Heterogeneous Robotic Teams for Exploration of Steep Crater Environments

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***Abstract*— This paper describes three projects that are concerned with the exploration of the interior of steep craters, with special focus on exploring lunar craters with heterogeneous robotic teams. Within the project LUNARES (Lunar Exploration System), a terrestrial demonstrator for a lunar sample return mission has been created. The task of fetching a soil sample from within a permanently shadowed lunar crater had to be accomplished by a heterogeneous team of robots consisting of a wheeled rover and a legged scout. By means of different locomotion principles, the unique skills of these systems have been combined in order to increase the overall performance in the team. The follow-up project RIMRES (Reconfigurable Integrated Multi-Robot Exploration System) develops a rover and a six legged scout in a co-design process. The key idea remains: Robots with different locomotion capabilities cooperate as a team, in order to explore permanently shaded craters at the lunar poles. The third project, SpaceClimber, focusses on developing a six-legged free-climbing robot for crater environments. The SpaceClimber robot is likely to be used as antetype for the scout system in RIMRES. For more detailed information on the projects, references are provided.**

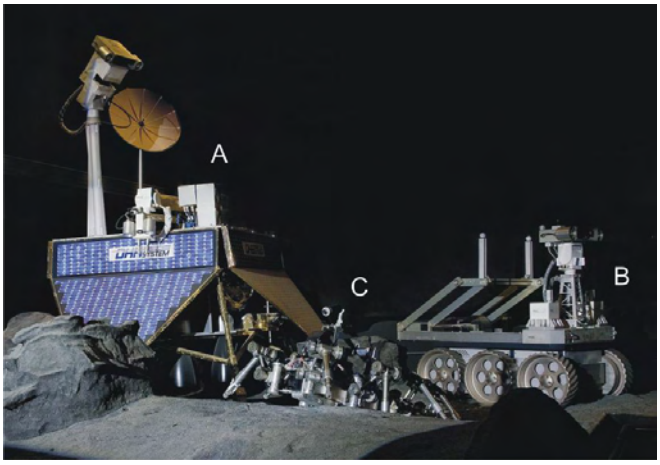


Fig. 1. LUNARES-Systems in artificial lunar crater test environment. A Lander mock-up with sensor tower and manipulator arm is installed (A). For mobility a wheeled rover (B) with parallel crank lever docking adapter and a legged scout (C) are used.

I. INTRODUCTION

Space exploration is currently dominated by exercising robots for fulfilling the scientific goals, since robots provide a better cost-efficiency for exploration along with lower risks for humans [1]. Robotic probes have already been send to extraterrestrial missions, Mars and Moon being the most prominent. Recently, Moon came into focus of scientific interest since the detection of possibly vast amounts of water ice at both lunar poles [2].

There are various approaches for lunar robotic technology of the next generation, including single robot systems like ATHLETE [3] and Scarab [4]. Multi robot systems are also under consideration, e.g. TRESSA [5] and the Robotic Contruction Crew (RCC) [6].

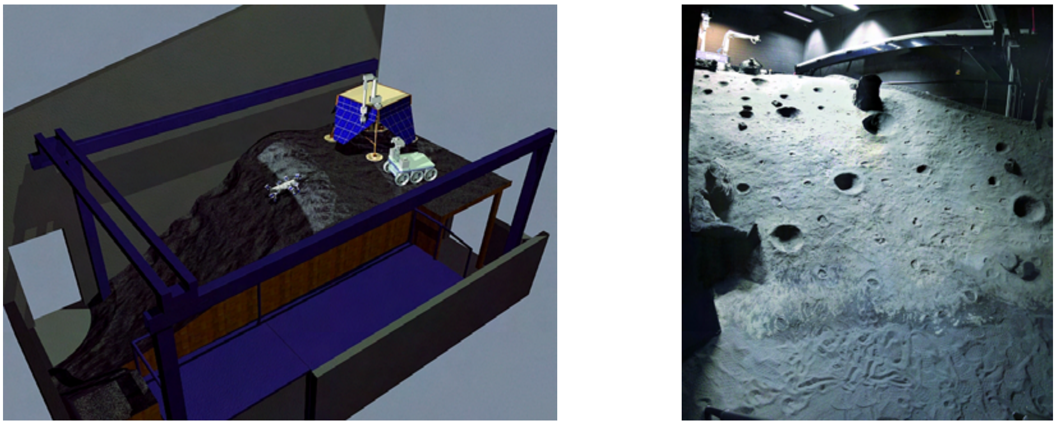
This paper presents the approach of a heterogeneous robotic team used for crater exploration at the lunar poles. The recently finished project LUNARES served the main purpose of demonstrating the general feasibility of the heterogeneous robotic team. This project is presented in the following section. Section III introduces the recently started project RIMRES and its current state of work. In this project a modular, heterogeneous multi-robot system is developed to provide high mobility on planetary surfaces. Section IV gives an overview of the SpaceClimber-project, developing a six-legged robot that is currently being developed for exploration of steep crater environments. In Section V this paper is concluded and an outlook on the next activities is given.

