ABSTRACT

On behalf of the European Space Agency (ESA), European space industry have been conducting Phase A and B level design work on a robotic lunar lander mission to a site close to the south pole of the Moon. Recent lunar orbiter missions have confirmed that this general region contains patches of terrain several 100 meters across which are in near-perpetual sunlight while being in close proximity of eternally dark low lying terrains (shadowed crater floors) which have been demonstrated by radar remote sensing and an impactor experiment to contain frozen volatiles. The projected ESA mission, referred to as ‘ESA Lunar Lander’ (LL) and scheduled for launch in 2018, is tasked to achieve an autonomous soft landing at one such favorably illuminated locale, followed by a multi-month long surface mission to characterize for the first time the lunar south pole region. Under contract to the German Space Agency DLR, a team of industry and academia from Germany led by Kayser-Threde, has recently performed a concept study for a small rover – the Mobile Payload Element (MPE) – that could be part of the lander payload. At a projected 10 kg of total mass, this vehicle would be far from the smallest rover to be operated on the surface of the Moon, following up on the Soviet Lunokhod’s and the crewed Apollo Lunar Roving Vehicles of the 1970’s, but also on the Indian Chandrayaan-2 rover scheduled for 2013. In mass and size, the MPE is however very similar to the US Mars Pathfinder MFEX (‘Sojourner’) micro rover technology experiment operated on Mars in 1997. The novel capability of the MPE – thus far not matched by any other planetary rover but eventually required for future robotic sample return missions – will be to acquire samples of lunar soil some distance away from the actual lander, and to bring them back to the spacecraft for analysis by on-board instruments. This will enable access to soils that are less contaminated by lander descent propulsion system plumes to increase the chances of detection of any indigenous lunar volatiles contained within the samples. Starting from the requirements imposed on the rover, this paper describes the trade-off performed on the mobility and overall system design, followed by a description of the conceptual design, the predicted mobility performance under lunar conditions, and plans for continued development in the 2012/2013 timeframe.
the lander for analysis by instruments there. This would enable access to samples that are not contaminated by lander descent propulsion system plumes to increase the chances of detecting any indigenous lunar volatiles contained within the samples. The Mobile Payload Element (MPE) was proposed by DLR as German in-kind contribution to the ESA Lunar Lander mission. In April 2011 DLR commissioned Kayser-Threde and its subcontractors to develop a conceptual design for this innovative sample fetching rover, in order to proof its feasibility. Mission analysis, payload definition and feasibility of the MPE were investigated within a phase 0/A study. The project was funded by the DLR Space Administration and finished its phase A in early 2012.

2. Scientific Rationale

Recently, the presence of H$_2$O and OH have been confirmed lunar polar regions using a combination of techniques such as orbital radar, infrared spectroscopy and targeted impact experiments (Jonas, 2009; Colaprete et al., 2010). To truly understand the nature of lunar polar volatiles, in-situ analyses are required, which also demand mobility in combination with dedicated sampling devices. To assist in the definition of the proposed ESA Lunar Lander mission, ESA commissioned the LEDT in 2009. The LEDT synthesized scientific goals and recommendations from earlier lunar mission assessment studies and prioritized the suggested science investigations for the mission. An important aspect has been and still is the notion that the ESA Lunar Lander shall address science and technology objectives, which would support a sustained future human lunar surface exploration (Carpenter et al., 2010, Fisackerly et al., 2011; Pradier, 2011). The LEDT considered that the use of mobility beyond 100 m could contribute to the high priority objective of identifying volatiles (Carpenter et al., 2010). This is because of the expected contamination of the surface regolith in the vicinity of the lander by the adsorbed engine exhaust gases (propellant and their decomposition products). Therefore, a mobile sampling capability through a robotic vehicle accommodating a sampling device was identified as an asset to the mission. This mobile system was subsequently referred to as the Mobile Payload Element (MPE).

