Lunar Rover with Multiple Science Payload Handling Capability

Aravind Seeni,
Research Engineer,
Institute of Robotics and Mechatronics, German Aerospace Center,
82234 Wessling, Germany.
Aravind.Seeni@dlr.de

Bernd Schäfer,
Project Manager,
Institute of Robotics and Mechatronics, German Aerospace Center,
82234 Wessling, Germany.
Bernd.Schaefer@dlr.de

Bernhard Rebele,
Research Engineer,
Institute of Robotics and Mechatronics, German Aerospace Center,
82234 Wessling, Germany.
Bernhard.Rebele@dlr.de

Rainer Krenn,
Research Engineer,
Institute of Robotics and Mechatronics, German Aerospace Center,
82234 Wessling, Germany.
Rainer.Krenn@dlr.de

A rover design study was undertaken for exploration of the Moon. Rovers that have been launched in the past carried a suite of science payload either onboard its body or on the robotic arm's end. No rover has so far been launched and tasked with "carrying and deploying" a payload on an extraterrestrial surface. This paper describes a lunar rover designed for deploying payload as well as carrying a suite of instruments onboard for conventional science tasks. The main consideration during the rover design process was the usage of existing, in-house technology for development of some rover systems. The manipulation subsystem design was derived from the technology of Light Weight Robot, a dexterous arm originally developed for terrestrial applications. Recent efforts have led to definition of a mission architecture for exploration of the Moon with such a rover. An outline of its design, the manipulating arm technology and the design decisions that were made has been presented.

1. INTRODUCTION

Ever since man began exploring extra-terrestrial bodies, numerous surface missions with mobile robots have followed. This includes rover missions such as the *Lunokhod-1, Lunokhod-2, Sojourner, Spirit and Opportunity* [1][2][3][4]. Many other surface robotic missions are being planned for the next decade. Some of the missions are the *Mars Science Laboratory, ExoMars, Chang'e-2* and *Chandrayaan- 2* [5][6][7][8].

The earlier rover missions were designed to follow a "science-on-the-go" approach. This involves performing experiments on interesting locations after landing with the available rover science instruments and tools. The Mars Exploration Rovers (MER) *Spirit* and *Opportunity* carried instruments like Moessbauer spectrometer, Alpha Particle X-ray Spectrometer, panoramic, microscopic cameras and abrasion tools. The payload remains integrated to the rover body throughout the mission. No payload has been deployed on the surface on a certain site yet for conducting experiments. It is thought that a "drop and go" approach of using the robot just as a mobile platform for rapid deployment of payload on several locations near landing site, in addition to the requirements traditional "science-on-the-go" methodology would be necessary to be performed by a robot in future missions. Such a mission can not only return science data with instruments available onboard, but also help in science return through portable payloads. Examples of conceptual portable payloads are an in-situ resource utilization demonstrator, radio frequency demonstrators that need to be transported by the robot and then dropped on the lunar surface. The robot after surface deployment of payload may help with the payload's deployment function and operation.

Payload portability could be realized using the robot's mobility and manipulation property. The payload could be carried using a flexible robotic arm and then driven, transported using the robot's wheels or legs. In this paper, a conceptual surface robotic mission to Moon with a lander-rover combination has been identified to accomplish some new science objectives and realize possibilities of payload portability with a mobile robot. The lander and rover are assumed to carry a suite of payload devices. Some devices onboard the lander will be carried and transported across by the rover and then deployed on the lunar surface. The rest need not be deployed, but needs close-positioning on different lunar rock or soil samples.

The institute has a long-standing reputation in technology and systems development for terrestrial robotic applications as well as on-orbit space experiments. With past experiences of developing technology [9][10] that includes the Light Weight Robots (LWR) [11], it was determined to perform this study on using existing technology to be spun-off to space applications. A lunar rover design study was conducted and some identified system concepts uses available off-the-shelf technology. The selection of the scientific payloads was motivated by an earlier study conducted together with the German space company Kayser-Threde. This paper summarizes the design of the lunar rover and the conceptualized mission architecture for a potential mission to Moon. The manipulation subsystem design is given particular focus since the LWR technology was analyzed for using as the rover's manipulator for the application of payload portability. An overall view of the design of the rover and subsystems is also provided.

2. MISSION REQUIREMENTS

The primary science objectives required traverse of a mobile platform for a minimum total of 100 m on the lunar surface during the mission. The primary objectives of the rover include deployment of portable payloads such as a pair of Radio-frequency Demonstrators (RFDs) for radio-frequency transmission on lunar surface, a 30-kg In-situ Resource Utilization Demonstrator (ISRU-D) as well as a minimum of five close-up analyses with a combination of Moessbauer spectrometer (MS), Alpha-Particle X-ray Spectrometer (APXS), Rock Abrasion Tool (RAT) and Microscope camera (MC) instruments on potentially interesting locations. All these primary objectives shall be completed within total mission duration of one lunar day. The secondary objectives assumed will be performed on availability of excess time, power and other resources after achieving primary objectives. The secondary objectives are the continuation of instrument placement on additional locations as required based on resource availability. The preferred operational site on the lunar surface would be on the near-side where sunlight is predominantly available most of the time. The rover operations start during the start of lunar day and end by the end of lunar night. The latitude and longitude traverse locations are science derived. Some of the aspects that affect the mission architecture are the type of surface landing, mobile platform, telecommunications strategy and power subsystem design of the mobile platform (Table 1). As listed in Table 2, the requirements drive selection of a particular subsystem and its design impact.

2.1. Landing Strategy

A lander-rover combination is assumed to be launched from Earth. The lander retro-rocket propulsion system would offer a soft-landing platform for the rover as well as the different science systems stowed in the body. Without a lander, soft-landing of the mission payloads will add to the complexity of the rover and portable payload systems design. The rover is stowed inside the lander's body and will egress to the lunar surface through deployable ramps. Other than the rover, the ISRU-D and one of the RFDs are also mounted inside. The availability of the lander offers flexibility in mission design with regards to communication architecture. A stationary platform as the lander could help in efficient data transfer than from the movable source itself. Since the landing site is on the near-side, implementation of a hybrid communication architecture comprising of both rover direct-to-Earth as well as rover-lander-Earth relay will be realistic.