II. LUNARES

The recently finished project LUNARES [7] had the aim to combine existing robots in order to build up a heterogeneous robotic team for a terrestrial demonstration mission. The goal of the demonstrations was to show the general feasibility of the chosen approach. Space qualification of the single systems was of no concern in this project. The following chapters only give an overview on the systems and the chosen demonstration mission. For more details and experimental results, the reader is asked to follow the given references.

A. Systems

The LUNARES-team (Fig. 1) consists of two mobile units: (1) a wheeled rover for energy efficient locomotion in moderate terrains, and (2) a legged scout robot – the Scorpion robot [8] – is employed to fulfill the task of climbing into an otherwise inaccessible area, more specifically the interior of a steep crater. Furthermore, the team provides a manipulator



(a) CAD model of the artificial crater environment. The environment provides slopes of 30° to 45° in the interior of the crater and a small plateau for rover movements. Floodlights (not displayed) with narrow angle simulate lighting conditions at the lunar poles.

(b) Panoramic view from the crater bottom of the Space-TestBed (STB)

Fig. 2. The Space-TestBed, CAD-Model and photograph of the interior of the crater

and a sensor tower on a landing platform, which itself is a wooden mock-up in the case of the LUNARES-project.

Existing robots were used, but modified to meet the requirements of the project. As wheeled rover system an industrial transportation platform has been used and modified by adding a sensor tower (providing a stereo video camera, a laser scanner and illumination), exchange of the pneumatic tires with metallic wheels and addition of a docking adapter for picking up the scout.

For usage of the Scorpion robot as LUNARES-scout, the microkernel MONSTER [9] has been employed for locomotion control of the scout. 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. MONSTER allows for merging different behaviors, so that changing postures (i.e. lean forward, change roll-angle etc.) do not affect the walking pattern.

Additionally, one leg of the scout has been equipped with a sampling device for picking up a geological sample. To be able to identify the relative position of the sample with respect to the robot, a laserscanner and a mikro-PC system have been added to the Scorpion robot.

The feasibility of this approach with a wheeled and a legged robot acting as a team for lunar crater exploration has been tested and successfully demonstrated in an artificial lunar crater environment. The crater design is derived from pictures of Apollo missions and data from real craters at the lunar south pole. The artificial crater provides slopes between 30° and 45° within the crater and a slope of 15° at the outer rim. The crater has been set up in a laboratory of $45\,\mathrm{m}^2$. Fig. 2(a) shows a CAD model of the artificial lunar crater environment with a grandstand for observing the experiments. In Fig. 2(b) a panoramic view into the main slope of the crater is given. To document experiments conducted in the environment, several surveillance tools have been installed: (1) a motion tracking system, (2) pan-tilt-zoom cameras and (3) a gantry crane that follows autonomously the system under test in order to give a constant top view video image and to provide the possibility for gravity compensation with counterweights. In [10] more detailed information is presented on automatic experimental data acquisition in the test environment.