3. System requirements and constraints

The allowable mass envelope for the MPE as part of the ESA Lunar Lander mission, including payload and supporting infrastructure, was limited to 12 kg for the Phase 0/A study of the vehicle led by Kayser-Threde (Claasen et al., 2010). Its stowage volume was constrained to 0.1 m$^3$. Depending on the exact choice of landing site, the MPE will experience a quasi-continuous illumination period of up to ~200 days, which is interrupted by darkness periods of less than 60h (ESA, 2010) due to local shadowing effects. Because of MPE’s low height the actual illumination conditions are however a matter of concern. Whether the Lunar Lander can provide power during darkness phases is still under discussion. Thus, the MPE had to be designed self-sustaining with respect to power. The most important functional requirements have been derived from the MPE Study Mission Statement (Claasen et al., 2010) and customer specification (Claasen, 2010) delivered by the contracting entity DLR. Based on the scientific rationale applied to the vehicle, the MPE has to be able to collect and transport at least five samples to the Lunar Lander, each within a distance of at least 100 m from the Lunar Lander. Navigation and autonomy functions shall be based on camera images. Further, the MPE shall be able to return to the Lunar Lander fully autonomously, which requires the MPE to be capable of safely traversing more than 100m without operator intervention. Finally the MPE was required to have an operational lifetime of 6-9 month.

Besides the functional requirements, several scientific objectives and requirements have been identified. The primary science objective for the collection of regolith samples is the search for volatiles admixed in the regolith. This, combined with the contamination of the near-surface regolith by lander propellant, drives the required operational range of the MPE as well as the requirement to sample subsurface regolith. Sampling from shadowed patches of terrain or under large boulders are possibilities to support this objective. A pre-selection of potential samples should be conducted by the MPE, so that only scientifically interesting samples are collected. Therefore instruments for the in-situ analysis of samples were initially planned to be accommodated on the MPE. Further instruments for field geological observations such as geochemical and mineralogical analysis would increase the scientific impact of the MPE and mark a unique aspect of the mission.

Several requirements have been identified as design drivers, increasing the complexity of the system and thus the risk of failures and additional costs. First of all the low mass budget of 12 kg significantly constrains the design. The Mars Pathfinder Sojourner micro rover had a similar mass. But Sojourner essentially was a single string design, only carried an instrument package of 1.1 kg and was not intended for sample acquisition. Further the requirement to sample in shadowed areas as well as to survive darkness periods leads to an overall (operative plus non-operative) temperature range of -180 °C to +40 °C for the MPE. The usage of radio isotope heat or energy sources is precluded on the mission. Thus the thermal environment together with the uncertain illumination conditions for MPE represent
the most severe design drivers. This is particularly applicable for the power supply and thermal control system design, to survive the occurring short darkness periods. In some situations this problem can be mitigated by the mobility of the MPE. As a mobile element it has the possibility to drive to more convenient locations, if the opportunity arises. In addition power provisions from the lander during darkness periods are proposed as corrective action.

4. Reference scenario

For the development of a mobile surface vehicle it is inevitable to establish a reference scenario. This is to consider the given requirements and boundary conditions, such as lunar environmental parameters. It is necessary to have a realistic background for the subsystem trade-offs in phase 0/A. The reference scenario includes assumptions, since not all boundary conditions are defined in this early stage of the project. Since the MPE would operate in close proximity of the lander (~100 m) it can be assumed that nearly all environmental parameters, which are defined for the Lunar Lander, are also valid for the MPE. Figure 1 shows the different subjects defined for the MPE reference scenario, mainly based on the data proposed in the Lunar Lander Environment Specification (LES) (ESA, 2010).

![Figure 1](image-url) The subjects defined within the reference scenario are mainly based on the LES (ESA, 2010)

The characteristic properties of the lunar surface near the south pole have been identified in a preliminary analysis. As no image data with resolutions better than 0.5 m - 1 m per pixel are available, some inferences on the terrain properties at the scale of the vehicle have been made, given that the south polar terrain represents the lunar highland, for which the Apollo 16 landing site is an example.