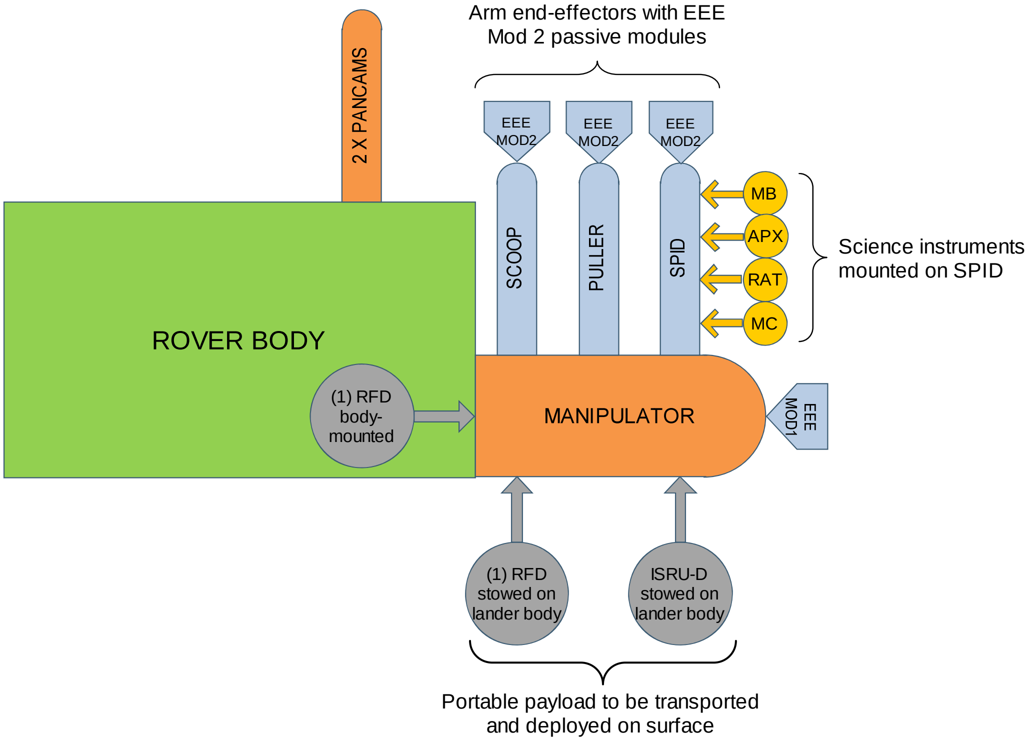

Fig. 1 Systems Architecture showing the different science components integrated to rover system. The manipulator or robotic arm is fixed to the front of the rover's body. One RFD is fixed to the lander and other carried onboard the rover. The ISRU-D is also stowed inside the lander. Both devices available onboard the lander – ISRU-D and RFD – would be later deployed by the robotic arm. The arm end-effectors – scoop, puller, SPID along with their EEE modules – are also shown. The SPID carries four science instruments to be able to position on samples. The rover also carries a pair of stereo PanCams to aid in navigation.

Table 1 Key mission architecture and rover system trades

Trade	Options assessed	Option selected	Rationale for selection
Landing strategy	Lander-rover, Rover-only	Lander-rover	Less design complexity; lander can provide a soft-landing house for the rover and its portable and integrated payloads
Science platform mobility	Wheel, tracks, legs, hybrid	Wheels	High stability and speed capacity
Number of science platforms	One, two, swarm	One	Less mission complexity, less number of objectives, traverse distance requirement less.
Science platform power generation	Solar arrays, primary batteries, RTG, fuel cells	Solar arrays	Sunlight available, solar cells are highly efficient with up to 30% conversion efficiency achieved at present
Telecommunications strategy	Rover direct-to-earth, rover-lander-earth, hybrid	Hybrid	Enables maximum flexibility in rover uplink/downlink communications

2.2. Mobile Platform

A wheeled rover is chosen as a mobile platform for the mission. A statically and dynamically stable mobility configuration, in this case, is very important owing to lifting and holding high loads at arm end. Traction is important for the rover's mobility performance on lunar regolith. Less traction gives rise to more slip, and thus cause problems with localization and navigation. However, traction for a wheeled system is not a problem on lunar surface. This is due to the properties of the lunar regolith. The lunar regolith density varies with depth from over 1.0 g/cm^3 at surface to 2.0 g/cm^3 at 20 cm below the surface. Its mean porosity is 40-43 % by volume. The cohesive bearing strength is density dependant and there varies with depth from 0.03 N/cm^2 at the surface to 0.3 N/m^2 at 20 cm depth. Therefore, traction is not a problem [12][13] and a wheeled configuration is selected. Due to this reason, with regards to the problem of wheel slippage, the mobility performance can therefore be accounted to minimal influence to the rover's navigational performance. The next quest lies in the number of wheels. A six-wheeled configuration is selected as it offers greater stability and obstacle traverse capability than a four wheeled configuration.

2.3. Payload Deployment and Instrument Placement Platform

The rover would deploy portable payloads such as ISRU-D and RFDs. After their deployment processes, the rover traverses different locations and performs science investigations with a suite of instruments and tools – MB, APXS, RAT and MC. A platform for manipulating all objects for both payload deployment and placement tasks is therefore necessary. All the tasks are thought to be complex and require high dynamic capacity. A simple 5-DOF manipulator as the infamous Instrument Deployment Device [14] of MER will not be able to perform such tasks. It was found that a robotic manipulator derived from existing in-house LWR technology would be capable of performing the tasks.

Table 2 Requirements and rover system design impacts

Requirement	System impact
100 m traverse, 1 lunar day mission duration	Platform type selection Power availability, landing period and time Navigation system
Limited stowage volume inside the lander	Rover and subsystems volume Subsystems stowage configurations
Launch capacity	Mounting rover and sensitive payload within lander structure as necessary, low rover mass
Multiple portable payload manipulation	Multiple end-effector to be carried
Payload portability	Manipulating arm load capacity End-effector exchangeability High dexterity, autonomy Power consumption

2.4. Payloads

The total allocated mass of the payload carried by the rover at the beginning of surface operations is estimated to be 17.7 kg. The allocated mass of the rover instruments and tools (MS, APXS, RAT and MC) is 2.3 kg with margins. A detailed description of the payload listed below is not required within the context of this paper and hence only an overall view is provided.

2.4.1. In-situ Resource Utilization Demonstrator

The feasibility of in-situ resource utilization of lunar regolith would be analyzed with the ISRU-D. A preliminary estimated mass of 15 kg was allocated for the device. It would be accommodated onboard the lander and would be deployed after landing by the rover on the lunar surface. The traverse rover distance requirement is 2 m from the lander. The ISRU-D is a self-operational device equipped with 10 ovens. The rover would collect regolith with the RM onboard a SSF. The regolith samples are the transferred in to the ovens' inlet one by one. Each oven requires 400 g of regolith and hence a total of 4200 g of regolith would be required to be collected by the rover. The ISRU-D later heats up the regolith for chemical analysis and elemental composition detection.