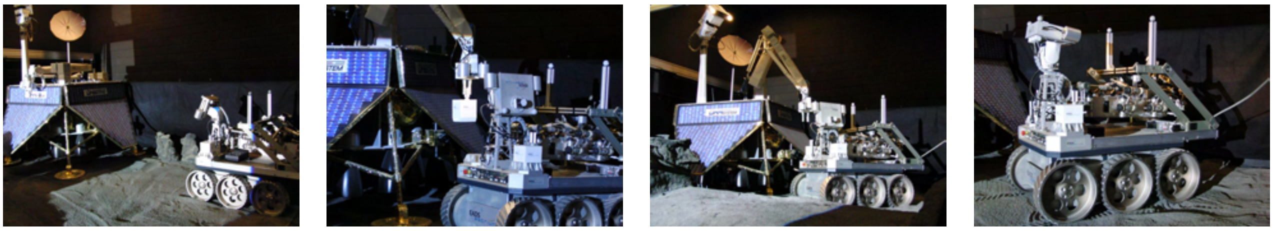
B. Demonstration Scenario

In the demonstration scenario, a lunar sample return mission has been simulated using the heterogeneous systems of the LUNARES team in the artificial crater environment. The mission steps are presented in detail in the following paragraphs.

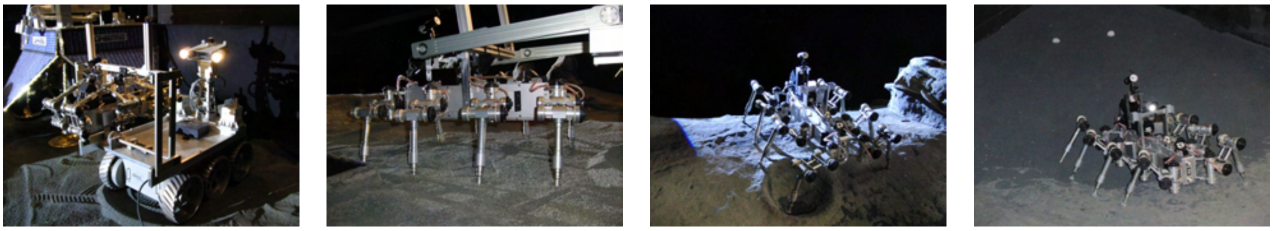
1) Autonomous Docking of Rover and Lander: At the start of the demonstration mission, the rover is situated in the vicinity of the lander, Fig. 3(a). In order to be able to equip the rover with a new payload (P/L), the rover has to be positioned in the workspace of the lander's manipulator. This is achieved by an autonomous docking, which makes use of the lander's laser scanner. The payloads used in the demonstration scenario are mock-ups representing scientific instruments of a real mission. By equipping the rover with different payloads, it is possible to configure the system for the current mission at hand. The docking approach and experimental results are described in detail in [11].

2) Payload Exchange on the Rover: After reaching the workspace of the lander's manipulator, the rover is equipped with a payload – Fig. 3(b). The P/L is picked from the lander and placed into a designated payload bay of the rover.

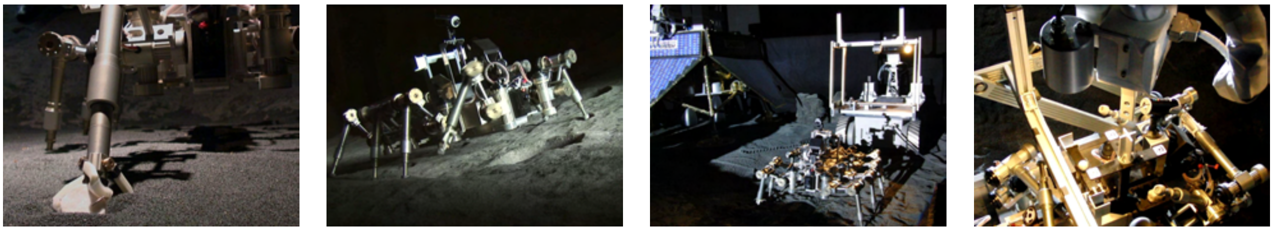
3) Movement of Rover and Scout to the Crater Rim: After finishing the task of reconfiguration, the manipulator arm is retracted, Fig. 3(c). Rover and docked scout then drive towards the crater rim. This demonstrates the ability of the wheeled system to move in an energy-efficient way in moderate terrain. Generally the rover should negotiate longer distances. However, due to space constraints in the Space-TestBed, the distance covered by the rover is limited to a



(a) Autonomous docking of rover to lander (b) Equipment of rover with new payload (c) The manipulator is retracted (d) Rover and scout on their way to the crater's rim



(e) Deployment of scout (f) Scout leaves docking adapter by changing its posture (g) Scout is about to climb into the crater (h) Scout arrives at crater bottom. Light is enhanced for the picture.



