LUNARES : Lunar Crater Exploration with Heterogeneous Multi Robot Systems

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Abstract

The LUNARES project emulates the retrieval of a scientific sample from a in a robotic mission. The reference of this demonstration scenario is the Shakelton crater at the lunar south pole, where samples of scientific interest are expected in permanently shadowed regions.

For accomplishment of such kind of mission an approach of a heterogeneous robotic team consisting of a wheeled rover, a legged scout as well as a robotic arm mounted on the landing unit was chosen. All robots act as a team to reach the mission goal. To prove the feasibility of the chosen approach, an artificial lunar crater environment has been established to test and demonstrate the capabilities of the robotic systems. Figure 1 depicts the systems in the artificial crater environment. For LUNARES , preexisting robots were used and integrated into a common system control.

A ground control station has been developed considering conditions of a real mission, requiring information of autonomous task execution and remote controlled operations to be displayed for human operators.

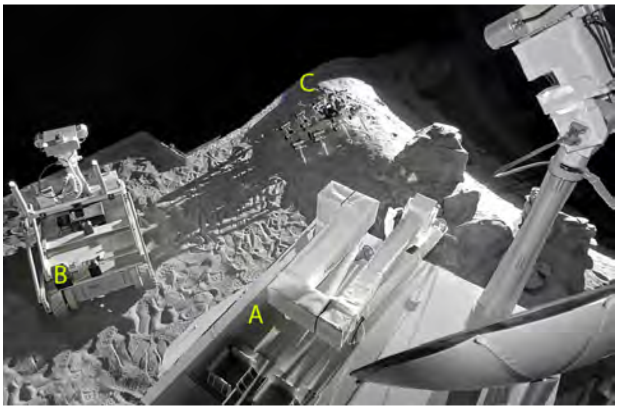


Figure 1. LUNARES systems: Landing unit (A), wheeled rover (B) and legged scout (C) in the artificial crater environment

1 Introduction

Water to be found on Moon would be a crucial requirement for extended human presence on Moon. By splitting up water into hydrogen and oxygen, fuel for spacecrafts as well as oxygen for human habitats might be obtained. Currently, evidence is growing for water ice on the lunar surface. In addition multiple theories try to explain a possible existence of water on the Moon:

J.R. Arnold [1], for example, names four main mechanisms building up deposits of water on the lunar surface: (1) water was brought down to the lunar surface as part of the meteoritic bombardment the Moon is exposed to, (2) hydrogen of the solar wind reacts with lunar oxides and leaves water molecules. (3) Cometary impacts and (4) outgassing of water from the lunar interior are also considered as sources. The latter one is considered to be the least probable source. At the same time, Arnold identifies effects that counteract building up significant deposits of water ice on the Moon. These include for example dissociation of H_2O molecules through photons. This leads to the assumption that deposits of water ice reside, if at all, at permanently shadowed areas of the lunar surface, as already described by Watson, Murray, and Brown in 1961 [23].

Additionally, several satellite missions indicate that regolith-bound water ice can be found in such permanently shadowed craters at both lunar poles: In 1996 the Clementine bistatic radar experiment suggested the presence of water ice at the lunar south pole [17]. Differences in the polarization of radar echoes from permanently shadowed and sunlit areas led to this conclusion. In 1998, measurements from Lunar Prospector implied the presence of hydrogen, possibly in from of water ice at both lunar poles [8].

In November 2009, the LCROSS mission [16] detected water ice in the Cabeus crater at the lunar south pole. In this mission a part of the satellite hit the ground of the permanently shadowed crater, resulting in an ejection of a material plume to be analyzed by the instruments of LCROSS. Additionally by the end of 2009, NASA announced the detection of several hundred tons of water ice at both lunar poles within the MINI-RF experiment that flew with India's Chandrayaan-1 mission [15].

Current satellite missions can detect water only indirectly. For direct detection of water, an in situ sample has to be taken and analyzed. It is clear that such missions will be executed by robotic systems since these missions for exploration of lunar environments operate with lower risk and higher efficiency compared to missions with direct human involvement [3]. Such robotic mission could include taking core samples and might give insight in the history of volatiles brought to Moon by asteroids and meteorites.

Various approaches are proposed to explore lunar craters. These approaches employ different means such as "classical" single rover systems, cooperative robotic systems, tethered systems and new hybrid approaches. Some of the approaches are presented in the following paragraphs.

Barlett et al. [2] intend to use a four wheeled rover with a drilling tower to explore the bottom of dark lunar polar craters. The Scarab rover is designed to be deployed directly in the interior of the crater. The rover will solely operate in dark regions, thus an Radioisotopic Thermoelectric Generator (RTG) for power generation will be used in the flight system. In various experiments Scarab proved to be able to safely overcome terrains with slopes of up to 20° on different soils [24]. The instrumentation is feasible to take 1 m drill cores and to demonstrate the extraction of water from the taken soil sample.

In October 2008 the robot CESAR was the only robot to fulfill all mission objectives of the *Lunar Robotic Challenge (LRC)* hosted by the European Space Agency (ESA). The robot uses a hybrid legged-wheel approach for locomotion in steep crater environments [19]. The objective of the LRC was to send a robotic device into a crater at the Teide Volcano on Tenerife to find and pick up 100 g of colored sand. The sample had to be delivered back to a designated site outside the crater. The challenge simulated missions where the scientific equipment has to reside outside of the crater itself; requiring robots to collect the samples. The robots in the challenge were remotely operated from a simulated ground control station.

With the TRESSA system, Huntsberger et al. [12] employ a team of three rovers to explore hard-to-access terrain. The system comprises a *Cliff-Bot* that is tethered down a slope by two so called *Tether Bots*. The tether bots act as anchors with winches for the tethering system. The cliff bot is equipped with an instrumented arm for scientific experiments to be conducted directly in the slope. The system proved to be able to successfully operate in steep canyon walls with slopes of up to 85°.

In comparison, the LUNARES project aims at a reconfigurable cooperative system of heterogeneous robots to accomplish the task of analyzing material from a permanently shaded region at the lunar south pole [5].

The system consists of three main elements: (1) a landing unit that has to transport all subsystems safely to the lunar surface and provide manipulation support using its robotic arm (2) a wheeled rover to allow locomotion in moderate terrain and to provide an energy efficient vehicle for long distance and (3) a legged scout robot that can advance into the dark areas of a lunar crater and return a sample from the crater bottom. The aim of the project was to provide a proof of concept based on existing technology, i.e. reusing existing robotic systems.

The subsystems involved are described in detail in Section 2. Section 3 gives an overview over the lunar crater testbed, that has been build up as simulation environment to demonstrate and test the feasibility of the approach within the project LUNARES . The demonstration mission conducted in the testbed is presented in Section 4. An overview on the readyness level compared to a real mission is described in Section 5 and finally the conclusion of the project as well as an outlook on following activities is given in Section 6.

2 Systems of the LUNARES Scenario

The following section describes the systems being part of the LUNARES mission. The section is subdivided into a description of the lander mock-up's superstructural parts, namely sensor tower and manipulator arm. Section 2.2 describes the wheeled rover system, which is used for longer distances in moderate terrains. Section 2.3 presents the details of the legged scout system (aka Scorpion). Finally, system and mission control elements of the LUNARES system are discussed in Section 2.4 and Section 2.5, highlighting the required functionality of a ground segment for a real exploration mission.

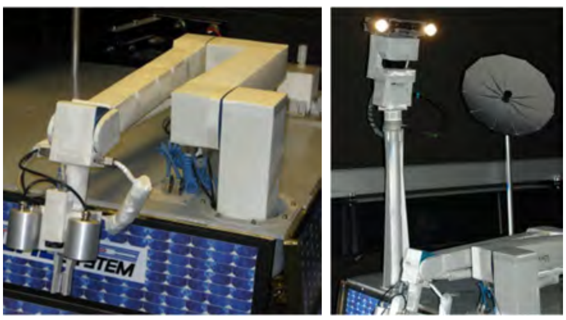
2.1 Landing Unit and Superstructural Parts

The landing unit is represented by a non functional mock-up and serves as mounting platform for the robotic arm and the sensor tower, these components are described in the following paragraphs. However, the design of the lander is inspired by a real landing unit, though in a 1:1.6 scale.

2.1.1 Lander Manipulator

The lander manipulator is a 6 DOF robotic manipulator (Figure 2(a)). The main tasks for the robotic manipulator in the LUNARES reference mission involves the following components:

- reconfiguration of rover by grasping a payload element from the lander and installing it at a special payload bay on the back of the rover.
- recollecting a payload by grasping the payload element from the back of the rover and placement of the element on the lander
- grasping the sample container from the back of the scout which contains the collected lunar sample, and transport of the sample container to the lander



(a) The 6 DOF lander manipulator in its space saving configuration on top of the lander mock-up

(b) The sensor system including a stereo camera, a 3D laser scanner and two spotlights

Figure 2. The lander's superstructural components

2.1.2 Lander Sensor System

The sensor system of the lander (Figure 2(b)) includes a pan-tilt unit which contains a stereo camera system, a laser scanner and spotlight for illumination. By swiveling the laser line over the scene, the reconstruction of static scenes of the environment is performed. The sensor system fulfills several tasks:

1. The stereo camera system provides camera images for the ground control station enabling a visual monitoring of the robotic systems, when the robots are in the vicinity of the lander[1].
2. The pan-tilt unit allows the ground operator to control the viewing direction in order to focus on parts of the scene that are of greater importance for the current task execution.
3. The 2D laser scanner works together with the tilt-unit as an imaging 3D-LIDAR (Light Detection And Ranging), thus providing dense 3D images of the vicinity of the lander, Figure 3. By using the values of remission, the 3D laser scanner can also be used as a convenient 3D feature tracker. For this purpose, retro-reflective markers are attached to the rover which enable an accurate tracking of the rover pose in the neighborhood of the lander (See also Figure 23 in Section 4.4).
4. The spotlight can be used to illuminate the close vicinity of the lander for improved imagery.

2.2 Rover

One of the preconditions of the LUNARES project was to reuse existing robotic systems. Therefore the LUNARES rover is based on an industrial mobile platform which was not designed as a lunar rover. The existing platform was utilized to demonstrate the basic idea of combining two different mobility systems, i.e. a wheeled rover for the coverage of larger distances in moderate terrain and the legged scout for the exploration of shorter distances in more difficult terrain (with more obstacles and terrain inclination). Nevertheless, the existing mobile platform had to be adapted to fit the demonstration requirements: (1) carry an additional payload (i.e. a lifting mechanism for the scout and the scout itself) of approximately 20 kg mass (14 kg for the scout and 6 kg for the lifting mechanism), (2) operate in very dusty terrain and (3) negotiate inclinations of about 15°.

