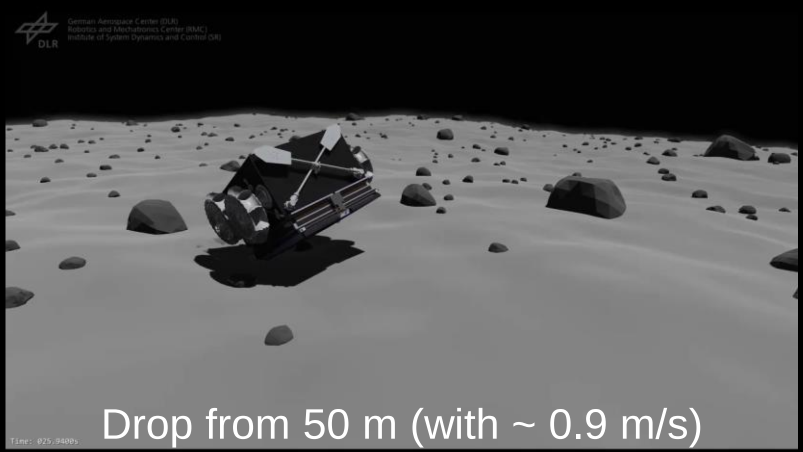


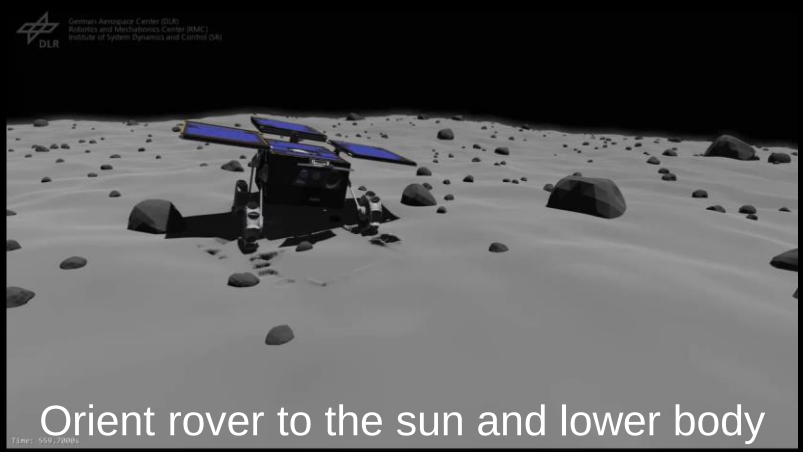
MMX Rover 'Idefix'
First wheeled rover mission in milli-g

A scout for JAXAs (M)artian (M)oon E(X)ploration sample-return mission

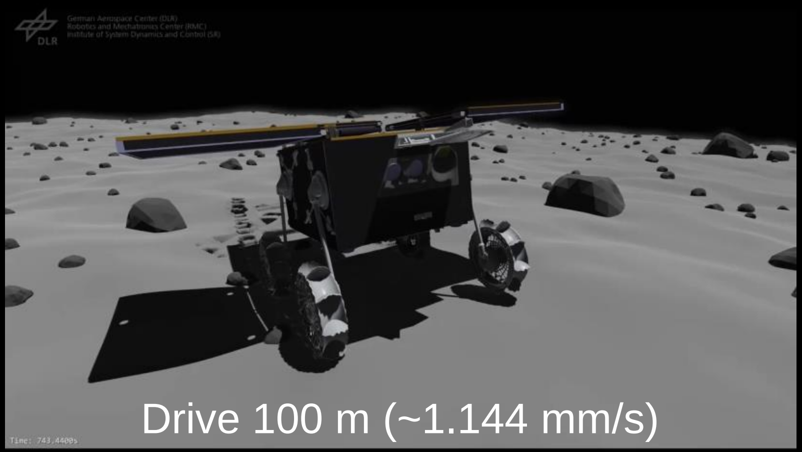


Drop from 50 m (with ~ 0.9 m/s)

Uprighting (from stored configuration)



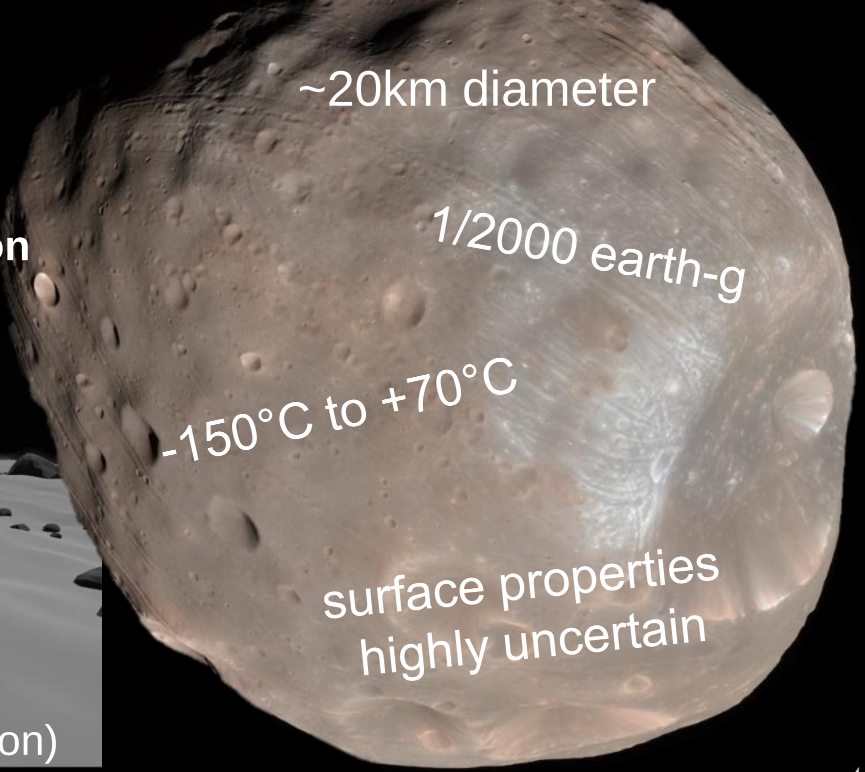
Orient rover to the sun and lower body



Drive 100 m (~1.144 mm/s)

Martian Moon Phobos

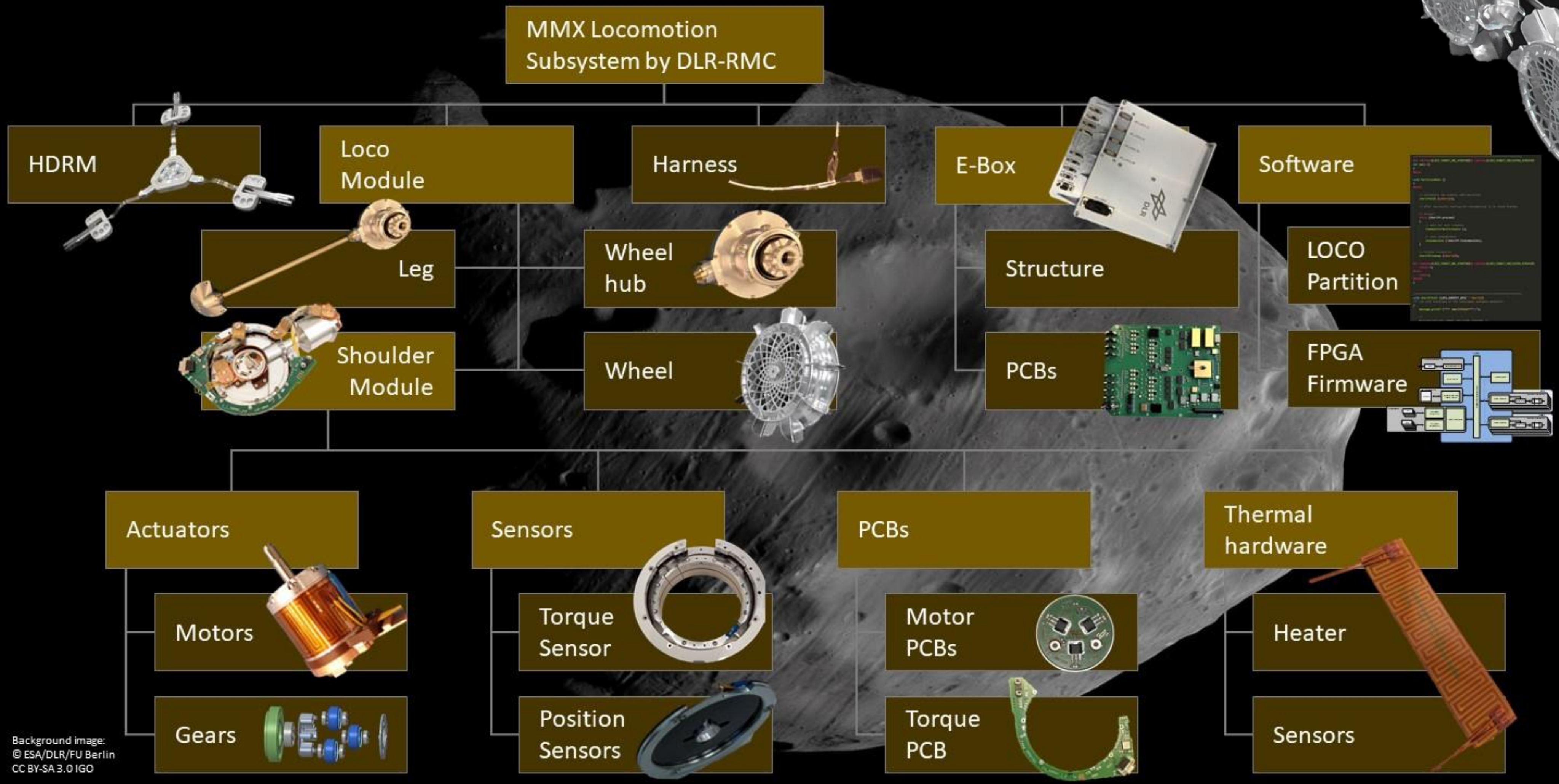
[MRO (NASA/JPL-Caltech/Arizona U.)]



