Cooperating Reconfigurable Robots for Autonomous Planetary Sample Return Missions

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Abstract—*In the project LUNARES (LUNAR Exploration Szenario), a technology demonstration of reconfigurable cooperating robots in extraterrestrial sample return missions is implemented using state-of-the-art robotic technologies. A reconfigurable robot team consisting of a lander equipped with a manipulator, a rover, and a climbing robot is tested and demonstrated in a lunar crater test environment at the DFKI Laboratories. The aim is to accomplish a sample return mission from an (artificial) lunar crater in an autonomous way. To achieve the aim, the existing robotic technologies have to be enhanced in different areas such as locomotion in rough terrain, autonomy, and cooperation. The work is in progress, in this paper we present the current state of the development. The project is funded by the German Space Agency (DLR[1]) and the Investment Association Bremen (BIG[2]). LUNARES is a cooperation between the DFKI GmbH, EADS Astrium GmbH, and OHB-System AG.*

Index Terms—*Reconfigurable Robots, Heterogeneous Robot Team, Space Robotics, Lunar Crater Exploration*

1. INTRODUCTION

In space exploration, sample return missions like STARDUST [1] or HAYABUSA [2] are of special scientific interest. Instead of sending humans on such missions, robots provide a better cost efficiency [3]. Up to now, these robots have been stationary (lander) or wheeled rovers. Apart from the Soviet lunar rover missions (Lunokhod Program) in the 1970s, all successful rover missions were Mars missions. The first successful martian rover system was the Sojourner Rover within the Mars Pathfinder Mission [4]. NASA's MER-Mission [5] (Mars Exploration Rover Mission) which started in 2003 is still ongoing with the two rovers Spirit and Opportunity.

NASA has identified robotic missions as important precursors for human missions on Mars and Moon [6]. For such missions, especially where the aim is to build up infrastructure, robotic cooperation and autonomous behavior are mandatory. Parker et al. present an architecture dealing with the task allocation problem in heterogeneous robotic teams [7]. They specially address the "site preparation task", which is the basis for further infrastructure construction. The approach to address this task is to use a heterogeneous team of robots which are able to assess, based on execution time, the ability of the team mates to cope with a certain assigned task.

All those missions have one similarity, they are using wheeled locomotion and they are not able to navigate very steep or rocky terrain. But these areas became focus of scientific interest on the moon because of the cryogenic environment in craters with enduring darkness. Data from Lunar Prospector [8] or Clementine [9] indicate the possibility of finding water ice bound to the regolith in such areas in craters at the lunar poles. The presence of water is important to support life on the moon or other planets.

With the first *ESA Lunar Robotics Challenge* [10] organized by the European Space Agency in October 2008, ESA showed interest in a mission where robotic systems advance into these areas. The goal of the challenge was to find and return a sample of 100g colored substrate out of a dark crater to a landing unit. DFKI's CESAR-Robot [11] (Crater Exploration And Sample Return) was the only one that succeeded in finding and returning a sample. The approach used there is a different one to that in LUNARES. CESAR is a remote-controlled hybrid legged-wheeled system, with resemblance to the Asguard robot [12], [13] whereas the LUNARES scenario takes a step ahead: An autonomous cooperative approach within a heterogeneous robotic team is pursued.

Current extraterrestrial robotic missions consist of a rover which is specialized in a single locomotion principle (wheeled locomotion) while carrying all instruments it could possibly need. Obviously this is inefficient in terms of energy consumption while moving. Furthermore, descending a steep crater with a wheeled system is hardly realizable. A comparison between advantages and disadvantages of legged robots [14] and rovers [15], [16] shows that wheeled locomotion is the best in planar environments whereas legged robots can cope with very rough terrain and slopes or even climb vertical planes [17]. This leads to the idea to use multiple robots specialized

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(i.e. a wheeled rover and a walking robot) in a given task or reconfigurable robots which can adapt to different tasks.

Huntsberger et al. proposed a heterogeneous robotic team for infrastructure / inter-robot servicing and repair [6]. The proposed approach was to use a six-legged robot to repair a wheel of a rover. They also indicated that the repairing skills could be used for repairing other units on the planetary surface. Repair capabilities contribute in an essential way to increase the durability of a robotic mission on the surface of a celestial body [18].

LUNARES aims at a demonstration of a heterogeneous, reconfigurable robotic team using state-of-the-art robotic technology. Autonomous multi-robot systems provide a higher efficiency in future space missions. At the same time, the overall costs of such a mission can be reduced while the reliability can be increased. [19], [20].

To demonstrate the capabilities of our reconfigurable robot system, a possible mission scenario was defined. The objective is to accomplish a sample return mission with a geological sample from a steep lunar crater taken in areas of enduring darkness.

