Towards a Modular Reconfigurable Heterogenous Multi-Robot Exploration System

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Abstract

In this paper we present the project RIMRES – Reconfigurable Integrated Multi-Robot Exploration System[1] and its current state of work. In the course of the project, key technologies for modular reconfigurable robotic systems for extraterrestrial exploration missions are developed and demonstrated under earth conditions. By means of the developed robotic systems complex tasks in uncooperative and difficult to access areas can be solved efficiently. The robotic system consists of two mobile units, a wheeled rover and a legged scout, additionally various payload modules are implemented. Via a uniform mechatronic interface payloads modules can be assembled to complex payloads systems or fixated to the mobile units. Additionally the two mobile units can connect via the interface and act as one robot. This paper starts with a short survey on current developments of robots for exploration of canyons and craters on celestial bodies and then gives a detailed overview on the work in the project RIMRES.

1 Introduction

Lunar Exploration – State of the Art, Goals and Objectives With recent satellite missions (LCROSS, Clementine) to the Moon the presence of water ice at both lunar poles has been confirmed through indirect spectral measurements. This water ice is to be found within permanently shaded regions of the lunar poles, thus in the interior of sufficiently deep craters. Though these first investigations have only been performed via remote sensing, these areas will ultimately need to be explored not only from orbit, but in-situ, meaning by landing and deploying mobile devices to establish a ground truth and to increase the knowledge about the distribution of this resource.

The main scientific objectives for such a mission in search for direct (in situ) evidence for water ice and for the characterization of the local/global environment have been described in literature[2] before [8] and comprise the characterization of:

- volatiles including the determination of the volatile composition (isotopic, elementary, mineralogically), the mapping of the local distribution and the identification of sources;
- mineralogical diversity at the landing site, including age, distribution, origin and composition;
- the lunar inner structure and dynamics;
- the lunar environment including dynamic processes, such as weathering and meteoroid impacts.

Based on these well established science objectives, some basic requirements for suitable exploration systems for the respective south polar environment have been estimated. These are for example:

- sustain the framework for scientific investigations (power, environmental protection, access to surface material e.g.)
- realize local surface coverage in the order of several tens of kilometers
- efficiently (e.g. power wise) negotiate a huge variety of terrain ranging from flat regolith-dominated areas to rough stone-covered steep slopes
- identify target areas for exploration and in-depth measurements and navigate in and out
- sustain a robust system, capable of surviving hazards and adaptable to not foreseen circumstances

Various approaches to realize such systems have been proposed in literature and realized for terrestrial demonstration so far. There are ”classical” singular systems pursued, for example the Scarab rover [2]. These systems are

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[1] Granted by German Space Agency (DLR), Grant No. 50 RA 0904

[2] see also Lunar Exploration Analysis Group, `http://www.lpi.usra.edu/leag/`

designed in a way that all locomotion capabilities as well as the sampling / sensing capabilities are installed on a singular system. An alternative approach is to use a team of robots to reach for hard to access areas and to distribute the scientific and technological tasks to different systems. Generally this yields a rover system specified for locomotion in moderate terrain and a scout system for exploring steep environments.

Abad-Manterola et. al. [1] propose a small two-wheeled rover as scout system to be deployed from a host platform such as the Mars Science Laboratory[3]. Their scout system is connected to the host rover via a tether system for retrieving the scout from steep environments. Winch, actuators for locomotion, on-board computer, and sensing devices (stereo camera and inertial measuring unit) are mounted in a main tubular body. A simple mechanism for gathering soil samples is mounted on a caster arm.

Huntsberger et. al. [7] propose a similar, yet different, approach of a system using two tethers from two anchor robots, that allow a so called *cliff-bot* to investigate steep slopes. In field demonstrations, the successful negotiation of slopes of up to 85° could be proven.

In [4] a heterogeneous robotic team constituting a legged robot as scout for access of the interior of steep lunar craters and a wheeled rover for energy efficient locomotion in moderate terrain are presented. The scout is a free climbing robot and uses no tethering system to overcome slopes of up to 35°. The system is evaluated in an earth demonstration setup.