Instruments of rover ‚Idefix'

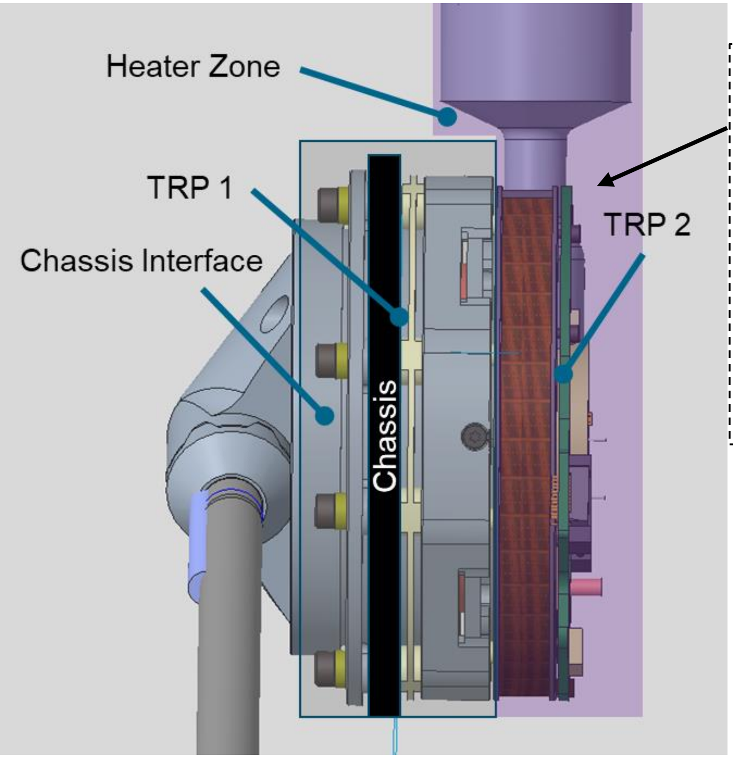
- RAX - Raman spectrometer to characterize the mineralogy of soil under the rover.
- MiniRAD – radiometer for thermal imaging.
- NavCAM - Stereo cameras for autonomous navigation and imaging science.
- WheelCAM - Wheel cameras for regolith science.

Locomotion Subsystem - Overview



Locomotion Module - Thermal Design Overview

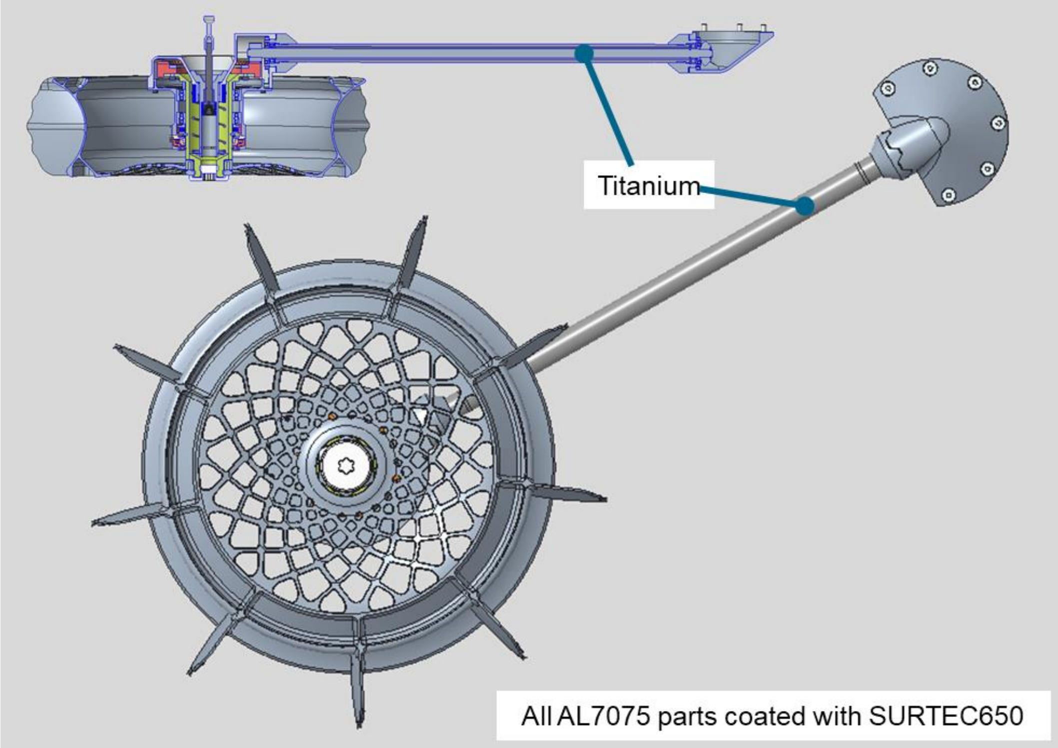
Locomotion Shoulder



<u>Heater Zone</u>

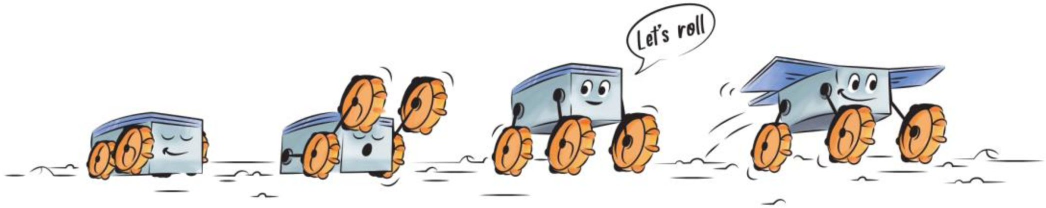
- Three heater areas
- Double layer heat foils
  - Cruise heater
  - Phobos heater
- SLI foils
- Thermal straps
- Conductive isolation

Locomotion Leg (including wheel hub and wheel)



- Two zones with each one temperature reference point (TRP).
- ‘Chassis Interface‘ consists of conductive isolation designs to reduce heat leakage from rover inside.
- ‘Heater Zone‘ includes actuators (two motor units), torque sensor, heat foils and additional electronics.
- ‘Heater Zone‘ provides all cabling connections to the rover and to the spacecraft for heating during cruise phase.

- Titanium increases R_{TH} of Locomotion Shoulder against Phobos ground.
- Only consists of passive components (no electronics).
- Material pairs sustain cold temperatures and prevent cold welding.
- Spring element design (e.g. for ball-bearings) keeps pre-load forces.



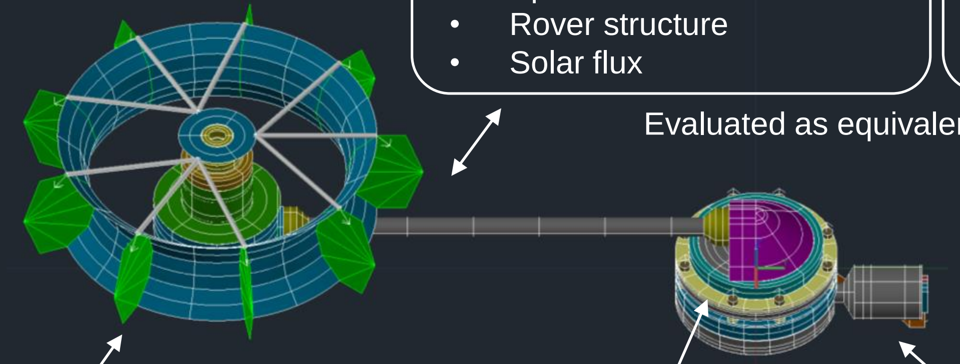
Locomotion Module - Thermal Environment

Locomotion module heat exchange

Radiation heat exchange (Cruise)
- Deep space
- Spacecraft structure
- Rover structure
- Solar flux

Radiation heat exchange (Phobos)
- Deep space
- Rover structure
- Phobos surface
- Solar flux

Evaluated as equivalent sink temperature

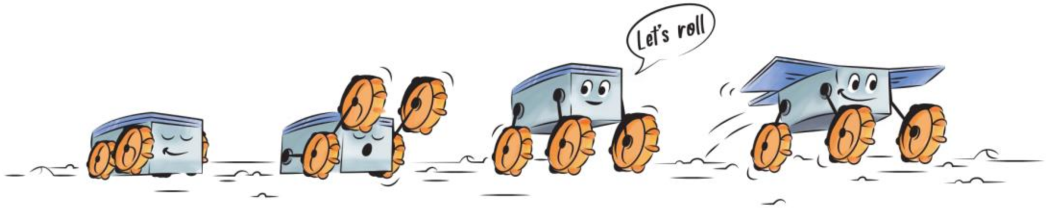


Conduction heat exchange
- Rover chassis through HDRM (Cruise)
- Phobos surface

Conduction heat exchange (Cruise and Phobos)
- Rover chassis through Locomotion shoulder

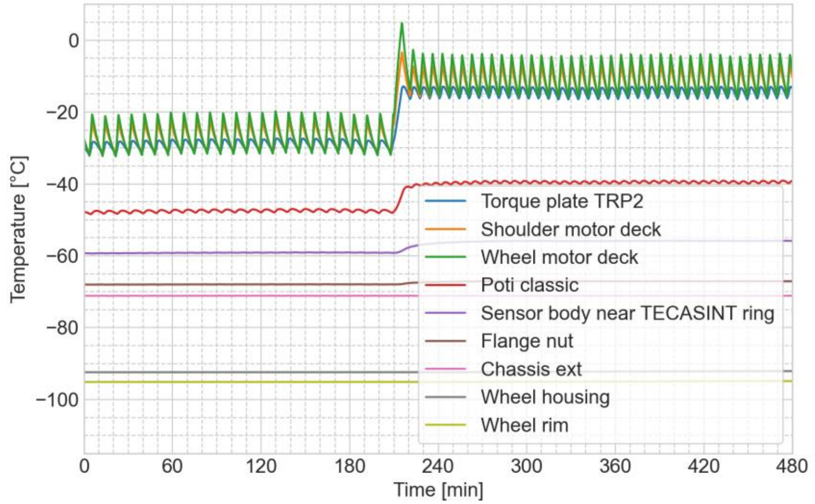
Radiation heat exchange (Cruise and Phobos)
- Rover inside

- Major Locomotion thermal interfaces
  - Conductive interface to Rover chassis (isolated from the Rover warm compartment)
  - Radiative interface to the external environment
- Severe low temperature environment for Cruise and Phobos phase