The LUNARES robot team consists of a landing unit (a mock-up fabricated by OHB-System) with a robotic arm, a wheeled rover (both delivered from EADS Astrium), and a legged scout (the Scorpion robot from DFKI [21]). Eventually, the team will exhibit autonomous behavior, thus being highly flexible in terms of unexpected situations. The mission control software provides autonomous failure reaction by switching into a state of manual control if no solution to the current problem can be found autonomously. The robotic systems are (re)configurable in different terms, for example by applying different payloads, using legs as manipulators or through coupling legged scout and wheeled rover.

The LUNARES mission starts after the lander has touched down on the lunar surface and the rover was unloaded. The rover is equipped with the scout. The first action for the manipulator arm is to equip the rover with scientific payloads (mock-ups). Afterwards, the walking scout robot is transported by the rover to the crater rim and decouples itself from the rover to move into the crater. The crater itself is too steep and rocky to be traversable by a wheeled robot. The scout climbs down into the dark areas, collects a sample, and brings it back to the rover. Then the rover picks up the scout to carry it back to the landing unit. Arrived at the landing unit, the manipulator grabs the sample which could be further investigated by the lander's instruments or sent back to earth.

2. Test Environment

To verify the methods and the system performance, a test environment was built (also referenced to as Space-TestBed / TestBed) which emulates a part of an average lunar polar crater. Since there are no high resolution pictures from telescopes or satellites, we used pictures from the NASA Apollo missions [22] to get a guidance in designing the crater. Figure 1 shows a comparison between our TestBed (top) and actual photographs from Apollo 16 (bottom).

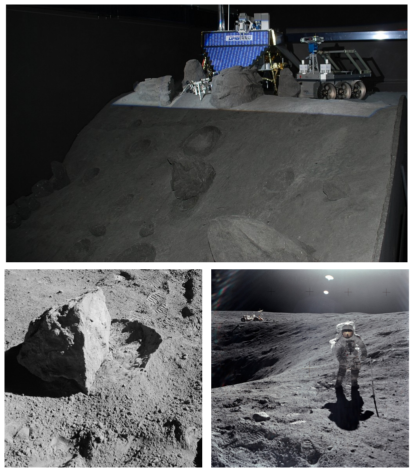

Fig. 1. The Crater Test Environment in comparison to moon pictures from NASA (Apollo 16), a flashlight was used to show the inner crater content, which otherwise would be to dark for the camera.

The artificial crater is situated in a laboratory of $45m^2$. The slope of the crater varies between 80% and 100%. A plateau, where the lander is placed and the rover is able to traverse a moderate rough terrain, is also featured. The slope with 80% inclination with smaller impact craters reflects the situation of miniature asteroid impacts on the moon. Additional rocks of different sizes and geometries can be placed on the slope, rim, and plateau. The rocks can either be fixed by screws to simulate rocks deeply buried in the ground or placed without any fixation.

In order to evaluate image processing techniques, the TestBed can be illuminated by floodlights with a color temperature of 6000K and a luminous flux of 49000lm (a 100W light bulb has a luminous flux of approx. 1300lm).

To evaluate the experiments in the test environment, a motion tracking system as well as five surveillance cameras (three of them with pan-tilt capabilities) have been placed in our laboratory. This ensures a good ability to analyze the experiments. The tracking system is used to deliver true positions of the robot and thereby evaluate the accuracy of the localization methods. Current software developments in our institute will allow to hold the point of view of the cameras automatically on the robot's position and record the video and telemetry data of the tested robot simultaneously to be able to reproduce the experiment with all recorded data.

The absolute position can also be used to control the position of a gantry crane which is located over the crater. The crane carries two of the cameras (for top and side view of the robotic system). It is also possible to attach a simple gravity compensation (realized by a counter weight) to the crane to test the robot's locomotion in low gravity environments like moon or other planets.

3. Robotic Subsystems

LUNARES is meant to use available technologies to demonstrate the abilities of reconfigurable robot teams especially in space robotics. The space qualification and usability in space is not addressed within the project. A goal is the identification of critical issues while demonstrating the feasibility of a heterogeneous robotic team for such missions and to prove that autonomous reconfigurable robot teams are able to reduce efforts and costs in future space missions. Another focus is an increased autonomy of the overall system and the cooperation of heterogeneous robots to accomplish complex tasks which a single robot could not cope with. In the following sections we want to present the three subsystems in more detail.

3.1. Lander with Robotic Arm

The landing unit in the LUNARES project is a scaled-down (1:1.6), slightly modified mock-up of the landing unit in the Mona Lisa project [23]. Located on top of the lander is a tower with a sensor head on a pan-tilt-unit. The head is equipped with a laser scanner, a 3D camera with two different baselines, and two lights for illumination (fig. 2).