Evaluation of modular systems It can be deduced from the afore-mentioned objectives and requirements, as well as from experiences made during earlier investigations, that the tasks to be performed by such a system are extremely diverse, which makes it difficult to design one single system that fits all needs. Performing a grouping of relevant subtasks, a possible division could be made between (1) general exploration tasks, (2) local surface analysis tasks (3) environmental analysis tasks (including geophysics). Each of these subtasks has different requirements, e.g. regarding the timescale of observations, the required surface coverage and the terrain to be negotiated. Consequently the optimized system-designs for each task are severely different. A modular system has been found to be a suitable compromise between the two extreme solutions for this problem, i.e. having three dedicated separate systems versus having one system that performs non-optimal in any case. The reasons for this are as follows:

- specialization (different tasks, see above) leads to increased energy efficiency for sub-tasks vs. generalization
- having separate systems and modules increases survivability if sub-modules are defect and allows to fulfill at least partially the required science objectives
- reconfigurability increases robustness of the whole system
- scientific investigations need time, thus task sharing means doing more science in the same time

The remaining question that has been discussed in the framework of this study is the degree of modularity. Several types and degrees of modularization and reconfigurability have been described in literature and are as follows:

1. atomic modularization with self-similar modules to
2. systems that continuously change their parameter set, e.g. their shape, but are otherwise rigid,
3. cooperating swarms of sub-robots (with and without specialization),
4. plug-and-play modularization where each subsystem constitutes one module and
5. extendable systems, where the general structure is fix and only end-effectors are interchangeable.

For the RIMRES system presented in this paper, a combination of the latter options has been chosen, which facilitates the usage of the same resources, thus favors a modularization that specializes on subsystems that provide resources, but at the same time reduces the system complexity compared to the molecular modularization.

2 Overview of the Proposed Heterogeneous Robotic Team

The RIMRES system addresses several aspects of a science mission on the lunar surface. One aspect of the system development is the surface mobility. By combination of different locomotion concepts, a wide range of surfaces can be negotiated, resulting in an increased scientific impact of the systems. More precisely, a wheeled rover is used for energy efficient locomotion in moderate terrain, whereas a legged scout is used for climbing in rugged terrain and steep slopes. In a lunar crater exploration scenario, during transfer from the landing unit to crater rim, the systems are connected via a mechatronic interface (section 3.3) providing electrical and mechanical connections. Having arrived at the area to be explored by the legged scout, the systems detach and are able to act as two independent systems, thus the high mobility of the legged system can be fully exploited.

A second aspect of RIMRES is the modularity of the system. All payloads are contained in a modular frame. These payload-modules provide two mechatronic interfaces for enabling the stacking of different payload-modules in order to form new, more complex payloads, section 3.4. Figure 1 illustrates the general idea behind the modular concept: Various modules and mobile robotic units can be connected via a uniform interface. By setting up a network of radio communication and relative naviga-

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[3] NASA JPL, `http://marsprogram.jpl.nasa.gov/msl/`

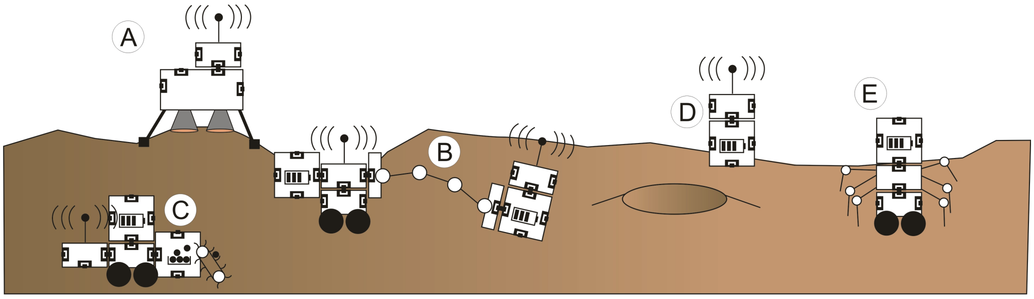

Figure 1. Schematic scenario for RIMRES. (A) The landing unit with mechatronic interfaces and a REIPOS module. (B) A wheeled rover deploys a REIPOS/energy module stack. (C) A rover with additional battery module and REIPOS module makes use of a sampling device. (D) Operating REIPOS module (with energy module). (E) Wheeled rover and legged scout with additional energy module traverse moderate terrain while being connected.

tion nodes (the REIPOS system, described in more detail in section 3.4), a basic infrastructure for extended science missions is established.