(i) Sample pick up in the crater (j) Scout climbs up the crater slope (k) Autonomous docking of Scout and Rover (l) Sample container is picked up by the landers manipulator arm

Fig. 3. Scenes from the LUNARES sample return demonstration mission. The mission provides autonomous behaviors as well as remotely controlled sequences. Especially positioning of the robots for docking, sampling and manipulation is achieved by autonomous approaches in order to enhance the performance of the systems.

few meters. Fig. 3(d) illustrates rover and scout collectively driving towards the crater's rim.

4) Undocking of Scout and Rover: Once the team consisting of rover and scout arrives at the crater rim, the scout undocks from the rover. Therefor the docking adapter mounted on the back of the rover is used. The parallel crank lever facilitates the scout's deployment onto the surface as depicted in Fig. 3(e). By adjusting the posture of the scout, it leaves the hook of the docking adapter, Fig. 3(f).

5) Scout Descends into Crater: After the detaching from the rover, the scout heads for the crater rim and enters the dark interior of the crater, Fig. 3(g). On the way to the bottom of the crater, small impact craters and rocks buried into the regolith have to be overcome or circumnavigated in the slope. 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, deeply buried rocks are simulated with rocks fixed to the surface – Fig. 2(b).

6) Sample Collection at Crater Bottom: Figure 3(h) depicts the arrival of the scout at the crater bottom. The normally dark environment is lighted up for better visibility on the picture. A scientific operator chooses a geological sample using the video image provided by the scout. In an autonomous approach behavior, the scout positions itself in front of the selected sample. When this coarse positioning is done, a fine detection of the samples's coordinates is executed. By using its laser scanner the scout generates a 2.5D-height map of its direct vicinity. The coordinates of the sample are extracted from the 2.5D-height map, to position the scout's leg on the sample of interest. After grabbing the sample with the integrated manipulator, the sample is placed in the sample container on the back of the scout, Fig. 3(i). More information on the sample approach and sample pick up is provided in [12].

7) 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 as depicted in Fig. 3(j). No tethering system is applied. However, due to calculation power the locomotion in the slope remains remotely controlled.

8) Cooperative Docking of Rover and Scout: After arrival at the rover, the scout turns its back to the rover as depicted in Fig. 3(k) to prepare for the autonomous docking procedure. For this procedure, the rover detects specific optical markers on the scout and commands the scout into a predefined docking pose. The docking procedure of rover and scout as well as experimental results are described in detail in [11].

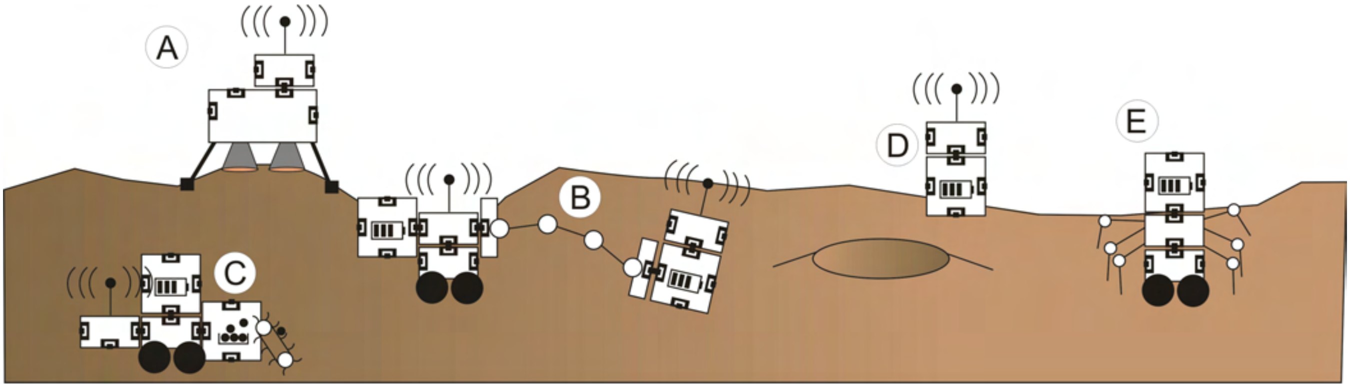


Fig. 4. Illustration of the envisioned RIMRES system. A: Landing unit with radio module and free module slots; B: Rover with radio module and additional battery module deploys radio beacon; C: Rover with additional battery and radio module makes use of a sampling module; D: Operating radio module stack; E: Connected rover and scout on their way to a crater for exploration.