The robotic arm (in parking position in fig. 2) enables a reconfiguration of the rover by applying different payloads to the designated bays. The position of the rover in front of the lander is measured by the laser scanner (see fig. 3 for an image obtained with the laser scanner). To place the payloads, visual servoing is employed using a video camera on the end effector of the robotic arm. The arm and the sensor tower are the two active components on the lander.

The lander system is equipped with a sensor tower carrying a laser scanner and a trinocular camera system with spot lights. All sensors are mounted on a pan-tilt-unit and are active sensors in terms of being able to control the gaze direction of the cameras. Especially the laser scanner mounted on the swiveling unit works as an imaging LIDAR and provides dense and accurate depth maps of the surroundings of the lander (fig. 3). Small retro reflective markers mounted at the rover produce bright spotlights in the intensity image which is additionally

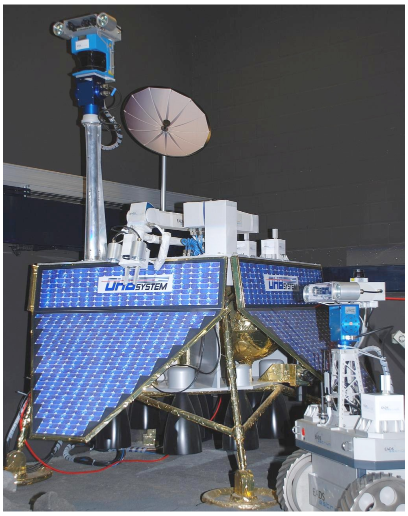

Fig. 2. Rover and landing unit in the test environment. On the lander mock up there is mounted a sensor tower with a 3D-laser scanner. A robotic arm is utilized for equipping the rover with different payloads.

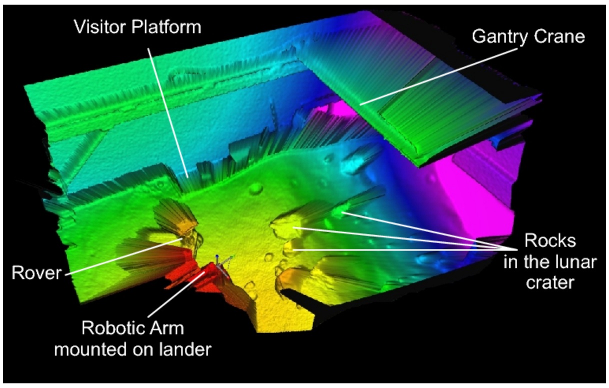

Fig. 3. 3D scan of the TestBed, taken from the sensor tower of the lander. A part of the lander with folded arm and the rover can be identified. The range of the laser scanner is sufficient to scan the whole TestBed, thus the gentry crane and the slope of the crater can be seen in the picture.

generated by the LIDAR. From these spotlights, an accurate pose estimation of the rover can be obtained - at least in the vicinity of the lander. This information is used to direct the rover to the lander and towards the work space of the manipulator of the lander. Once arrived at the work space of the manipulator, vision-based and more accurate techniques are used to reconfigure the rover and the scout. For this purpose, visual servoing (section 5.1) is applied and a camera mounted at the end effector is used for the last steps.

3.2. Wheeled Rover

The rover in LUNARES serves the purpose to overcome greater distances in a terrain which has moderate slopes and obstacles. In this way, an energy-efficient locomotion principle can be applied. Due to lack of space in the TestBed, the distance is only indicated. The rover is equipped with a sensor tower, two payload bays, and a cargo area where the legged scout is transported. A side-effect of the usage of already existing robotic systems is that these systems are not best possible matched to each other. The cargo bay of the rover, for example, has a height which the scout is not able to overcome by itself. The dimensions of the rover are $600mm \times 800mm$ (W$\times$D) with a height of $400mm$ (cargo bay) and $930mm$ (top of sensor tower), respectively. To overcome this difficulty, we came up with a parallel crank lever to lift the scout onto the rover. In fig. 4 the rover with docking adaptor and docked scout is shown.

The rover is a modified version of a previously built EADS transport platform, which now serves as a substitute for an actual space-qualified rover. The locomotion system of the rover comprises two PowerCube drives controlled via CAN bus. Furthermore, the rover contains a sensor head with a trinocular stereo camera system and a Hokuyo laser scanner, as well as two spotlights. All these components are mounted on a pan-tilt-unit which is controlled via the same CAN bus.