2.4.2. Radio Frequency Demonstrator

A pair of RFDs would be also deployed on the surface with the help of rover arm. The RFDs enable demonstration of wireless, radio-frequency transmission between two stationary points on Moon. Each RFD would be deployed on surface after allowing a clearance of 60 m between them. The RFDs are equipped with self-deploying antennae within an overall cylindrical body. After placement with robotic arm on surface, the device senses touchdown and deploys four antennae. The RFDs are fully autonomous in deployment and operation.

2.4.3. End-effectors and exchange modules

The applications of deployment of ISRU-D and RFDs, close-positioning of science instrument as well as regolith collection by the robotic arm requires multiple end-effectors to be carried onboard the rover to satisfy all requirements. Three end-effectors will be carried onboard the body of the rover. They will be exchanged or disposed off to the lunar surface as necessary. The three end-effectors are the Puller, Scoop and Scientific Payload Interface Device (SPID). They serve deployment, regolith collection/filling and instrument placement respectively. The SPID carries four instruments that are arranged like the fingers of a human hand. The arrangement can also be compared to be similar as in design of the Position Adjustable Workbench [15] of ESA's *Beagle 2* Mars lander [16].

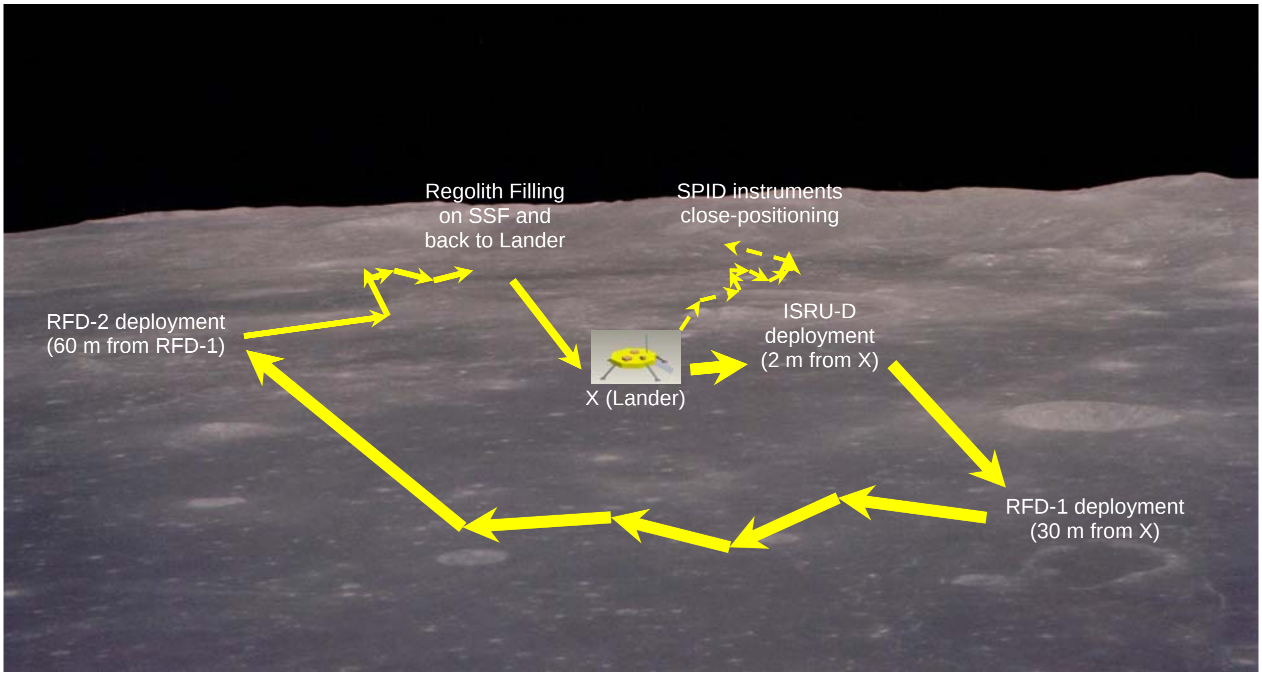

Fig. 2 Illustration of rover's tasks on lunar surface

To facilitate end-effector exchange, End-effector Exchange (EEE) modules are fixed to arm end and all end-effectors. An active module attached to the robotic arm end helps in locking with any of the passive modules of the end-effectors that would be originally stowed onboard the rover's body. The location of stowage of the end-effectors is in front of the rover and enables the manipulating arm to steer within this workspace for all lodging and dislodging purposes.

2.4.4. Sample Storage Facility

The SSF is an integral part of the rover's body structure that would help in storing the collected regolith for ISRU-D analysis. The SSF is a hollow, cylindrical pipe integrated within the rover's box vertically. A hopper on top minimizes spill-over of regolith during transfer from arm's scoop to the SSF. The SSF volume required was estimated to be for storing the 4200 g of regolith required. The volume of the cylinder is as low as 0.00145 m^3 (1.5 liters) to allow storage of 4200 g of regolith. The density of lunar regolith is assumed to be 2900 kg/m^3 [17] for the estimation. The SSF has integrated piezo-electric mechanisms for a mechanical transfer of the regolith from the cylinder to the arm's scoop through the facility's outlet. The piezo-mechanism supports regolith transfer to the scoop in low gravity. Also sensors arranged along the radii of the outlet provide information about scoop location below it.

3. ROVER OPERATIONS

The lander accommodating the rover, instruments and demo packages (Fig. 1) is assumed to be launched to Moon that is followed by a controlled descent to the surface. The top-level stages of operations are the rover egress, ISRU-D deployment, RFDs deployment, sample collection/filling in ISRU-D ovens and instrument close-positioning (Fig. 2). The rover would perform systems checkout and egress to the surface through ramps deployed from the lander's body. After reaching the surface, the rover retrieves the ISRU-D that is stowed inside the lander and deploys it on the surface. The ISRU-D transfer operation and deployment on lunar surface would then be followed by deployment of two RFDs. In launch configuration, one RFD would be carried by the rover onboard and deployed immediately on the surface after ISRU-D deployment process. The other RFD will be available on the lander and transferred by the rover manipulator (hereafter RM) after returning to the lander and manipulated. It is preferred to have the second RFD onboard the lander due to space limitations on the rover's body. Both RFDs will be placed in opposite sides of the lander at a distance of 30 m to enable a distance of 60 m between both. After the initial deployment of ISRU-D and two RFDs, lunar regolith collection and transfer to ISRU-D operation will be performed. The ISRU-D is designed with ovens that heat regolith and analyses its composition. Regolith collection is performed by the rover at different locations and fills them in the ovens.

After oven-filling process, the rover will traverse different regions on lunar surface and position instruments (MS, APXS, RAT, MC) closely to rocks and soil. A step-by-step rover activity and time allocation list is provided in Table 3.

