RIMRES: A Modular Reconfigurable Heterogeneous Multi-Robot Exploration System

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Abstract

This paper describes the current state of the project RIMRES[1] and is meant to give an overview of the state of integration, the aspects of modularity and reconfigurability as well as the challenges still to be tackled. Within the project, a complex earth-based demonstrator system for a lunar multi-robot exploration scenario is built up, demonstrated, and evaluated. A novel approach is pursued in which a wheeled and a legged system can be combined into a single system via an electro-mechanical interface (EMI). When detached, both systems can act independently and take full advantage of their respective locomotion system. Apart from the mobile units, modular immobile payload units (so-called payload-items) are developed that can be used to (1) assemble various scientific payloads and (2) to enhance or expand the capabilities of the mobile units. The payload items are interconnected with each other or with the mobile units via the same EMI. The scenario that is demonstrated within RIMRES envisions a lunar crater exploration where the wheeled system is used to transport the highly mobile six-legged scout system to the crater rim. The scout is then deployed and starts to climb down into the crater to explore the permanently shaded regions of the crater.

1 Introduction

Considering reconfiguration already in the design phase of a system, higher system performance and robustness can be achieved. Even without reconfiguration explicitly accounted for in the design phase, there are examples of reusing the remaining capabilities of a spacecraft demonstrating that reconfiguration is a possibility to recover from errors. In the Japanese Hayabusa sample return mission[2], several reconfiguration actions during the mission were necessary. For example, after failure of ion thrusters, the components were reconfigured to combine the remaining capabilities in order to still be able to correct the trajectories of the spacecraft.

[1]Reconfigurable Integrated Multi-Robot Exploration System
[2]`http://hayabusa.jaxa.jp/e/index.html`

Figure 1. Parts of the RIMRES-System: Hybrid wheeled-leg rover Sherpa, legged scout CREX and immobile payload-items for building infrastructure and expanding the capabilities of the mobile systems.

A critical issue for planetary modular and physical reconfigurable systems is a *reliable and robust physical interface* for attaching and detaching the single modules. This was also identified by Yim et al. [1], however, explicit experiments concerning dust robustness and reliability of the mechanisms is up to now a sparsely covered topic in literature. For RIMRES, an electro-mechanical interface (EMI) was developed to connect the subsystems with each other. The EMI is tested with extreme dust accumulations and proved to be reliable under those conditions [2].

Another critical issue for planetary exploration is *surface mobility*. Stationary probes (pure landing units) can only provide scientific data for a limited range on the surface, typically in the range of an attached manipulator arm. Opposed to that, mobile systems are capable of traversing relatively long distances and can therefor extend scientific reward of a mission. Critical issues for mobility on planetary surfaces are

- energy efficiency,
- robustness and reliability, and
- the ability to negotiate a wide range of terrains.

These requirements are partly contradictory: On the one hand, wheeled or tracked locomotion provides relatively energy-efficient locomotion when compared with legged locomotion, but is limited in the range of traversable terrains. On the other hand, legged locomotion allows a very strong terrain traversal capability, even free climbing on vertical slopes is possible [3], but due to a higher number of actuators and the need for actively maintaining the body height even when standing still, the energy efficiency of those systems is worse compared to wheeled systems.

There exist various approaches to combine the advantages of wheeled and legged locomotion, in the majority of the cases by designing hybrid wheeled-leg [4] or legged-wheel [5] robots. In RIMRES, this is only one part of the approach: Sherpa is a wheeled-leg rover that can actively adapt to the environment. The active suspension system can further be reconfigured to act as a sensing device, see section 3.1 for more details. The second part of our approach of increasing the surface mobility incorporates *reconfiguration* and *cooperation*: A legged scout can be attached mechanically and electronically to the wheeled rover, constituting a combined system. In this way, the scout can be transported in an energy-efficient manner to scientifically interesting places such as steep craters. Once arrived at the destination, the scout is detached and both systems act independently [6]. In a former approach with systems not specifically designed for cooperative tasks, this already proved to be a feasible approach [7].

2 System and Mission Overview

The aspired mission in RIMRES tries to simulate typical elements of a situation in an exploration mission and/or infrastructure build up. The mission is operated from an earth-bound (mission) control center, which communicates with a system control station at the lunar surface. This system control station is the focal point for communication of all robotic systems that are part of the mission: two mobile subsystems and four immobile payload-items.

The two mobile subsystems are a wheeled rover and a legged scout. Both systems can act completely independently from each other, but at the same time a close electro-mechanical connection between both systems can be established combining both separated systems into one combined system. Further reconfiguration abilities are added by the introduction of modular payload-items that can extend the capabilities of the mobile systems or can be used to create payloads during the mission. These payloads can either be part of a science mission or represent basic infrastructure elements, e.g. for communication.