Special attention has to be paid to the illumination conditions on the expected landing sites. Due to the low sun elevation on the lunar south pole the actual illumination is strongly depending on the local horizon and on the observer height. To set up an illumination scenario for the phase 0 trade-offs all available sources of data on illumination of the south pole were considered. All analyses come to a more or less quasi-continuous illumination period of about 230 days interrupted by different darkness periods.

Mazarico et al. 2010 analyzed spots on the lunar south pole concerning their illumination conditions on surface level (0 m) and 10 m above the surface. They identified, that the most illuminated spot on the lunar south pole is lying in a region called “Connecting Ridge”, which is also a probable landing site for the Lunar Lander. Despite Mazarico et al. 2010 found spots on the lunar south pole with uninterrupted sunlight of several months, the MPE trade-offs take into account a quasi-continuous illumination period of 200 days interrupted by darkness periods of 60 h as a conservative assumption. The landing date of the mission is selected to maximize the illumination window (Fisackerly, 2011). The MPE is therefore intended to be designed in a way that it can fulfill all primary mission goals within the first illumination window. It is further assumed that at least 28 days of uninterrupted illumination at surface level are between possibly occurring 60 h-darkness periods. Within this illuminated phase MPE shall be able to fulfill its primary mission goal and collect 5 regolith samples. Figure 2 shows the illumination barcode pattern assumed for MPE, resulting from the assumptions mentioned above.

![Figure 2](image-url) Illumination barcode assumed for the MPE reference scenario, based on a 60 h darkness period assumption. Actual illumination conditions, which depend on the landing site and local shadowing, are likely to be more favorable.

Not only environmental conditions have to be defined in advance, also assumptions for MPE operation, communication and power have to be established. Derived from the requirements written in the MPE Mission Statement (Claasen et al., 2010) and Specification (Claasen, 2010) as well as from the environmental conditions a first operational scenario was defined. Beside the operational scenario, scenarios for communication and power were developed. Overviews of the rover operational and communication scenarios, as derived for the MPE, are given in Figure 3
Figure 3: The MPE operations scenario was derived from the available environmental specifications and mission requirements to have a reference for functional requirements. The reference scenario includes traversing small craters up to 4 m in diameter, overcoming obstacles up to 12.5 cm height and traversing slopes up to 15° and local shadows.

Figure 4: The MPE communication scenario does not foresee direct to earth communication due to mass constraints. All communications from the ground station to the MPE are relayed through the lander. The MPE uses two different bands to communicate with the lander. A low bandwidth bi-directional command and control channel in UHF-band, and a high bandwidth channel for science and navigation data in S-band.

5. MPE model payload

Following from a science consultation done during the Study, the scientific tasks required from the MPE can be given as follows, in order of priority:

- Acquisition of regolith samples with landing-induced contamination being below the detection limit of the associated volatile-seeking instruments on the lander.
  - Sampling must be possible from both illuminated and locally shaded terrain.
  - Sampling must be possible also from the subsurface and from underneath large boulders.
- Following their acquisition, samples must be protected from sun illumination to minimize loss of volatiles.
- Documentation of the samples acquired by multispectral close-up imaging of the sample site, ideally before and after sample acquisition.

A trade-off led to the selection of a ‘mole’ type regolith sampling device, which could be a close re-built of the PLUTO (Planetary Underground Tool) subsurface sampler developed for the Beagle 2 Mars lander of ESA’s Mars Express mission (Richter et al., 2002). The mole is advantageous in that it is low mass, low power and imposes no significant reaction loads onto its carrier vehicle. Moreover, surface as well as subsurface sampling is possible.