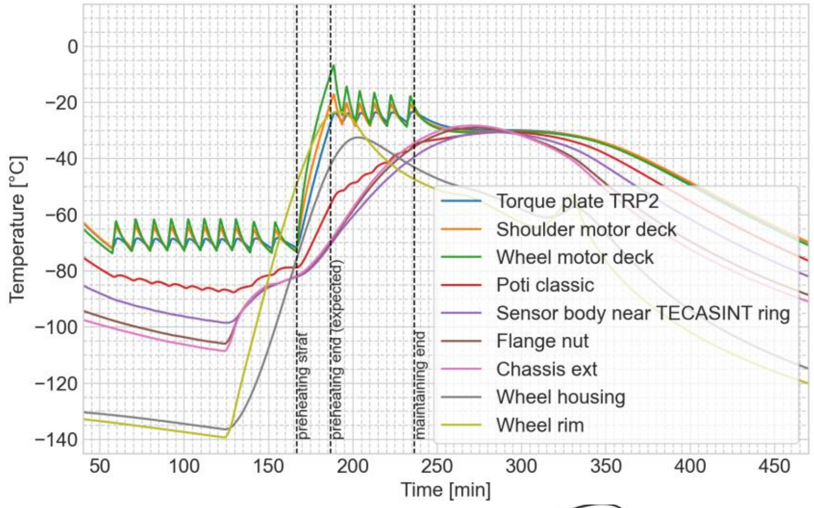


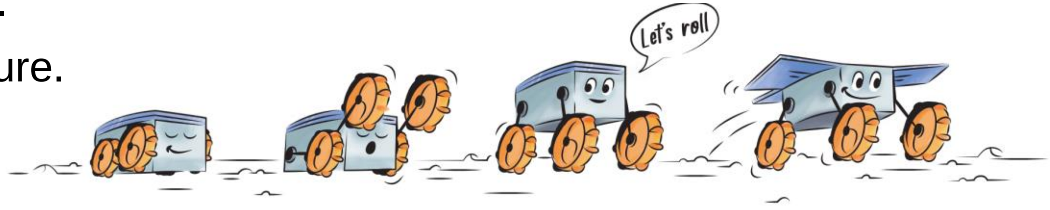
Locomotion Module - Thermal Environment

- Cruise environment
  - MMX Rover is nominally under shadow during the Cruise.
  - Equivalent sink temp min: approx. – 120°C
  - Conductive interface temp min: approx. –70°C
  - With the cruise heater, Locomotion is maintained above non-Op temperature.
  - For the operation, Locomotion is pre-heated to the Op temperature.



- Phobos environment
  - Phobos day/night cycle drives its thermal environment.
    - One Phobos day lasts 7.65 earth hours.
    - 300 cycles for the total mission time of three earth months.
  - Critical low temperature during the Phobos night.
  - Equivalent sink temp: approx. −135 … 20°C
  - Conductive interface temp: approx. −95 … 0°C
  - With the phobos heater, Locomotion is maintained above –75°C.
  - For the operation, Locomotion is pre-heated to the Op temperature.

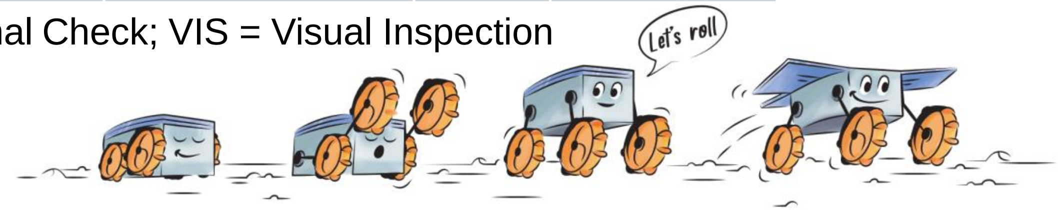




Engineering Model Tests

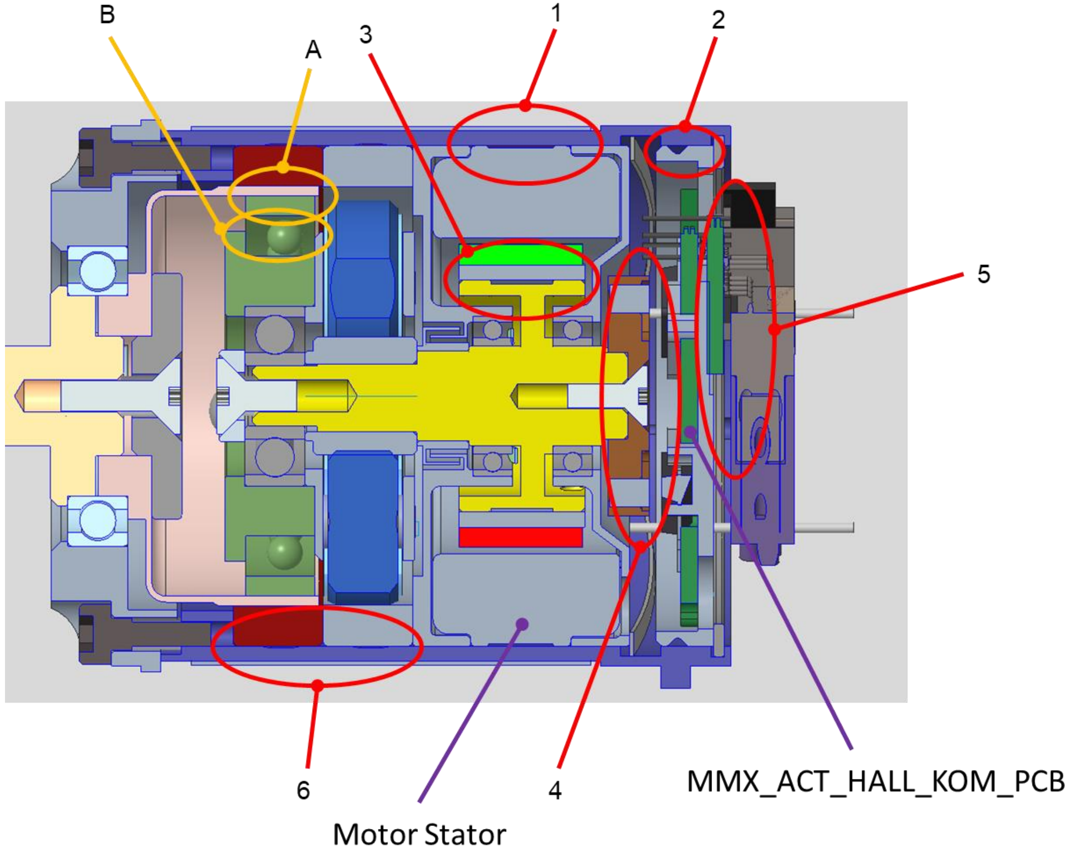
Thermal Testing EM Hardware						
Test	**Environment**	**Motor**	**Torque Sensor**	**Potentiometer**	**Ebox**	**HDRM**
Deep Temperature (-70°C)	Ambient	FT ✓ (Hallsensor)	-	PFC/VIS ✓	-	-
Thermal Cycle (~ -130°C)	Nitrogen	FT ✓ (Hallsensor)	-	PFC/VIS ✓	-	-
Deep Temperature (~ -140°C)	TVAC	PFT/VIS ✓	PFC/VIS ✓	PFT/VIS ✓	-	-
HDRM Thermal Functionality (~ -104°C)	TVAC	-	-	-	-	FT/PFT/VIS ✓
Torque Sensor Functionality	Ambient	-	FT ✓	-	-	-
Locomotion Module Thermal Balance	TVAC	FT ✓	-	PFT/VIS ✓	-	-
Locomotion Module Thermal Functionality	TVAC	FT ✓	-	PFT/VIS ✓	-	-
Locomotion Ebox Thermal Balance	TVAC	-	-	-	FT ✓	-
Locomotion Ebox Thermal Functionality	Ambient	-	-	-	FT ✓	-
QM Performance Setup Pretest	TVAC	-	-	FT (Classic Poti) ✓ (Temperature Drift)	-	-

FT= Functional Test; PFT = Post Functional Test; PFC = Post Functional Check; VIS = Visual Inspection



EM Motor Unit - Deep Temperature Test

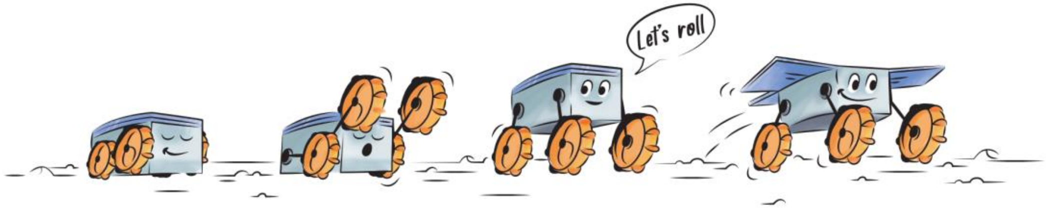
- Min. non-op. is limited by DELO epoxy and motor stator component.
  - Datasheet values are guidelines, not strict limits.
- Rover's battery not designed for such temperatures during Phobos night.
  - Ongoing mission risks and uncertainties, leading potentially to lower temperatures.



Motor Unit – Datasheet Temperatures

Location	Component	Min. non-operation	Min. operation	Max. operation	Max. non-operation
A	Braycote Micronic 601 EF	-80°C	-80°C	+204°C	+204°C
B	Fomblin Z25	-75°C [2]	-75°C [2]	+260°C	+260°C
1-6	DELO Duopox SJ8665	-40°C [1]	-40°C [1]	+180°C [1]	+180°C [1]
-	Motor Stator	-40°C [1]	-40°C [1]	+125°C	+125°C
-	MMX ACT HALL KOMP PCB	-55°C	-40°C	+125°C	+125°C
-	Structural material AL7075	-	-	Short Term +120°C Long Term +90°C	Short Term +120°C Long Term +90°C