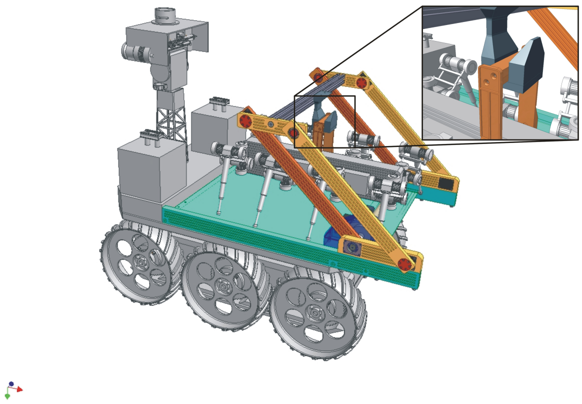

Fig. 4. CAD model of rover with docked scout. The docking adapter is realized as a parallel crank lever, allowing to keep the scout parallel to the cargo bay of the rover. The docking is passive by means of a hook and a bail.

3.3. Legged Scout

The Scorpion [21], [24], [25] serves as the scout in LUNARES. Scorpion is an eight-legged walking robot for hazardous outdoor terrain with three active and one passive DOF per leg. It uses a biomimetic control concept which allows a very flexible, robust walking behavior in various terrains. The walking gaits of the Scorpion robot are based on research on walking patterns of real scorpions [26]. Figure 5 shows the Scorpion in its actual design used for LUNARES.

The robot can be controlled by giving simple directional commands which are processed by the low-level locomotion control. The Scorpion serves mainly as a test platform for different locomotion patterns before transferring them to another robot. Due to the limited computational power of the robot itself, autonomous high-level behavior has to be executed on an external computer.

In LUNARES, Scorpion is used substitutionally for a legged space-qualified robot, acting as a scout in a real lunar mission. The DFKI Bremen is currently developing a more appropriate space-qualifiable, free-climbing robot which could be used as a scout for a real LUNARES-like mission [27].

Fig. 5. The eight-legged scout "Scorpion". Each leg has 3 active DOFs and is equipped with an elastic spring component in the shank which is also used for ground contact detection. On the front legs there are mounted grippers used for sample acquisition.

3.4. Reconfigurability of the Subsystems

We distinguish between four different aspects of reconfigurability which are described in the following sections. The main focus in LUNARES is on the two first mentioned types of reconfigurability. We are not considering a total reconfigurability for LUNARES where robots are completely composed of replaceable modules [28] since the intention was to use existing robots of the project partners.

3.4.1) Reconfigurability of a subsystem itself: A subsystem (robot) is said to be reconfigurable if parts of the subsystem can be used in different ways. In case of the legged scout, for example, the front legs are reconfigurable by using them for locomotion and manipulation. Due to the claws, it is possible to utilize the leg as a manipulator for picking up a geological sample. The claw itself is also reconfigurable since it can also be used to enlarge the contact area of the feet when walking on loose gravel or sand.

3.4.2) Reconfigurability of payloads: The exchange of payloads on a given system is considered to be a reconfiguration of payloads. The following example shows an extension of the reconfigurability of payloads: Given the availability of a camera module, an energy module, and a communication module, a robot can make use of these modules while traversing the planetary surface. If the robot has reached the desired site where it should accomplish a certain task it could combine these modules, deploy them, and use this newly created module to get an external view on the currently executed task.

3.4.3) Reconfigurability beyond the mission-lifetime: Reconfigurability beyond mission-lifetime aims at reusing robotic systems in missions following the one the robot was originally intended for. To achieve this aim, a great amount of modularity has to be implemented. By using modules with a standard interface, a gradual assembly of a planetary infrastructure is made possible.

The basic robotic systems may be equipped with new modules. This way, existing robots on planets can be reused for new activities by sending new modules to the planet.

3.4.4) Reconfigurability preceding a mission (reusability of components): The reconfigurability preceding a mission is related to the reconfigurability beyond the mission-lifetime. Here the modules are designed in a way that allows to build up robots in an easy way. Existing modules can be attached to easily build up a robot for a specific purpose (i.e. security surveillance or missions to other planets). By establishing this concept, well-known modularity concepts of software engineering can be transferred to robotic hardware.

4. Robot Control

4.1. System Control

The control of the systems is based on the Functional Reference Model (FRM) [29], [30] defined by the European