[1]Up to now, the operator at ground control only receives monoscopic cameras. However, for future enhancement of the system a visual control through a stereoscopic display is possible

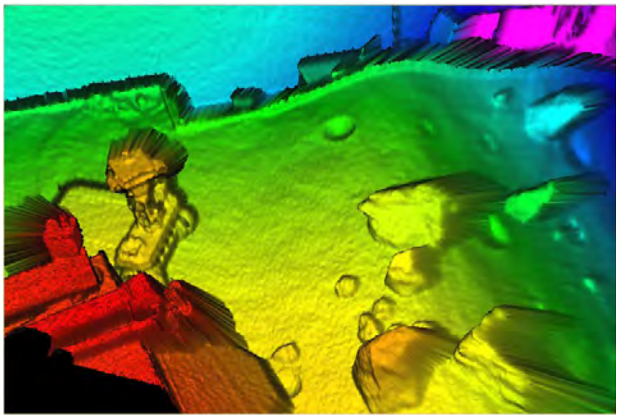


Figure 3. Scan data provided by the 3D laser scanner showing parts of the lander (red, lower left corner), the rover in front of the lander, and parts of the crater rim (right half of the picture).

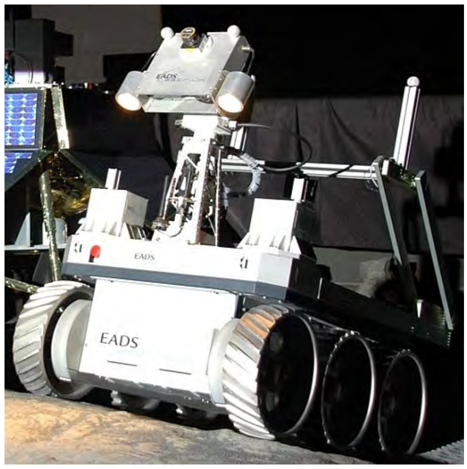


Figure 4. Image of the LUNARES rover reaching the crater rim and looking into the crater where the scout is working.

This resulted mainly in modifications to the traction systems, which are actually still not applicable for a real lunar mission. Figure 4 shows the modified LUNARES rover.

For intelligent and cooperative behaviour, the rover was equipped with an additional processing unit and additional sensors. The sensor system of the rover comprises a sensor head including a stereoscopic camera system and a laser scanner. The sensor head is mounted on a pan-tilt unit. Additionally, an inclination sensor allows to detect hazards resulting from too large ground inclinations. To support the self-localization of the rover an Inertial Measurement Unit (IMU) including an accelerometer and a gyro based on Micro-Electro-Mechanical-System (MEMS) technology were added.

The pan-tilt unit enables the control of the viewing direction of the camera system as well as the usage of the 2D laserscanner as an imaging 3D LIDAR. The data of the laser scanner are mainly used for reactive obstacle avoidance and sensor data driven emergency stops.

The camera serves two purposes: (1) It allows the monitoring of the operation via the ground control station. (2) It is required for the autonomous docking behaviour between rover and scout. This is discussed in more detail in Section 4.4.

Rover Control

The rover is one of four robotic subsystems in the LUNARES system architecture is embedded into the system control which will be described in Section 2.4.

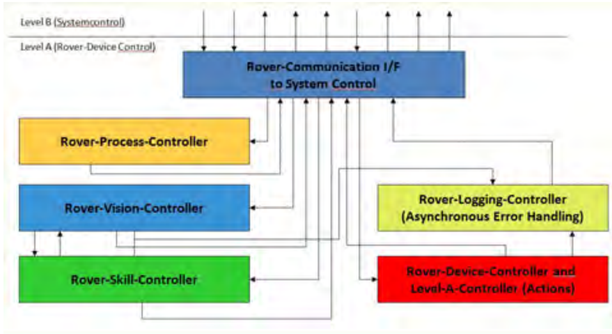


Figure 5. Control system of the rover hosted on the rover on-board computer.

The structure of the rover specific control is depicted in Figure 5. The rover is controlled by five components:

1. The rover device controller (level A controller) controls the H/W of the rover, the movements, reactive emergency behaviors, spline-interpolation, trajectory generation, the pan-tilt unit and the data acquisition of the 3D imaging LIDAR.

2. The rover skill controller is a scheduler that controls the execution of skills such as the autonomous scout-docking behavior depending on the specific tasks.

3. The rover vision controller acquires image data from the stereo camera system and distributes these data via WLAN.

Figure 6. Cubic splines and circle segments are used to generate more complex trajectories for the rover

4. The rover process controller starts and stops all processes of the rover's on-board computer and performs a health check of all components of the rover.

5. The logging controller of the rover records all incoming and outgoing messages and generates an asynchronous error signal to the higher levels of the system control in case of severe error signals from one of the components of the rover control.

6. The rover communication interface provides a central interface program to the higher levels of the system control.

Rover Motion Planning

The level A controller of the rover provides different types to control it's motion, i.e. velocity control (left and right wheels control, jog-rate etc.), control of certain distances at defined velocities, as well as more complex trajectories which can be assembled from simpler trajectory parts. Possible parts can be segments of circles as well as cubic splines which reach a certain point with given heading direction (Figure 6).

The general concept of motion planning of the rover consists of three main steps:

- Depending on the task a trajectory is planned, either automatically as it is the case during the automatic docking to the lander mockup, or controlled by the operator from ground.

- The trajectory is transferred to the controller which commands the motion system and the specific velocities for the left and right wheel system (differential drive).

- During the motion execution the motion is monitored via the odometry system which estimates a rough information of the position and heading direction of the rover.

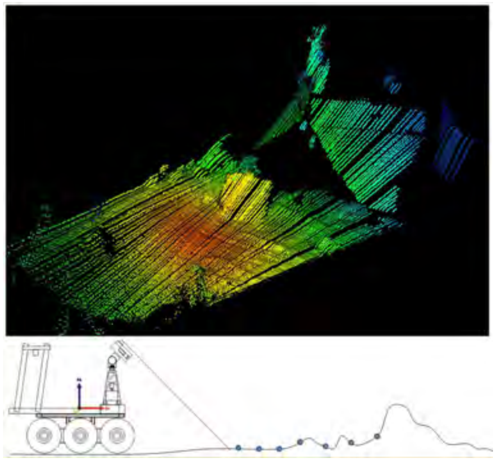


Figure 7. Collecting several laser scans while driving and combining these scans to a 3D reconstruction using the rover's odometry provides enough information in order to assess the terrain.

In the vicinity of the lander, the estimation of the rover position and heading direction is supported by the 3D laser scanner of the lander system which estimates the rover pose from retro-reflective markers. Sensor data is processed and monitored to apply a reactive emergency behavior that stops the rover. Potential reasons for an emergency stop are:

- Loss of WLAN connection checked by continuous pinging the system control at the lander.

- Obstacles in front of the rover detected by the laserscanner.

- Too large inclination indicating the start of a crater rim or any other obstacle which has not been not detected by the laserscanner.

The reactive emergency stop-behavior gathers range information from the 3D laser scanner and assembles a rough estimation of the terrain in front of the rover using the self-localization resulting from the rover odometry. The 3D data allows to extract information whether there is an obstacle, a hill or the beginning of a hole (e.g. a crater). This principle is shown in Figure 7.

The ground control station (Section 2.5) provides different methods for monitoring and control the rover. A mission involving the rover contains automatic tasks and interactive tasks which are monitored or even solved by the operators. The LUNARES system does not include autonomous path planning and obstacle avoidance with trajectory replanning. In-

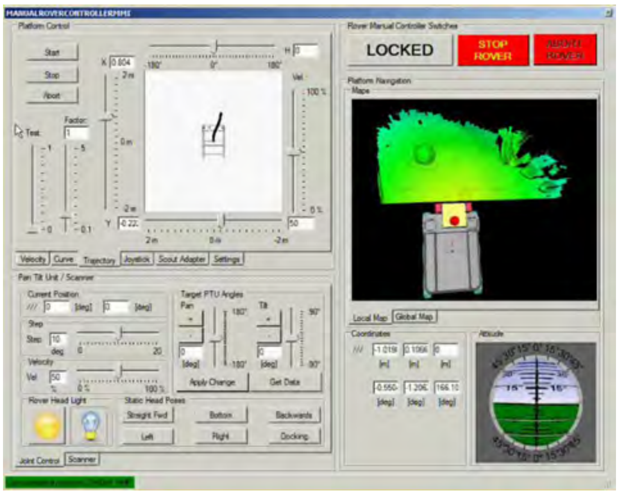


Figure 8. MMI at the ground control station dedicated to rover. The MMI provides monitoring (e.g. artificial horizon, lower right) and trajectory planning (white area, top left). The window in the top right area shows the acquired 3D-data from a scan while not driving. The planned trajectory can be applied to the simulated rover in the 3D scan image.

stead, for safety issues, every movement of the rover is preceded by the acquisition of a 3D range image.

This image supplies the ground operators with a good impression of the near terrain and is used to plan a small trajectory which does not exceed 1.5 m (Figure 8). This movement can be simulated on ground and finally send to the flight system which executes the planned trajectory. Unforeseen hazards can still be avoided by the emergency system of the rover.

2.3 Scout

The Scorpion robot [13, 14] serves as legged scout in the LUNARES mission. Scorpion is an eight-legged biomimetic walking robot. Each of its legs has three active DOF and one passive DOF in the lower leg. The locomotion control employs the biological inspired pattern generator and reflexes for efficient locomotion. The following paragraphs describe the modifications that have been executed in order to adapt the existing robot Scorpion for the LUNARES scenario. Figure 9 shows the Scorpion as fully equipped LUNARES -scout.

Scout's Basic Locomotion Principle

The scout's locomotion is controlled by a microprocessor running a micro-kernel for behavior-based control of robots [20]. The higher behavioral levels are executed on an embedded PC separately. This principle of separation is biological inspired: Human or animal locomotion and reflexes are produced in the spinal cord, whereas higher level understanding is located in the brain. In case of the Scorpion the microprocessor replaces the spinal cord and the higher level behaviors are executed on the PC system.