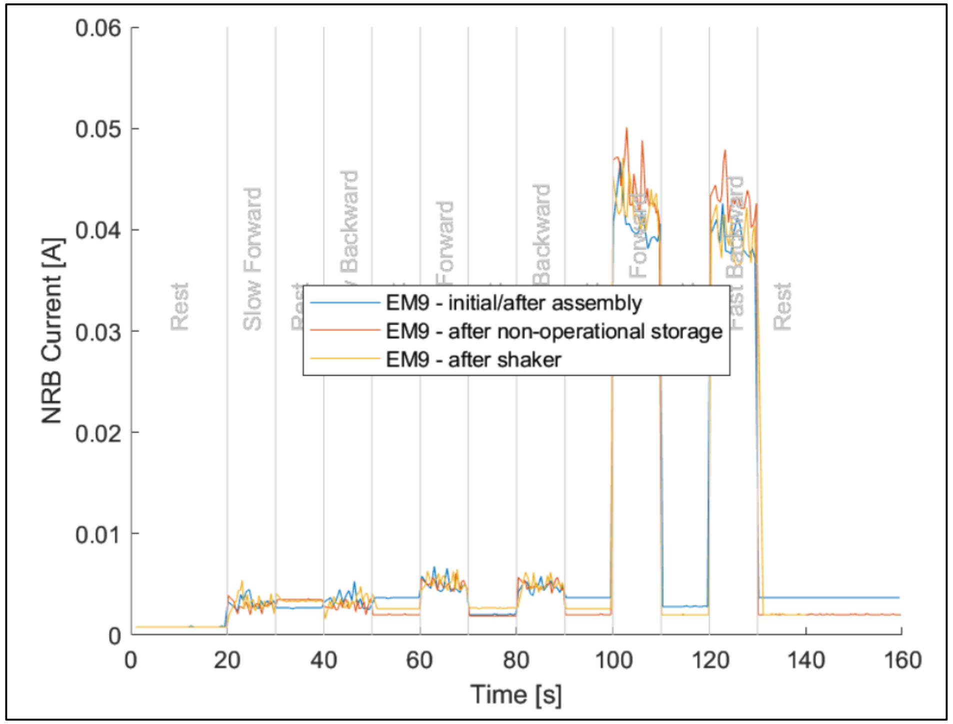
[1] Datasheet Orientation; [2] Pour Point



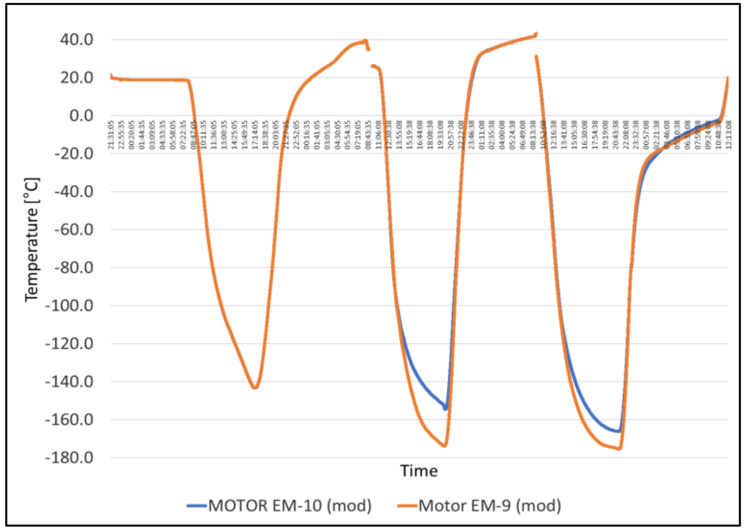
EM Motor Unit - Deep Temperature Test

- **Test objective:** Evaluate functionality, behavior, and visually inspect Locomotion EM motors before and after passive exposure to temperature cycles, including a low point of < -140°C @TRPs.
- **Environment:** Vacuum level <1.0 E-5 mbar; three separate temperature cycles
- **Result:** No significant alterations in functionality, and visual inspections revealed no changes.