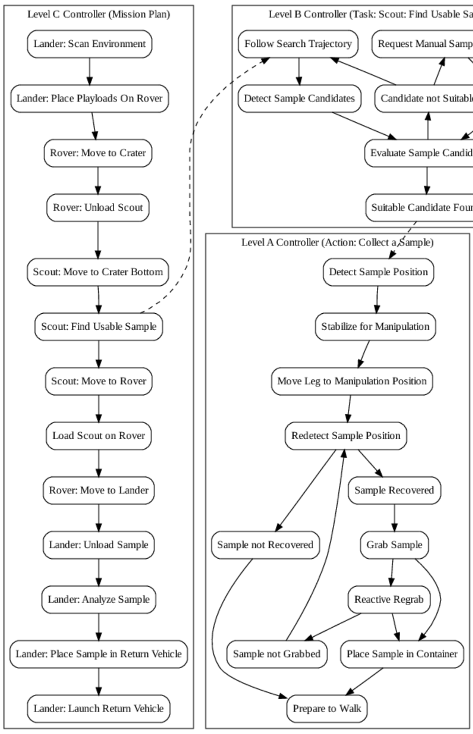

Fig. 6. Example of the Mission Control divided into Level C: Mission, Level B: Tasks and Level A: Actions. For Level B and A, one example is depicted in more detail.

Space Agency (ESA). FRM divides autonomous robot control into three layers, examples of these layers, taken from LUNARES are given in fig. 6. The layers are organized in three layers: “Mission Layer” (Level C), “Task Layer” (Level B) and “Action Layer (Level A)”

The Action Layer defines basic actions like movements or gripping. The Task Layer is responsible for sequences of actions and defines tasks composed of actions. The Mission Layer is responsible for the overall mission execution and is itself composed of tasks. Due to this approach, the Level B and thereby also Level C Controller can make use of the existing Level A Controllers (original control software of subsystems).

The three main columns of information flow typical for the FRM 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 layer. 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 sent and evaluated.

In addition, the FRM plans for 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.

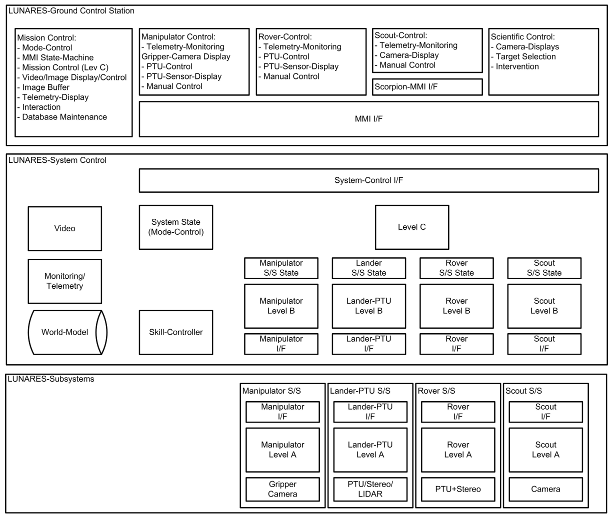

Fig. 7. Overview of the LUNARES control architecture: Bottom: Subsystem control with all level A controllers of rover, scout, lander, and manipulator. Middle: System control with level B and C, and other support functions like monitoring, telemetry, vision server, world model and skill controller. Top: LUNARES ground control distributed over several workstations.

Besides the three control levels, the LUNARES system control also features 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 includes 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 7 depicts the main components of the system architecture.

The level B, i.e. the task controller, applies a PHP script interpreter. So each 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 sent to the level A, which normally understands numeric data and parameters only.

4.2. Ground Control Station

The LUNARES ground control station is based on the ground control station developed for the ESA underwater model of EUROBOT [31] which demonstrated astronaut assistance operations on a COLUMBUS mock-up of the International Space Station. Currently, the LUNARES implementation of that control station provides a manual controller for all robotic subsystems, a mode controller, a mission controller, and planner, as well as a vision controller MMI for all camera systems.

4.3. Manipulator Control

The manipulator level A controller of the 6DOF manipulator mounted on the lander runs on a QNX operated embedded PC. The arm itself comprises six PowerCube modules and an electric clamp gripper. The level A controller provides all actions related to basic movements of the arm. This includes Cartesian and joint-wise interpolated arm movements, the gripper control, and an open interface to the interpolation cycle of the arm control. This interface enables the direct and fast control of the manipulator via a SpaceMouse interface or even haptic interfaces as demonstrated for the ECoS control station [31]. The same interface is also used for the visual servoing that solves the grasping of the payloads of the LUNARES scenario.

4.4. Rover Control

The level A controller of the rover provides several actions for the movement of the rover, as well as for the pan-tilt-control. The motion control includes velocity-based control as well as motion control along trajectories modeled by cubic splines. The laser scanner can be directed towards the ground in order to work in a slicing mode, where obstacle avoidance is performed. For navigation purposes, the rover is able to sweep the laser scanner over the ground, thus providing local dense depth maps of the environment, which will be used for navigation in the near future. For internal state estimation, the rover controller has access to an inertial measurement unit (IMU) and an inclinometer.