Table 1: Model payload for the MPE

<table>
<thead>
<tr>
<th>Model Payload</th>
<th>Budget [kg]</th>
</tr>
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<tbody>
<tr>
<td>Stereo Camera w/o Filter Wheel</td>
<td>0.252</td>
</tr>
<tr>
<td>LED-illumination</td>
<td>0.053</td>
</tr>
<tr>
<td>Camera Payload Subtotal</td>
<td>0.305</td>
</tr>
<tr>
<td>Sampler Mole with electronics (based on PLUTO mole system, see figure 5)</td>
<td>1.218</td>
</tr>
<tr>
<td>Close Up Imager (based on ROLIS close-up imager or MER MI, see figure 6)</td>
<td>0.176</td>
</tr>
<tr>
<td>Close Up Imager Electronics</td>
<td>0.240</td>
</tr>
<tr>
<td>Scientific Payload Subtotal</td>
<td>1.634</td>
</tr>
<tr>
<td>Total Mass</td>
<td>1.939</td>
</tr>
</tbody>
</table>
6. Subsystem Trade-Offs and Design Iterations

For the composition of the MPE concept the five main rover subsystems were carefully studied and traded. Those were:

- chassis type
- sensor package and autonomy
- computing power
- power supply
- thermal system

Based on the subsystem trade-offs conducted during phase 0 the MPE Baseline Concept Phase 0 was composed by the following subsystems:

- 4-wheel active chassis with wheels
- Power supply with fixed solar generators plus secondary battery
- Thermal control system with active heating and passive insulation
- Redundant UHF + S-Band communication between rover and Lander
- Sensor suite and autonomy concept called “Improved Precision Approach”
- BAE RAD750 3U SBC as onboard computer

The choice of a 4-wheeled architecture with active suspension is built upon prior pre-development in the ESA technology program of a similar, low mass device (the Mobile Instrument Deployment Device, MIDD, Richter et al., 2006, see Figure 8) as well as on recent US rover concepts (Barlett et al., 2008). Active suspension, i.e. accommodating the wheels on levers that can be positioned relative to the rover cab, has several advantages, in that this feature can be used for compact stowage and subsequent deployment of the vehicle, as well as for positioning/pointing of the vehicle on-board payload.
MIDD engineering model shown during integration with shifted front wheels (left) and during locomotion tests (right). The right picture also shows the Kapton cable as connection to the lander. The right front wheel is swiveled backwards (Richter et al., 2006).

The power supply with solar panel and secondary battery is a robust solution with a high TRL. Compared to a tethered power supply it allows a maximum of maneuverability for the MPE. The chosen thermal system is widely experienced and provides a minimum of complexity and weight. For TM/TC a bidirectional UHF communication link to the lander is chosen. In order to transmit scientific data, an S-band downlink supplements the communication subsystem. The Improved Precision Approach for the autonomy functions provides a good compromise between required resources, TRL and robustness. It relies on the stereo camera, wheel encoders and an inclinometer as sensor suite. This approach is well balanced with the chosen processor BAE RAD750, which provides a good solution concerning processing power, TRL, power needs and mass.

The mass budget for the MPE Phase 0 baseline revealed that with ~17 kg (incl. margin) the mass requirement of 12 kg was exceeded by far. As a result, mainly the locomotion and power supply subsystems were simplified as well as redundancies were discarded for the resulting MPE Phase A baseline, while the performance was maintained. During phase A the main

Figure 8: MIDD engineering model shown during integration with shifted front wheels (left) and during locomotion tests (right). The right picture also shows the Kapton cable as connection to the lander. The right front wheel is swiveled backwards (Richter et al., 2006).

Figure 9: MPE concept evolution during phase 0 and A

7. MPE Configuration

8.1 Overview

As already defined during phase 0, the MPE concept resulting at the end of phase A is designed as a 4-wheeled rover with an active chassis. This means that the MPE is able to actively adapt each single wheel to the surface or align its attitude to the respective situation. Furthermore a compact stowage envelope becomes possible. Due to the low Sun elevation on the lunar south pole the MPE’s solar generators are attached to the left and right side walls of the center box. The lower halves of the solar generators are fix 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. Figure 10 shows the main components of the established MPE rover concept.
8.2 Structure

All subsystems and payloads are mounted to a central body, which consists of an aluminum base plate and provides the thermal, mechanical as well as electrical interfaces to the Lunar Lander and carries all occurring loads. The housing of the avionic box is highly integrated as part of the MPE structure. It will be designed in a way that it can serve as load carrying element. On its top it mounts the interface to the LL robotic arm, which allows grasping the rover in stowage configuration and lower it to the lunar surface. Besides that the avionic housing provides mounting slots, radiation shielding and thermal insulation for most electronic components. As baseline Al-CFRP honeycomb panels form the remaining sides of the central box and divide several compartments for the battery and the Mole sampler. The aluminum baseplate as well as the upper panel of the central box further serve as radiators.