Table 3 Tasks time allocations overview

Rover activity	Elapsed time for completion [Earth hours]
System checkout and rover egress from lander to surface	12.0
Panoramic imaging of area near landing site	0.5
Collect ISRU-D from lander by the RM and deployment of ISRU-D at 2 m (approx.) from lander feet	1.0
Panoramic imaging at ISRU-D location	0.5
Deploy RFD available onboard to the surface at 30 m (approx.) from the lander	15.0
Imaging of area and deployed antennae check	1.0
Drive back to lander	12.0
Collect RFD stowed in lander with RM	1.0
Rover drive for 30 m (approx.) and deploying the second RFD similar to the first, preferable at a location in the opposite direction of first RFD location with 60 m (approx.) clearance between both	15.0
Imaging of area and deployed antennae check	1.0
Arm end-effector replacement. The puller is dislodged and thrown to the surface. The scoop is lodged to the end.	1.0
Drive and area survey for presence of required amount of regolith	12.0
Scooping of 4200 g regolith samples and collection onboard the rover's SSF	12.0
Rover driving to ISRU-D and transfer of regolith to its ovens with scoop	24.0
RM end-effector replacement of scoop with SPID. The scoop is dislodged and thrown to the surface	1.0
Driving of lunar rover to different locations, investigations of lunar rocks and soil with instruments (12 times in each vicinity at 180 minutes each)	108.0
TOTAL	217.0

The navigation of rover would be performed with PanCams mounted on the rover's mast assembly. For all these tasks, it is necessary to have a robotic arm to be carried onboard the rover. The requirement is cumulative time duration of 217 hrs for completion of primary objectives. An average traverse speed of the rover of 15 cm/s is assumed in this estimation process. An excess of 100 hrs is available for batteries recharge, rover obstacle negotiation and data relay.

4. ROVER SYSTEMS

The rover's body is a rectangular box measuring 0.80 m in length, 0.48 m in width and 0.30 m in height (Fig. 3). The box encloses the avionics, batteries, thermal control components and sensors within the hollow structure. It holds the solar arrays and the stowed RM on top in launch configuration. The rover base-plate provides a body clearance of 240 mm from the surface. The maximum height of the rover from the wheel base to the top of the deployed mast assembly is 1.2 m. The maximum width of the rover between the edges of the solar arrays is approximately 1 m. The maximum longitudinal length of the rover is estimated as 1.5 m. The SSF is integrated within the body of the rover. The hopper and the outlet extend above and below the box partly. The SSF's total height is 0.6 m. All the four science instruments are mounted to the end of a dexterous, anthropomorphic RM that is itself mounted to the front of the rover's body. To aid end-effector exchange possibility, all the end-effectors are initially mounted in front of the rover's body structure to allow the arm to manipulate and grasp them. All the end-effectors are stowed here. The location can be reached conveniently by the robotic arm for end-effector exchange. The arm is fixed on the front sides to prevent any possible contact with the payload mounted on the front of the body. In stowed configuration, it is mounted on the top of the body and maintains a small clearance to not contact the fragile solar arrays. A pair of PanCams is mounted on top of the mast assembly and assists in navigation of the rover and arm, along with a pair of HazCams in front. The mast assembly along with the PanCams, unlike mounting symmetrical to the rover's body, is mounted on the body sides. This approach is thought to have no impact on the rover's navigation capabilities, since it depends entirely on the orientation of the cams. The communication antennae are permanently deployed and relay data to the lander or to an Earth station. A concise rover subsystem summary is provided in Table 7.

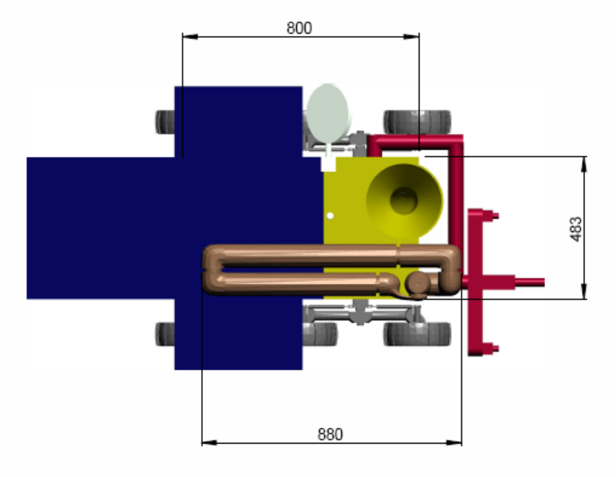

Fig. 3 Configuration of lunar rover with RM

4.1. Mobility subsystem

The mobility subsystem of the rover consists of wheels, wheel actuators, bogies, steering mechanisms, motor controllers, sensors and electronics. The proposed configuration for the mobility assembly is a 6x6x4 configuration. The rover has 6 wheels of which 6 are motored for longitudinal forward/backward motor. 4 wheels on the rear and back are steered with an additional identical motor. All six motors provide a nominal rover speed of at least 15 cm/s. On the whole, six brushless DC motors power the mobility subsystem. Surface terrain characteristics, rocky or smooth, greatly influence the mobility performance. Since the wheel actuator drives the rover during the whole mission, the performance of it in terms of output power, energy consumption and efficiency should not be compromised. The motor selected for the rover is the in-house developed *RoboDrive* [9]. The wheels are supported by two parallel longitudinal bogies on the sides and a traverse bogie at the back. There are eight *Robodrive* motor variants available that is selected for a particular application based on load and power requirements. The nominal torque and speed of this motor are 900 mNm and 8000 rpm respectively. The other variants can be used for applications such as the joints of the RM. Different variants of the *Robodrive* motor is selected for powering the RM joints.

4.2. Manipulation subsystem

4.2.1. Operational requirements

The manipulator is used as a payload “transporting” and “positioning” device. The design of the manipulator or the arm of the robot has to satisfy many operational requirements like high load capacity at arm end, modularity for end-effector exchange, high dynamic capacity for manipulating objects within a given workspace and high autonomy. Also, it has to be robust and reliable. The joint actuator should be highly efficient. The heat emitted from motors, electronics should be maintained minimum for low thermal control requirements. The power consumption levels of these motors should be also low.