The overall system in RIMRES is a technology demonstration and will be used under earth conditions. However, for demonstration and validation, an artificial lunar crater (surface area 105m^2) with realistic slopes and lighting conditions has been set up in the DFKI laboratories.

The anticipated mission has the following outline of actions. The rover transports the scout to the rim of a lunar polar crater, where it is detached from the rover. The scout then climbs into the permanently shaded regions of the crater to conduct in-situ measurements for finding water ice. During the transport by the rover, the scout is fully functional, thus its scientific instruments can also be used during the transport phase. The rover's manipulator can be used to assemble scientific payloads from so-called payload-items. For the demonstration scenario, four types of payload-items are implemented: (1) A battery module for extending the range of the mobile units and for powering the assembled science packages, (2) a communication/navigation item (REIPOS, section 3.3.2), (3) a camera module, simulating a data-generating science payload, and (4) the mole subsurface sampling system that already flew on the Beagle-2 mission is planned to be implemented in the RIMRES framework.

In RIMRES, reconfiguration aspects are part of various layers. Firstly, the overall system and team of robots can be reconfigured by either *stacking* of payload-items (onto each other or onto the mobile systems) or by *docking* the legged scout and the wheeled rover. Secondly, on subsystem level the individual systems are capable of different operating modes which we also describe as reconfiguration property: (i) the wheeled rover can be reconfigured in the sense that the active suspension system can be used in various ways to propel the robot - in addition its manipulator can be used for handling the payload-items as well as for locomotion support and supervision of the system (ii) the legged scout is reconfigurable in the sense that the legs used for locomotion are equipped with gripper elements and using a gripper mode are able to pick up geological samples at a site of interest.

3 RIMRES – A System of Systems

As stated above, RIMRES is constituted from different robotic systems that can combine and reconfigure in multiple ways. The central component for reconfiguration is a robust and reliable electro-mechanical interface (EMI). The EMI developed for RIMRES is described in detail in [2], [8]. There is an active and a passive face of the EMI which each are identical throughout the subsystems of RIMRES.

This section mainly focuses on the wheeled rover

Figure 2. Current state of Sherpas integration study. In this picture the active suspension is used to step onto an obstacle. The arm is used to actively influence the center of gravity for improved stability.

Sherpa as the central device in the reconfigurable system RIMRES. The reconfiguration possibilities of the system itself are highlighted. Furthermore, a brief overview of the legged scout robot and the singular payload-items is provided.

3.1 Four-Wheeled Rover Sherpa

The wheeled rover Sherpa is a key team member in our multi-robot system. It is responsible for transporting the legged scout to the crater rim and for transporting payload-items. The wheeled rover is also required to assemble payloads on demand using the manipulator arm attached to the central tower.

Sherpa makes use of an active suspension system that allows to select from a set of *locomotion modes* depending on the current terrain situation. These modes range from various *postures* to enhance the relation of center of gravity and center of the support polygon to substantially different *drive modes*, for example planar omnidirectional movements or inchworming modes, [9]. Figure 2 displays the current state of the integration of Sherpa.

Several elements of reconfiguration are present in the design of Sherpa. First of all, it is obvious that the active suspension system can be regarded as a reconfiguration device: One possibility is to reconfigure the footprint of the rover according to the challenges the current terrain imposes on the rover. This can be seen as a *posture reconfiguration*. Furthermore, the active suspension can be used to actually propel the robot: instead of just using the wheel actuators, the suspension actuators can be incorporated into locomotion, as for example in an inchworming fashion or for undulating behaviors.

A second major part of reconfiguration is the manipulator arm attached to the rover's main body. Its primary use is to handle the payload-items that are attached to the four EMIs located around the central tower. By manipulation of the payload-items, various scientific and infrastructural payloads can be assembled. Furthermore, the arm can be used as a fifth limb, thus reconfiguring an arm into a leg. In a third configuration, the manipulator's palm camera that is normally used for grasping the payload-items in a visual servoing process can be used to allow a human operator to supervise the rover system, thus the arm serves as a hazard cam in this configuration. Additionally, payload-items attached to the arm can increase the abilities of the manipulator, i.e., scoops, sophisticated gripping elements, or other tools (these types of payload-items are currently not planned to be integrated within the RIMRES project).