The MPE body size is mainly driven by the avionic box, the required solar panel area and mole sampler. In stowed configuration, the MPE must fit in its allocated accommodation envelope on the Lunar Lander, measuring 660mm x 560mm x 360mm. Figure 12 shows the MPE main dimensions.

Figure 10: MPE in deployed configuration together with its main components

8.3 Locomotion Subsystem

The active chassis allows deploying the MPE in a wide stretched and very stable configuration for driving operation as well as stowing in the compact volume of the lander. Front and rear wheel levers of the active chassis are driven by one deployment actuator each, which move the MPE to its different driving positions. They are also utilized to unfold the MPE from stowage to deployed configuration. Due to weight reasons only the two front wheels are steerable. This allows two steering modes (see figure 12): the normal, Ackermann steering mode is used during regular locomotion on the lunar surface. Both front wheels are actuated in parallel. In the so called “fork-lift” mode the rover pivot point lies between the rear wheels and allows precise alignment of the mole sampler and the rear-mounted close-up imager. Locomotion and steering actuators are integrated within the wheel, which contributes to the sizing of the wheel diameter, in addition to mobility considerations. The active chassis enables the MPE to align its attitude to the lunar surface (e.g. while driving on a slope) or to align its solar generators towards the sun for efficient power generation. Thus the MPE has to drive with different lever positions. For that reason the steerable front wheels are attached to parallelogram levers while the rear wheels can be mounted to simple levers. The parallelogram kinematic of the front levers keeps the steering axis always perpendicular to the surface and enables to operate the MPE in every adjustable chassis clearance (see figure 13).
Figure 10: The MPE supports two different steering modes: Ackermann and Forklift (left). The front parallel bogies are designed such that the steering axis is always kept perpendicular to the surface (right).

8.4 Power Supply System

Since the lateral CFRP panels do not carry any significant loads, those panels are used to mount the solar cells. First analyses of the power supply system ascertained that the lateral faces of the MPE main body alone are not sufficient to provide enough solar generator area. Thus deployable solar panels are attached on both lateral sides of the MPE with latches and lightweight spring mechanisms in order to extend the solar generator size. They will be stowed until the MPE will be placed into operation on the lunar surface. The solar panels do not have any tracking mechanism for permanent alignment to the sun. In battery charging mode the entire rover will be aligned to the sun using its active chassis, to gain ~25 W solar power. A cutout in the deployable panels gives access to the LL robotic arm interface, while the MPE is in stowed configuration.

Beside the solar generators mentioned above, the power supply system consists of a secondary battery (160 Wh), an umbilical connector towards the lander, PCDU and solar power electronics. The secondary battery serves as storage for the electrical energy collected by the solar arrays. It is charged during charging mode, where the MPE aligns its solar generator to the sun or by excess power during periods of low power consumption. Since the power only generated by the solar arrays is not sufficient for most MPE operational modes, the secondary battery supplies the rover systems with additional energy in those phases, e.g. in driving mode. As soon as the battery reaches a certain discharge level the MPE has to interrupt its normal operation and switch into charging mode.