4.2.2. System requirements

The arm has 7 degrees of freedom that enables transportation and *in-situ* instrument positioning of science payload. The arm consists of 7 joints arranged in an R-P-R-P-R-P-P configuration (R=Roll, P=Pitch). For lifting a payload stowed on to the lander – ISRU-D and RFD – PanCam images will be used to provide the exact 3D location and the surface normal of the intended contact location with respect to the rover’s coordinate frame. For positioning of SPID instruments on to a rock or soil sample, a pair of wide-angle stereo imaging HazCams is provided at the rover’s front. In the mission layout, all transport, sampling, science operations concerning RFDs deployment, ISRU-D deployment, ISRU-D regolith filling and instrumental science on lunar rocks are tasks to be handled by the RM. These tasks are thought to be quite complex and time-consuming considering the nature of the payload to be handled. For example, deploying the ISRU-D and RFDs requires precision to be able to be lifted remotely from the narrow attachment points. Another requirement is the ability of the arm to place any instrument or end-effector on a target within one command cycle.

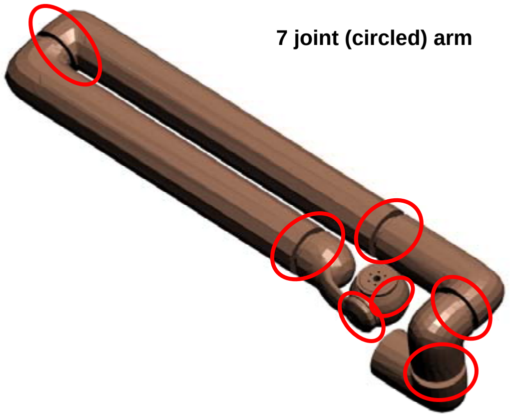

Fig. 4 Stowed configuration of RM. This configuration allows low storage volume requirement on top of the rover’s body.

4.2.3. RM design and operations

The proposed robotic arm is based on the well-known LWR technology [9][18][19]. LWRs are being developed commercially for many terrestrial applications. With some modifications, such technology could also be used for the lunar rover. The RM is mounted in the front of the rover's body. It facilitates transport of payload devices and manipulation of lunar rocks and samples. It is integrated with one of the following end-effectors – Scoop, puller and SPID – and could be changed depending on task requirements. Changing end-effectors i.e. lodging and dislodging is possible through an End-Effector Exchanger (EEE) mechanism. This mechanism is mounted at the arm's end and acts as an interface between the RM and one of the fixed end-effectors. A maximum reach distance of 1.4 m is possible for close-positioning of SPID instruments. The instrument positioning configuration is shown in Fig. 6. The width of each link is 0.08 m. The main components of the RM are its joint actuators, links, sensors and avionics. The motor in the joint actuator is the *Robodrive* (Fig. 5) proposed also for mobility wheel drive with slight modifications. For lunar applications, the power requirement is low due to relatively low motor loads in lunar gravity. Assuming an average power requirement of 4 W for each motor including its electronics and sensors, the total requirement would be 28 W. The various specifications of the RM are summarized in Table 4.

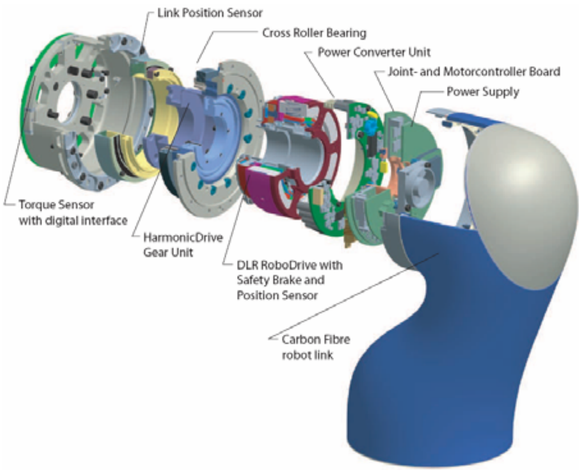

Fig. 5 Internal components of the rover RM's joint derived from LWR and brushless DC *Robodrive* motor technology.

The 15 kg ISRU-D will be unstowed from the lander by the RM, carried and deployed to the surface with the help of "puller" end-effector. Regolith collection is done with a scoop. During launch, the arm is stowed above the rover's body to occupy less volume with lander's stowage area (Fig. 4). Also the puller is pre-mounted to the arm's end (not shown in figures). This can be later dismounted and exchanged with a scoop. The scoop is again dismantled and exchanged with the SPID. A "use and throw" strategy is followed for the end-effector i.e. they would be thrown to the lunar surface after use. The arm is necessary to have highly modular for end-effector exchange purpose. This is possible through the EEE mechanism available as active and passive components in the arm and end-effectors respectively. The scoop collects lunar regolith for the ISRU-D ovens. The rover navigates to different locations on the lunar surface and different samples are collected from different locations through the scoop. They are poured into the inlet of a storage facility available on top of the rover. The regolith is then transported to the ISRU-D and the collected samples are taken in fixed quantities by the scoop from the outlet of storage facility at the bottom of the rover. The regolith is then poured into the inlet of the ovens. To determine the feasibility of the robotic arm to and successfully reach the top and bottom of the SSF onboard the rover, some preliminary pose calculation and determination of joint angles were performed. It was found that the RM's configuration is capable of reaching the targets (Fig. 7, Fig. 8). In the future, the pose has to be optimized for the best possible configuration to be achieved for each maneuvering task.

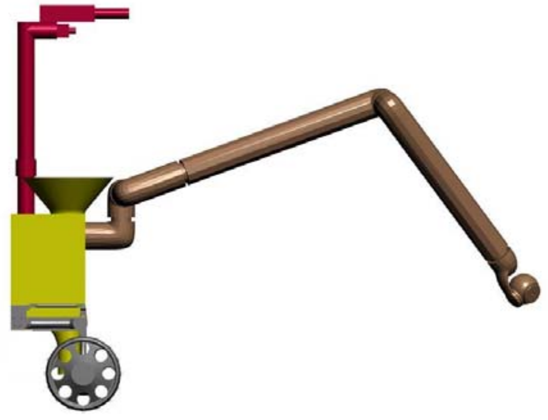

Fig. 6 Deployed configuration of RM. This pose is achieved for close instrument positioning fixed to the SPID. There are four instruments and tools necessary for in-situ sampling fixed to the SPID – MB, APXS, RAT and MC.

A thorough knowledge of the robotic arm's motion dynamics is necessary prior to its intended operations. It is expected that the arm joints' physical parameters such as damping, friction, and stiffness would change over time with variations in temperature, velocity of motion and material degradation in extreme lunar environment.