Beside real-time capabilities and reflexes, the micro-kernel also offers an inverse kinematics layer which is used to describe the scout's rhythmic movement patterns in Cartesian coordinates.

This inverse kinematics layer is important for the climbing task of the robot, because it prevents the feet from slipping due to a reduction of tension between the legs while walking.

The micro-kernel allows to write multiple inputs to single hardware drivers using different merging functions, e.g. the normal posture of the robot is written to the joints, the walking itself is defined as offsets to this position. The micro-kernel merges both values by adding and relays the value to the inverse kinematic resulting into the final control values for the joints.

Due to this approach an automatic merging of walking patterns is possible. Thus, forward- and sideward-walking can be combined to a diagonal walking pattern. The posture (e.g. body height, lean forward, tilt angle, etc.) can be set independently from walking patterns.

The representation of the movements allows to modify the walking speed by changing the frequency of the curve and to modify the step height by changing the amplitude.

Reflexes for Secure Locomotion

In order to enable a secure locomotion in crater slope of up to 35°, several reflexes had to be implemented or adapted. Already existing reflexes were the *hole reflex* and *stumbling correction*, additionally a *ridge reflex* and a *balance reflex* were introduced specially for the locomotion in steep environments with obstacles.

The *hole reflex* is triggered when, due to the state of the walking behavior, ground contact of a foot is expected but not measured by the linear potentiometer in the spring-damped lower leg (passive DOF). As a result the reflex stretches the leg until ground contact is measured. The "opposite" reflex is the *ridge reflex*: This reflex is triggered, when in touchdown phase of the leg ground contact is sensed before it is expected. In this case the reflex inhibits further stretching of the leg in order to keep the body of the robot in level.

The *stumbling correction reflex* is triggered when a leg is stuck in swing phase. To detect this, the

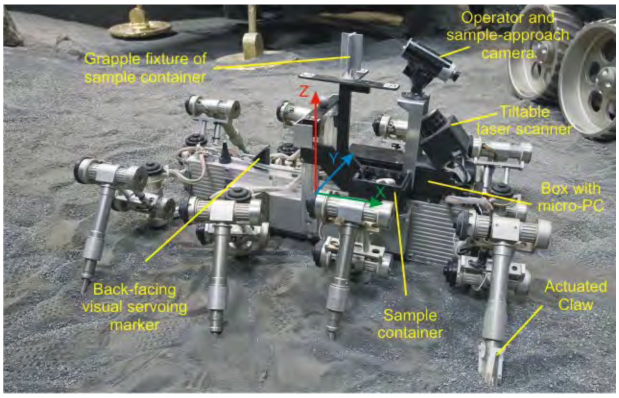


Figure 9. Scorpion robot: Scout system for LUNARES . One of the eight legs is equipped with a gripper for sample pick up. The sample container with a grapple fixture for the lander's arm is mounted on the scout's back. Main sensors are an operator camera, also used for automatic sample approach and a tiltable laser scanner.

currents of the thorax joint are measured and compared with a threshold. If the current raises above the threshold, the basal and distal joints are moved reflex-like in order to lift the foot over the obstacle, i.e. the foot swings with a much higher amplitude over the obstacle like when using the regular gait pattern. A second indication to trigger this reflex is the difference of actual position and desired position of the foot.

The *balance reflex* shifts the body accordingly to the slope of the terrain in order to keep the load as equally distributed on all legs as possible.

Reusing a Leg as Manipulator

The complex system of an walking robot can increase its advantages with the adaption of an functional element on the footprint. With this element, e.g. grabber or sensor, the legs of the system can perform as a manipulator or sensor arm. Furthermore, a robots gripping device can support locomotion, when used to increase the footprint of the robot.

For the LUNARES scenario, the Scorpion is equipped with a gripper. The main function of this device is to collect probes on the ground and to place them in a container on the robot. More information on the gripping device is provided in [5].

Autonomy Framework for the Scout

The Scorpion's task requirements within the scenario exceeded the existing online processing capability of the Scorpion. To handle this issue, a software framework was introduced. This framework provided the communication infrastructure to remotely control the Scorpion and eventually allowed the introduction of high level action commands such as "collect sample" - a command which is executed after the position of this sample was determined (described in Section 4.5).

This framework also allowed the distribution of software on different processing units such as workstations or embedded PCs, and also allowed for conducting simulation experiments with "hardware in the loop", e.g. using the real sensors of the robot for a obstacle detection task, while controlling the robots in simulation.

Additional Sensors

In order to fulfill the task of detecting a sample autonomously as described in Section 4.5, the scout has been equipped with a laser scanner. Since the laser scanner was added to the existing robot in the project, a compact additional module has been designed, consisting of controller electronics, a power converter, a digital servo motor and the laser scanner itself.

The controller is executed on a microcomputer with a Linux operating system and uses wireless communication to connect to the mission control station. This enables the controller to be embedded into the control station and communicate within the autonomy framework (see Section 2.3).

The pan-tilt laser scanner unit is controlled by a high level software module, which collects the information of the laser scanner and constructs a height map. This map is then used for localization of samples (see Section 4.5). Similarly, the camera output is processed by another high level software module, which controls the approach of the scout (see Section 4.5).

2.4 System Control

The control of the systems is based on the Functional Reference Model (FRM) defined by the European Space Agency (ESA) [22, 9]. FRM divides autonomous robot control into three layers:

- Mission Layer (Level C)
- Task Layer (Level B)
- Action Layer (Level A)

In case of LUNARES , the Action Layer defines basic actions like movements or gripping. The Task Layer is responsible for sequences of actions and defines tasks like "go to the next position while avoiding obstacles" or "deliver sample". The Mission Layer is responsible for the overall mission execution. It de-

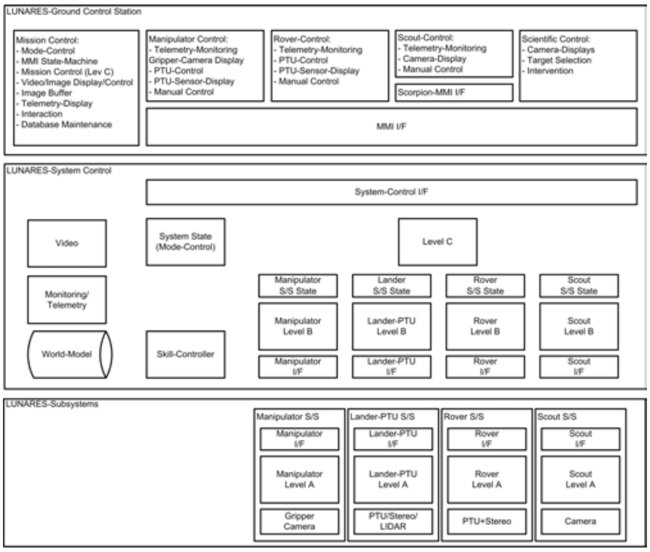


Figure 10. Overview of the LUNARES control architecture: Bottom: Subsystem control with all level A controllers of rover, scout, lander, and manipulator. Middle: System control with level B and C, and other support functions like monitoring, telemetry, vision server, world model, and skill controller. Top: LUNARES ground control distributed over several workstations.

fines which task is executed when and how to handle dependencies of tasks between all robots. Due to this approach the Level B and C Controllers can make use of the existing Level A Controllers.

Also the three main columns of information flow (forward control, nominal feedback, non-nominal feedback) typical for the FRM [22] have been implemented for the LUNARES control system. The first column is the feed forward control which sends commands from the top (mission level) via level B to the bottom (action level close to the robotic hardware).

The second column of the FRM is the nominal feedback channel which is implemented as a synchronous communication channel where nominal responses to the commands of the feed forward command channel are send and evaluated. Normally, this channel serves to acknowledge simple commands, or to generate errors. In case of an error generated by a lower level, the next higher level has to react on that error, or in case of no possible error recovery, the error has to be reported to the next higher level.

In addition, the FRM foresees a third column which is called the non-nominal feedback channel. On that channel, asynchronous error messages can be generated, which are reported from a lower level to the next higher level. Again, the next higher level can try to recover from the problem if possible. This channel is the most complicated due to its asynchronous character.

For the LUNARES system control, this has been solved by a simple error handling mechanism so far and should be enhanced in the future. Besides the three control levels, the LUNARES system control also contains a global state machine which controls different operating modes and error states of the system. The overall mode controller comprises vector states which contain component states for every subsystem. This allows an error handling for single subsystems whereas other subsystems operate in nominal automatic or manual operating mode.

Furthermore, the system control contains a world model database, a skill controller which provides a library of higher skills (such as cognitive skills for grasping or docking) and a monitoring controller which gathers telemetry information from the system itself and all connected subsystems, i. e. the different robots. The telemetry data is permanently analyzed and is used to throw asynchronous error messages. A vision server collects all video and image related data and provides a central service for all other skills and functions that need these type of data. Figure 10 depicts the main components of the system architecture.

The Level B Controller (i.e. task controller), applies a PHP script interpreter. So every task is coded as a small PHP snippet of code. Via network communication these scripts call actions of the level A controller and skills of the skill controller. On this control level, most of the data representations are symbolic, like "move to payload-bay". By accessing the world model database from the task script, the Level B controller resolves the symbolic data and obtains the corresponding numeric data. This type of data is then send to the Level A, which normally understands numeric data and parameters only.

2.5 Ground Control Station

The benefit of robotic missions is the ability to achieve various mission objectives within the same mission based on a mission specific set of programmable robots and payloads. The LUNARES mission foresees for instance to retrieve samples from a crater relying on a heterogeneous robotic team including the remote system control and a ground control station. The Ground Control Station (GCS) has to support the LUNARES mission activities at different levels: (1) generate the mission database and the associated mission tasks, (2) edit and verify the mission timeline, (3) execute the mission timeline in a supervised autonomy mode, (4) direct control of all the subsystems. These features are not specific to the LUNARES mission but can be found for a wide variety of robotic missions. The LUNARES GCS integrates these requirements and has been used within the experiments to prepare the missions and to execute automatically the mission timelines including manual recovery actions.

2.6 Operational Concept

Using state-of-the-art robotic systems for mobility and manipulation, only a low level of autonomy can be expected, especially in an unstructured environment like the moon. The knowledge about the mission and their subsystems has then to be shared among the elements of the whole system including the operators:

1. Complex operations which cannot be performed autonomously by the robots are coded in the Level B Tasks of the system control
2. Complex operations which can be performed autonomously by the robot are coded in the Level A actions of the system control as well as simple operations
3. The generation of the mission structure leading to the timeline (Level C Timeline) which necessitates reasoning capabilities is performed by the operator
4. Mission execution which requests as well analysis capabilities is supervised by the operator. The operational concept is based on the supervised autonomy which shall involve the operator in all critical phases of the mission.

