MOBILE PAYLOAD ELEMENT (MPE): CONCEPT STUDY OF A SMALL, AUTONOMOUS AND INNOVATIVE SAMPLE FETCHING ROVER

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ABSTRACT

The Mobile Payload Element (MPE) is designed to be a small, autonomous and innovative rover of ~15kg for planetary exploration. Its novel capability is to acquire clearly documented samples from surface as well as subsurface locations, and to bring them back to its lander for further analyses. Although the ESA Lunar Lander served as reference scenario for the MPE development, it is compatible to any alternative landing mission with a similar mission profile.

The MPE has a four-wheeled configuration with active suspension and can be tele-operated or navigate autonomously. The current MPE Delta Phase A focusses on the development of the locomotion subsystem and the avionics. The project team also details the concept designs for a dedicated MPE close-up imager and sample transfer mechanism. In addition a concept for an Autonomy Payload Experiment (APE) is being established as an option to enhance the MPE's autonomy functions.

1. Introduction

In early 2011 the German Space Agency DLR commissioned Kayser-Threde with the feasibility study of a Mobile Payload Element. As industrial prime, Kayser-Threde has assembled relevant German industrial and institutional competences in space robotics and lunar science for this study. The Mobile Payload Element is designed for exploration of the environment and sampling in the vicinity of the envisaged landing site. Although the ESA Lunar Lander served as reference scenario for the MPE development, it is compatible to any alternative landing mission with a similar mission profile. One potential flight opportunity for MPE would be the Russian Luna-Resource Mission.

Based on the results of the MPE Phase 0/A study, the current MPE developments continue in the frame of a Delta Phase A. The work focusses on the further development of the MPE locomotion subsystem and the miniaturization of its avionics. The project team also details the concept designs for a dedicated MPE close-up imager and sample transfer mechanism. In addition a concept for an Autonomy Payload Experiment (APE) is being established as an option to enhance the MPE's autonomy functions. The MPE Delta Phase A will run until fall 2013. This paper describes the MPE rover concept with focus on the results of the current Delta Phase A at the time of the congress.

2. Reference Scenario

As a first step in the MPE Phase 0/A study a reference scenario was defined, which served as realistic background for the subsystem trade-offs. Beside environmental conditions, also assumptions for the MPE operation, communication and power have been defined.

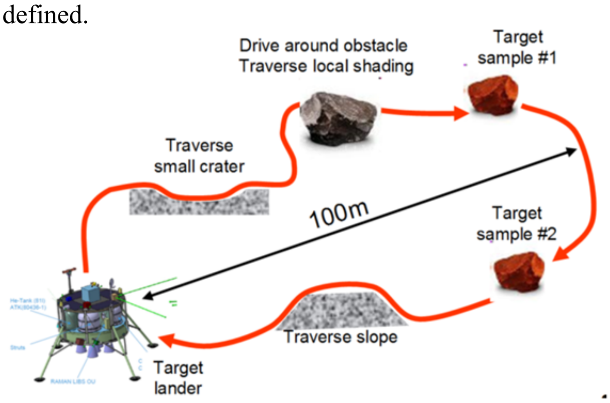

Figure 1: MPE model sampling cycle

As part of the reference scenario a model sampling cycle was established. The MPE shall be able to traverse small craters, slopes and local shadows to reach two scientific interesting objects about 100m away, take one sample and bring it back. This sampling cycle shall be traversed at least five times, to gather the required 5 Regolith samples.

Special attention was paid on the challenging illumination conditions on the envisaged landing site, the lunar south pole. Based on all available illumination analyses it is assumed that the landing date can be selected to maximize the duration of the first illumination window. The MPE therefore is designed to fulfill all primary mission goals within this first illumination window, before a first regional darkness phase occurs. This strategy avoids the risk of an unsuccessful rover mission, if the MPE or even the lander is being damaged during the critical darkness survival period.

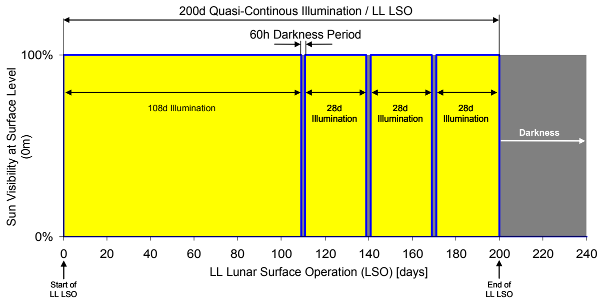

Figure 2: MPE illumination bar-code pattern

3. MPE Model Payload

In cooperation with the lunar science consultant R. Jaumann, the user requirements, pertaining to the MPE, were prioritized. As a result, the scientific tasks required from the MPE can be given as follows:

- Acquisition of regolith samples from illuminated and locally shaded terrain as well as from the surface, subsurface and from underneath large boulders
- Documentation of the samples
- In-situ characterization of the sample material

Addressing all three scientific tasks leads to a model payload, which exceeds the P/L mass target of 2kg, formerly derived from ESA Lunar Lander requirements. For that reason the in-situ characterization ability was abandoned. The characterization will be conducted by instruments, located on MPE's landing vehicle. This leads to following MPE model payload:

- A Camera Payload, comprising a stereo camera with LED-illumination for field-geology type investigations
- A Scientific Payload, comprising a Mole sampler for the sample acquisition and a Close-Up Imager for the sample documentation

The defined model payload serves as realistic background for the MPE system design and represents the scientific needs, which are largely independent from a specific mission. If a specific flight opportunity arises for MPE, its payload will be adapted to the specific mission needs.

4. MPE Overall Configuration

For the composition of the MPE concept, the main rover subsystems were carefully studied and traded. At the end of the Phase A the MPE Concept Phase A was established and its feasibility in context of the ESA Lunar Lander was proven. The ongoing MPE Delta Phase A takes this baseline as starting point for the further development of the MPE subsystems.

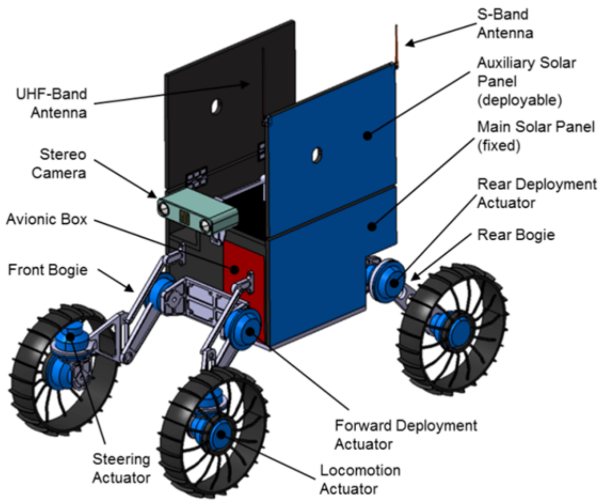

Figure 3: MPE in Deployed Configuration

The MPE is designed as a 4-wheeled rover with an active suspension. This means that the MPE is able to actively adapt each single wheel to the surface and thus align its attitude to the respective situation. All subsystems and payloads are grouped around a central body, whose Aluminum base plate provides the thermal, mechanical as well as electrical interfaces to the landing vehicle and carries all occurring loads.

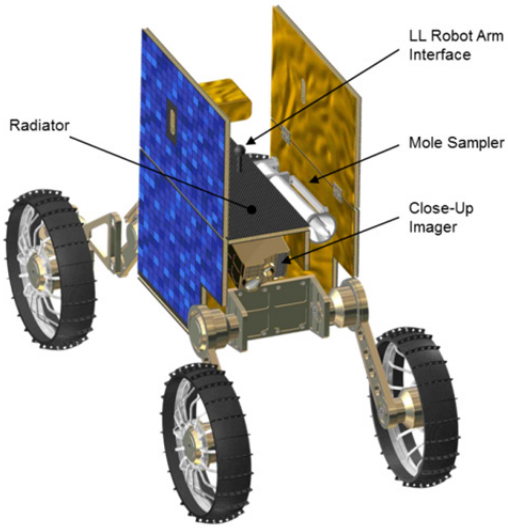

Figure 4: MPE P/L Accommodation

Due to the low Sun elevation at the lunar south pole, the MPE solar generators are attached to the left and right side of the center box. The lower halves of the solar generators are fixed while the upper halves are deployable. Those parts are in stowed position during launch and transfer phase to keep the MPE within the required stowage volume. The housing of the avionic box is highly integrated as part of the MPE structure.

On its top, the avionic box mounts an interface for grasping and lowering the MPE to the lunar surface by a robotic arm. Besides, the avionic housing provides radiation shielding and thermal insulation for most electronic components.