8.5 Thermal Control System

The thermal control subsystem (TCS) of MPE is completely passive. Heat switches connect the battery and electronic box to the upper radiator and aluminum baseplate on the bottom of the rover, to get rid of dissipating heat during the hot case. Both radiators are well shaded from lateral sunlight by the solar generator panels. Small panels on the front and back ends of the radiators will additionally protect them from solar radiation (please note: those panels are not shown in the graphics). The electronic box and the batteries are well insulated with MLI to survive the cold case without heating. During launch and transfer phase the MPE is thermally connected to the Lunar Lander via a thermal plate, mounted on the baseplate below the avionic box. First thermal analyses revealed, that the passive TCS allows the MPE to operate for about 2 hours in complete darkness, e.g. for sampling or traversing shadows. It can also hibernate regional darkness phases up to 5 h. After 2 h resp. five 5 h the first MPE components cool down below their specified operational resp. non-operational temperature ranges. Reliable operation or a safe awakening from hibernation cannot be guaranteed anymore. Implementing electric heaters, in order to keep thermal sensitive components, especially the battery, for a longer time within their specified operational temperature range, increases the MPE hibernation capability up to ~14h. However, for a safe hibernation of the upper mentioned 60 h darkness phase it is necessary, to increase the current battery capacity and thus would increase the MPE weight by about 5kg.

8.6 Communication

The MPE communication system consists of two communication links (see figure 4). The UHF system is bi-directional between Lunar Lander and rover and intended for TM/TC, with a bandwidth of 9.6 Kbit/s. The S-band system is a pure down-link for transmission of data packets with ~512 Kbit/s. Self-deploying strap antennas are installed on the upper edge of the
deployable solar generators. The necessary transceivers are based on lightweight CubeSat components, which are sufficient for the short range transmission between MPE and Lunar Lander.

8.7 Onboard computer

The phase 0 baseline onboard computer trade-off was reassessed, after further data became available for the Aeroflex Gaisler GR712RC dual-core CPU, which now is the current selection for the MPE. Despite the GR712RC having a slightly lower DMIPS rate (240 at 100 MHz vs. 260 at 132 MHz) it offers the availability of two floating-point units and thus improves performance for computationally intensive algorithms compared to the Rad750, which does not have an FPU (?). Another benefit of using the GR712RC is the wide variety of interfaces within the LEON3FT design. These interfaces would have to be added to the RAD750 solution by additional hardware, leading to a not yet quantified mass penalty. Further, preliminary information from the manufacturer suggest that the GR712RC may have a significantly lower power consumption compared to the Rad750.

8.8 Sensor package

The Phase 0 navigation trade-off was concluded with a concept called “Improved Precision” as baseline. This concept uses fused odometry and visual servoing (?) for localization, as well as stereo matching for obstacle avoidance and for mapping. The resulting sensor package includes a stereo camera (1024 x 1024 px sensor, 120°FoV) combined with a LED-lighting, wheel and body encoders as well as an inclinometer. The stereo camera is placed on the front side of the MPE in a height of 495 mm. It is fixed mounted via a bracket and has no pan/tilt capabilities due to mass constraints in the base line. The belonging lighting is integrated in the camera housing between both camera head.

8.9 Operational modes

The MPE rover operation is structured in three modes. Nominal modes are tele-operation and autonomous navigation. As it is sufficient to fulfill the scientific goals, it is envisaged that the tele-operation mode will be primarily used in the first part of the mission. The use of autonomous functions will be increased later during the mission to address the technological objectives.

In tele-operation mode, the rover takes individual commands or command sequences and sends status updates back to the ground station in regular intervals. The nominal effective travel speed in tele-operation mode is ~5 mm/s, which includes transmission and operator decision times. In the autonomous operation mode the command sequences for execution are generated by the rover itself instead of being issued by ground control. There is a distinction between nominal autonomous operation and autonomous safing mode. In the first case the mode is initiated by an operator and may or may not maintain communication with the Ground Station. In the other case, the mode is initiated by a trigger like e.g. a number of communication timeouts.
three different parts: local navigation is responsible for creating local traversability maps, which are then used to generate command sequences using a local path planner and path following controller. Visual Servoing is another autonomous mode, which can be used in the vicinity of known marks, e.g. attached to the lander or its robotic arm. The rover positions itself in a known position relative to those marks. This mode can be used to e.g. position the rover near the lander’s robotic arm for sample delivery. Long range navigation is responsible for the exploration strategies and long range planning. This includes providing waypoints for the local navigation and performing higher level planning like illumination based planning. This meets the requirements to traverse entirely autonomous, e.g. for technology demonstration, landing site return or autonomous safing. In the autonomous mode a nominal MPE velocity of ~7 mm/s is expected.