In order to improve the safety and the reliability of the mission, the operator shall be able to manage the system from full automatic (automatic execution of the timeline) to full manual (direct commanding of all the subsystems including the sensors). In case of errors and contingencies, or for complex operations beyond routine activities, the operator shall be able to stop the mission, to operate manually the faulty subsystem, and to resume the mission.

The GCS shall also be user friendly in order to reduce the training effort and to increase the operational safety. The primary operation of the Man Maschine-Interface (MMI) consists of selecting an operational mode or context (i.e. Standby, Automatic, Manual) with the mode controller in which the modes and their transitions are represented as a finite state machine. The accessibility of the commanding tools (i.e. manual controller or vision server) or part of them is set according to the operational modes.

As the LUNARES mission involves several robots that could operate in parallel the mission responsibilities are shared among several operators: (1) mission director for supervising and monitoring the mission state and delegating activities to the Mission Operators, (2) mission operators for commanding directly the robots in specific mission phases. The ground control station has then the capability to involve several operators in a coordinated way for monitoring and commanding a mission.

2.7 Functions

The operational functionality consists of standard system status telemetry (TM) monitoring and the remote manual commanding of the subsystems (TC). To interact with the environment the operator can command the subsystems from the GUIs.

Each robotic and sensor subsystem has a dedicated GUI to configure and command that subsystem. The remote operator can obtain situational awareness of the worksite environment by viewing images from the head cameras of the rover, the scout and the lander. The mission preparation steps and the mission configuration, planning and execution are performed via dedicated GUI interfaces.

2.8 Architecture

The control station architecture applies the Thin Client Three Tier (TCTT) architecture model (Figure 11). In this architecture the three levels *User Interface*, *Domain Application* and *Data Access* are strictly separated (Three Tier). According to the selected TCTT architecture model, the implementation of each function is split into a kernel application and a GUI unit.

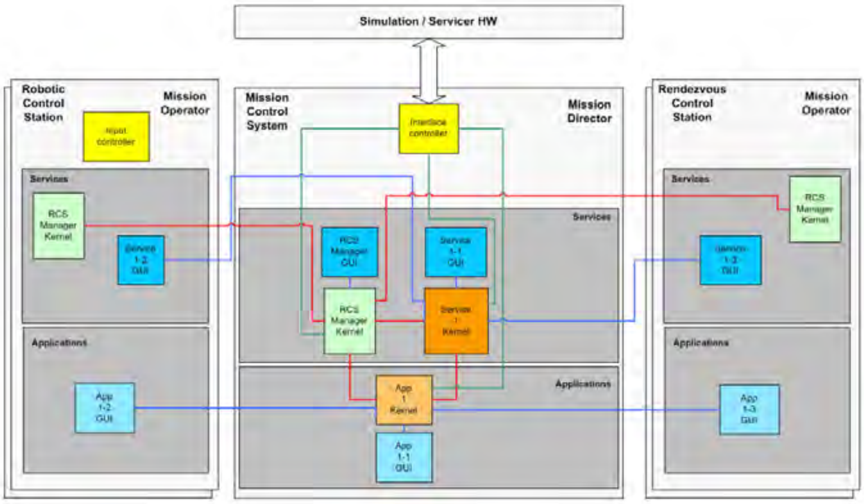


Figure 11. Basic Architecture of the robotic Ground Control Station

The kernel application runs the main processing related to the function while the GUI unit enables the GUI-based commanding of the kernel application. The GUI units are not linked to each other but only with their dedicated kernel application. In addition the kernel and GUI applications are shared between the core applications which manage the basic functionalities and the robot applications which directly depend on the robot. While the core applications are robot independent or fully configurable, the robot applications are either partially configurable or need a re-design according to the robot needs.

The communication between the kernel applications as well as between the kernel and the GUI applications rely on the design patterns (i.e. observer and mediator patterns). In order to reach the multi-operator capability the GUI of the subsystems to be commanded by additional operators are started on a parallel control station and linked to their kernel application, while the kernel application remains on the central control station of the mission director.

2.9 Configurability

The control station provides a variety of configuration files for the definition of the environment, mode control and mode transition, telemetry, and commanding. Robot commands are specified as macros in an Excel sheet. The assembly of binary telemetry streams coming from the system control is defined via another Excel sheet. The sheet holds information about subsystem, name, position, type, length, and monitoring values (warning and error minimum and maximum limits). The mission database (access file) contains the path definitions of the manipulator and the rover, intermediate points used in the Level B tasks, as well as the position of objects (i.e. payloads) on the subsystems (i.e. lander, rover).

Figure 12. MMI environment with the Mission Controller (left) and the camera controller of the Head and the Manipulator (right). Error and warning messages are displayed in upper part of MMI, status messages are displayed at the bottom, the upper right provides commanding tools to be opened in the central workspace.

2.10 MMI environment

The main MMI consists of fixed areas split around the screen (Figure 12). (1) error and warning messages, (2) status message, (3) commanding tools, (4) monitoring, (5) workspace in the center where the commanding tools can be opened and used. The commanding tools are selectable according to the current

Figure 13. Ground Control Station in a multi-operator configuration. Above the monitors the related subsystems are pasted into the photograph.

mode of the control station, so the operator can only select context specific operations. This allows to ease the utilization of the MMI and to increase the operational safety. So, different workspaces can be configured for the different mission phases like planning, monitoring, or commanding of a subsystem.

In multi-operator mode the ground control station is started on two computers allowing a parallel monitoring and commanding of the LUNARES application scenario (see Figure 13). The MMI environment is the same for both control stations. The *Director MMI* has full functionality over the robotic system and can distribute rights to the operators of the subsystems. The *Operator MMI* is configured according to the role assigned by the director, so the operator has only access to the commanding tools of the subsystem he is in charge of.

3 Test Environment and Test Equipment

The scenery for experiments conducted in LUNARES is an artificial lunar crater environment called *Space Testbed* (STB). The STB simulates the conditions at lunar polar regions. The surface of the STB consists of hard rocks with gray basalt chips as regolith substitute including stones and small craters. The STB provides slopes between 30° and 45° (Figure 14).

In addition, a lighting system is installed which is able to create very bright areas (14500 lux at 10 m/12^o per spotlight) at the crater rim as well as complete darkness in the interior of the crater in order to simulate the lighting conditions at the lunar polar regions.

A visitor platform is installed allowing to spectate the experiments and demonstrations. The control center is located below the crater. Thus, the operators have to depend on sensor data from the systems for control and supervision, resulting in a situation similar to real mission scenarios.

The STB is equipped with supervision tools to acquire experiment data for evaluation of the systems under test. To collect, archive, and synchronize the experiment data and to control the cameras a software is implemented called STB-Control. The test equipment is controlled automatically in order to support the operators. The equipment comprises

- a Motion Tracking System (MTS),
- two Pan-Tilt-Zoom (PTZ) cameras,
- a fixed observation camera,
- and a gantry crane equipped with an observation camera and a tracking camera.

The following paragraphs provide a rough overview of the automatic surveillance system, [7] offers more detailed information.

3.1 Automatic Supervision Using Pan-Tilt-Zoom Cameras and a Motion Tracking System

Besides position determination of the scout in the slope, the MTS is used to automatically focus the PTZ cameras on the robot under test. Therefor, the position of a reflective marker fit to the robot is tracked by the MTS and its position is used to align the cameras. The continuous video material from different points of view including a constant bird's eye view (Section 3.2), combined with the recorded trajectory helps to improve locomotion in the slope by discovering malfunctions and improving walking behaviors.

The camera alignment is realized by a camera calibration using the known position of the reflective markers and their position in the camera image. Thus, the extrinsic parameters describing the position and orientation of the camera in the coordinate system of the MTS (WCS) can be calculated and can be used to transfer the positions of the markers into the camera coordinate system (CCS). The following sections describe the algorithm used to detect the markers within the camera image, the CMA-ES optimization [11] of the extrinsic parameters and the final camera alignment on the markers in the CCS which have been realized by a spherical coordinate transformation.

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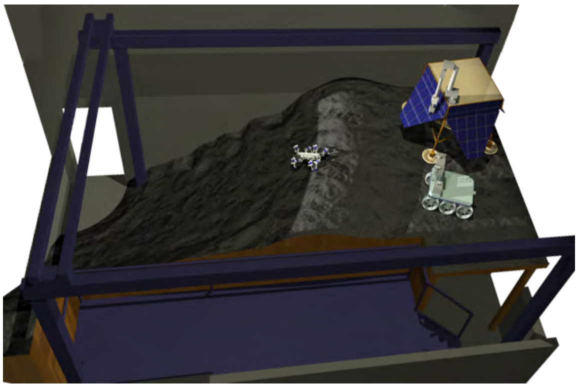


(a) CAD-model of STB, including landing unit, rover and legged scout.

(b) Panoramic view from within the crater. The picture is stitched from several single shots.

Figure 14. Space Testbed (STB): CAD-model and view from interior. The main slope is 30° to 35°, the environment additionally provides a slope of 45° (special area in lower left corner of CAD-picture)

system of the MTS (WCS) can be calculated and can be used to transfer the positions of the markers into the camera coordinate system (CCS).

The following sections describe the algorithm used to detect the markers within the camera image, the CMA-ES-optimization [11] of the extrinsic parameters and the final camera alignment on the markers in the CCS which have been realized by a spherical coordinate transformation.

Detection Algorithm

The camera calibration requires a reliable detection of the markers used by the MTS. Therefore, the cameras are equipped with infrared emitters and the infrared cut filters of the cameras are switched off. The detection algorithm uses a run-length encoding algorithm to build horizontal intervals of pixels, whose brightness reaches a certain threshold, and an union-find algorithm to connect the intervals to regions [10]. The detection algorithm allows the collection of passpoints which consist of a marker position in the WCS and its corresponding pixel in the camera image. These passpoints are used during the optimization to rate the different camera positions.

Optimization of the extrinsic parameters

The CMA-ES optimization uses a camera calibration function containing the intrinsic parameters of the camera, which have been extracted from the data sheet, and the six extrinsic parameters describing the position and orientation of the camera in the WCS.