9) 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 autonomous 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.

10) 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, as depicted in Fig. 3(l). The sample is then transferred onto the landing unit. This process is performed autonomously, a visual servoing approach allows to determine the exact position of the sample container with respect to the manipulator.

C. Conclusions

The project LUNARES dealt with the topic of using a heterogeneous team of robots to cope with the task of fetching a soil sample from within a permanently shadowed crater at the lunar south pole. The system that has been build up consists of previously existing robots, that were modified to achieve the given task. LUNARES showed, that even with existing robots, the chosen approach in principle is feasible [12]. Only minor modifications were needed to achieve the task with not specifically designed robots. The experiences made in the LUNARES project can directly be exploited for projects such as SpaceClimber and RIMRES, being described in the subsequent chapters.

III. RIMRES

RIMRES [13] picks up the ideas of LUNARES and additionally addresses the modularity of the systems. The purely mechanical connection of rover and scout in LUNARES is extended by introducing a mechatronic interface, providing a mechanical connection as well as data and energy connections. Utilizing the interface, two robots can closely connect and act as one single robotic system, as well as two independent systems when needed. Figure 4 illustrates an envisioned scenario for the RIMRES system.

A. Systems

As opposed to LUNARES, in RIMRES the new mobile units are meant specifically for the purpose of forming a tightly coupled team. Thus this requirement is considered in the design phase already. Parts of the systems can be switched off during connection to save energy, i.e. the legs of the scout and parts of its sensors not needed when coupled with the rover can be shut down.

Because of the tight coupling of rover and scout via the mechatronic interface (data, electrical and mechanical energy connection), there are multiple ways to enhance the redundancy. In case of rover sensor faults, the scout could take over control of the rovers actuators and navigate the rover/scout team using its own sensors. Alternatively, the rover could directly control the scout's legs while both robots are coupled, allowing the rover to make use of the sampling device in the scout's legs. Figure 5 on the next page shows an artist drawing of the RIMRES system: A rover with connected scout is visible in the foreground. The rover is about to set out a module stack, while the connected scout analyzes a small rock with its front legs. A second scout climbs a slope in the background.

The following paragraphs give an overview of the planned design of the systems. A wheeled rover, a legged scout and additional payload modules representing scientific and functional modules will be implemented.

1) Rover: For RIMRES, a rover is designed from scratch. This rover will feature four wheels each one suspended by an actuated parallel kinematic. These "legs" of the rover can be actuated with four degrees of freedom (DOF), allowing an adaption to slopes and providing the ability to actively lift a leg from a stuck situation. Additionally, big obstacles can be overcome. By using spindle drives, the actuators of the rover do not require energy for keeping the rover's body height.

The wheels of the rover will be equipped with sophisticated adaptronics. Thus the wheels can adapt their stiffness to changing ground properties as well as to changing mass of the rover. For example the rover's mass is changed by docking and undocking of the scout, whose mass will be around 20 kg.

On top of the rover there will be four payload-bays implemented, each providing a mechatronic interface for placement of the immobile payload-modules. To be able to handle the modules, a robotic arm is implemented in the center of the robot. The scout system will be situated beneath the rover, coupled with the rover via the mechatronic interface. The placement of the scout will be designed in a way, that the scout is still able to use its front pair of legs as manipulators/sampling device.

2) Scout: The scout design will follow the design of the SpaceClimber, a six legged robot currently under development, see also Section IV. To allow for coupling with the rover, a mechatronic interface will be implemented on the back of the scout.