8.10 Sample fetching and close-up imaging

Main objective of the Mole sampler is to gather regolith samples, possible containing Volatiles, which the MPE will bring to the Lunar Lander for deeper analysis. Volatiles are very temperature sensitive. For detection of the Volatiles with the lander-based instruments the samples have to be protected against warming-up. Even though the Regolith sample will be enclosed in the mole, the mole itself has to be protected from warming up by solar radiation, too. For that reason the Mole is accommodated in a bay between the two solar generators. There it is well shaded by the deployable solar generators when the MPE is in driving configuration. For sampling the Mole deploys afterwards (?) into sampling position. This will be done via a 1-DOF mechanism. The rear-mounted close-up imager of the MPE central body is tilted in order to get close to interesting objects and to observe the position where the mole shall sample.

Figure 13: Close-up imager observing Mole sampling

8. Weight reduction possibilities and MPE system extensions

According the MPE Mission Statement (Claasen et al., 2010) the MPE rover mass together with payload and infrastructure is limited to 12 kg. The summarized mass budget of the current MPE concept derived from the phase A study is presented in table 2. It is seen that while MPE is providing the full performance stipulated by the given requirements its mass exceeds the limitation. Thereby it has to be noted that, even if lighter rover concepts as the presented MPE concept are feasible, further weight reductions always lead to significant cut-backs concerning the MPE functionality and its reliable operation. For that reason further weight reductions were not recommended from the view of the study team, in line with the recommendations of the review team.

<table>
<thead>
<tr>
<th>Table 2: Summarized mass budget</th>
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<tbody>
<tr>
<td>Mass Budget MPE Concept</td>
</tr>
<tr>
<td>Camera Payload</td>
</tr>
<tr>
<td>Scientific Payload</td>
</tr>
<tr>
<td>Rover (w/o Payload)</td>
</tr>
<tr>
<td>MPE (Rover + Payloads)</td>
</tr>
</tbody>
</table>

During the concept development the study team identified some approaches to reduce the MPE’s weight, but which are not recommended, for the reasons mentioned below:

- Simplify Locomotion Subsystem (e.g. semi-active chassis, passive chassis, no chassis, skid steering)
- Tether as power supply
- Further power safings (reduction S/G size, battery size)
- Customization of avionics (integration of avionic components; use of synergy effects)

Mainly the limited stowage volume on the Lunar Lander drives the need of stowing the MPE with an active chassis. When considering a mass reduction by simplifying the locomotion system it should be kept in mind that the removal of the deployment motors means, that the rover lacks the inherent deployable chassis. Thus it exceeds the compact stowage envelope allocated on the lander. Furthermore the chassis can not adjust its
center of mass, when driving along slopes, adjust its position for an improved operation of the payload as well as align the solar generators for optimized power generation anymore. By switching to a concept with skid-steering a lot of energy would be wasted and the risk of digging in during a turning motion increases enormously. → Reviewer 2, 29 → INPUT RIL

Implementing a simple unroll-only tether as power supply would limit the rover operational range to a few tens of meters around the Lunar Lander. Collecting 5 samples within a radius over more than 100 m would not be possible with such a system. At a first sight the use of an un/up-rolling tether seems to be a possible way to improve the situation. In Germany such a concept is only at very conceptual stage and has a low TRL. In addition, implementing an up-rolling tether bears the risk of regolith, sticking to the tether, is jamming the up-roll mechanics. In this case the rover has to pull the tether to get back to the lander, which might destroy the thin cable or clamp the tether between stones. In both cases the rover would be lost. → Reviewer 2, 31 → INPUT RIL

For those reasons the identified weight reduction possibilities are not recommended by the study team. They lead to non-compliance of essential requirements, significant cutbacks in MPE’s performance, cost impacts and an increased operational risk.