For eventually increasing the safety of robotic celestial surface operations, increased system autonomy is needed. The autonomy is addressed within the project in a sliding autonomy approach, see section 4.2.

In the course of the development of the RIMRES-system a demonstration mission similar to that shown in the LUNARES-project [4], [6] will be conducted. In the demonstration, the cooperation of the systems during docking procedures between rover and scout as well as the scouts high mobility in an artificial crater environment will be demonstrated. Furthermore, the legged scout will take a geological sample in an environment that is not accessible for the wheeled rover and return the sample back to the rover for transfer to the landing unit. During the exploration of the hard to access crater area by the scout, the rover will set up a scientific instrument, the Pluto-Mole-module, see section 3.4.

The aspects of the RIMRES-project can be subsumed as follows:

- Advanced surface mobility
- Cooperation of heterogeneous robots
- Autonomy of the systems
- Modularity and reconfiguration of the systems
- Setup of a basic science-supporting infrastructure

3 Hardware Systems

In this section, the hardware of the RIMRES-system is described. First the mobile units, namely rover and scout are presented. Subsequently some of the immobile units of the overall system are outlined.

3.1 Rover

This section deals with the wheeled rover design for the heterogeneous robotic team. First the general rover design is presented, then the planned ”intelligent” wheel is discussed.

Basic Rover Design Concept Figure 2 shows the current CAD-design of the RIMRES rover. The rover provides an active chassis system. The chassis system consists of four independent ”legs” each of which is equipped with a wheel. The legs can be actuated with six degrees of freedom (DOF). This allows for an active adaption to slopes and provides the possibility of lifting each wheel separately to free the rover from stuck situations or overcoming big obstacles.

Figure 2. CAD-design study of the RIMRES rover. The rover provides four wheels mounted on an active/passive chassis system. Mounted beneath the rover in this CAD-drawing is the six legged scout robot. Shown on top are five payload modules (dark boxes).

Spring deflection elements in the chassis system allow for passive adaption to small irregularities in the ground. Note that the wheels displayed in the figure are mock-ups and are to be replaced with the intelligent wheel described in the next paragraph. All DOF of the system have a high gear reduction and are self-inhibiting, thus the energy efficiency of the wheeled system is kept even with the increased maneuverability.

The rover provides four docking ports for immobile payload units. These units are manipulated with the central manipulator arm. The end-effector of the arm is constituted by the mechatronic interface, that connects mechanically and electronically to the modules, see also section 3.3. The arm is designed in a way, that it is able to support locomotion, for example by using the arm as a leg that supports against downhill slippage when driving along a slope.

Intelligent Wheels for a Lunar Rover The wheel development for the RIMRES rover is based on the experience that has been gathered with flexible metal wheels at DLR Bremen during former ExoMars-project work and Lunar Rover studies for MoonNEXT. It is taking into account the main requirements that arouse from the system (e.g. mass) as well as the terrain conditions (e.g. surface material density) and is based on numerical calculations with the TPM (Tractive Prediction Model) and tests with the SWT (Single Wheel Test Bed) [11].