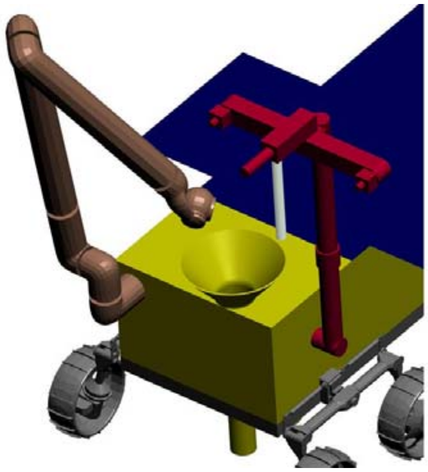

Fig. 7 RM in Scoop-over-mill configuration (Scoop not shown). This arm pose allows transferring the regolith from scoop to the SSF's hopper inlet. During the transfer process the outlet of the SSF remains closed. After the collection is complete, the rover moves to the ISRU-D to fill the ovens.

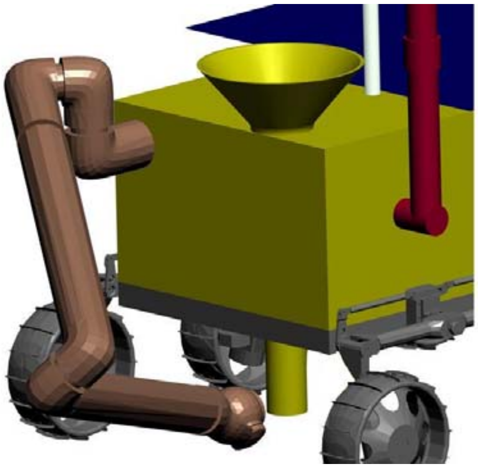

Fig. 8 RM in Scoop-below-mill configuration. The scoop (not shown) that is fixed to the arm's end approaches the outlet of the SSF. Sample collection with the scoop is initiated after detection of the scoop exactly below the outlet. This is done through optical sensors located on the SSF's outlet. The regolith fall from the container to the scoop in low-gravity condition is supported by piezoelectric actuation mechanism that will be integrated within the body of SSF.

The two-jointed ROKVISS onboard the ISS offered results [20] on the *Robodrive* joints' performance under ISS conditions where the operating temperature on-orbit ranges between -20°C to +30°C. Currently, tests have indicated that the joints are operational up to a temperature of +135°C. It is envisaged that after providing safe thermal control structure, lubrication, active thermal cooling, the motor could be well within the safe operational limits with high performance. During the later phases of the project, these joints will be validated for operation in very higher temperatures.

Table 4 Specifications of the RM derived from LWR technology

Specification	Dimension
Load capacity at low velocity	15 kg
Load-to-weight ratio	~1:1
Degree of Freedom	7
Axes	R-P-R-P-R-P-P
Maximum arm reach distance	1.4 m
Actuator	*Robodrive* integrated with Harmonic drive gear
Joint sensors	Angle: 2, Torque: 1
Wrist sensor	6-DOF Force/Torque sensor
Brake	Electromagnetic safety brake
Error Tolerance	1 mm
Repeatability	50 µm
Positional accuracy	1.5 mm
Control	Position, Torque, Impedance control

4.3. Power subsystem

The rover was designed to function between the latitude ranges of 45°N and 45°S. The location of operation is on the near-side where there is presence of sunlight. The power system should be designed to provide energy for the various experimental processes planned in quick successions within the limited mission timeframe. The total duration of mission of one lunar day implies that the rover power will die out by the start of lunar night. Primary batteries, in this case, are least suitable because they are heavy and no continuous power is generated. Radioisotope thermoelectric generators or RTGs are most preferable for higher latitudes. But they are expensive and have low technological maturity. In addition, adequate thermal control techniques must be provided to dissipate the excess heat. This affects the simple thermal control architecture and increases the overall system mass. The most preferred option would, therefore, be solar arrays that utilize available solar energy for power generation. Now-a-days, improvements in achievable conversion efficiencies of solar cells have been made.

Table 5 Estimated power requirement of rover subsystems

System	Average Power [W]	Peak Power [W]
Mobility	19.8	118.8
Manipulation	33.0	132.0
Mast Assembly and PanCams	17.6	17.6
Microscope camera	3.3	10.0
APX Spectrometer	1.65	10.0
Mössbauer Spectrometer	2.2	10.0
Rock Abrasion Tool	12.1	25.0
Scoop	2.2	10.0
EEE-active	1.1	8.0
Communication system	27.5	27.5
Avionics, HazCams and other sensors	5.5	5.0
Thermal subsystem	20.0	40.0
SSF mechanisms	16.0	16.0
TOTAL	161.95	429.9

The subsystem power requirements are listed in Table 5. The subsystem uses a standard 28V DC bus. Ni-Cd rechargeable, secondary batteries will be used to power the other systems. The rover solar array consists of triple junction cells made of Gallium Indium Phosphide, Gallium arsenide and Germanium ($GaInP_2/GaAs/Ge$). They offer the best efficiencies with current values above 30%. The arrays are designed to be foldable to occupy less volume. The design allows the arrays be folded half-way and can be fully deployed on the surface. The entire array area is divided into four panels. One of the panel remains on top of the box, whereas three panels are hinge-actuated and deployable. During rover motion, the wheels could potentially kick-off dust in low lunar gravity as can be seen from the experience with Apollo Lunar Roving Vehicle. The dust could settle on the top of the solar arrays. However, taking into account of the rover velocity, such situations are not expected and therefore, dust removal tools are not required.

4.4. Structure and Thermal Control subsystem

The average temperature variation of the lunar surface in the mid-latitudes varies from 220 K to 254 K. The monthly variation range near the equatorial latitudes is ±140 K [21]. All lunar locations experience an equal day and night period of 13.6 Earth days, except at the poles. The noon-day Sun traces a path on the equatorial surface with essentially no seasonal variation [22]. The nominal incident solar flux on the surface is 1371 W/m^2 [23].

Table 6 Preliminary rover system design budgets

Payload	Nos.	Nominal Mass [kg]	Margin [%]	Total Mass [kg]
Instruments and Tools				
MC	1	0.5	10%	0.6
APXS	1	0.3	10%	0.3
MS	1	0.5	10%	0.6
RAT	1	0.7	10%	0.8
RFD[*]	1	4.0	20%	4.8
Supporting hardware				
Thermal insulation	-	1.0	15%	1.2
Thermal hardware	-	1.0	20%	1.2
End-effectors and Interfaces				
EEE active (fitted in RM)	1	1.0	20%	1.2
Puller (with EEE passive)	1	2.0	20%	2.4
Scoop (with EEE passive)	1	2.0	20%	2.4
SPID (with EEE passive)	1	2.0	20%	2.4
SUBTOTAL	10	14.5		17.9

Rover Subsystem	Nominal Mass [kg]	Margin [%]	Total Mass [kg]
Mobility	24.4	20%	29.3
Manipulation	12.2	20%	14.6
HazCams, Sensors and Avionics	7.1	20%	8.5
Structure and SSF	16.3	20%	19.6
Power	16.3	20%	19.6
Thermal Control	3.2	20%	3.8
Communication	6.1	20%	7.3
SUBTOTAL	85.6		102.7