The MPE concept presented herein is a weight optimized solution, which fulfils all requirements except weight. Analogous to the weight reducing measures, several MPE extensions were identified, which impact the overall mass but provide a valuable benefit to the mission. If the tight mass restrictions may be loosened in future and more mass is available for the MPE than currently projected, the options listed in table 3 can improve the MPE performance, boost the scientific as well as technologic outcome and raise the public outreach of the mission.

### Table 3 MPE system extensions

<table>
<thead>
<tr>
<th>MPE System Extension</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redundant avionics</td>
<td>+ Increase reliability</td>
</tr>
<tr>
<td>Active thermal system / heaters</td>
<td>+ Improve hibernation capability</td>
</tr>
<tr>
<td>Pan/tilt-unit on mast</td>
<td>+ Extended FoV; 360° stereo vision</td>
</tr>
<tr>
<td></td>
<td>+ Visible inspection of wheels and body possible</td>
</tr>
<tr>
<td></td>
<td>+ Improve reliability of autonomous operation</td>
</tr>
<tr>
<td>FPGA coprocessor</td>
<td>+ Higher resolutions/framerates for images</td>
</tr>
<tr>
<td>Filter wheel for stereo cam</td>
<td>+ Scientific benefit</td>
</tr>
<tr>
<td>Panoramic camera (alternative to pan/tilt unit)</td>
<td>+ 360° FoV</td>
</tr>
<tr>
<td>Inertial Measurement Unit (IMU)</td>
<td>+ Measuring MPE rotational velocity improves self-localization; compensates errors due to wheel slip</td>
</tr>
</tbody>
</table>
9. Conclusion

As a result of the MPE study work conducted during phase 0 and phase A, a rover design in the 14kg class is the lightest feasible concept, which complies with the majority of the requirements given to industry. Despite the MPE concept presented herein exceeds the mass requirement of 12kg, it is the best possible compromise from the view of acceptable risk, performance and weight. As the MPE is the first rover designed to fetch samples for return to the lander and in addition operating under the extreme harsh lunar south pole environment, it incorporates innovative approaches to lead the mission to success. The locomotion subsystem, the autonomy functions as well as the MPE operational concept are examples for Germany’s competencies in space robotics. Furthermore, the MPE concept is able to carry and operate a reasonable scientific payload to produce a meaningful scientific outcome of the mission beside the technology demonstration.

To reach the challenging mass limitations of ~10 kg for the rover plus additional ~2 kg for the payload as close as possible, 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 redundant in the frame of the mass target. But it has to be obtained from redundancies within most parts of the avionic.

Again, we like to note that rover concepts below the weight of the presented MPE concept are feasible but not recommended by the study team. Lighter rover concepts have a significantly reduced functionality and increased operational risk.

Relaxing the mass restrictions would significantly help to improve the MPE reliability by adding more redundancies. In addition it would allow a more capable science payload, being able to perform limited sample characterization. A possibility to boost the MPE robotic performance would be to equip MPE with an Autonomy Payload Experiment (APE), to demonstrate fast autonomous driving, after the “science mission” is accomplished. This APE would comprise a FPGA coprocessor for real-time image processing and a pan/tilt unit for the stereo camera, preferably combined with a camera mast to extend the FoV. An Autonomy Payload Experiment would significantly improve MPE’s autonomy and safety features as well as the technological outcome of the mission.

Despite MPE can accomplish its primary mission goals within a ~28 days lasting phase of continuous sunlight, its capability to hibernate darkness phases of several 10 hours by implementing active heaters is under current investigation. However, it is certain that a hibernation capability of ~60 h will lead to a further mass increase of MPE. If it becomes necessary that MPE has to survive long darkness phases completely self-standing and without lander support, the consequences must be analyzed carefully.

For this reason, we will proceed with the concept design in an extended phase A starting in autumn 2012. Therein the MPE and Lunar Lander mission timelines shall be synchronized, using a dedicated MPE illumination analysis as baseline. Further the interface requirements of both spacecraft will be refined. In this context special attention will be paid on the sample handling and transfer from MPE to the Lunar Lander robotic arm. Beside that, for the temperature critical MPE components suitable EEE-parts will be identified, together with their probable qualification effort and necessary breadboards.
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