The RIMRES rover has been conceptualized for negotiating diverse terrain on the lunar surface, ranging from soft soil at the rims of fresh craters and on slopes to more compact soil in intercrater areas or areas with high surface coverage of stones. Furthermore, the rover will have a flexible configuration in the form of interchangeable payload modules as described in section 3.4, as well as a scout, which can be attached and detached from the rover, leading to a large range for the total system mass. Since the wheels on the other hand are normally optimized for a certain mass and underground in terms of their stiffness and geometry, it has been found to be advantageous to incorporate adaptability of the wheels to these changing requirements. The goal is to design a wheel with an effective, flexible and robust performance under all conditions, which led to the conceptualization of the so called ”intelligent wheel”. By incorporating a range of sensor-elements (e.g. pressure sensors and strain gauges), the ”intelligent wheel” would be able to measure its state in terms of surface pressure and deformation and is enabled to react to maintain an optimized state by changing its stiffness via sophisticated adaptronics.

Furthermore, once the general infrastructure for a sensorized wheel has been realized, even more sophisticated instrumentation, e.g. conductivity or temperature sensors, as proposed by Buehler et al. [5], could be incorporated into the wheel design, which would provide additional scientific investigations while rolling the wheel over the surface material.

Figure 3. Integration study of the SpaceClimber robot. SpaceClimber is the antetype for the RIMRES scout system. A sensor head will be added for the prototype.

3.2 Scout

The scout system of the proposed heterogeneous robotic team is a six-legged walking and climbing robot. The design of the robot follows a parallel development of the SpaceClimber project [3]. Figure 3 depicts the current design of the SpaceClimber as antetype for the RIMRES-scout.

The key element of the legged robot is the actuator design based on RoboDrive[4] motors. The developed actuator provides a high ratio of output torque to weight (28 Nm cont. torque to approx. 500 g overall weight of the actuator module). The actuator module provides integrated 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 main task of the scout system 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 within the project LUNARES [6].

3.3 Mechatronic Interface

The mechatronic interface (MI) is a central element for modularity in the RIMRES system. The MI is used for several connections: (1) Rover and scout connect via the MI to form a tightly coupled system, (2) the MI is used to fixate the payload modules (section 3.4) onto the

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[4] http://www.robodrive.de/en/

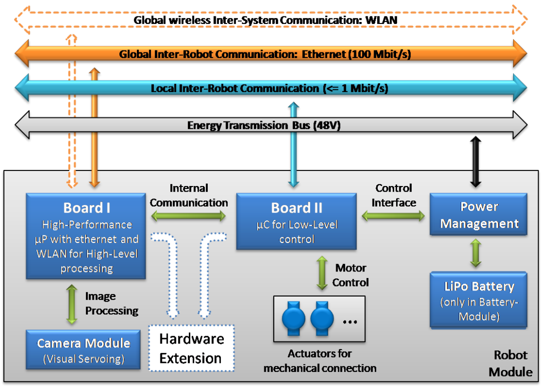

Figure 4. Overview of the module communication and power management architecture

rover, (3) the manipulator arm on the rover has a MI as end-effector, allowing the manipulation of the modules, (4) the MI serves the purpose to stack singular payload modules to form more complex payload units.

The mechatronic interface provides several connections in order to enable close coupling of the singular RIMRES systems:

- Mechanical connections for fixating modules and mobile units to each other,
- Data connections for communication via ethernet (global communication, GLC) and RS422 (local communication, LOC),
- Energy connections for sharing energy sources via a common energy bus.

3.4 Modules

Along with two mobile units, rover and scout, the RIMRES system provides immobile payload modules. These modules can be stacked via a mechatronic interface to built up more complex payloads from the singular modules. Additionally, the modules can be attached to the rover as well as to the scout.

For the RIMRES demonstration system, a battery module is planned to represent an energy harvesting module (e.g. solar-module) for the immobile payload stacks and to prolong operations in shaded regions. 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, see next paragraph. The PLUTO Mole system [9] that flew with Beagle-2 in the Mars Express mission, will be incorporated in a module frame in order to demonstrate the feasibility of the modular approach of scientific payload design.

Figure 4 displays the general structure of each payload module as well as the communication layout for the inter module communication. In general, in the term ”modules” the mobile units rover and scout are included as well.