System	Total Nominal Mass [kg]	Mass with Component Margin [kg]
Payload	14.5	17.9
Rover	85.6	102.7
TOTAL	100.1	120.6

---

[*] Only one RFD will be mounted on the rover. The other RFD would be stowed onboard the lander

Table 7 Rover subsystems summary

Subsystem		Description
Mobility	Type	Six-wheeled chassis. 6 wheels actuated for forward/backward motion, 4 wheels steerable
Manipulation	Type	Dexterous, anthropomorphic, 6-DOF arm. Technology derived from LWR technology. R-P-R-P-R-P-P configuration with *Robodrive* actuated joints
Power	Bus Voltage	28V
	Solar array type	4 panels mounted on top of body. 3 panels deployable, 1 fixed
	Solar cell type	$GaInP_2/GaAs/Ge$
	Battery type	Ni-Cd
Thermal control	Active system	Thermoelectric coolers
	Passive systems	Aluminum, aerogel coatings
Communications	Architecture	Hybrid: Relay through lander, direct rover-to-earth communication
	Bandwidths	8/256 kbps forward/return to/from lander, 1 kbps rover return to lander
	High-gain antenna type	Phased array
Navigational sensors	PanCams	2 stereo imagers mounted on mast assembly
	HazCams	4 wide-angle stereo cams
Command and Data Handling	Microprocessor	Radiation hardened PC – e.g. RAD750 PowerPC [26]
Structure	Body material	Carbon-fiber reinforced plastic composite
	Body layer	Double-layered with insulation

Temperature on the surface varies widely depending on location and is influenced by the day-night cycle. Since the mission is planned for one lunar day operations after assuming rover operations to start on the first lunar day, the day-night cycle variations need not be taken considered for thermal control system design. The structure and thermal subsystem will be designed only for bearing the hot temperature. On a lunar day, the mean temperature would be as high as 380 K and can rise to a maximum of 400 K. The surface emissivity factor of the sun exposed surface is 0.9 [21][24]. In addition to the solar environmental conditions, the structure should be able to withstand axial (~15 g) and planar (~10 g) launch loads within the launcher. The body of the rover is a rectangular hollow box made of carbon-fiber-reinforced-plastic composite. The box is made up of a double shelled layer. The avionics systems and batteries are mounted within the inner shell. During all the hot lunar days, sufficient thermal control should be provided for this warm box to prevent overheating of electronics, sensors and other sensitive devices.

The rover is provided with a reflective coating on the exterior of the body as a passive control. Two properties of importance are the IR emissivity and solar absorptivity. Coatings on the surface should be able to effectively radiate internally generated heat. Also, low absorptivity is required for minimizing the effects of variations in solar radiation. A polished Aluminum film having emissivity properties of 0.03 and absorptivity of 0.09 is selected. An insulation barrier made of Silica Aerogel is provided between the inside and outer shells of the rectangular box. During the vast amounts of time of work, the rover generates large amounts of heat internally within the various subsystems. An active thermal system is provided with thermoelectric coolers in the avionics, communication, batteries, instruments, as well as the motors part of the mobility and manipulation subsystem.

4.5. Communication subsystem

A robust communication system design is necessary for a mission of this kind, since any failure could lead to no science return. A “hybrid” communication architecture is proposed for relaying data through a stationary platform (lander antenna) as well as direct rover-to-Earth. This architecture is suggested to enable maximum flexibility. Whilst data sent from Earth shall be from one ground antenna, the return link has two options. One option is through lander relay and another direct-to-earth communication by onboard transmitter. The only problem with this architecture was envisaged is the mass increase in the system. For direct-to-earth link, the rover would carry a steerable high-gain antenna and an X-band transceiver. A phased array high gain antenna is selected, since it enables faster and better precise steering [25] than a parabolic reflector.

Operations like instrument placement cannot be performed within lander's line-of-sight. Hence direct-to-Earth communication is accommodated as for operational redundancy. Here the presence of an orbiter is not envisaged and therefore neglected. For relay through lander, the rover would require an omni-directional antenna (VHF/UHF). This antenna is mounted on top of the rover's body as high as possible to maintain maximum line of sight distance with the lander. It can also receive commands directly from Earth at a low data rate (X-band). The envisaged uplink/downlink bandwidths are 8/256 kbps respectively.

4.6. Systems design budgets

The rover and payload preliminary mass budget is provided in Table 6. Table 7 summarizes the rover's subsystems.

5. CONCLUSION

An overview of the rover designed for both payload deployment and instrumental science has been provided. An advanced dexterous arm derived from existing technology for carrying out the various complex tasks has been described. The payload and rover subsystems all require space-qualified components. Detailed design on the SSF is a task that has been planned for appropriate regolith storage and transfer. New navigation strategies for increased autonomy on surface by the arm and the rover have to be addressed. This would be a goal for the institute and advancements have been made with existing 3D image processing technology.

6. ACKNOWLEDGEMENTS

Some parts of the work presented in this paper were conceptualized and performed by the Institute of Robotics and Mechatronics during the project "Lunar Robotic Payload", under sub-contract to the space company Kayser Threde Munich (DLR Contract No. 3464757 with support of German Space Agency). The authors would like to acknowledge and express their thanks for their support. The authors are also grateful to Manfred Schedl for offering his thoughts during the course of work.

7. REFERENCES

[1] Grayzeck, E., "*Luna 17/Lunokhod 1*," NSSDC Master Catalog Search, National Aeronautics and Space Administration, 2008 [online database]. URL: http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1970-095A

[2] Grayzeck, E., "*Luna 21/Lunokhod 2*," NSSDC Master Catalog Search, National Aeronautics and Space Administration, 2008 [online database]. URL: http://nssdc.gsfc.nasa.gov/nmc/masterCatalog.do?sc=1973-001A

[3] Cook, R. A., and Spear A. J., "Back to Mars: The Mars Pathfinder mission," *Acta Astronautica* Vol. 41, No. 4-10, August-November 1997, pp. 599-608 [online journal]. DOI: 10.1016/S0094-5765(98)00069-1.

[4] Cook, R. A., "The Mars exploration rover project," *Acta Astronautica* Volume 57, Issues 2-8, July-October 2005, p. 116-120 [online journal]. DOI:10.1016/j.actaastro.2005.03.008 Infinite Possibilities Global Realities, *Proceedings of the 55th International Astronautical Federation Congress*, Vancouver, Canada, October 2004.