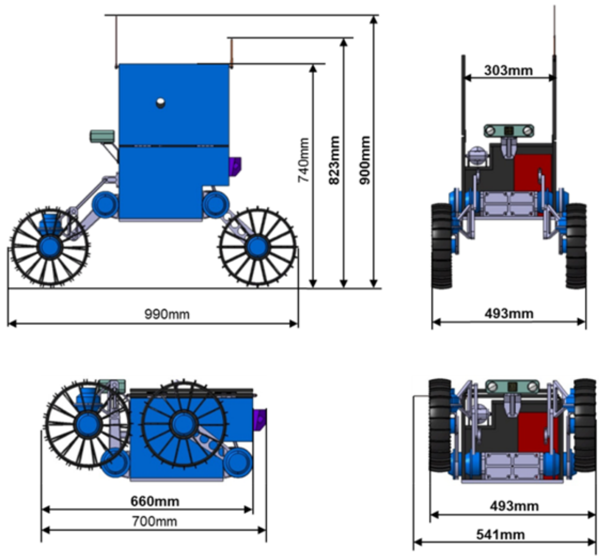

Figure 5: MPE main dimensions

The active suspension allows deploying the MPE in a wide stretched and very stable configuration, for driving operations, as well as stowing MPE into a compact volume on its lander. It further enables the MPE to align its solar generators to the sun for efficient power generation or its payloads towards scientific interesting objects.

To keep the mass low, only the two front wheels are steerable, which allows two steering modes. The normal, 'Ackermann', steering mode is used during regular locomotion on the lunar surface while the second, 'fork-lift' mode, allows precise alignment of the payloads.

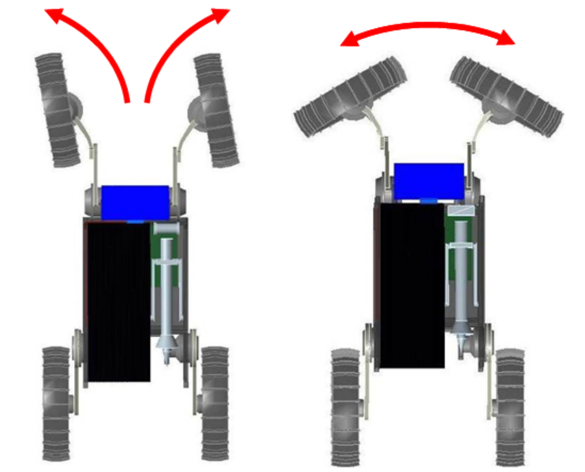

Figure 6: MPE steering modes: Ackermann (left) and fork-lift (right)

Locomotion and steering actuators are integrated within the wheel, which contributes to relative large wheel diameters for advanced mobility. The steerable front wheels are attached to parallelogram levers. They allow operating the MPE in every adjustable chassis clearance.

Table 1: MPE subsystem overview

Power Supply System
Solar generators (fixed + deployable): 25W Secondary battery: 160Wh
Active Thermal Control System
Operation in shaded regions: ~2h Survivable darkness periods: ~13h
Communication
UHF-band (up/down): 9.6kbit/s S-band (down): 512kbit/s
Onboard Computer
LEON3FT GR712RC
Sensor Package
Stereo Camera (1024 x 1024px sensor, 120° FOV) LED flash lighting 2 axes inclinometer Wheel and body encoders

Beside the solar generators, the power supply system consists of a rechargeable battery, which enables the MPE to operate independent from sunlight. This is necessary to traverse local shadows or to acquire samples from dark areas. The thermal control subsystem of MPE was supplemented by electric heaters, to increase the hibernation time of regional darkness periods up to ~13h. Further MPE can operate ~2h hours in complete darkness to take samples from shades areas.

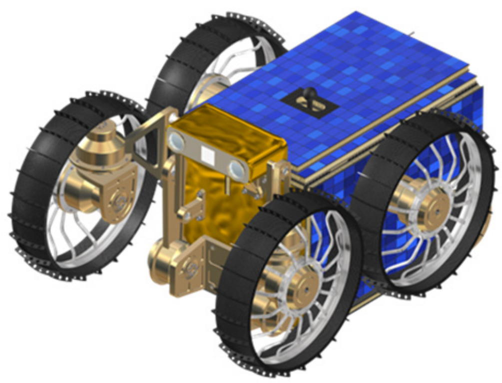

Figure 7: MPE in stowed configuration

The installed sensor package allows the MPE to be tele-operated from earth or to operate autonomously. The autonomous functions can support the tele-operator and help to avoid critical situations. In autonomous mode the MPE performs a local navigation by establishing local maps from own stereo images in order to avoid obstacles and to plan its local movement. Those local map patches are composed to a global map, which is necessary for self-localization of the MPE, if the contact to its lander is interrupted. With the aid of the global map, MPE can easily find the way back to the lander and re-establish communication.