Relative Interferometric Positioning Module For the utilization of the RIMRES system on solar system objects (e.g. Moon, Mars) the navigation of the system as well as the communication between the systems has to be supported. As there is no regular GPS available, an orbiting satellite infrastructure may provide a standard navigation service. However, due to the complexity of such an installation, an autonomous navigation system is preferred. The proposed system is able to support the relative navigation of the mobile units in a certain region.

By taking regular terrestrial navigation system of the pre-GPS era as an example, an interferometric high frequency radio system is formulated. The REIPOS (Relative Interferometric Position Sensor) system consists of several sensor units, that are mounted on the mobile RIMRES units as well as on deployable payload or instrument modules.

For a navigation measurement, two units are exchanging radio signals with each other. Every REIPOS sensor is equipped with an spacial distributed antenna array, for receiving the radio signal with a temporal distribution on the single antennae. An internal high frequency computational system compares the received signal from all antennae and detects the time differences of their arrival. With the knowledge of the spacial relationship of the antennae, the direction of the incoming transmission can be reconstructed.

Additionally to the direction of a unit, the distance between two units is measured. This is carried out by determining the round trip time needed to sent a signal from one sensor to the other sensor and back again. A critical issue of this approach is the high speed of light and the relatively small distances between the sensors (approx. 100-500 meters). The time measurement has to be accurate within a few nanoseconds. Furthermore, the internal electronic signal delays of the sensors have to be known in this timescale.

To enable high timing requirements, two design features have been identified:

- Highly synchronous send and receive ability on one sensor,
- Fast analog processing on the partner sensor for the return-signal.

The concept of this system is shown in Figure 5. The synchron send and receive ability shall be accomplished by an FPGA on the master Sensor 1. Here the true multi execution feature of such a hardware can help by the time synchronous output and input of digital signals. After a certain amount of random bits have been send out and

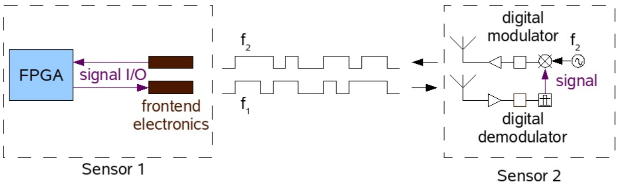

Figure 5. Schematic concept of the REIPOS distance measurement. Full duplex signal round-trip with bit-code signals for best time correlation performance.

received, a subsequent algorithm will correlate these two data streams within the time domain. The appropiate electronics of the partner sensor consists only of a receiver that listens on one frequency (f_1) and a transmitter that sends on another frequency (f_2). A direct connection between these two stages ensures an absolute minimum of delay in the transponder Sensor 2.

With the knowledge of the direction of the incomming signal transmission and the distance to the other sensor, a polar coordinate is created that provides the relative navigation information between the two units. Although the accuracy of the system will decrease with higher distances between the units, the REIPOS will deliver at least the information, in which direction the mobile unit shall move to reach a certain target point. An additional feature will be the medium range data link, as the high frequency radio system allows of course also the transmission of data packages.

Modular Payloads The modularization of the payload has been found to be of extreme importance, allowing a quick reaction on new findings during an exploration mission, via the interchange of payloads of different types as well as the build-up of independent module-stacks, which can perform investigations at a certain site, while the rover moves on. An investigation of the suitability of payloads for modularization has been performed which was also used to provide some parameters for the further sizing of e.g. the battery packs or the communication nodes.

In principle, all currently existing types of payloads are suitable for modularization, ranging from geophysical experiments to spectrometers for mineralogy and analytical instruments to investigate the chemistry of a sample. However, some requirements and peculiarities have come out of the survey, which are for example:

- The masses for one modular instrument (without the module housing itself) range from 2 to 7 kg.
- The energy-demand depends on the application. For stand-alone geophysical applications for example 10000 Whrs are needed (for operations of ≈2 yrs.)
- Some instruments have requirements for placement on the targets or for sample feeding, which has to be taken into account into the module-design
- Modules need to be equipped with environmental protection means (thermal, dust, electrostatic discharges), if they are to be used for stand-alone applications
- Instruments will have to be operated autonomously

In the framework of the RIMRES demonstration we will proof that modularization of a payload is also feasible in practice, by modifying the existing PLUTO-mole [9] and incorporating it in one of the hardware modules to be built.