[5] Volpe, R., "Rover Technology Development and Mission Infusion Beyond MER," *Proceedings of the IEEE Aerospace Conference*, Big Sky, MT, USA, 2005 [online database].URL: http://hdl.handle.net/2014/37528

[6] Barnes, D., Battistelli, E., Bertrand, R., Butera, F., Chatila, R., Biancio, A. D., Draper, C., Ellery, A., Gelmi, R., Ingrand, F., Koeck, C., Lacroix, S., Lamon, P., Lee, C., Magnani, P., Patel, N., Pompei, C., Re, E., Richter, L., Rowe, M., Siegwart, R., Slade, R., Smith, M. F., Terrien, G., Wall, R., Ward, R., Waugh, L., and Woods, M., "The ExoMars rover and Pasteur payload Phase A study: an approach to experimental astrobiology," *International Journal of Astrobiology*, Vol. 5, No. 3, 2006, pp. 221-241 [online journal]. DOI: 10.1017/S1473550406003090.

[7] Kumar, V., "Indo-US Cooperation in Civil Space," *Proceedings of the 2nd Space Exploration Conference*, Houston, Texas, USA, 4-6 December 2006 [online database]. URL: http://www.nasa.gov/mission_pages/exploration/main/2nd_exploration_conf.html

[8] Liu, X., and Ding, T., "Investigation of Coordinated Control of Lunar Rover Locomotion," *Abstracts of the 9th ILEWG International Conference on Exploration and Utilisation of the Moon*, ICEUM9/ILC2007, Sorrento, Italy, 2007, pp. 136.

[9] Hirzinger, G., Brunner, B., Butterfaß, J., Fischer, M., Grebenstein, M., and Landzettel, K., Space Robotics – Towards Advanced Mechatronic Components and Powerful Telerobotic Systems, *Proceedings of the 6th International Symposium*

on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS), Montreal, Canada, 2001.

[10] DLR-RM, DLR Institute of Robotics and Mechatronics Status Report 1997-2004, Part 1, November 2004 [online database]. URL: http://www.dlr.de/rm-neu/en/desktopdefault.aspx/tabid-3757/

[11] Albu-Schaeffer, A., Haddadin, S., Ott, Ch., Stemmer, A., Wimboeck, T., and Hirzinger, G., "The DLR Lightweight Robot: Design and Control Concepts for Robots in Human Environments," *Industrial Robot: An International Journal*, Vol. 34, No. 5, 2007, pp.376-385.

[12] Johnson, S., and Chua, K., "Properties and mechanics of lunar regolith," *ASME Journal of Applied Mechanics*, Vol. 46, No. 6, 1993, pp. 285-293.

[13] Ellery, A., An Introduction to Space Robotics, Praxis Publishing Ltd, Chichester, UK, 2000, pp.33.

[14] Baumgartner, E. T., Bonitz, R. G., Melko J. P., Shiraishi L. R., and Leger P. C., "The Mars Exploration Rover Instrument Positioning System," *Proceedings of the 2005 IEEE Aerospace Conference*, Big Sky, Montana, 2005 [online database]. URL: http://hdl.handle.net/2014/40500

[15] Pullan, D., Sims, M. R., Wright, I. P., Pillinger, C. T., and Trautner, R., "*Beagle 2: The Exobiological Lander of Mars Express*," SP-1240 Mars Express: A European Mission to the Red Planet, ESA Publications Division, ESTEC, Noordwijk, The Netherlands, 2004, pp. 176-178.

[16] Wilson, A., "Mars Express: A European Mission to the Red Planet," SP-1240, ESA Publications Division, ESTEC, Noordwijk, The Netherlands, 2004.

[17] Boldoghy, B., Kummert, J., Varga, T., Szilagyi, I., and Berczi S. Z., "Practical realization of covering lunar buildings for ensure levelled temperature environment," Proceedings of 38th Lunar and Planetary Science Conference, League City, Texas, March 2007 [online database]. URL: http://www.lpi.usra.edu/meetings/lpsc2007/pdf/1380.pdf

[18] Albu-Schaffer, A., Bertleff, W., Rebele, B., Schafer, B., Landzettel, K., and Hirzinger, G., ROKVISS - robotics component verification on ISS current experimental results on parameter identification, *Proceedings of IEEE International Conference on Robotics and Automation*, May 2006, pp. 3879 – 3885.

[19] Hirzinger, G., Butterfass, J., Fischer, M., Grebenstein, M., Haehnle, M., Liu, H., Schäfer, I., and Sporer, N., A Mechatronic Approach to the Design of Light-Weight Arms and Multifingered Hands, *Proceedings of the IEEE International. Conference on Robotics and Automation*, San Francisco, USA, 2000, pp. 46-54.

[20] Rebele, B., Schaefer, B., Albu-Schaeffer, A., Bertleff, W., and Landzettel, K., "Robotic Joints and Contact Dynamics Experiments: Lessons Learned from ROKVISS," Proceedings of the "9th Advanced Space Technologies for Robotics and Automation (ASTRA) Workshop," ESTEC, Noordwijk, The Netherlands, November 2006.

[21] Heiken, G. H., Vaniman, D. T., and French, B. M., Lunar Sourcebook: A User's Guide to the Moon, Cambridge University Press, USA, 1991, pp. 34 – 36.

[22] Tobery, E. W., Pantano, D. R., Dottore, F., Ryes, J., and Creel, R., "Heat Rejection Concepts for Radioisotope Power Systems On the Lunar Surface," 4th International Energy Conversion Engineering Conference and Exhibit (IECEC), AIAA Publication, San Diego, California, 26-29 June 2006.

[23] ESA NEXT Team, "NEXT Lunar Lander with in-situ Science and Mobility: Phase A Mission Study, Lunar Environment Specification," NEXT-LL-LES-ESA (HME)-0001 (1), 20 February 2008, pp.10.

[24] Pantano, D. R., Dottore, F., Tobery, E. W., Geng, S. M., Schreiber, J. G., Palko, J. L., Utilizing Radioisotope Power System Waste Heat for Spacecraft, NASA GRC Report, NASA/TM—2005-213990, Cleveland, Ohio, October 2005 [online database]. URL: http://gltrs.grc.nasa.gov/reports/2005/TM-2005-213990.pdf

[25] D. Bapna, M.C. Martin, and W.L. Whittaker, "Earth-Moon Communication from a Moving Lunar Rover," Proceedings of the 42nd International Instrumentation Symposium, May 1996, pp. 613-622 [online database]. URL: http://www.ri.cmu.edu/pubs/pub_888.html

[26] BAE Systems, "RAD750", Microelectronics Reliability & Qualification Workshop, Manhattan Beach, CA, USA, December 2008 [online database]. URL: http://www.aero.org/conferences/mrqw/2002-papers/A_Burcin.pdf