The main task of the scout is to access areas that are not reachable by the wheeled system. This includes steep craters as well as elevated planes. In general the scout can use its front legs as sensing devices, for example by implementing the external optical head of a combined Raman-LIBS (Laser Induced Breakdown Spectroscopy) spectrometer. The laser source and electronics for analysis could be placed in the scouts body. However, in RIMRES this analysis tool will be represented by a sampling device similar to that one implemented on the Scorpion robot [7].

3) Additional Modules: Along with two mobile units, the RIMRES system provides immobile payload modules that can be attached to the rover as well as to the scout. The modules can be stacked using the mechatronic interface and deployed by the rover. This way, more complex scientific packages consisting of different modules may be set up in order to be deployed on the lunar surface.

A battery module is planned to represent an energy harvesting module (solar-module) for the immobile payload stacks and to enable longer operations in shaded regions for the mobile units. A radio module will be implemented, featuring data relay as well as navigation functionalities. The REIPOS (Relative Interferometric Position Sensor) will be able to detect the direction and distance of other REIPOS-Modules, thus building a rudimentary navigation infrastructure. Camera modules will represent scientific payloads to be placed on the lunar surface, for example seismic experiments. The PLUTO Mole [14] that flew with Beagle-2 in the Mars Express mission, will be incorporated in a module frame in order to demonstrate the modular approach of scientific payload design.

B. System Control

As described above, the RIMRES-System consists of different mobile and immobile subsystems, constituting a reconfigurable, modular overall system. To be able to control the system, a representation of the current system configuration has to be mapped in the software. A new module in a module network has to be made known and propagate its functionalities to the existing system of modules. A ”new” module can enter or leave a system of modules by

- reaching or leaving the range of the radio signal
- mechanically (dis)connecting to (from) another module

The software framework will support communication between two modules providing the possibility of using individual modules as relay station, remote software updates, control of modules by other modules, search for modules with specific functionalities and other control options. The communication of modules can be divided into remote communication (of modules that are not connected via the mechatronic interface) and direct communication via the mechatronic interface.

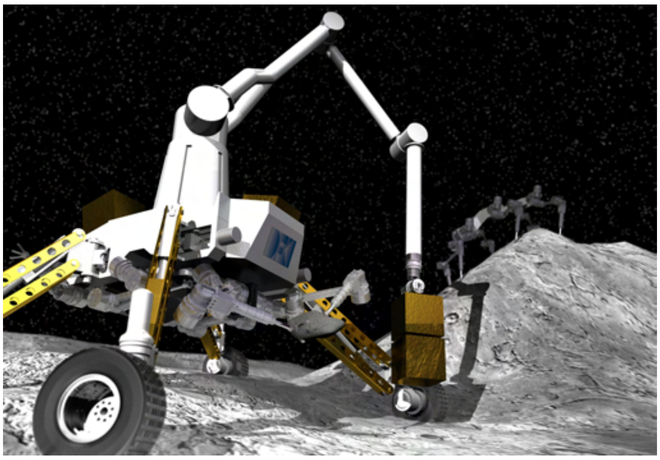


Fig. 5. RIMRES-scenario in an artist drawing. The rover in the foreground is about to set out a stack of two modules. The connected scout beneath the rover analyzes a small rock sample. In the background, a second scout climbs a slope to steep for the wheeled system.

The control system incorporates human interaction and support as well as autonomous behaviors of the systems. The concept provides a continuum of autonomy levels, ranging form full autonomy to direct (tele operated) control. There are three main events, that induce the change of autonomy level:

- Human initiated autonomy switch (the operator demands for control)
- Planned autonomy change (the mission time line provides a change of the autonomy level)
- Robot initiated autonomy change (the robot recognizes, that it cannot fulfill its task under the given circumstances)

Especially the robot initiated autonomy switch requires research on the self-assessment of the robot. The concept and first results of the pursued sliding autonomy approach are described in more detail in [15].