4.5. Scout Control

The Level A Controller of the Scout is divided into two parts. The legs and thereby locomotion are controlled using a MPC555 micro controller, while the position control of the legs is implemented in an FPGA. The micro controller is executing the MONSTER[3] micro kernel developed by the DFKI [32] which allows a real time execution of drivers for sensors and motor control as well as execution of behaviors like movement patterns.

The movement patterns are similar to the output of Central Pattern Generators [26], a set of rhythmic repeating curves describing the movement of the legs. Additional reflexes provide a stable locomotion in rough terrain. The most important reflexes are a “stumbling reflex” and a “hole reflex”. The first of which detects if a leg is stuck in a flight phase and tries to overcome the obstacle causing the reflex while the latter tries to get the foot to the ground if the ground contact is not sensed where it was expected.

[3]MicrOkerNel for Scabrous-Terrain Exploring Robots

5. Experiments

5.1. Vision-Based Reconfiguration

So far, two main types of reconfigurability of the heterogeneous robotic system are addressed in the LUNARES project. The first aspect aims at the reconfiguration of the two mobility systems, i. e. the scout can be carried by the rover, can leave the rover, and, after gathering some samples, has to return to the rover which brings the scout and the sample back to the lander. The second aspect aims at the reconfiguration of payloads, which is demonstrated by exchanging payload dummies between lander and rover, and a sample box between scout and lander.

For both purposes, the grasping of objects and the docking between two mobile robots, a visual servoing [33] approach is applied. This technique has the advantage that neither a hand eye calibration nor any internal camera calibration is necessary. 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. In each image there is a set of n markers $\{(m_x^1, m_y^1)^T, \cdots, (m_x^n, m_y^n)^T\}$ obtained. 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):

$$\begin{aligned} \pi \quad : \quad & \mathbb{R}^6 \to \mathbb{R}^{2n}, \\ & (x, y, z, \alpha, \beta, \gamma) \mapsto (m_x^1, m_y^1, \cdots, m_x^n, m_y^n)^T. \end{aligned} \tag{1}$$

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 is reduced 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.

$$\Delta(c) = \left(D\pi(c_0)^T D\pi(c_0)\right)^{-1} D\pi(c_0)^T \cdot (\pi(c_0) - \pi(c)). \tag{2}$$

The Jacobian $D\pi(c_0)$ can be determined by applying test movements along all six directions. Figure 8 depicts the result of the visual servoing approach for a simple payload pasted up with four markers.

The next figure (9) shows the movements of the visual markers during the visual servoing process. The process runs on standard PC hardware (Pentium Core 2 Duo) at 10 Hz. The process converges after approximately 10 s. The accuracy is high enough to perform a “blind grasping” afterwards.

The second reconfiguration, i. e. the docking between rover and scout, can be solved in a very similar way. The same type of markers are attached to the scout and are observed by the rover camera system. The correction values $\Delta(c_0)$ for the positioning of the scout will be directly sent to the scout that

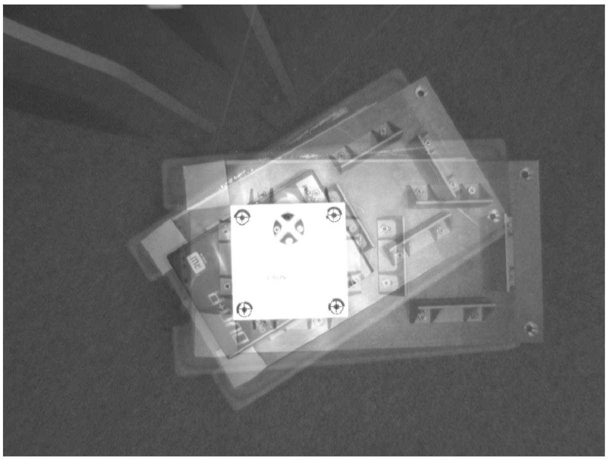

Fig. 8. Overlay of the reference image used for the teaching process of the Jacobian and the image of the camera view after successful control of the manipulator. The visual servoing was able to perfectly align the marker locations whereas the differences of the background clearly show the different situations.

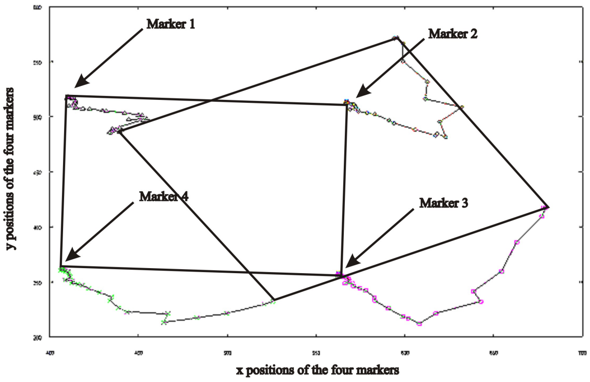

Fig. 9. Positions of the markers in the image plane tracked during the visual servoing process.

moves accordingly. If the correction values are small enough for a certain number of iterations, the correction will be stopped and the scout can be attached to the docking adapter. Currently, first experiments on this approach are running with encouraging results.