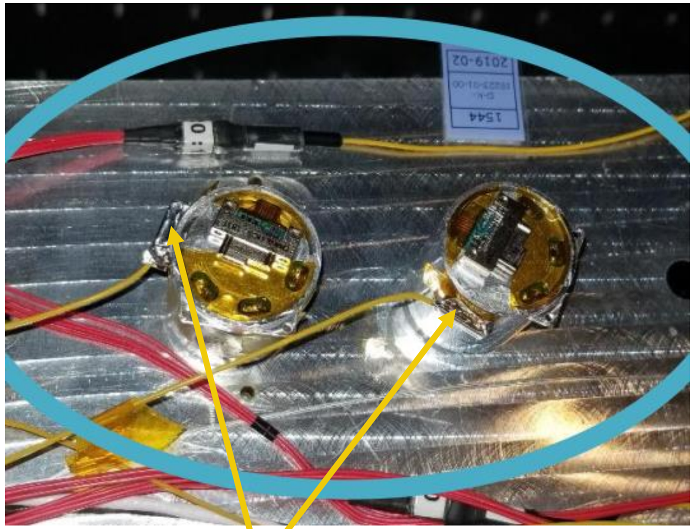
NRB Current Comparison Results



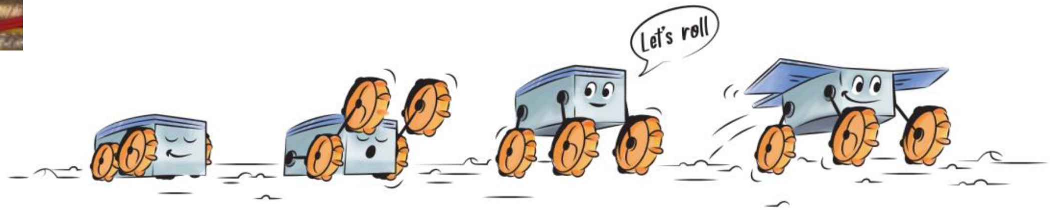
TRP Temperature Cycles



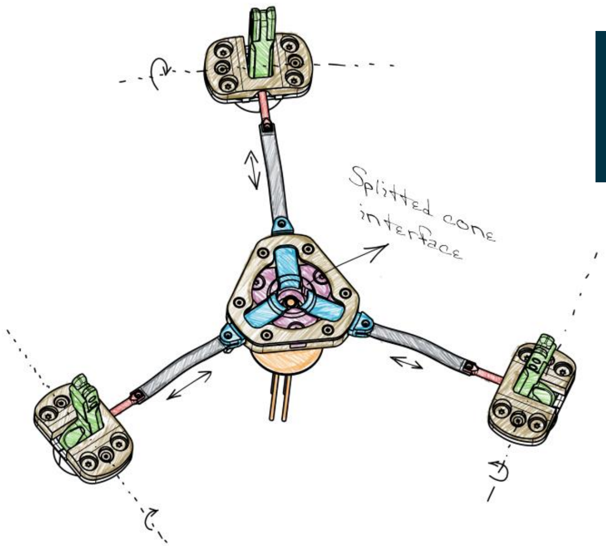
Locomotion EM Motors in TVAC



TRPs

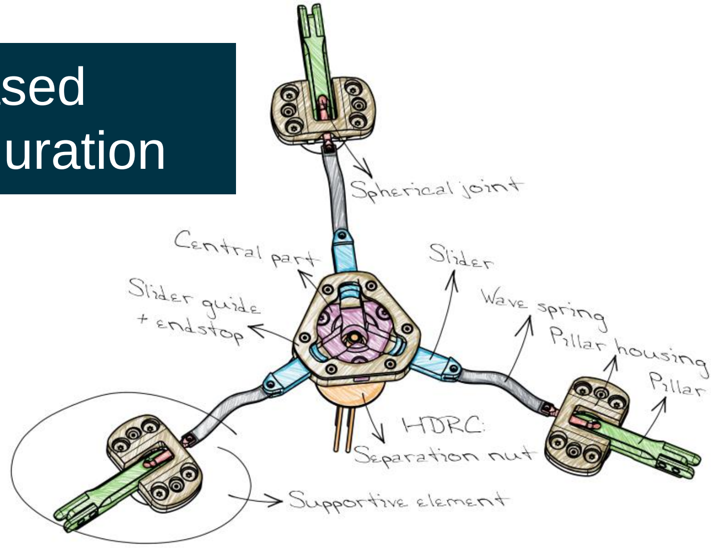


EM HDRM - Cold Functionality Test

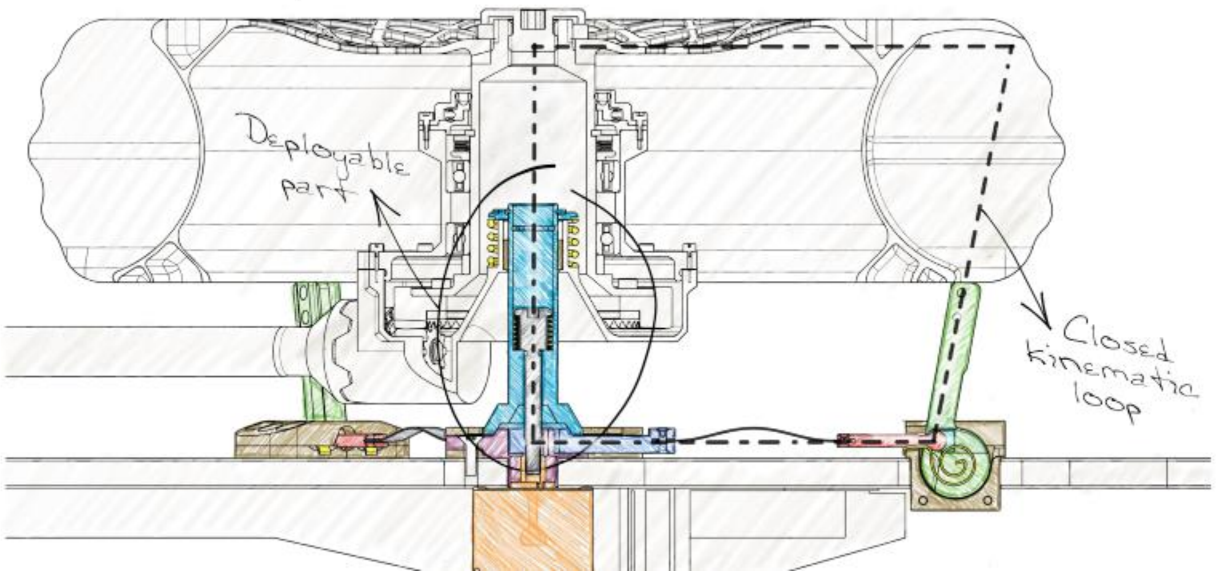


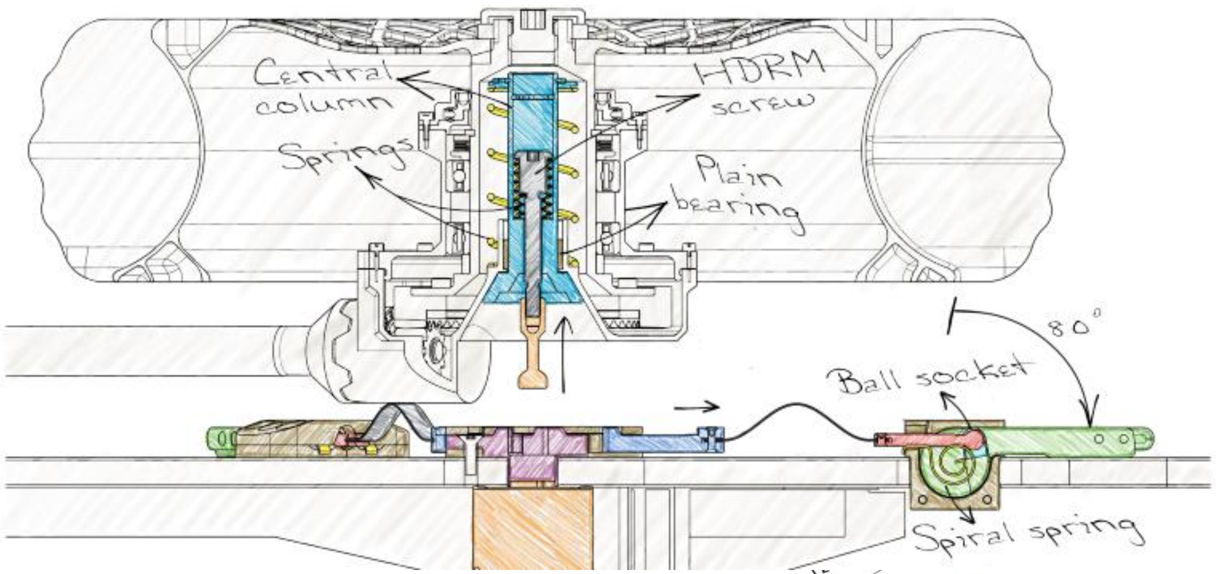
Stowed configuration

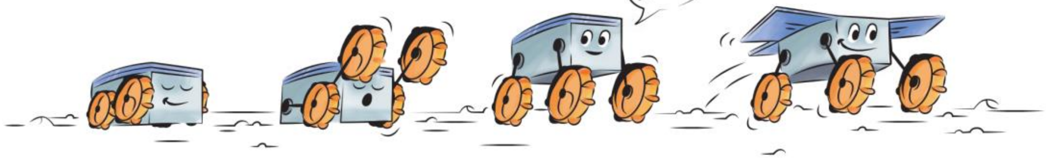
Released configuration



- Protect wheels and drivetrain from vibration and impact
- Dissimilar material approach
- 0.25Nm of rectraction torque at each pillar



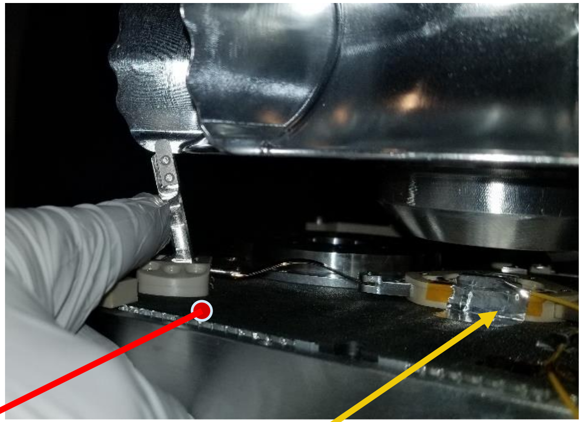


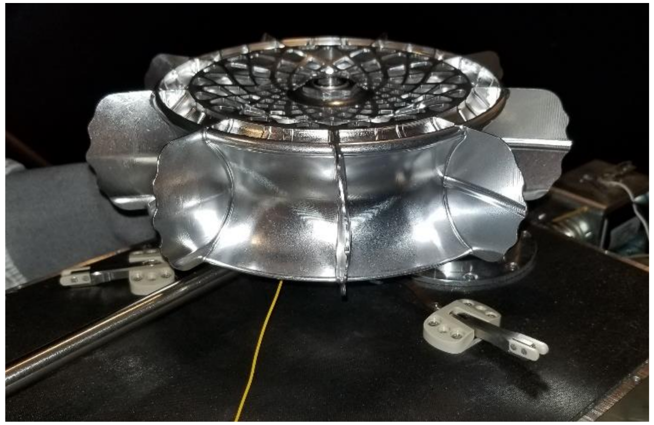


EM HDRM - Cold Functionality Test

- **Test objective:** Proof release functionality of the HDRM at EM level
- **Environment:** Vacuum level <1.0E-5 mbar; temperature below -104°C @TRP
- **Result:** Out of three releases, two failed due to one blocked pillar.
- **Reason:** The opening angle between the pillar and the pillar end stop was to sharp allowing the pillar joint to self-lock, when released under thermal load.

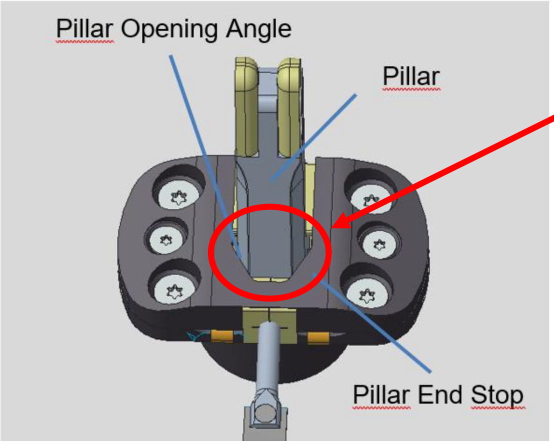
Visual inspection after 3. release test





TRP

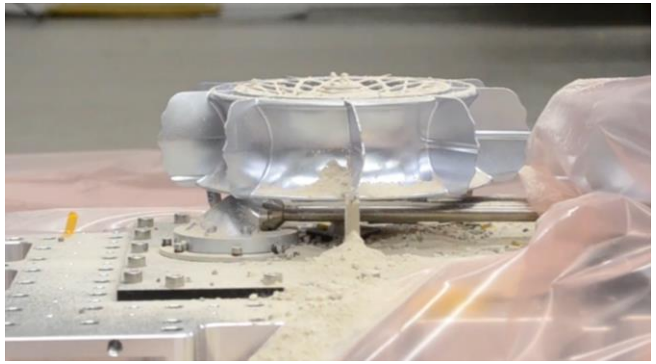
Pillar mechanism in first EM design

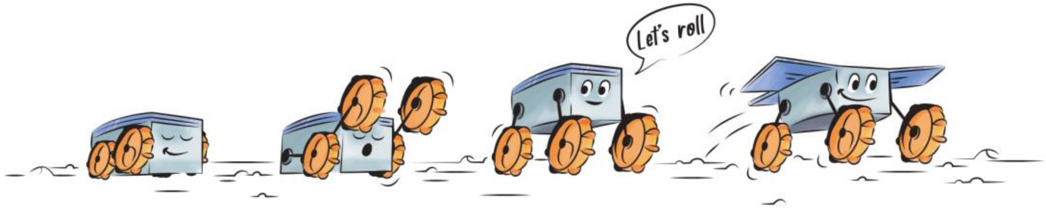


Solution: The opening angle was mechanically adjusted to prevent the self-lock behavior. Instead of a cone shape, **a flat surface for the end stop** was designed.

➢ The new design was extensively tested with modified EM HDRM and QM/FM HDRMs.

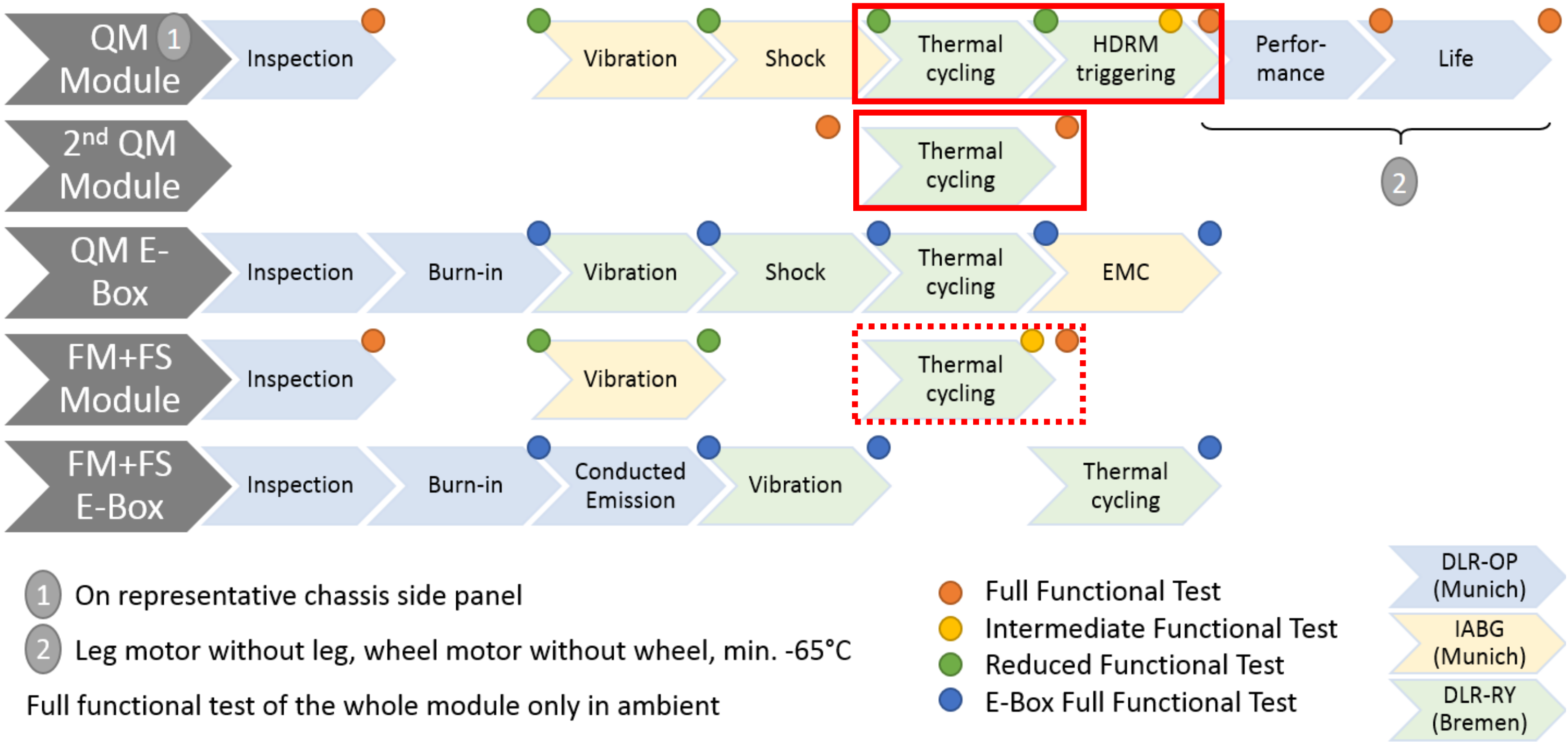
HDRM sand release test

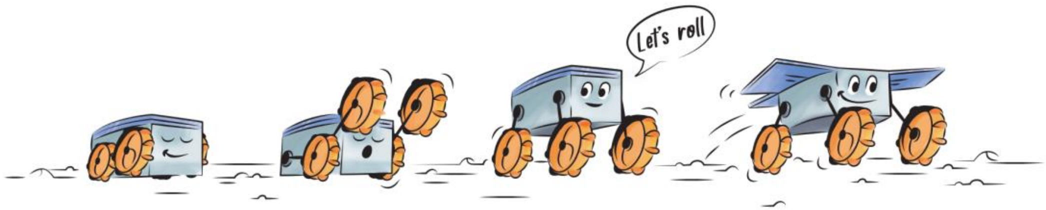




Qualification & Acceptance Test Campaign

- 4 overlapping test tracks
  - 1x QM & 1x FM+1x FS E-Boxes
  - 4x QM & 4x FM+2x FS Loco Modules
- 9 test facilities
- 150 lab days
- 6 months (01/22 – 06/22)
- 20 engineers