The objective of the Mole sampler is to collect regolith samples, possibly containing volatiles, to be transferred to the landing vehicle for in depth analysis. Samples can be acquired from the immediate surface as well as from the near subsurface down to several 10's of cm of depth. The Mole design is using heritage from the PLUTO sampling Mole system, flown on the Beagle 2 Mars lander of the ESA Mars Express mission. To protect the regolith sample enclosed in the Mole from warming up by solar radiation, it is accommodated in a shaded bay, between the solar generators. For sampling, the mole is deployed aft into the sampling position, via a 1-DOF mechanism. The close-up imager is also rear mounted, to get close to scientific interesting objects and observe the mole while sampling.

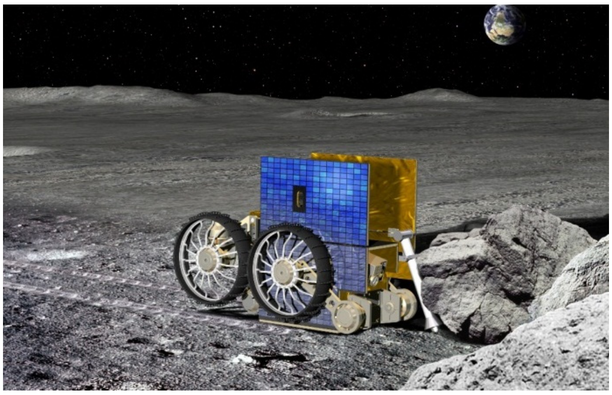

Figure 8: MPE in sampling mode

To approach the challenging mass limitations of ~10 kg for the rover, plus additional ~2 kg for the payload, which were formerly stipulated by the ESA Lunar Lander, the MPE concept has to be classified as a technology experiment. Like Sojourner, it does not offer redundancies for all subsystems. The locomotion subsystem, camera system and solar generators can be designed to show some fault tolerance. However, it is not possible to fully avoid all critical single point failures within the given mass envelope, especially in the context of the avionics system.

Table 2: Summarized mass budget

Mass Budget MPE Concept	Mass incl. Margin [kg]
MPE (Rover + Payloads)	15,777
Rover (w/o Payload)	13,525
Camera Payload	0,305
Scientific Payload	1,948

The summarized mass budget is shown in table 2. It has to be noted that even if lighter rover concepts as the current MPE concept are feasible, but further weight reductions lead to significant cut-backs concerning the MPE functionality and reliable operation. For those reasons further weight reductions are not recommended from the view of the study team, which also has been confirmed by the DLR review team.

5. Actuator Design

The MPE actuators are based on permanent magnet synchronous motors, developed at DLR-RMC, being combined with very low backlash Harmonic Drive (HD) gears. Those so-called "Innen-Läufer-Motoren" (ILM: German for "inside rotating motors") are well suited for highly dynamic tasks involving frequently reversing motions and high efficiency [5]. The proposed technology is based on the ROKVISS actuation unit [1], which has been returned to earth after six years operation in space in early 2011. It was further developed and adapted for the DexHand [4] and MASCOT.

Aside high performance, low weight and low losses, two properties of the ILM units are very interesting for their application within the MPE chassis. First, the high torque capacity of the motors allows applying short and very strong "kicks" that could free the unit in case of cold welding within the bearings or the HD-stage. Of course, in this case the power electronics has to be designed to supply large currents for a short time. The second advantage is that the low number of mechanical components reduces the probability of failure.

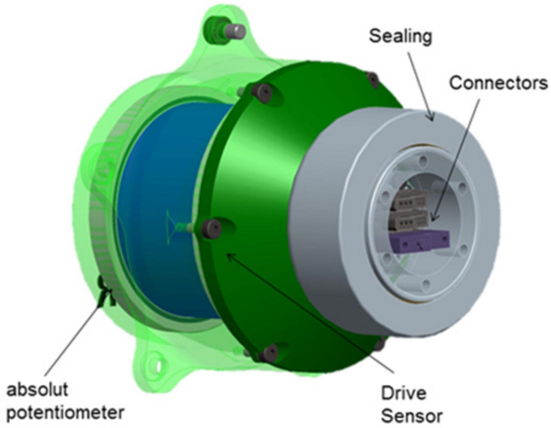

Figure 9: DLR-RMC ILM38 space unit

The rotor bearing and the Wave Generator bearing of the HD are the most crucial elements since the associated friction has to be overcome by the motor torque directly. Evaluating different sealing types led to the decision, to implement a PTFE based sealing combined with a labyrinth in the MPE actuator unit.

The current MPE baseline foresees 10 ILM 38 units (see figure 9), which meet the prescribed actuation margins according to ECSS and consider the increased breadboard testing loads on earth compared to the lower operational loads on the Moon. For weight reduction reasons the smaller ILM25 motor units could be used as wheel and steering actuators for a future MPE flight model, but only if the applicable ECSS requirements can be tailored. The MPE bogie and steering actuators feature an additional drive side potentiometer, to provide absolute position information for the position control algorithms. Since the wheel actuators are speed-controlled, they only require the relative commutation sensor, which is inherent to all actuator units.