5.2. Adaption of Walking Patterns in Steep Slopes

In the past, the angles of the three joints of each leg were controlled via scalable Bézier splines in a way similar to the approach of central pattern generators. In this way, the foot points of the legs move in circular arcs relative to the body of the robot as depicted in fig. 10.

This movement is sufficient for moderate terrain but not the best possible for climbing in difficult terrain like lunar craters since the circular movement leads to twisting which is a reason for increased slipping. Adaptations of the walking patterns lead to an improved climbing in steep slopes. To maintain the grip of the robot in the slope, the feet have to move in parallel to the robot's body. Therefore we implemented an inverse kinematic layer and are now able to use the Bézier splines to describe

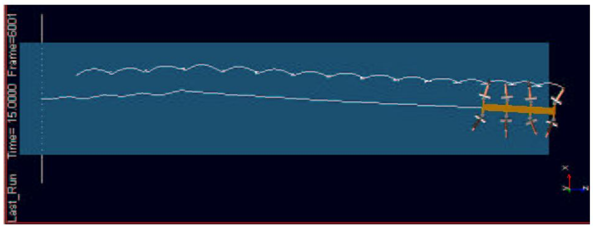

Fig. 10. Movements of feet relative to SCORPION's body, from [21]. The movement of feet in circular arcs around the body leads to increased bracing which in turn leads to increased slippage. By establishing an inverse kinematic layer, we are now able to easily move the feet parallel to the body.

the movements of the feet in Cartesian coordinates (one spline per dimension), thus simplifying the generation of appropriate locomotion in steep terrains while maintaining the ability of overlaying curves, which takes place after the calculation of the desired joint angles.

5.3. Slip Detection at Scout's Feet

To be able to make comparisons between the grip of different types of feet for the scout, we established a slip detection unit. The slip detection is implemented by making use of a two-axis accelerometer which is placed at the tip of a scout's foot.

Since the foot can freely rotate, we combine the values of both accelerometers axes geometrically to get an overall acceleration value. For analysis, the data is plotted with zero mean value, thus the signal oscillates around zero.

Figure 11 shows the plot of a run of the Scorpion in our artificial lunar crater. Plotted are the digitalized raw values from the analogue acceleration sensor outputs over time. The regular movements of the leg with accelerometer can be seen in an interval of about five seconds (see top plot). A three second frame with typical slip data and that resulting from a foot step is magnified (central plot). The bottom most plots show the step data (left) and the slip data (right).

From these data analyzed in time domain, we can already obtain differences in normal footsteps and spikes in the data resulting from slippage of the foot over the surface of the crater. While a footstep causes a dedicated single occurrence of oscillations, the slipping of a foot causes a greater number of oscillations with a shorter duration each but with a longer overall duration of the slippage itself. This is a typical slip-stick phenomenon. A filtering algorithm has been implemented and is able to distinguish between slippage and foot steps. However, we will integrate the data of the Scorpion's touch-down sensors to improve the method.

5.4. Sample Acquisition

To fulfil the aim of returning a sample from within the crater, the scout was equipped with appropriate instruments to be enabled to pick up samples and carry them back to the rover. For sample acquisition, a gripper was implemented at the front legs of the Scorpion, see fig. 12. For detection of an

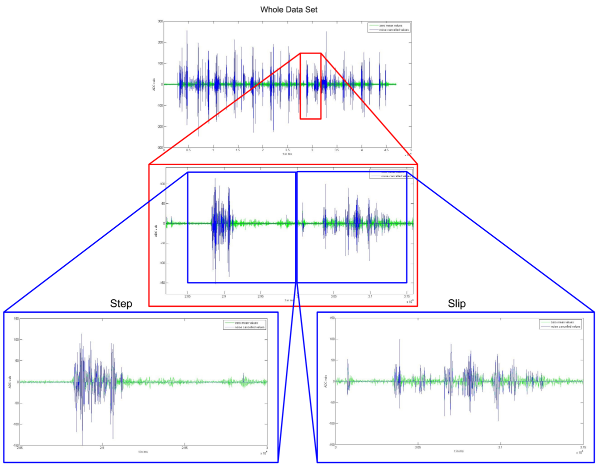

Fig. 11. Slip data of an experiment with the scout in the TestBed. Plotted are ADC ($\pm 1.2g$ digitalized by a 10bit ADC) values against time. On top there is the whole data set from the one-minute experiment. In the middle, a frame with data from a step, and the following slippage, at the bottom of the picture a comparison of both data sets can be seen in a 1.5 second frame each.