IV. SPACECLIMBER

The goal of the SpaceClimber project is the development of a biologically inspired, energy-efficient, free-climbing robot for steep slopes. SpaceClimber should prove that walking robotic systems present an option for future missions on difficult terrain, in particular missions in craters or rock fissures. The robotic system that is developed should be able to conquer irregular slopes of up to 80% and should be in

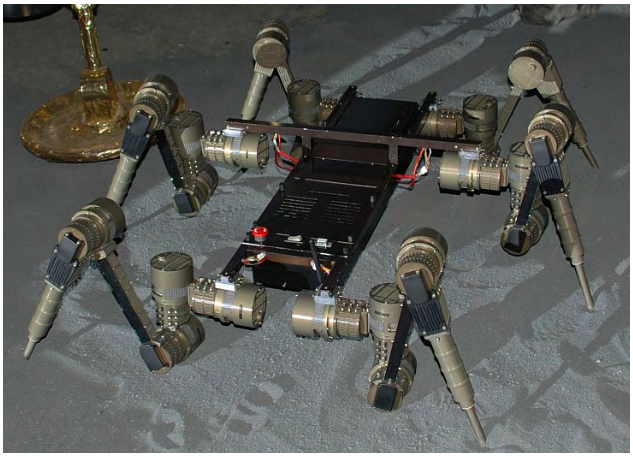


Fig. 6. The integration study of SpaceClimber in the Space TestBed. The legs are fully integrated and operational. The body itself is up to now a "carrier-platform" for the legs and central electronics. It is to be replaced with a new body including one DOF for lifting the front third of the torso.

a position to navigate with local autonomy using built-in sensors [16].

SpaceClimber is a six-legged walking robot with four active DOF per leg plus an additional passive DOF in the lower leg, Fig. 6. The morphology of the robot has been determined with evolutionary strategies. In simulation a fitness function for minimizing energy consumption was set up to evaluate the locomotion on flat ground and walking on slope of 30° up and down, respectively. For the evolution, certain constraints were defined: (1) The system should have six legs, (2) each leg consists of four joints in a given orientation with respect to the body and (3) the six legs are mounted in three pairs of two symmetrical legs. The parameters that were influenced by the evolutionary process were (1) the length of the last link and the lower leg (the first three joints are connected to form a shoulder joint), (2) the horizontal position of a leg-pair, (3) the vertical position of a leg-pair, and (4) the width of a pair of legs. Simultaneously with the morphology, walking patterns were learned to optimize the locomotion in both, flat ground as well as slopes. More details on the evolutionary design of the robot are given in [17].

The actuators for the joints of the robot provide a BLDC motor with a harmonic drive gear. The actuator modules furthermore provide electronics containing power electronics, electronics for sensor data acquisition as well as an FPGA for implementation of control algorithms, logging capabilities and communication with other actuators and the central processing unit. The power consumption of the joints is 30 W, 18 W and 13 W while exerting 23 Nm, 16 Nm and 12 Nm at 3 rpm respectively [18].

V. CONCLUSION AND OUTLOOK

In this paper we reviewed the LUNARES project and the achievements of this first approach of a heterogeneous team of robots for space application. In LUNARES an artificial lunar crater environment has been set up to test the feasibility of the chosen approach. A wheeled rover is used to overcome moderate terrain and slopes in an energy efficient way. A legged scout, equipped with sampling/sensing devices, is used to advance into the permanently shaded regions of a lunar crater. In these regions a sample is taken or in situ measurements with integrated sensor equipment are undergone.

The RIMRES project picks up the idea of heterogeneous robots acting as a team for crater exploration. In RIMRES, a new rover and a scout are developed, these systems are able to connect to each other and further immobile payload-modules via a mechatronic interface. The autonomy of the systems will be addressed in a sliding autonomy framework, providing autonomy continuously ranging from remote control to full autonomy. The SpaceClimber robot in a modified version will serve as scout system in the RIMRES scenario.

The next steps in the project RIMRES are to finish the concept phase and finalize the design of rover, mechatronic interface and system control. The modifications of SpaceClimber to suit the needs of the RIMRES scout will be of interest in the near future.

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REFERENCES

[1] 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.

[2] NASA.gov – Mini-RF. Exploring the lunar poles. `http://www.nasa.gov/mission_pages/Mini-RF/multimedia/feature_ice_like_deposits.html`, March 2010.

[3] Brian H. Wilcox, Todd Litwin, Jeff Biesiadecki, Jaret Matthews, Matt Heverly, Jack Morrison, Julie Townsend, Norman Ahmad, Allen Sirota, and Brian Cooper. ATHLETE: A cargo handling and manipulation robot for the moon. *Journal of Field Robotics*, 24(5):421, 2007.