QM Module Thermal Cycling Test – Specifications

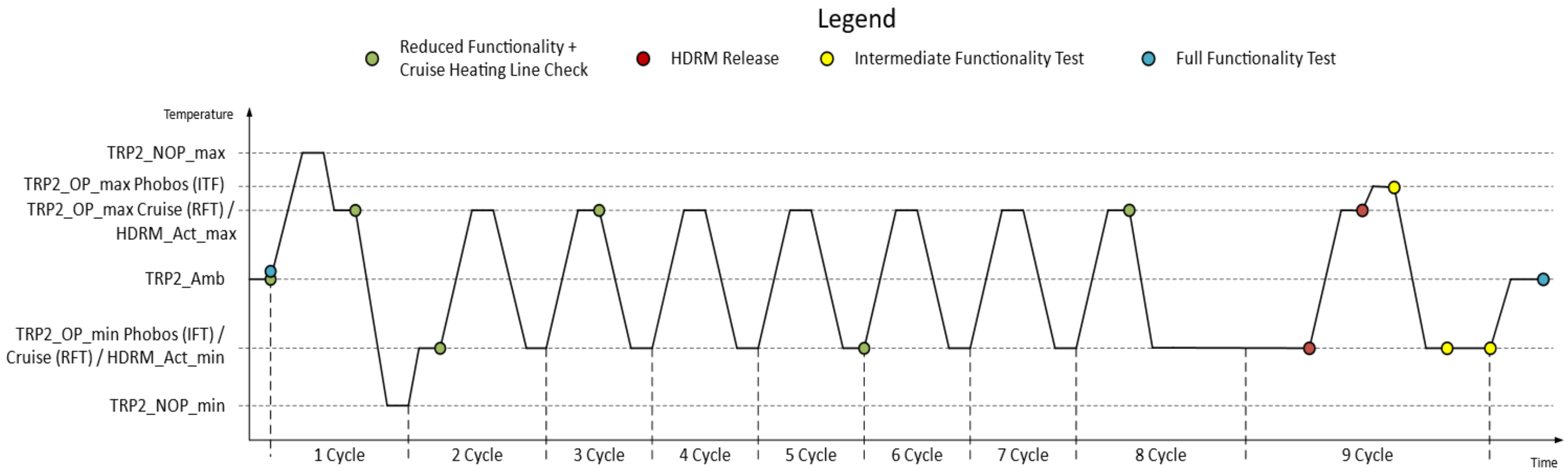
One thermal cycling test conducted for all Locomotion Modules (4x QMs; called A, B, C and D)

Note: HDRMs are in prelocked condition

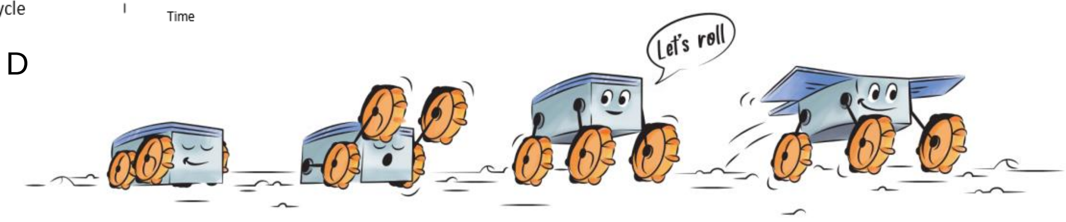
- Nine cycles, four different functionality tests
- Independent TRP1 and TRP2 temperature targets
- Three separate target values TRP2 for non-operational temperature.
- Representative chassis only available for Locomotion Module A and B.
  - Aluminum plate used for C and D
    - ➢ Different thermal behavior

Temperature cycling range for TRP2

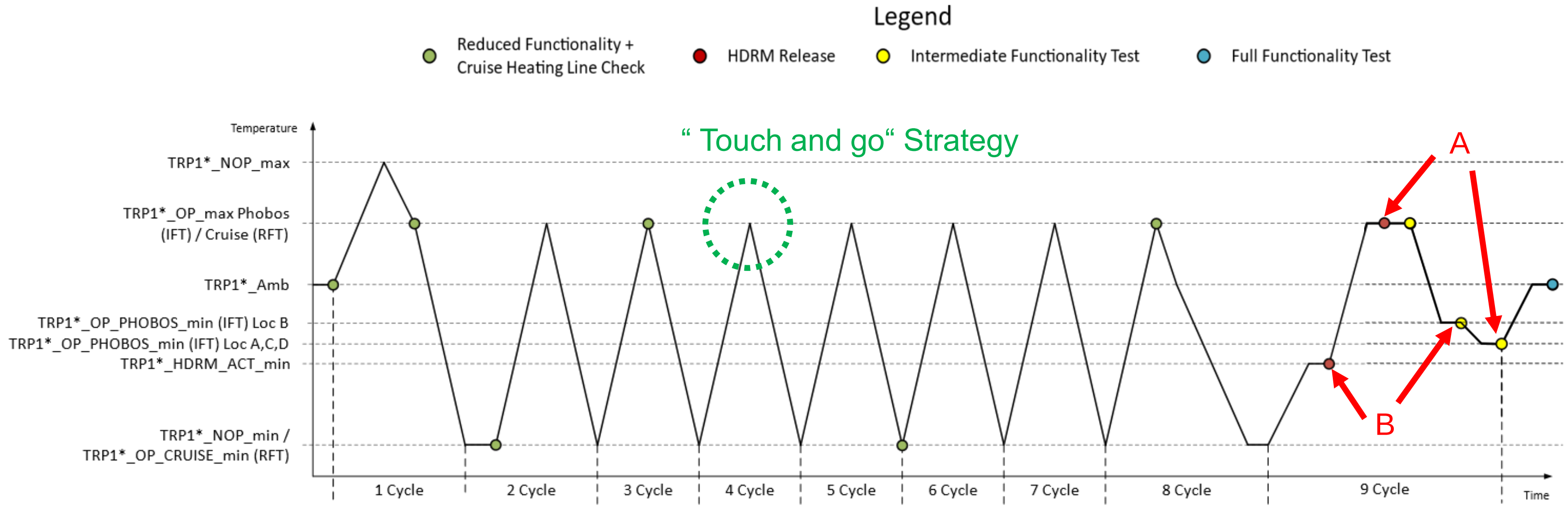
TRP2	Qualification Temperature		
	Representative Chassis		Non-representative Chassis
	A and B		C and D
TRP2_NOP_max	+85°C		
TRP2_OP_max_Phobos (IFT)	+80°C		
TRP2_OP_max Cruise (RFT)	+70°C		
TRP2_HDRM_Act_max	+70°C		
TRP2_OP_min Phobos (IFT)	-35°C		
TRP2_HDRM_Act_min	-35°C		
TRP2_OP_min Cruise (RFT)	-35°C		
TRP2_NOP_min	-55°C	-50°C	-80°C



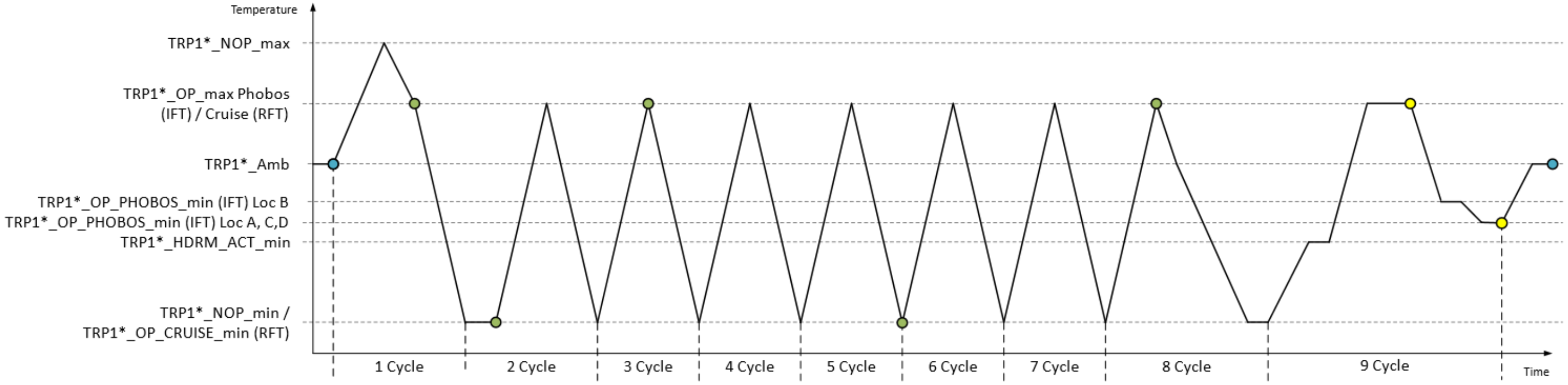
Thermal cycle test parameter TRP2 for Locomotion Modules A, B, C, D