Each camera pose is rated by transferring the 3D point of the collected passpoints into the camera image and compares the calculated image coordinates with the desired ones. Thus a set of extrinsic parameters is rated by the average deviation over all passpoints in pixel-related units. If rough start parameters are supplied, a deviation of 6.79 to 7.84 pixel is achieved (Figure 15(a) and Figure 15(b)). This fitness value can be further improved by optimizing the algorithm which is responsible for the passpoint collection.

Camera Alignment

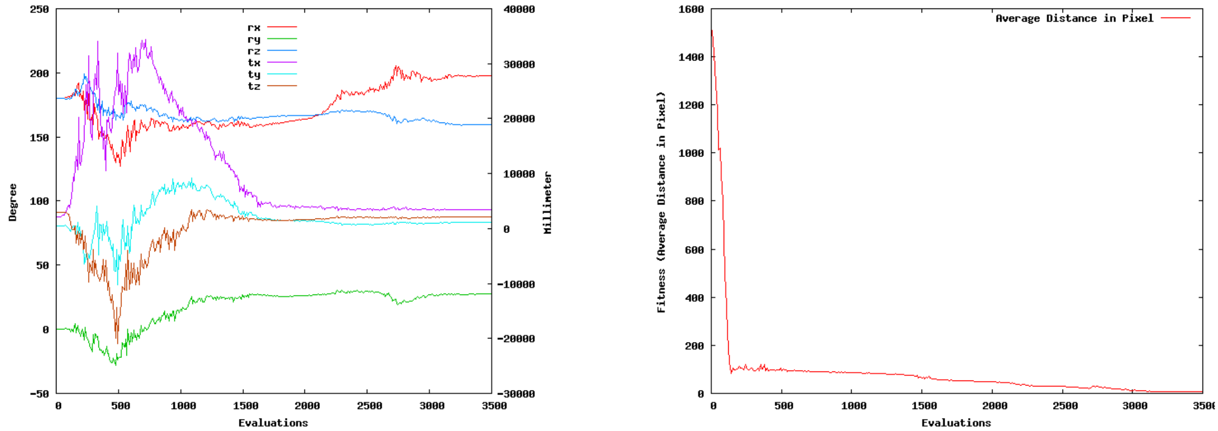
To focus each camera on a 3D point within its coordinate system, modified spherical coordinates are used. Mapping function (2) restricts the tilt angle ϑ to $[-90, 90]$ and the pan angle φ to $[-179, 180]$ using the right-handed coordinate system shown in Figure 16. Together with the calculated camera pose this mapping function allows a fast, calculation cost-effective and accurate alignment on each marker-equipped robotic system within the STB.

$$
\begin{aligned}
\vartheta &= -\arctan\frac{z}{\sqrt{x^2+y^2}} && -90^\circ \leq \vartheta \leq 90^\circ \\
\varphi &= \begin{cases} \arccos\frac{x}{\sqrt{x^2+y^2}} & y \geq 0 \\ -\arccos\frac{x}{\sqrt{x^2+y^2}} & y < 0 \end{cases} && -180^\circ < \varphi \leq 180^\circ
\end{aligned}
\tag{1}
$$

with $x^2 + y^2 \neq 0$

3.2 Automatic Robot Tracing using a Gantry Crane

The gantry crane's purpose is to autonomously trace the scout during movements in the slope in order to



(a) Optimization of the extrinsic parameters

(b) Fitness optimization from a distance of 1509.54 to 6.79 pixel (4446 evaluations in 0.08 seconds)

Figure 15. Optimization of the extrinsic parameters using CMA-ES and camera coordinate systems

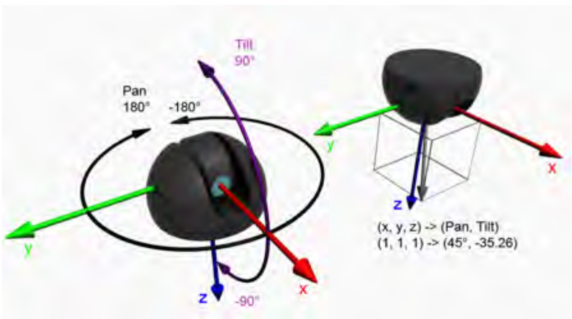


Figure 16. Coordinate system of the PTZ cameras in standing and hanging orientation, direction of rotation, and an example mapping on point (1,1,1)

maintain a constant top view. In LUNARES , the crane is used only for documentation, but in later projects it can be used to provide a simple simulation of lower gravity for the robot by using a counterweight and deflection rollers. Therefor, it is crucial for the gantry crane to reside over the robot all the time, even when the robot is moving. A tracking camera is utilized to capture the infrared light reflected from a retro-reflective marker on the robot and emitted from an IR source, mounted next to the camera.

The detection algorithm (Section 3.1) is used to determine the marker position in the tracking camera image. The center position of the marker has to be kept on a constant reference position in the image in order to automatically trace the robot. Since the gantry crane needs absolute desired positions as control input, a transformation from image to world coordinates is necessary.

If the actual position of the robot is used directly for the new desired position of the gantry crane, an error would remain, which is proportional to the speed of the robot. This is due to the time the gantry crane needs to reach the desired position, while the traced robot is still moving. For this reason, the velocity of the robot has to be taken into account. The velocity is calculated using the actual position and the last known position as well as the time between measurements which is defined by the control frequency of the gantry crane. A constant speed between two measurements is assumed.

However, the gantry crane is not designed for realtime interactions. The control frequency is limited to 4 Hz and a delay between command and action of around 0.5 s can be observed. In order to cope with uncertainties and to realize a smooth tracing, a particle filter similar to [21] is used.

The algorithm uses a linear perceptual model. This improves the dynamic behavior compared to a Gaussian weighting. Afterwards, a resampling step filters out poor predictions and draws new ones. The motion model uses the actual velocity added with Gaussian noise and position to move each particle. The new desired position results from the average of all particle positions.

4 Sample Retrieval from a Permanently Shadowed Lunar Crater

In this section, a reference mission for the LUNARES scenario is presented, then the steps of the LUNARES demonstration mission are described. Additionally, three key elements of the mission are described in detail: Section 4.3 displays the exchange of rover's payloads and the handling of the sample container through the lander's manipulator arm. Section 4.4 demonstrates the autonomous docking of rover to lander and scout to rover. Finally, Section 4.5 shows how the sample pick up in the crater bottom is accomplished.

4.1 Reference Mission

The choice of a lunar mission, which is used as reference for the system of LUNARES and its successors, is established with the help of the following selection criteria (ordered by importance):

1. Maximum scientific payload possible
2. Realisation of the mission in a realistic time frame
3. Visionary character, specifically the inventiveness level
4. Public Outreach Value

Some robotic missions which are in the long term planning (e.g. the ones that are necessary for the build up of a lunar infrastructure for a permanent lunar base), are seen as non-realistic in the near future and from the standpoint of science they are seen as unattractive. Because of this, missions which are orientated around "hot" scientific topics are given the priority. The mission objectives of this narrowed choice of missions are:

1. Deployment of a Geophysical Environment Package (GEP) with seismometers and thermal flux-sensor.
2. In-Situ analysis of soil samples or sample return to a central measurement station (e.g. Geo-Chronology, interstellar particles in the lunar regolith)
3. Sample-return mission for samples from the landing zone (Measurement station on the Lander or with a sample-return module)
4. Radio telescope, more specifically an antenna array for radio science
5. Measurements in the earth magnetic field tail
6. Astro-habitat with biological experiments in a radiation environment

From this list, mission 2 was chosen. In addition, the possibility for a sample-return mission was investigated. As destination for the mission, the rim of the Shackleton Crater has been chosen (Figure 17).

The mission profile foresees that a wheeled rover drives to the rim and deploys a walking robot. After this the walking robot descents into the crater and takes a sample in the shadowed area, which it takes back to the wheeled rover. After this, the walking robot is merged with the wheeled rover again and the combination drives back to the lander. After arrival, the lander's robotic arm takes the soil sample and places it in the central analysis unit or in the sample-return vehicle.

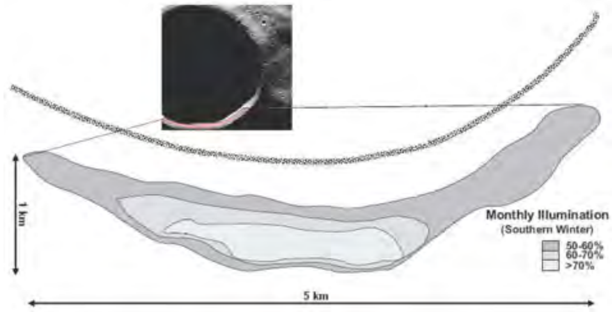


Figure 17. Illumination Characteristics at the Shackleton Crater Rim, picture taken from [4].

4.2 LUNARES Demonstration Mission

Figure 18 illustrates the demonstration scenario in eight subsequent steps. The following paragraphs give a more detailed description of each step, and thus provide a detailed summary of the complete LUNARES demonstration scenario.

Starting Position

The landing procedure on the surface of the moon is not part of the LUNARES demonstration. Also, due to space limitations, the rover egress is not addressed. Instead, the demonstration scenario starts after the rover has been deployed on the lunar surface. For the demonstration the rover is in view distance to the landing unit simulating the arrival of the rover from another mission part in order to be reconfigured for the next part. Figure 18(a) shows the start configuration.

Rover Docks to Landing Unit

The rover has to be equipped with payloads from the lander. For that purpose the docking procedure between lander and rover has to be initiated. Initially, the lander extracts the rover's relative position and generates a trajectory for the rover. Then, the lander leads the rover into the workspace of the lander's manipulator to allow for payload exchange, see Section 4.4 for more details.

Payload Exchange on the Rover

After reaching the workspace of the lander's manipulator, the rover is equipped with a payload (P/L)

(Figure 18(b)). The P/L is picked from the lander and placed into a designated payload bay of the rover (Section 4.3). The payloads used in the demonstration scenario are mock-ups representing scientific instruments in a real mission. By equipping the rover with different payloads, it is possible to configure the system for the current mission at hand.