6. Wheel Design

The design requirements for the MPE wheel are to provide ground interaction with the regolith found in the lunar south pole area. The wheel needs to withstand the static and dynamic loads during operation, launch and transfer. Furthermore, both wheel and interface need to be able to withstand temperature cycles between -160ºC and +130ºC. The nominal velocity of the rover is given as 5.4 mm/s in tele-operated mode. The terrain that the MPE will be travelling on is likely to be a mix of lunar soil with varying degrees of softness around small impact craters and around boulders. The area of the wheel, which is in contact with the ground, should be as large as possible to minimize sinkage. However, the diameter is limited to 250 mm by the working space of the chassis and the stowage of the system, calling for optimization of the wheel width.

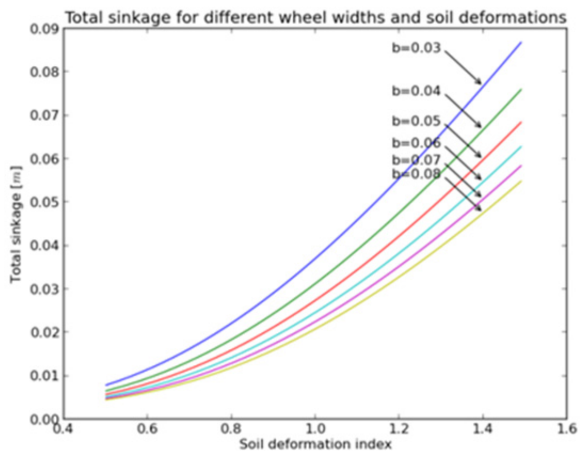

Figure 10: Wheel sinkage with varying wheel width

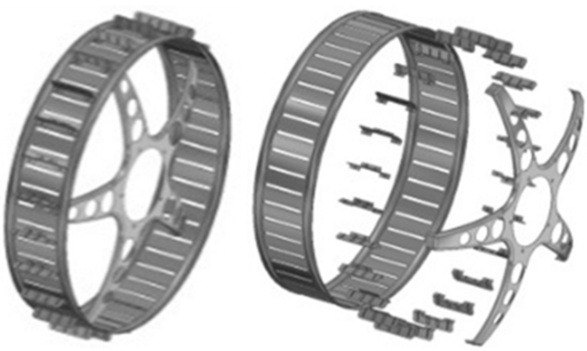

Figure 11: MPE wheel design

Figure 10 shows the total predicted static wheel sinkage in lunar Regolith for different wheel widths b and soil deformation indices n [10]. The finally chosen MPE wheel design is shown in figure 11. It has a width of 60 mm and a grouser length of 10 mm. When manufactured from Titanium alloy, the wheel has a total mass of 160 g.

7. Integrated Avionic Design

Due to the compact nature of the MPE it is necessary to customize the rover avionics, which comprises the minimal set of electronics to meet the required functionality. The major design drivers for the development of a customized low-weight avionic system are:

- Minimal volume and mass.
- Efficient use of solar & battery power with a minimal energy wastage on unused functions.
- Prevention of fault propagation and in-built fault tolerance whenever possible
- Extreme non-operational cold environment

The system is divided into four subsystems inter-connected by a backplane, which also acts as a ground bar and the rover's electrical starpoint.

The power system provides power via a quasi-regulated primary bus. The primary power bus is supplied either by regulated power from the solar panels or by discharge current from the secondary battery. Because of MPE's physical design, only the left or right solar generator will be illuminated simultaneously by the sun. For that reason each solar genaerator feeds an independent MPPT regulator to ensure a regulated power supply, which is independent from the illumination conditions (e.g. shadowing, dust, etc).

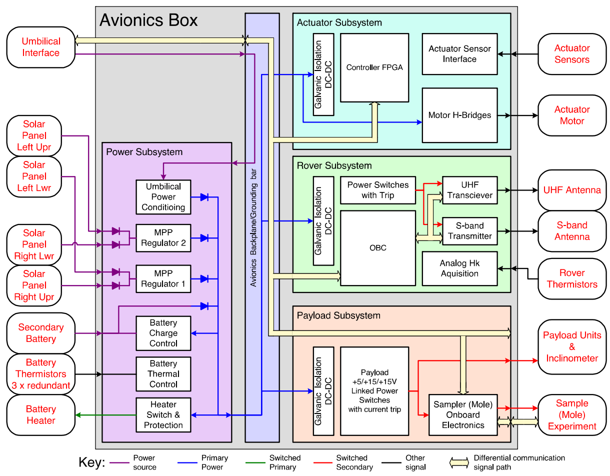

Figure 12: Avionics system diagram

The primary power supply powers the Rover Subsystem (commuications and OBC), Actuator Subsystem (low level actuator control) and Payload Subsystem (payload power control and interfaces). Each subsystem is galavanically isolated from each other for fault tolerance and EMC reasons. The OBC can completey disable the Payload and Actuator Subsystems and trigger individual payload or communication units via current LCL switches. In standby mode, which is the minimum power consuming configuration for charging the battery, only the Power Subsystem and the OBC are running.