QM Module Thermal Cycling Test – Specifications



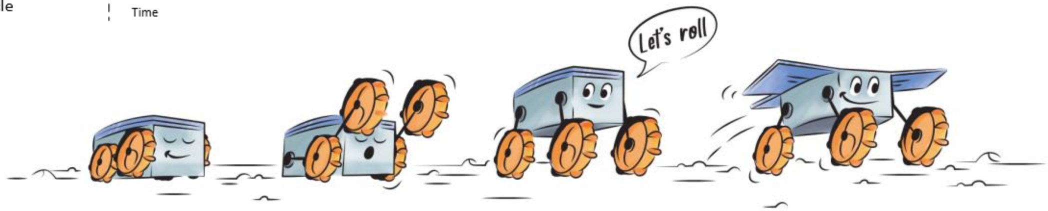
Thermal cycle test parameter TRP1* for Locomotion Module A + B



Thermal cycle test parameter TRP1* for Locomotion Module C + D

Temperature cycling range for TRP1*

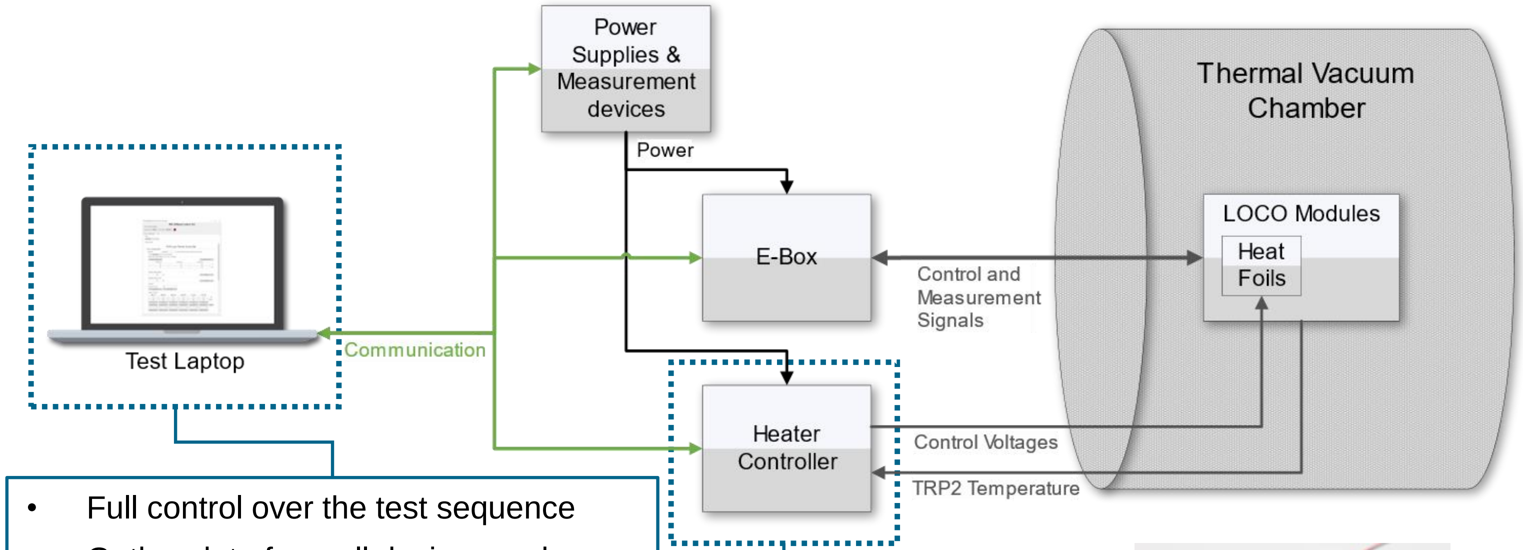
TRP1*	Qualification Temperature		
	Representative Chassis		Non-representative Chassis
	A	B	C and D
TRP1*_NOP_max	+85°C		
TRP1*_OP_max_Phobos (IFT)	+70°C		
TRP1*_OP_max Cruise (RFT)	+70°C		
TRP1*_HDRM_Act_max	+70°C	N/A	N/A
TRP1*_OP_min Phobos (IFT)	-100°C	-60°C	-100°C
TRP1*_HDRM_Act_min	N/A	-110°C	N/A
TRP1*_OP_min Cruise (RFT)	-125°C		
TRP1*_NOP_min	-125°C		



QM Module Thermal Cycling Test – Control Infrastructure

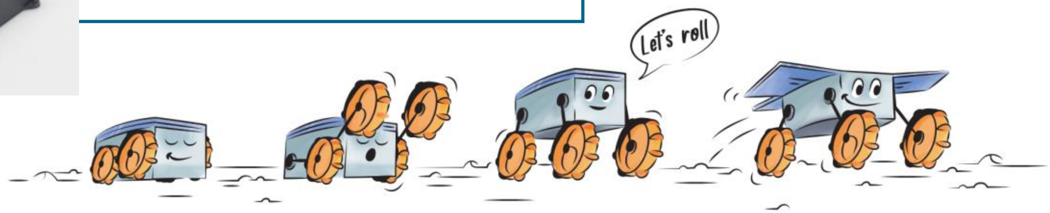
Test hardware for interfacing the Locomotion modules

- Multiple network capable power supplies and measurement devices
- Engineering Model of the Electronic Box (E-Box) for Loco module actuation
- Custom made control electronics for the TRP2 temperature control via the Rover heating line (‘Heater Controller’)
- Test notebook running python software with graphical user interface as central test control device



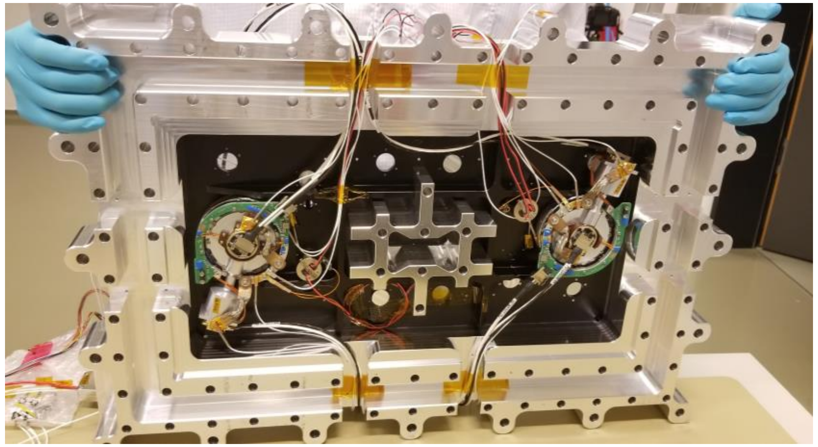
- PI temperature control
- Six independent channels to cover the FM/FS tests.
- Master/Slave operation mode. Channels can be configured to take control over other channels.
- Fixed output mode for each channel.
- Runs even if the control software on the test laptop fails -> Protects the modules from dangerously low temperatures at any time.
- Ensured that TRP 2 reaches stable target temperatures prior to TRP 1 „Touch and Go“ target.

- Full control over the test sequence
- Gather data from all devices and generate log files.
- Control of the functional tests.
- Remotely controllable to enable test surveillance and -control at any time.



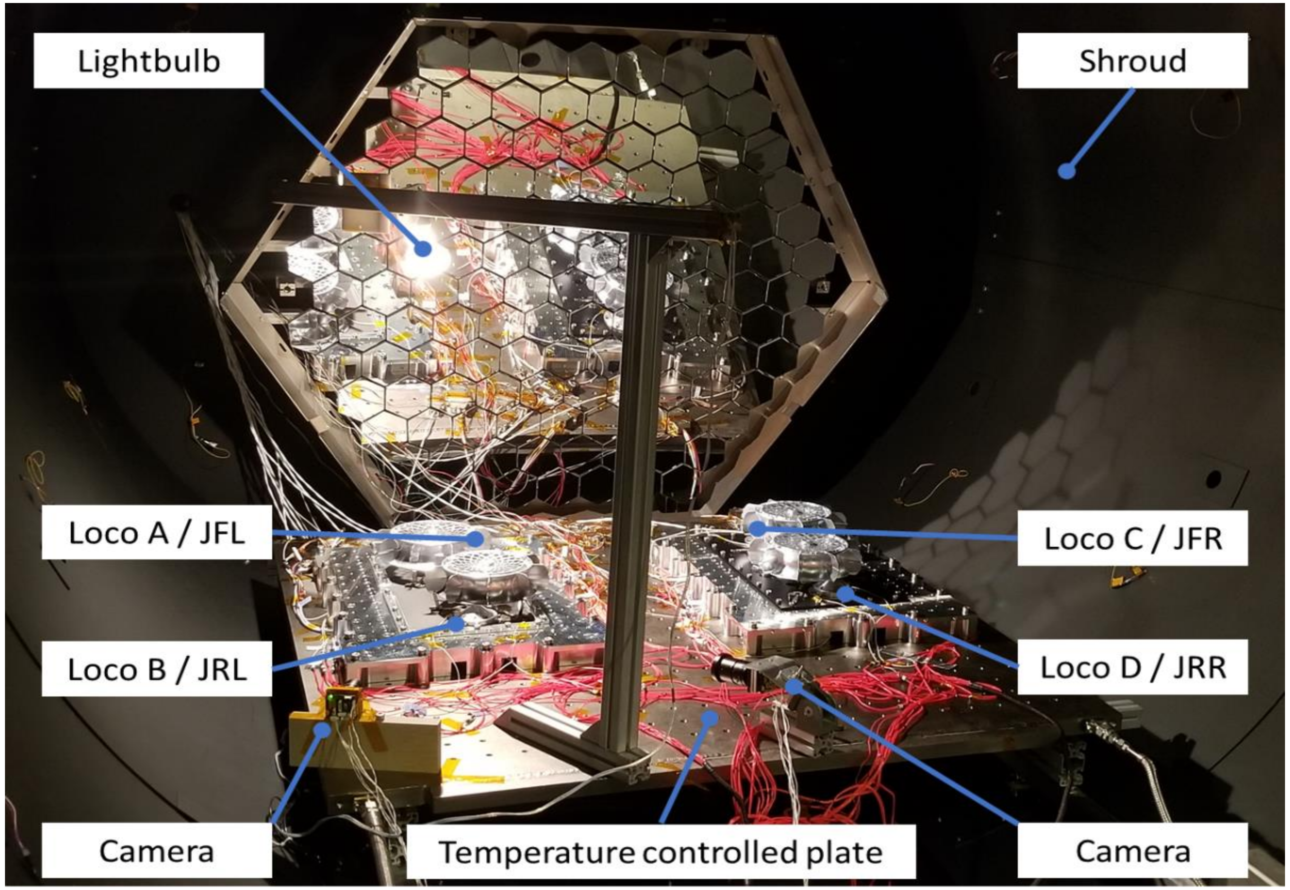
QM Module Thermal Cycling Test – Test Setup