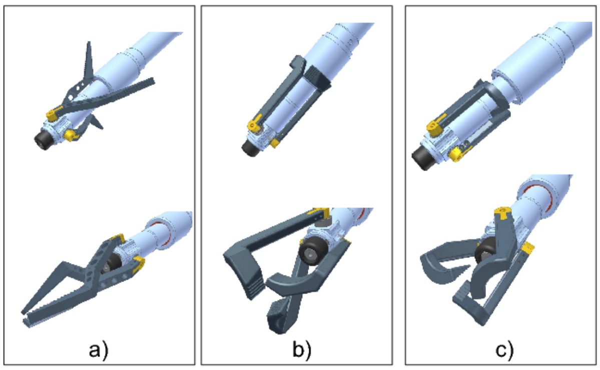

Fig. 12. Three different versions of Scorpion's claws. Experiments showed the clearance between shaft and tip of the first claw to be to great for damage free climbing in very rough terrain.

object of interest, a 2D scanning laser range finder (Hokuyo URG-04LX) with a tilt unit facilitating 3D scans is used. The first version of the claw fully integrated into the scout's lower leg and the implemented laser scanner can be seen in fig. 5

To detect a suitable stone for grabbing, an expectation value for the measurement of the laser scanner is computed assuming a more or less even terrain. A fitting difference between the actual measurement and the expectation indicates a suitable stone to be collected as a sample. This method was successfully implemented on the six-legged robot Scarabaeus [34]. Due to the same micro kernel (MONSTER [32]), which is used on both systems, a migration from Scarabaeus to Scorpion is easily realized.

The grabbing behavior which is executed by the MONSTER Microkernel after retrieval of the sample position is a behavior implemented as a state machine which consists of several states shown in fig. 6 as an example for a level A controller.

The behavior also exhibits a reactive control part. The reactive part in the grabbing state, for example, tries to ensure a successful grip. When the sample slips away in the gripping process, the claw is stretched out a bit more and another attempt to grip the sample is carried out. A second scan state after the lifting of the leg is necessary because during the "Move Leg to Manipulation Position" state the robot could tilt, thus changing the relative position of the leg to the sample.

6. Conclusion and Future Work

Experiments have proven the capabilities of the subsystems and their ability to cooperate and to traverse difficult terrain. In demonstrations up to now, the trajectories of the manipulator arm and the rover were predefined and the Scorpion was remote-controlled. Current developments cope with the autonomy of the systems where the level C and B controller software itself is finished. The implementation of tasks and some missing actions for the level A controllers are under development.

We successfully implemented algorithms based on visual servoing to autonomously pick up and place payloads on rover and lander, respectively. The algorithms for moving the scout into docking pose are also based on visual servoing, still due are experiments in this field to tune the control parameters.

Currently, we analyse the data from the accelerometers in the feet offline in time domain using Matlab with the aim of an evaluation of different feet. An algorithm for slip detection has already been implemented and showed a good performance working on time domain data.

In future steps, we are planning to integrate the slip detection into the robot control in order to adapt the walking pattern to different ground surfaces and inclinations. By further processing of the data, analysis in frequency domain and incorporation of different sensor types, we will build up a system which serves two main purposes: First the detection of slippage for generating locomotion reflexes and second the underground validation by interpretation of the collected sensor data. Using this approach, the autonomous locomotion of the Scorpion in the crater will be enhanced.

By the end of the project, the scout will be able to navigate in the crater in order to descend into it and climb back to the rover autonomously. This will be achieved by an visual odometry approach combined with the identification of some landmarks which need to be specified (lights, radio beacons, etc.).

Even though the project is not finished yet, we were able to identify key technologies which have to be developed in order to be able to launch a space mission using reconfigurable robots.

To advance the modularity of robotic systems, a standardized, mechatronic interface is needed to ensure energy and signal distribution and also to fixate modules to the robot. Given this interface, robots able to carry and interface those modular payloads are needed.

Some space exploration scenarios include construction of infrastructure on other planets. These scenarios range from setting up a seismic sensor array to building up a complete base camp before human arrival. To be able to accomplish such missions, the robots have to be very robust and durable. Also, to be able to have different robot setups for different tasks, for example, first for deploying sensors, then to build up more complex structures, the modular approach can cover all these tasks without sending a specialized robot for each task to other planets.

Other topics have to be investigated, too. This includes new navigation approaches and inter-robot localization for exchanging modules. Communication has to be stable and robust and should work over long ranges (possibly supported by self-deployed communication nodes).

Autonomous behaviors could be used for various tasks: Point-to-point navigation, exchange and deployment of modules, or module clusters without mobility, etc.

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