8. Autonomy Payload Experiment

According to the reference scenario, the rover has to travel about 100 m in difficult terrain, taking a sample and returning it to the landing module for analysis. Theoretically, driving and navigation can be done purely tele-operated, since the physical round-trip communication latency to the Moon is less than three seconds. However, due to necessary processing chains on Earth, the real latency is about 10-15 s and the communication bandwidth is limited to 512 kbit/s.

Due to the very ridged mass restrictions and scarcity of power, the baseline MPE concept is equipped with a fixed mounted stereo camera, owing a wide field of view (FoV) of 120°. Further, it was decided for an Leon3FT (GR712RC) on-board computer, to compute depth images and ego motion of the rover by visual odometry for either supporting tele-operation or for autonomous waypoint navigation. Supported tele-operation means that the rover automatically stops in front of obstacles or if slip is detected by comparing visual odometry with wheel odometry. In the autonomous waypoint navigation mode, the user just selects a target, e.g. by clicking in the image, and the rover finds its way fully autonomously [2]. This mode can also be used for homing, if the sample is retrieved or as a safety feature, if the communication to the landing module fails.

However, this baseline solution, which resulted from the massive weight and power restrictions, does not enable full autonomous operation of the MPE. The fixed mounted camera only permits autonomous navigation as long as the rover always finds a traversable path within its field of view. Further, the on-board computer can only support tele-operations at slow driving velocities, because of its low processing power.

The Autonomous Payload Experiment (APE) extends the baseline navigation by adding a pan-/tilt unit [3] and speeding up image processing by an FPGA implementation. Due to the pan-/tilt unit, the FoV can be narrowed to 50°, which increases accuracy. Due to the FPGA, an advanced, dense stereo matching method like Semi-Global Matching [8] [7] can be implemented, even for higher resolution images. This again increases accuracy and robustness in low textured regions. The current terrestrial Spartan 6 implementation processes images with a resolution of half a million pixels and 128 pixels disparity range with almost 15 frames per second [9]. The space version is designed for matching images with 512 x 512 pixels and 64 pixels disparity range with 5 frames per second. In the proposed configuration, the stereo camera covers an area up to 2 m in front of the rover with a depth accuracy between 0.75-5 cm.

Additionally, the FPGA implements stereo rectification, image compression for sending all image data with 1.5 Hz to Earth for further processing, and a sparse optical flow for supporting visual odometry. All complex, but less time consuming operations will be performed on the on-board computer.

In the baseline concept, the nominal autonomous rover speed would be just 0.007 m/s, due to the limited processing power. In contrast, the APE enables the rover to a theoretical top speed of 1.6 m/s. However, in reality the rover speed would be limited to avoid dynamic effects and dust turbulences. However, the high speed of visual navigation would improve robustness, accuracy and shorten the mission time.

9. Illumination Prediction

One of the challenging aspects of the lunar south-pole location is the illumination conditions. The sun inclination of around 3º over the horizon is leading to a complex and dynamic illumination situation at ground and rover level. Small boulders of 10 cm in height cast a shadow of around 2 m on flat ground. With the assumption of 708 h for a lunar day, the sun travels 0.5 º/h along the horizon, which is the same as its viewing angle. The tip of the shadow of a boulder 1 m in size will thus move 17 cm/h. Ground illumination is preferred to perform safe navigation. Also the rover must avoid going into areas which will be shadowed for longer periods, where the solar panels cannot generate any power. It can be assumed, that the landing site is probably free of local larger obstacles, due to the hazard avoidance of the lander. However, it is one of the scientific goals of the MPE to take samples in permanently shadowed areas. Being able to predict the illumination conditions is therefore a safety critical aspect of the rover design.