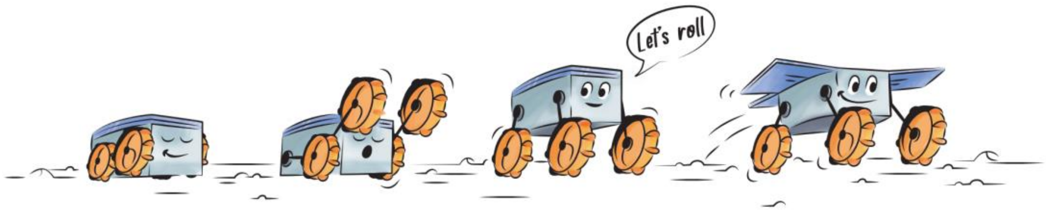
Test Setup Preparation



Test Setup Specifications	
Locomotion Hardware	4 QM Modules (1x EM Ebox)
GSE Harness	58 Test Cables (+36 for Hardware) 149 Connector Pins @ Feedthrough ~ 12 m length between endpoints
Ext.Temp. Sensors	33x PT100 (8x TRPs)
GSE Devices	5x Multimeter (1x Multichannel) 4x Multichannel Power Supplies 2x Cameras 1x Test Laptop 1x Oscilloscope (for HDRM release) 1x Heater Controller 1x TVAC Temperature Datalogger
Test Duration	400 Hours (16.67 Days)

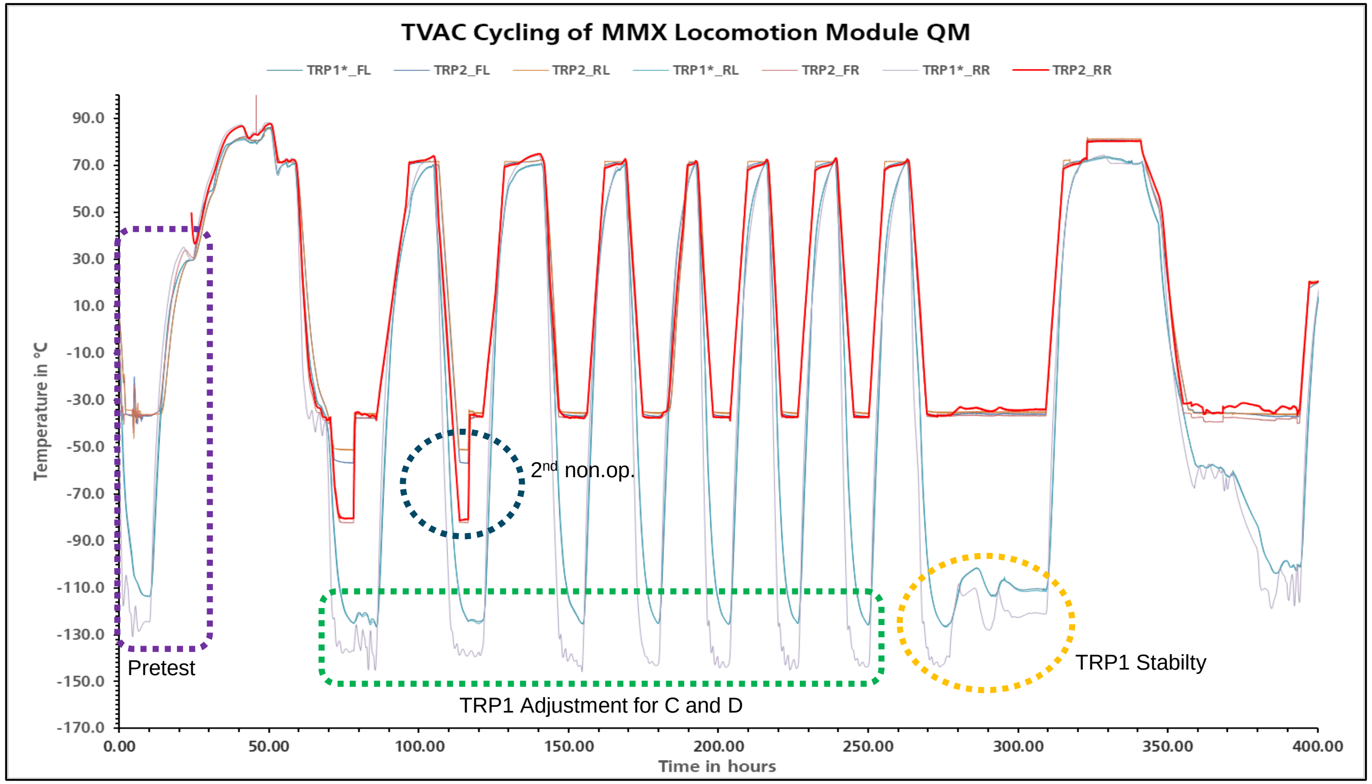
QM Module Test Setup Inside TVAC



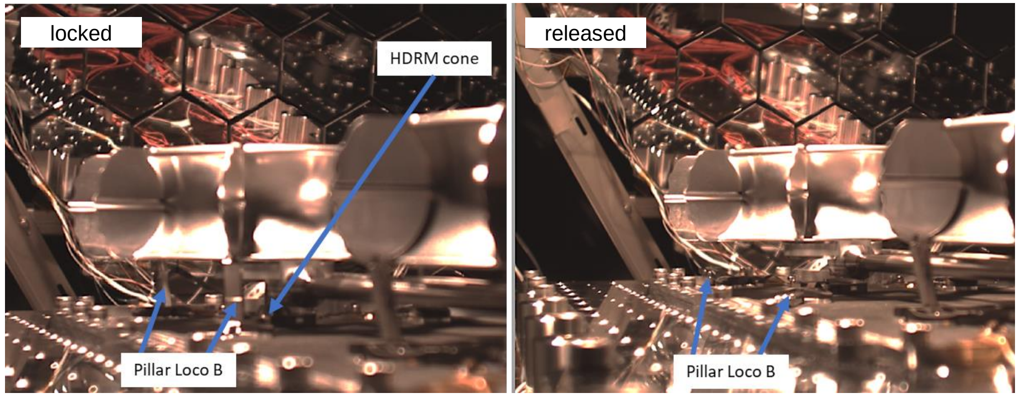


QM Module Thermal Cycling Test – Test Results

- All HDRMs successfully released
- Test requirements passed
  - Adjustment of TRP1 min. temperature for module C and D due to thermal behavior
  - Some functionality test (e.g. motor units) influenced by test cabling grounding issues; confirmed pass later
- One position sensor (foil potentiometer) showed discontinuous measurements in low temperature range.
  - ➢ Third redundant component, disconnected in the FM/FS Modules

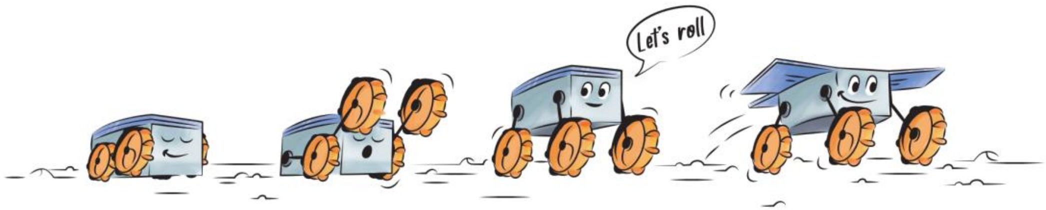


HDRM release inside the TVAC with -110 °C at TRP1



Thermal Cycling Test Requirements

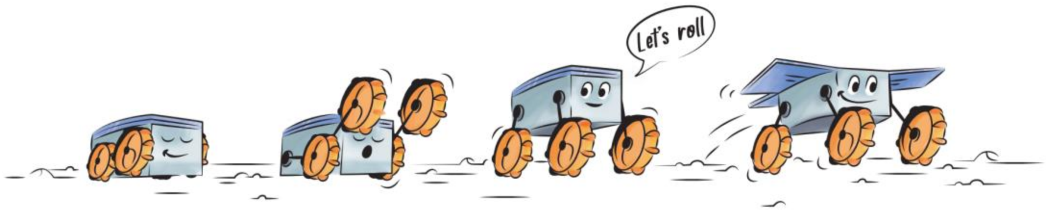
No.	Requirement
R12-14	Compliant to temperature stability & rate of change, vacuum pressure level.
R15-17	Functional tests successfully performed.
R18	HDRM successfully released.
R19	Cruise heating line is electrically connected.
R20	Phobos heating line is functional.
R21	Integrity of internal temperature sensors verified.
R22	Full performance of internal temperature sensors checked.



Conclusion and Outlook

- No prior heritage on deep temperatures for LSS components (e.g. motor unit).
  - Some components have undergone testing beyond the specifications outlined in the datasheet.
  - Hardware design proved to be robust and only minor changes needed to be made.
- Qualification campaign of the LSS was successfully completed in June 2022.
  - Some minor issues were revealed.
  - ➢ Failure of the foil potentiometer in cold temperature required adjustment of the FM.
  - ➢ GSE Harness grounding issues solved for acceptance tests.
- LSS fully integrated in rover.

- Tests on rover level (PFM test campaign) will be completed in October 2023.
- MMX rover ‘Idefix’ will be shipped to Japan in November 2023.
- Launch in September 2024.
- The rover will be separated from the JAXA spacecraft in 2027.



THANKS FOR YOUR ATTENTION. QUESTIONS?

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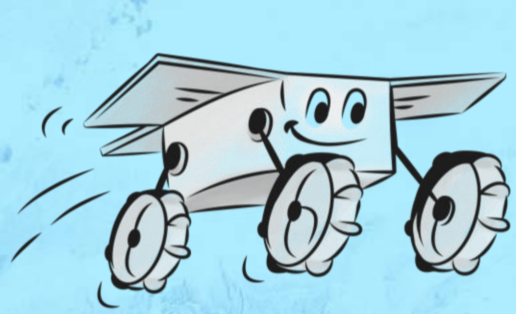

DLR

Publications – Locomotion Subsystem

Locomotion Subsystem

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