[4] 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.

[5] Terry Huntsberger, Ashley Stroupe, Hrand Aghazarian, Mike Garrett, Paulo Younse, and Mark Powell. Tressa: Teamed robots for exploration and science on steep areas: Field reports. *J. Field Robot.*, 24(11-12):1015–1031, 2007.

[6] Terry Huntsberger, Ashley Stroupe, and Brett Kennedy. System of systems for space construction. *2005 IEEE International Conference on Systems, Man and Cybernetics*, 4:3173 – 3178 Vol. 4, Oct. 2005.

[7] Florian Cordes, Steffen Planthaber, Ingo Ahrns, Sebastian Bartsch, Timo Birnschein, 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 2009.

[8] Dirk Spenneberg and Frank Kirchner. Scorpion: A biomimetic walking robot. In VDI, editor, *Robotik 2002*, volume 1679, pages 677–682. VDI, 2002.

[9] Dirk Spenneberg, Martin Albrecht, and Till Backhaus. M.O.N.S.T.E.R.: A new behavior-based microkernel for mobile robots. In *ECMR 2005*, 2005.

[10] Alexander Dettmann, Stefan Haase, and Frank Kirchner. Automatic robot supervision within a lunar crater environment. In *Proceedings of the ISR/Robotik2010, accepted*, Munich, Germany, 2010.

[11] Thomas M. Roehr, Florian Cordes, Ingo Ahrns, and Frank Kirchner. Cooperative docking procedures for a lunar mission. In *Proceedings of the ISR/Robotik2010, accepted*, Munich, Germany, 2010.

[12] Sebastian Bartsch, Florian Cordes, Stefan Haase, Steffen Planthaber, Thomas M. Roehr, and Frank Kirchner. Performance evaluation of an heterogeneous multi-robot system for lunar crater exploration. In *Proceedings of the 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS'10), accepted*, Sapporo, Japan, 2010.

[13] Florian Cordes, Daniel Bindel, Caroline Lange, and Frank Kirchner. Towards a modular reconfigurable heterogenous multi-robot exploration system. In *Proceedings of the 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS'10), accepted*, August 2010.

[14] Carol R. Stoker, Lutz Richter, William H. Smith, Larry G. Lemke, Philip Hammer, Brad Dalton, Brian J. Glass, and Aaron Zent. The Mars Underground Mole (MUM): A Subsurface Penetration Device with In Situ Infrared Reflectance and Raman Spectroscopic Sensing Capability. In S. Mackwell & E. Stansbery, editor, *Proceedings of the Sixth International Conference on Mars*, volume 34 of *Lunar and Planetary Inst. Technical Report*, March 2003.

[15] Thomas M. Roehr, Yuping Shi, and Frank Kirchner. Using a self-confidence measure for a system-initiated switch between autonomy-levels. In *Proceedings of the 10th International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS'10), accepted*, August 2010.

[16] Sebastian Bartsch, Timo Birnschein, Florian Cordes, Daniel Kuehn, Peter Kampmann, Jens Hilljegerdes, Steffen Planthaber, Malte Roemmermann, and Frank Kirchner. SpaceClimber: Development of a six-legged climbing robot for space exploration. In *Proceedings of the 41st International Symposium on Robotics and 6th German Conference on Robotics, (ISR Robotik-2010), accepted*, 2010.

[17] Malte Roemmermann, Daniel Kuehn, and Frank Kirchner. Robot design for space missions using evolutionary computation. In *IEEE Congress on Evolutionary Computation. IEEE Congress on Evolutionary Computation (IEEE CEC-2009), May 18-21, Trondheim, Norway*. -, 2009.

[18] Jens Hilljegerdes, Peter Kampmann, Stefan Bosse, and Frank Kirchner. Development of an intelligent joint actuator prototype for climbing and walking robots. In *Mobile Robotics - Solutions and Challenges. 12th International Conference on Climbing and Walking Robots and the Support technologies for Mobile Machines (CLAWAR-09), September 9-11, Istanbul, Turkey*, pages 942–949. o.A., 2009.