Movement of Rover and Scout to the Crater Rim

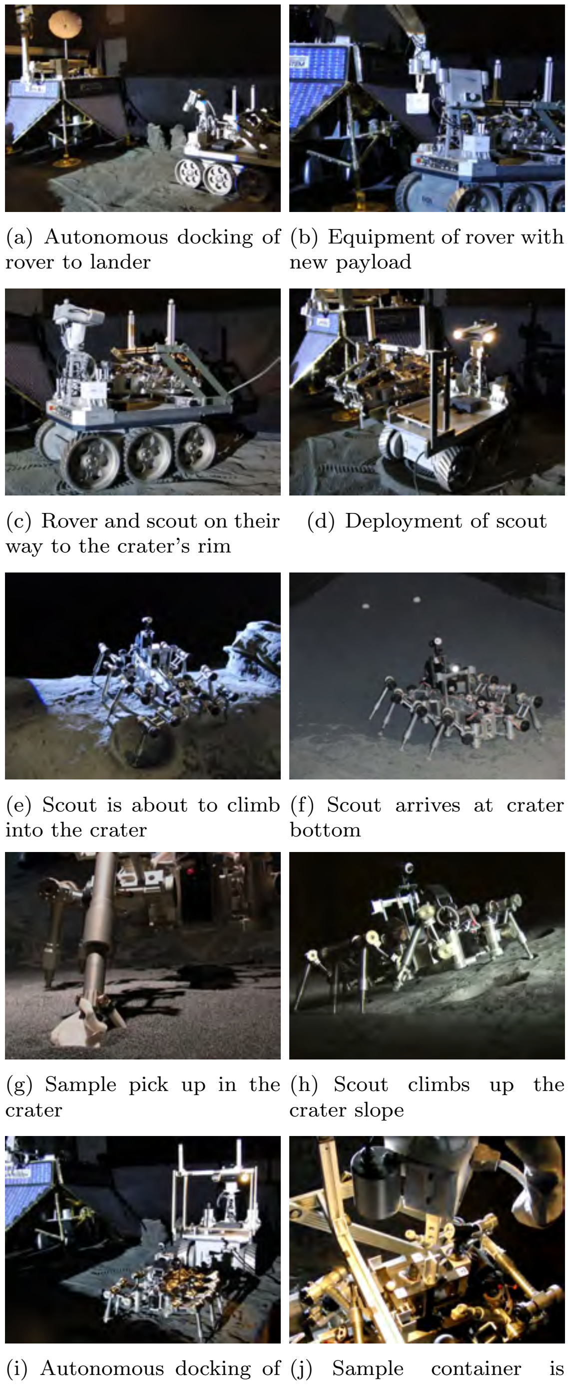
When the rover is equipped with a new P/L, rover and docked scout drive towards the crater rim. In principle, the rover is able to negotiate moderately rough terrain and can travel longer distances in an energy efficient way compared with the legged scout. However, due to space constraints in the LUNARES mission the distance to be covered by the rover is limited to several meters. Figure 18(c) illustrates rover and scout collectively driving towards the crater's rim.

Undocking of Scout and Rover

Once the unit consisting of rover and scout arrived at the crater rim, the scout undocks from the rover (Figure 18(d)). The docking adapter allows the scout's deployment onto the surface. The process of detaching the scout from the rover is described in Section 4.4.

Scout Descends into Crater

After the undocking, the scout has to overcome the crater rim (Figure 18(e)) and enter the dark interior of the crater. To arrive at the crater bottom the scout has to safely climb down the crater slope which is covered with small rocks and small impact craters. In the LUNARES mission the movements of the scout in the crater slope are remotely controlled by an operator, using the camera which is mounted on top of the scout.



(a) Autonomous docking of rover to lander
(b) Equipment of rover with new payload
(c) Rover and scout on their way to the crater's rim
(d) Deployment of scout
(e) Scout is about to climb into the crater
(f) Scout arrives at crater bottom
(g) Sample pick up in the crater
(h) Scout climbs up the crater slope
(i) Autonomous docking of Scout and Rover
(j) Sample container is picked up by the landers manipulator arm

Figure 18. Scenes from the LUNARES sample return demonstration mission

Sample Collection at Crater Bottom
After arriving at the crater bottom (Figure 18(f)) a scientific operator chooses a geological sample using the video image provided by the scout. The scout positions itself in front of the selected sample, using a visual servoing approach (Section 4.5). When the coarse positioning is done, the scout executes a fine detection of the samples's coordinates by making use of its laser scanner (Section 4.5). When the coordinates of the sample are determined, a leg is used as manipulator to place the sample into a sample container on the scout's back (Figure 18(g)).

Scout Climbs Back up the Crater
When the sample has successfully been collected and stored in the sample container, the scout starts to climb the crater slope and back towards the rover. The scout climbs freely in the crater slope (Figure 18(h)), i.e. no tethering system is applied. However, it remains remotely controlled.

Cooperative Docking of Rover and Scout
After arrival at the rover, the scout turns its back to the rover (Figure 18(i)) to prepare for the autonomous docking procedure as described in Section 4.4. For this procedure, the rover detects the four markers on the scout and commands the scout into a predefined docking pose. When the scout is in the correct pose, the hook of the docking adapter is lowered so that the scout is able to hang itself into the hook.

Return of Rover and Scout to Landing Unit
Similar to the initial procedure, rover and scout collectively drive back to the landing unit using the docking procedure between rover and lander. The docking process ends, when the rover and thus the scout's sample container are within the workspace of the lander's manipulator arm.

Transfer of Sample Container to Landing Unit
The last step of the LUNARES demonstration mission consists of unloading the sample container from the docked scout (Figure 18(j)) and to transferring the sample onto the landing unit. The process is performed autonomously, a visual servoing approach allows to determine the exact position of the sample container with respect to the manipulator (see Section 4.3).

4.3 Automatic Payload Exchange

One of the main goals of the LUNARES system and the corresponding reference mission was to demonstrate the cooperation between a team of heterogeneous robotic subsystems all working together in order to achieve a common goal – collecting a sample from the inner of a lunar crater and returning the sample to the lander for further analysis.

For this purpose, the robotic subsystems had to be reconfigured by the system. One example is the exchange of payload dummies. The most important step concerning the exchange of payloads is the return of the sample container to the lander.

Manipulation is based on a visual servoing approach [18], avoiding the need for a thoroughly performed calibration of the camera systems. However, instead of calibration, a teaching phase is necessary which replaces the calibration.

The LUNARES visual servoing approach detects visual markers in monocular camera images. The markers are black filled circles on white background with a binary ring code around the circle. An adaptive binarisation technique followed by blob analysis generates a set of marker hypotheses which can be identified very robustly by their ring codes. Every image contains a set of n markers $\{(m_x^1, m_y^1)^T, \cdots, (m_x^n, m_y^n)^T\}$. For any static scene, the locations of these markers only depend on the configuration of the manipulator as long as the camera is mounted to the end effector. Thus, the marker locations can be regarded as the result of the perceptual kinematic map π (PKM):

$$\pi : \mathbb{R}^6 \to \mathbb{R}^{2n}, \quad c \mapsto (m_x^1, m_y^1, \cdots, m_x^n, m_y^n)^T. \quad (2)$$

where

c :	$(x, y, z, \alpha, \beta, \gamma)$
x_r,y_r,z_r:	robot coordinates (WKS)
α,β,γ:	rotation around x_r,y_r,z_r-axis
m_x^n, m_y^n:	x/y-image coordinates of the n-th feature

The grasping can be solved as a fixed movement starting from a well-known reference position $c_0 \in \mathbb{R}^6$. Therefore, the task of grasping reduces to the recovery of the reference position. By linearizing the PKM around that reference configuration c_0, the following direction $\Delta(c)$ in the configuration space is obtained. Moving the end-effector in that direction minimizes the differences between the current marker locations and marker locations of the reference image.

$$\Delta(c) = \left(D\pi(c_0)^T D\pi(c_0)\right)^{-1} D\pi(c_0)^T \cdot (\pi(c_0) - \pi(c)). \quad (3)$$

The Jacobian $D\pi(c_0)$ can be determined by applying test movements along all six directions. Figure 19 depicts the result of the visual servoing approach for a payload with four markers attached.

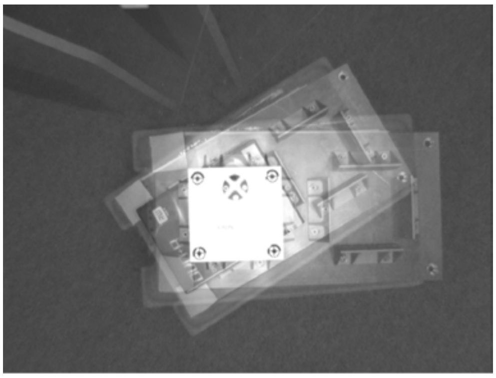


Figure 19. Overlay of the reference image used for the teaching process of the Jacobian and the image of the camera view after successful control of the manipulator. The visual servoing was able to perfectly align the marker locations whereas the differences of the background clearly show the different situations.

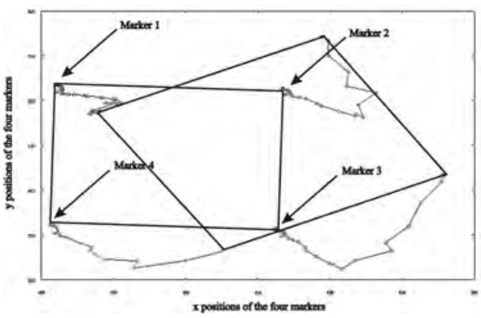


Figure 20. Positions of the markers in the image plane tracked during the visual servoing process.

Figure 20 shows the movements of the visual markers during the visual servoing process. The process runs on standard PC hardware (Intel Core 2 Duo) at 10 Hz and requires approximately 10 s for convergence. The accuracy is high enough to perform a "blind grasping" through a predefined trajectory afterwards.

4.4 Autonomous Docking Procedures

In the LUNARES reference mission, the global mission goal is achieved by splitting the task into several sub tasks which are solved by specialized robotic subsystems. For instance, the required high degree of mobility is achieved by splitting up the requirement into two different mobility systems the rover for larger distances in moderate terrain and the scout for shorter distances in more difficult terrain.