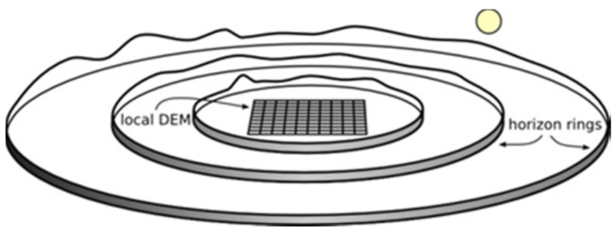

Figure 13: Terrain model for illumination prediction

As stated in Vanoutryve et al. [6] the illumination conditions of any particular site will be highly dependent on the local shape of the terrain. The concept of the MPE illumination prediction is to use a combination of digital elevation maps (DEM) and horizon models for different distances (see figure 13). The DEM is centered at the lander location and has the size of the operational area of the rover. The horizon rings are also centered around the lander location, but only provide a maximum terrain elevation for an angular subsection. The advantage is that the angular resolution is independent of the distance and forms a compact representation of the environment model. Multiple rings are required to compensate for parallax errors over the operational area of the MPE.

The elevation model is generated after the exact landing location is known based on LRO data, sensor data from the descent of the lander as well as after landing, using images from the lander's stereo camera. The elevation model is updated with local elevation models from the stereo image processing of either the APE or the rover autonomy system.

10. Sample Transfer

Once a regolith sample has been taken with the Mole, the Mole system would be retracted into the transport configuration, followed by return of the MPE to the lander. During this time, the sample remains stored in the Mole front tip. Direct illumination of the Mole by the sun is largely avoided due to the mole's accommodation in a shaded bay on the rover cab, minimizing temperature changes to the sample.

It is postulated that the lander spacecraft associated with the MPE mission application is equipped with a robotic arm, for initial placement of the MPE onto the surface as well as to support purely lander-based science. To be able to work in concert with the MPE, a suitably designed end effector of the lander robotic arm is required, which shall accept the regolith sample delivered by the Mole upon return of the rover.

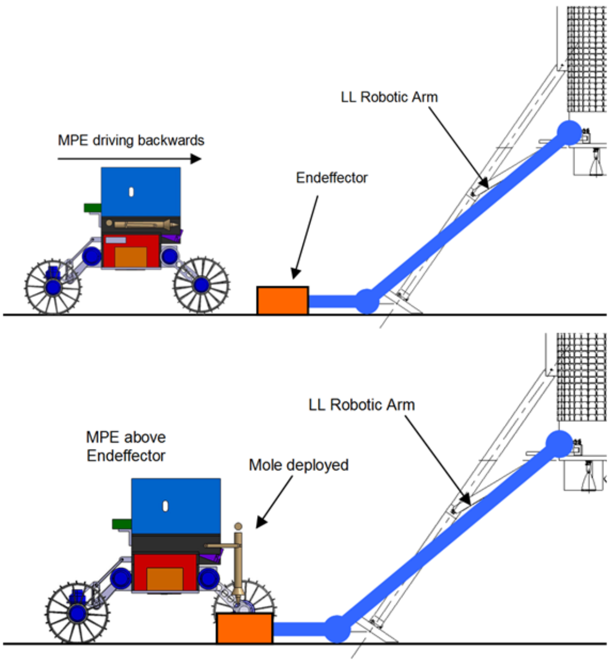

Figure 14: Sequence of sample discharge from the rover to the lander

A possible end effector concept for the arm to capture the granular sample is shown in figure 15. It is purely passive and does not require actuation elements. To transfer the sample, the lander robotic arm positions the end effector onto the surface. The Mole system is once again deployed in sampling position and the Mole tip is positioned over the end effector by rover motion. Then the Mole hammering mechanism discharges the sample from the sample chamber into the end effector, as in the PLUTO design for Beagle 2.

Spring-loaded blades on top of the end effector are displaced during the process, which close again after the Mole is retracted, thereby again protecting the sample from direct solar illumination. A similar, passively actuated set of spring-loaded blades forms the bottom of the end effector. They provide the discharge port for removing the sample once the arm maneuvers to the inlet ports of analytical instruments on the lander, which analyze the samples delivered by the MPE rover.

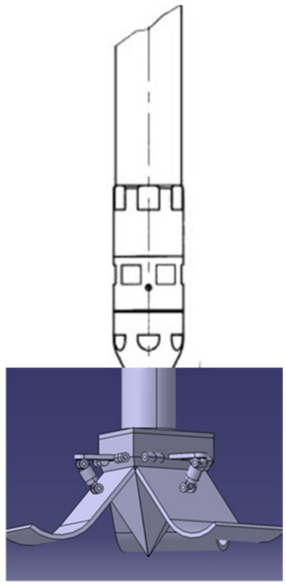

Figure 15: End effector (below) interfacing with the Mole during sample discharge

11. Close-Up Imager

In order to characterize the sampling site before and after the sampling process, to determine the structural, textural and compositional characteristics of the Regolith and to investigate alterations of the Regolith due to volatile processes, the MPE rover will carry a narrow-angle multispectral Close-Up imager (CUI). In addition, a wide-angle rear-camera is accommodated in the same housing, to provide images for tele-operated backward driving. Both cameras are currently designed by DLR's Institute of Planetary Research.