4 System Control

The system control constitutes two main parts: (1) The modular software framework (SWF), that is used to enable the communication in the RIMRES system with changing morphologies (scout and rover connected or separated, immobile modules connected etc., section 4.1) and (2) the sliding autonomy framework, that supports varying degrees of autonomy for the systems, section 4.2.

Additionally to the above described relative navigation for short and medium distances, a concept for wide range star-navigation is investigated within RIMRES. This concept is presented in section 4.3.

4.1 Modular Software Framework

As described above, the RIMRES-System consists of different mobile and immobile subsystems, constituting a reconfigurable, modular overall system. In this paragraph, the term module also includes the two mobile systems rover and scout. To be able to control the overall system, a representation of the current system configuration has to be mapped in the software.

There are two ways, a module can be connected to another:

- The modules are physically connected via the mechatronic interface (with or without intermediate modules)
- The modules do not have a physical connection, thus the communication is done wireless (i.e. via REIPOS)

If a module enters the system, its functionalities, limitations and possible neighboring modules have to be made known and propagated via the existing network 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,
- by powering up (down).

The software framework will support communication between two modules providing the possibility of using

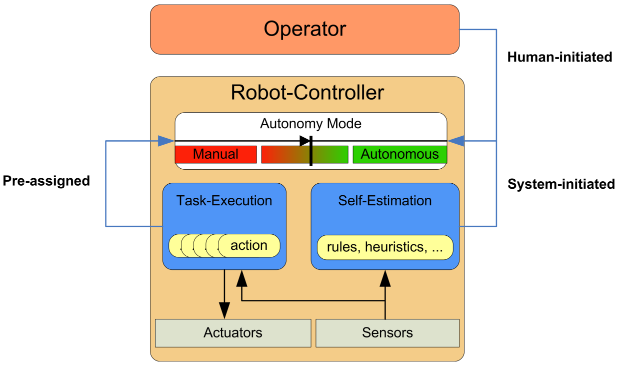

Figure 6. Basic concept of sliding autonomy for RIMRES system. The autonomy level can be changed by a human operator, through a pre-assigned switch in the mission time line and due to new assessments of the success-probability of current task.

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.

4.2 Sliding Autonomy Approach

Since the robotic systems are meant to be as autonomous as possible while at the same time allowing for human interaction a concept for varying autonomy levels has to be developed. The proposed framework spans a continuum of autonomy levels ranging from tele operated human control to full autonomy of the system.

Figure 6 depicts the basic concept of the sliding autonomy framework for the RIMRES system. In general, there are three reasons for a change in the autonomy level of the robot. (1) The *human initiated autonomy switch* describes the demand of the human operator to get (partial or full) control over the robot. The human operator is able to demand control at any time of the current mission. (2) It is also possible to define a autonomy switch in the mission time line. This *pre assigned autonomy switch* is used for monitoring certain autonomous actions via video signals or other sensor data. (3) The *system initiated autonomy switch* is used, when a system recognizes that the current task can not be fulfilled under the given circumstances. Eventually, the robot can call other mobile units for help, however, in RIMRES call for advice will be limited to the human operator.

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 [10].

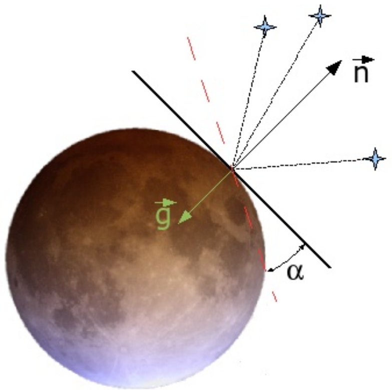

Figure 7. Concept of an autonomous navigation system, including a star-tracker and an inclinometer for the local horizontal measurement.

4.3 Autonomous Wide Range Star-Navigation Concept

The REIPOS system, as described above, is a navigation method that enables the relative navigation between several units. Due to its operation principle it is difficult, to cover long distances for the navigation. Thus a transit or a long range exploration of a mobile unit far away from its landing site requires a global navigation system.