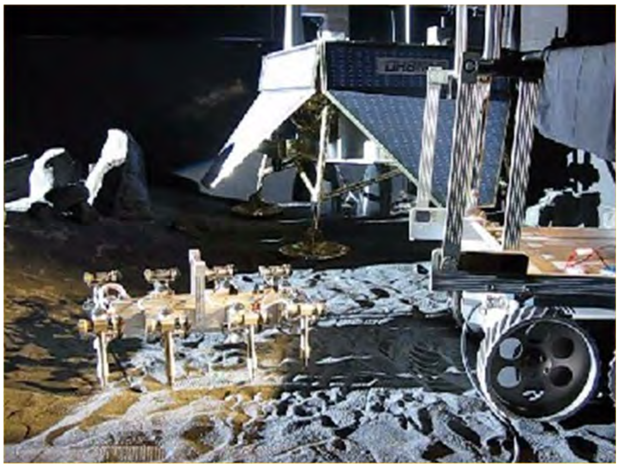


Figure 21. Typical situation for the docking between the scout and the rover.

This splitting however, requires new capabilities of the robotic subsystems. In this section two autonomous and also cooperative behaviors of the robotic subsystems shall be discussed. The first behavior is the docking between the scout and the rover which is required after the scout has returned from its crater exploration. Second is the autonomous docking of the rover to the lander in order to reach a working position from which the lander manipulator can reach the sample canister.

Docking of Scout to Rover

The scout and the rover have not been specifically designed for a docking procedure. However, the LUNARES mission required the scout to dock to the rover. Different possibilities for docking procedures have been evaluated, e.g. such as the scout walking onto the rover.

Here we present the final choice for the docking procedure, which requires the scout to approach the rover by stepping backward. This eliminates the possibility to use the scout's visual sensors for the docking procedure. Instead, the vision system of the rover acquires images of the docking scout and generates correction manoeuvres of the scout to reach a certain goal position. From there a mechanical hook is able to lift the scout to the back of the rover.

The autonomous docking procedure has to perform within given constraints. These constraints depend on the mechanical docking mechanism, i.e. the docking adapter. The adapters capability to deal with position errors and to compensate for such errors define with what precision the scout has to get to the target position. In order to increase robustness of the given docking scenario we identified three critical elements: (1) the predefined actions of the docking procedure, (2) design of the docking adapter and its ability to compensate for alignment errors, (3) fallback safety range for scout's pose correction.

While predefining the actions, the docking procedure has to account for errors in the x-alignment as well as in the z-alignment within some limitation[2], i.e. the final procedure requires security distances for the mechanical docking, so that the risk of a collision of docking adapter and the scout's docking handle is minimized. Eventually and for a worst case scenario, the scout has to maintain a fallback range for manual pose correction leading to the semi-autonomous docking approach.

The overall docking procedure comprises multiple steps. For the start of the docking procedure the rover's camera requires capture the scout and the visual markers attached to the scout. Then, the rover takes control of the scout movements by applying a visual servoing approach. The control target is to reach a certain target position with the scout such that the position of the visual markers is identical to the marker positions of a reference image which has been taken during a teaching phase of the visual servoing approach. The visual servoing approach is exactly the same as described in Section 4.3.

A training phase is required to generate the Jacobian matrix of the PKM to linearise the mapping function around the target configuration. For that purpose several test movements along six different degrees of freedom in positive and negative directions have been performed to setup the Jacobian of the PKM. As a controller we utilized a proportional controller.

Once the position has been successfully reached, a number of predefined actions will be executed[3]:

1. scout shifts its body forward (approx. 2 cm away from the rover), to increase the clearance between its handle and a lowered hook,

2. moving down the docking adapter including a clearance distance (approx. 3 cm),

3. scout shifts its body backward (approx. 5.5 cm) to guarantee that the scout's handle has contact to the lowered docking adapter's hook,

4. docking adapter lifts the scout (12°) just so that the scout's legs do not touch the ground anymore,

[2]The coordinate system is depicted in Figure 9

[3]Since the scout has play in joints the distances of the pose changes are only approximate.

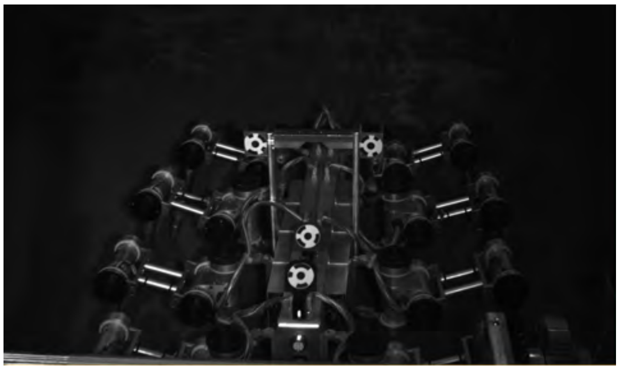


Figure 22. The scout as seen from the rover camera. The coded ring markers are clearly visible in the image and extracted from the rover's image processing system.

5. scout folds its legs into docking position so it can be loaded onto the rover,

6. docking adapter lifts the scout into its final docking position.

The docking procedure will be performed with disabled reflexes, to allow for the predefined posture setting.

Docking of Rover to Lander

The second autonomous docking manoeuvre concerns the placement of the rover in front of the lander in order to achieve a sufficiently precise starting point for the manipulation and sensor based grasping of the payloads or the sample canister. For that purpose a certain accuracy of the rover position in front of the lander has to be reached.

The docking between rover and lander is solved by utilization of the lander's sensor system. Here, the lander acquires a range image from the 3D laser scanner providing two types of information: (1) 3D information for every pixel, and (2) the intensity of the reflected laser pulse. Especially the latter enables the detection of special retro-reflective targets in the scene. Four of these visual markers have been placed at the rover and can easily be detected by the rover to lander docking skill. Using the 3D positions of the detected markers, a graph matching method [6] has been implemented to assure an identification of the single markers, Figure 23. Finally, a pose estimation of the rover with respect to the lander system is obtained.

Using this pose information, a spline trajectory is planned to reach the desired target position from the current pose of the rover. However, due to drift errors

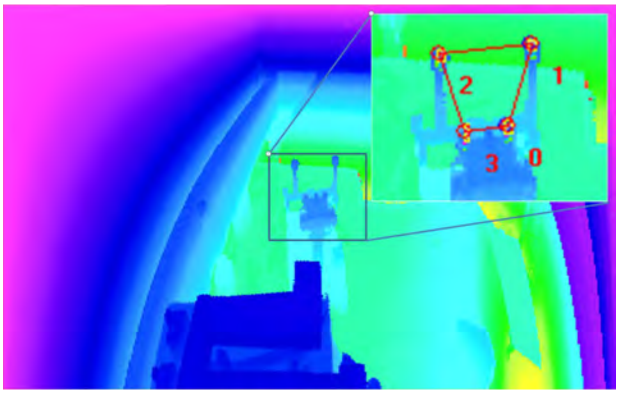


Figure 23. Laser scan image with detected marker configuration for graph matching

in the rover's odometry, that trajectory is only iteratively executed. In one step, the rover only drives along half the pre-planned trajectory. After that distance, a new measurement with the 3D laserscanner is applied and a new trajectory is planned.

This process is repeated until the distance between target position and current position is below a certain threshold. If the position has been reached, the orientation is corrected in a similar manner. After 3-4 iterations, the rover reaches the target with a precision of about 2 cm which is sufficient for further reconfiguration steps and the unloading of the sample canister.

4.5 Sample Pick Up by a Legged Scout System

Before collecting samples, the robot has to position itself in front of an sample of interest. This sample is selected by a human operator using a graphical user interface. Afterwards, the robot starts an automatic approach to the sample until the scout is close enough to grab the sample.

The approach is vision based and utilizes a single camera with an analog transmitter and receiver. Due to limited processing power on the scout robot itself, the computer vision algorithms are executed on an external processing system, a flight system would have to embed such system into the deployed robots itself. Wireless transmission is used for the camera images. Transmission can be easily affected by other wireless systems, and result in image distortions. To cope with these distortions a particle filter was used to track the sample's position in the camera image.

The sample detection process can be separated into three steps:

1. Detect the object
2. Update the particle filter with the position in the image (if detected)
3. Control the scout's movements

Step one is accomplished currently by a threshold on image brightness, it is assumed that samples of interest have different color compared to "regular" stones in the scenario. After selecting the sample of interest, the characteristics are saved and used to find the same object in subsequent images. After the threshold was applied to the camera image, fitting objects are searched beginning at the expected position of the object. The starting point is extracted from the particle filter, which includes a movement model of the object in the camera images.

Only if an object fitting to the characteristics of the selected sample is found, the particle filter and its movement model are updated (step two).

The final step is the control of the scout. Depending on the object's distance to the target area (the area where the gripper can reach the sample), values for the forward speed and turn values are set appropriately.

Figure 24 shows a labeled camera image of the approach, extracted objects are highlighted in the image (green colored areas from brightness threshold), the points are the single particles of the particle filter, the cross marks the expected position of the sample extracted from the particle filter and the box marks the target area where the robot stops moving when the sample resides in that box for some time. The only light comes from some infrared diodes attached to the camera on scout's back (bright spot is visible in the image).

When the robot reaches its final position, it notifies the Ground Control Station, which then can initiate the actual collecting procedure. After finishing the approach, the location of the target sample has to be determined with high precision to allow for sample pick up. It can be assumed that the manipulation will take place in a planar environment. Hence, that target sample can be easily determined after generating a height map of the environment, given a certain region of interest (ROI). One of the influencing factors for the ROI is the accuracy of the approach. Experiments showed that manipulation works best for sample distances of 22 cm in a straight line of the scout's right thorax joint ('shoulder' joint). This knowledge allowed the definition and extraction of the ROI. Currently a target area of 121 cm^2 (11 cm$\times$11 cm) applies.

The scout uses the mounted laserscanner driven by a servo motor to extract an distance image of the environment, which is subsequently transformed into a height map. The essential procedure to extract a sample's position consists of the following steps:

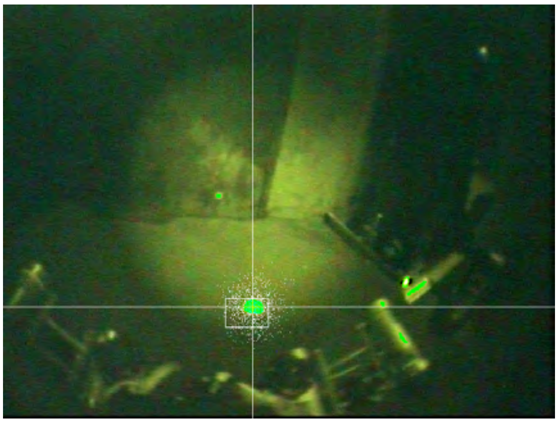


Figure 24. Labeled camera image of the approach action (post processed in brightness and contrast). Around the green highlighted object to approach to, the particles of the filter are displayed as white dots. The approach ends, when the object is completely in the goal region (white rectangle)

1. Extraction of a laser scan of the direct environment within a horizontal range of $\pm 30°$
2. Transformation of the scan data from the world coordinate system into the robot coordinate system
3. Generation of the height map in the robot coordinate system
4. Extraction of the region of interest, defining the allowed manipulation area of the scout
5. Extraction of the local minimum within the ROI
6. Extraction of the region around the local minimum to extract the likely target center

The height map is actually transformed into a grey scale image to allow further processing steps such as median filtering (Figure 25). During the sample pickup process the operator can get hold of the images and validate the extracted final target position. If no object can be extracted, the operator will receive an error message. Additionally, if the operator identifies a false positive, he can initiate a second scan.