The CUI and rear camera are accommodated on the backside of the MPE, focusing towards the Mole resp. providing a wide-angle rear view. Due to those different and contradictory viewing requirements (narrow vs. wide angle) and because of reliability aspects, a two-lens/two detector-configuration turned out to be the most favorable design approach.

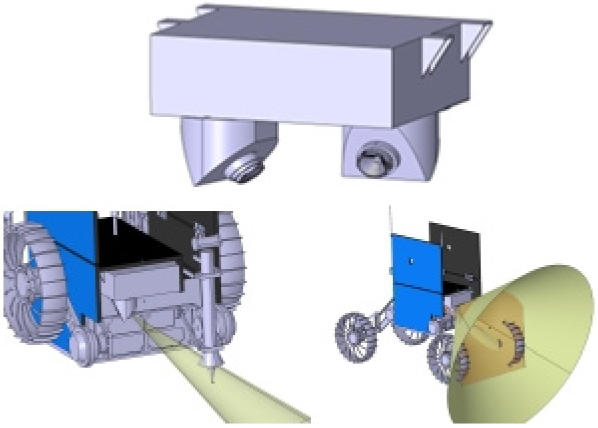

Figure 16: Current CUI and rear camera designs together with their associated FoVs

The Close-Up camera head consists of a 1920 x 1080 pixel CMOS sensor with a 6.5µm pixel pitch. With a planned optics having 17.85° circular FoV (15.4° x 8.7° rect.) and a focal-length of 45mm (TBC) the imager is able to resolve 33µm per pixel at sampling distance. Multispectral imaging is achieved by an illumination device, implemented with LEDs arrays centered at four different wavelengths (e.g. 470nm, 530nm, 640nm and 805nm). Thus the CUI is able to map the compositional heterogeneity of the lunar surface and also illuminate the shadowed regions where adsorbed volatiles are expected.

The rear camera shall observe the surface area behind the MPE having at least both wheels in sight. This requires a wide viewing angle (89° circ.) with a large DoF (f#8 → 5 cm to infinity). The camera head will have a resolution of less than 280000 pixels (e.g. 512 x 512) to keep the data rate low. The camera is connected via a SpaceWire I/F to the OBC, where the further data processing and handling will be done. The mass of the camera is currently assumed to be less than 0.73 kg (with margin) with a peak power consumption lower than 8 W during multispectral imaging. In order to reduce the complexity of the electronics it is currently evaluated, if the same detector can be used for the rear camera and CUI.

12. Summary

As a result of the MPE study work, performed by Kayser-Threde and its German partners, a rover design with ~15kg is feasible. The established MPE concept is the best possible compromise between performance, redundancy and weight. It is the first rover designed to fetch samples under the extreme harsh lunar south pole environment. The locomotion subsystem, the autonomy functions as well as the MPE's operational concept are examples for Germany's competencies in space robotics. Furthermore, the MPE is able to carry and operate a reasonable scientific payload in order to produce a meaningful scientific outcome. It provides access to a vast area of undisturbed as well as uncontaminated scientifically interesting targets, which are inaccessible for a meaningful analyses by the lander based instruments alone. Further, the possibility to observe the MPE by its lander or the lander by the MPE, provides an immense public outreach potential.

The current MPE Delta Phase A concludes in fall 2013. An outline of a possible succeeding breadboarding phase was proposed to the German Space Agency and is still pending. The MPE activities presented herein were kindly funded by the German Space Agency DLR under contract 50JR1212.

13. Abbreviations and Acronyms

APE	Autonomy Payload Experiment
CUI	Close-Up Imager
DEM	Digital Elevation Model
DLR	German Aerospace Center
DLR-RMC	DLR Institute of Robotics & Mechatronics
EMC	Electro-Magnetic Compatibility
ESA	European Space Agency
FoV	Field of View
HD	Harmonic Drive
ILM	Inside Rotating Motor
LCL	Latching Current Limiter
LED	Light Emitting Diode
LRO	Lunar Reconnaissance Orbiter
MASCOT	Mobile Asteroid Surface Scout
MPE	Mobile Payload Element
MPPT	Maximum Power Point Tracking
OCB	Onboard Computer
P/L	Payload
PTFE	Polytetrafluorethylen
ROKVISS	Robotics Component Verification on ISS
TBC	To be confirmed
UHF	Ultra High Frequency

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