This service may be provided by a fleet of satellites, orbiting the planet, or by terrestrial antenna ground stations. Drawbacks of these solutions are high installation costs and increased complexity of the infrastructure. On the other side, the mobile unit is able to determine its position by itself. This requires a star-tracking system and a sensor for the local horizontal (pitch and roll) information. Within RIMRES, a possible implementation of a planetary star-tracking navigation is studied in form of a theoretical examination.

Figure 7 displays the principle of the anticipated method. The star-tracker determines the orientation of the mobile unit with respect to the fixed star background. Therefore a normal vector $\vec{n}$ can be defined representing the main axis of the star-tracker sensor. In a perfect horizontal mounting of the star-tracker on the planetary ground, the vector $\vec{n}$ defines the position of the unit on a spherical body. However, due to surface roughness, the status of the rover wheels, and other mechanical influences, the star-tracker sensor will not be perfectly horizontal during the measurement. An additional inclinometer sensor provides the information about the pitch and roll angles (displayed as combined deviation angle α) of the vehicle with respect to the local gravity vector $\vec{g}$. Knowing this data, the normal vector $\vec{n}$ can be corrected. Together with the local time, a fully consistent solution can be calculated for the latitude and longitude position of the

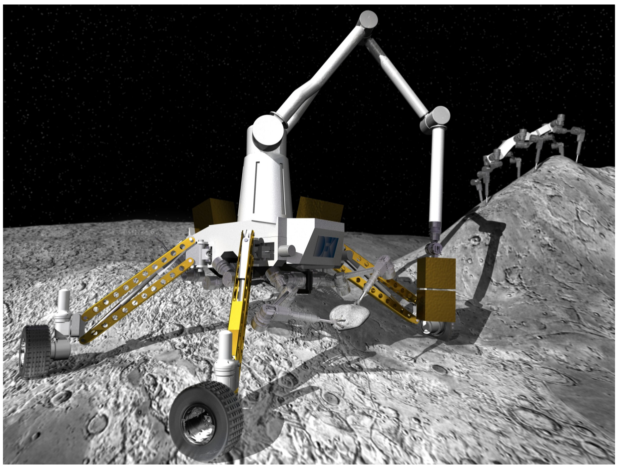

Figure 8. Envisioned scenario for the RIMRES-system: A legged scout is mounted beneath the wheeled rover and analyzes a geological sample. Meanwhile the rover deploys a two-module stack on the surface. In the background a second scout is climbing a steep slope.

mobile unit on the planetary surface. All measurements can be done autonomously without any additional infrastructure, as long as an undisturbed view of the sky is available.

The key element of this concept is a star-tracker sensor as utilized on almost every spacecraft that is launched today. Depending on the design of an interplanetary transfer spacecraft and the lander unit, such star-tracker may be also integrated on the descending unit. A rover that is leaving the lander can make use of that star-tracker sensor if it is embedded in a modular frame. With the RIMRES modular concept, the ”recycling” of hardware for different mission phases (interplanetary transfer, navigation on the planetary surface) is already addressed.

The accuracy of such global navigation systems depends on the angular resolution of its components and the radius of the planet. For the moon, an accuracy of several hundred meters can be expected with state-of-the-art hardware of star-trackers and inclinometers (about 1 arcminute resolution).

5 Conclusions and Future Work

In this paper we presented the overall concept of the RIMRES system. RIMRES aims at a heterogeneous robotic system with high surface mobility and a sliding autonomy approach. The system is built up in a modular way in the sense that payload and instrument modules can be assembled and rearranged to form scientific payloads. The system is reconfigurable in the sense, that the (in principal independent) systems rover and scout can closely connect and act a singular system.

Figure 8 depicts the final RIMRES-system in an artist interpretation. In the next steps, the rover design will be finalized and the prototype will be integrated. Meanwhile the software developments will further progress for the planned demonstration of the systems in a complex simulation environment.

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