5 Potentials for a Real Lunar Mission

The realisation of a robotic Moon mission necessitates the timely development and qualification of a series of technologies, which do not possess the required high development status. More precisely, for the start of

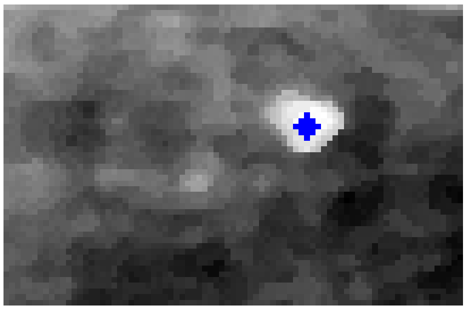


Figure 25. Resulting grey scale image. The centre of the detected sample is marked by an diamond-shaped marker.

Phase C (actual mission planning), a TRL (technology readiness level) of 5 - 6 is required, representing a technology demonstrator or prototype which has already been tested in a representative environment. The identification of technologies which do not have a sufficient TRL level is necessary to minimize the technical and programmatic risks associated with a system development.

In the LUNARES study critical technologies and requirements for the realisation of a multiple-configuration robotic concept were investigated and a stepwise plan for the development was elaborated.

For the LUNARES project, three mission classes have been investigated:

1. Single Moon exploratory missions, e.g. for spectral analysis of surface samples from a Moon crater or even sample return of these samples.
2. The construction of a scientific Moon infrastructure
3. Cargo transportation for support of human missions

For handling of surface samples by the walking robot and the lander, an appropriate gas tight moveable sample container has to be developed. By this it can be ensured that no volatile gases are lost during transport from crater bottom to landing unit.

For the lander, the rover, and the walking robot a higher-level system control of the board computer via an appropriate ground station for automation and robotics has to be developed.

For appropriate programs for technology verification, the DLR program On-Orbit-Verifikation (OOV[4]) is very suited. For this program the German Small Satellites Platform TET[5] can be used. On

[4]http://www.dlr.de/rd/en/desktopdefault.aspx/tabid-2265/3376_read-9781/

[5]http://www.dlr.de/rd/en/desktopdefault.aspx/tabid-2274/3396_read-5085/

the ESA side, there is the Technology Research Programme (TRP), which is specifically for early technology development, or the General Support Technology Programme (GSTP), which is for the development of more developed technologies for market ready products. The following demonstration methods for components, subsystems or the complete LUNARES follow-on system are applicable:

- Software-based simulations
- Earth-based component tests
- Piggy-back Technology Flight Opportunities for component in-orbit tests
- Test campaigns for system prototypes on the Earth

For the qualification and testing philosophy, the classical qualification with structure- and thermal models, engineering model, qualifications model (QM) as well as a flight model (FM) is recommended.

6 Conclusion and Outlook

The project LUNARES provides a terrestrial demonstrator to evaluate the feasibility of a heterogeneous robotic team for lunar crater exploration. Existing robots not specifically designed for the chosen mission scenario have been employed.

The systems came from different project partners. Despite the differences concerning hardware as well as control approaches of the systems, an overall system containing the different subsystems was successfully implemented in the presented project. In numerous demonstrations the combination of the various subsystems were constituted successfully.

For the purpose of experiments and demonstrations, an artificial lunar crater environment comprising realistic slopes and illumination has been established in the project. The testbed is equipped with various surveillance sensors such as video cameras and a motion tracking system. Automated experiment documentation has been implemented in the testbed.

A docking procedure for a walking machine and a wheeled rover was developed. It is based on visual information from the rover's camera system, which is used to control the legged scout. Furthermore, a docking procedure allowing the precise placement of a rover in front of a landing unit was developed using the lander's sensor system. For exchanging payloads and sample containers between rover, scout, and landing unit, visual servoing methods were implemented.

During the project, important experiences with locomotion of walking machines in crater environments were made and the locomotion principle was significantly improved. With appropriate control mechanisms even the Scorpion robot, not explicitly designed for this terrain, was able to climb in the artificial crater with slopes of up to 35°. The locomotion was safe and reliable, even with leg failure, the robot could negotiate the slope with the remaining seven legs.

Overall, LUNARES successfully demonstrated the feasibility of the chosen approach. In the project RIMRES we want to further pursue the idea of heterogeneous robotic systems. Here mobile systems will be newly developed in a co-design process. This allows for a closer coupling between rover and scout. A standardized mechatronic interface and a connection providing interfaces for exchange of data and energy will be developed. An additional focus will be the modularity of the system, several payload modules, each equipped with the mechatronic interface, will be developed.

References

[1] James R. Arnold. Ice in the lunar polar regions. *Journal of Geophysical Research (JGR)*, 84(B10):5659–5668, September 1979.

[2] P. Bartlett, D. Wettergreen, and W. L. Whittaker. Design of the scarab rover for mobility and drilling in the lunar cold traps. In *International Symposium on Artificial Intelligence, Robotics and Automation in Space*, February 2008.

[3] Andrew J. Coates. Limited by cost: The case against humans in the scientific exploration of space. *Earth, Moon, and Planets*, 87(3):213–219, 1999.

[4] Doug Cooke. Exploration lunar architecture. In *Proceedings of the NASA Advisory Council Workshop on Science Associated with the Lunar Exploration Architecture*, Feb. 27–March 2, 2007 2007.

[5] Florian Cordes, Steffen Planthaber, Ingo Ahrns, Timo Birnschein, Sebastian Bartsch, and Frank Kirchner. Cooperating reconfigurable robots for autonomous planetary sample return missions. In *ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots (ReMAR-2009)*, London, United Kingdom, June 22-24 2009.

[6] Thomas H. Cormen, Clifford Stein, Ronald L. Rivest, and Charles E. Leiserson. *Introduction to Algorithms*. McGraw-Hill Higher Education, 2001.

[7] Alexander Dettmann, Stefan Haase, and Frank Kirchner. Automatic robot supervision within a lunar crater environment. In *Joint 41st International Symposium on Robotics and 6th German Conference on Robotics (ISR Robotik-2010), June 7-9, Munich, Germany*, Munich, Germany, 2010.

[8] W. C. Feldman, S. Maurice, A. B. Binder, B. L. Barraclough, R. C. Elphic, and D. J. Lawrence. Fluxes of fast and epithermal neutrons from lunar prospector: Evidence for water ice at the lunar poles. *Science*, 281:1496–1500, September 1998.

[9] L. Ferrarini and E. Carpanzano. Reference models for the supervision and control of advancedindustrial manipulators. In *American Control Conference*, volume 4, pages 2440–2444, 1999.

[10] C. Fiorio and J. Gustedt. Two linear time union-find strategies for image processing. *Theoretical Computer Science*, 154(2):165–181, 1996.

[11] N. Hansen and A. Ostermeier. Completely derandomized self-adaptation in evolution strategies. *Evolutionary Computation*, 9(2):159–195, 2001.

[12] T Huntsberger, A Stroupe, H. Aghazarian, M. Garrett, P. Younse, and M. Powell. Tressa: Teamed robots for exploration and science on steep areas: Field reports. *J. Field Robot.*, 24(11-12):1015–1031, 2007.

[13] Bernhard Klaassen, Ralf Linnemann, Dirk Spenneberg, and Frank Kirchner. Biomimetric walking robot scorpion: Control and modeling. In *Robotic and Autonomous Systems Journal*, 2002.

[14] Ralf Linnemann, Bernhard Klaassen, and Frank Kirchner. Walking robot scorpion - experiences with a full parametric model. In E.J.H. Kerckhoffs, editor, *15th European Simulation Multiconference: Modelling and Simulation*, pages S.1012–1018, Prague, Czech Republic, June 6-9 2001. International Society for Computer Simulation -SCS-.

[15] NASA.gov – Mini-RF. Exploring the lunar poles, March 2010.

[16] NASA.gov – Mission Update. Lcross impact data indicates water on moon. NASA Homepage, 11/2009.

[17] S. Nozette, C.L. Lichtenberg, P. Spudis, R. Bonner, W. Ort, E. Malaret, M. Robinson, and E. M. Shoemaker. The clementine bistatic radar experiment. *Science*, 274:1495–1498, November 1996.

[18] A. C. Sanderson and L. E. Weiss. Adaptive visual servo control of robots. *Robot Vision*, pages 107–116, 1983.

[19] J. Schwendner, F. Grimminger, S. Bartsch, T. Kaupisch, M. Yuksel, A. Bresser, J. Bessekon Akpo, A. Dieterle, S. Schmidt, M. Seydel, and F. Kirchner. Cesar: A lunar crater exploration and sample return robot. In *Intelligent Robots and Systems. IROS 2009*, St. Louis, Oktober 2009.

[20] D. Spenneberg, M. Albrecht, and T. Backhaus. M.O.N.S.T.E.R.: A new behavior–based microkernel for mobile robots. In *ECMR 2005*, 2005.

[21] S. Thrun, D. Fox, W. Burgard, and F. Dellaert. Robust monte carlo localization for mobile robots. *Artificial Intelligence*, 128(1-2):99–141, 2001.

[22] Gianfranco Visentin. Autonomy in ESA Planetary Robotics Missions.

[23] Kenneth Watson, Bruce Murray, and Harrison Brown. On the possible presence of ice on the moon. *Journal of Geographical Research (JGR)*, 66(5):1588–1600, 1961.

[24] David Wettergreen, Dominic Jonak, David Kohanbash, Scott Jared Moreland, Spencer Spiker, James Teza, and William (Red) L. Whittaker. Design and experimentation of a rover concept for lunar crater resource survey. In *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*, January 2009.