In the final stage of expansion, the wheels will be reconfigurable subsystems of the rover. There are two major parts concerning the reconfiguration of the wheels: (1) The wheels actively can adapt their stiffness in order to react to (a) changes in the environment, for example softness of the soil, and (b) changes in the rover's mass due to (un)docking of the scout. A further reconfiguration capability is (2) to use the wheels as sensors for characterization of soil properties. This can be achieved by using the sensory disposition of the wheels needed for case (1) in combination with the active DoFs of the suspension system. By this, a bevameter-like sensing device can be created from the combination of wheel and swing unit.

Finally, the rover can be reconfigured using payload-items. For example, additional sensors can be attached via one of the in total six EMIs of Sherpa, i.e., using an additional battery pack to extend the operational time of the system.

3.2 Six-Legged Scout CREX

The six-legged scout is the second mobile system in RIMRES. It is based on the SpaceClimber robot [10] and adapted to the requirements of the multi-robot system RIMRES, e.g. for reconfiguration and docking to Sherpa, an EMI has been placed at the back of CREX.

Apart from the reconfiguration of the overall system by (un)docking CREX and Sherpa, CREX also provides several reconfiguration capabilities by itself. Firstly, gripping elements are employed in the front legs in order to be able to pick up geological samples. Thus, the legs used to propel the robot can be reconfigured to be used as manipulation/sampling devices.

Via the EMI on its back, CREX can be connected to the wheeled Rover. However, the EMI can also be used in the same manner as on Sherpa: arbitrary payload-items can be stacked onto CREX for extending its capabilities. This ranges from additional batteries to specialized sensors for a task at hand. In later stages, it is possible to integrate a second EMI on the belly of the Scout system in or-

Figure 3. CREX robot in artificial crater environment. CREX is equipped with an electro-mechanical interface for attaching to Sherpa and for carrying payload-items.

der to be able to dock specific sampling devices. By using the high degree of mobility of the system, these devices can be positioned precisely over a spot of interest. Figure 3 shows the integrated scout robot CREX in DFKI's Space Exploration Hall.

3.3 Modular Payload-Items

The modular payload-items are cubic modules with an active EMI in the bottom face and a passive EMI in the top face [2]. By stacking the payload-items, different scientific payloads and infrastructure elements can be assembled. All payload-items come with a processing unit (Gumstix) for high-level intelligence and a microcontroller to support low-level intelligence. As part of the low-level intelligence an internal communication protocol has been designed which allows to infer the current topology of a stack of payload-items (a so-called payload) from the EMI connections, and control basic operations such as opening and closing the mechanic latch to attach an active EMI to a passive one. These capabilities are exposed to higher level of control, to allow for more complex reconfiguration activities.

The following sections briefly describe the four specialized module types that are currently under development for RIMRES.

3.3.1 Battery Module

Within the earth demonstration scenario of RIMRES, battery modules are used as replacement for energy-harvesting payload-items. In later stages, additional solar modules for actually harvesting energy are conceivable. A battery module always constitutes the basis of a payload stack, since functional modules and energy modules are separated within the modular framework of RIMRES. While seemingly a simple device, the battery module requires intelligence regarding the power switching. It is possible to connect multiple systems and multiple battery modules at the same time. Each payload-item can be a power sink while the battery modules can be a power source as well. In order to protect the systems from uncontrolled charging and connecting two power sources with different power levels at the same time, a power management system has been set up [8].

3.3.2 REIPOS

The REIPOS[3] class of payload-items serves two purposes. (1) It can determine the direction and distance of other REIPOS modules, thus enabling a relative positioning system [11]. (2) Communication structures can be built up by making use of the REIPOS capability to route messages between the single nodes. Thus, also a REIPOS payload-item itself is reconfigurable regarding its functionality. A REIPOS item always needs at least a battery module to constitute a functioning payload unit.

3.3.3 Science Modules

In order to simulate science payload-items, a camera payload-item is integrated in RIMRES as primary example for a science module. The camera payload-item is a placeholder for more sophisticated scientific equipment, but it demonstrates the core feature: attached to a battery payload-item it can form an active payload. This payload is seamlessly integrated into the system control and communicates within the framework. Using a general message bus which is used by all subsystems it can receive control commands from the mission control: here, by orienting the camera that is mounted on a rotational table and retrieving images. Thus, the acquisition and distribution of gathered data can be proved.

A secondary scientific device is the mole subsurface sampling device that already flew on the Beagle-2 mission. This device is made available by DLR-RY and is planned to be integrated into a standardized RIMRES modular payload-item in order to demonstrate a ”real” science payload in the modular robotic system RIMRES.

3.4 Combinations of Subsystems

To conclude the above statements, table 1 displays the currently possible physical combinations of subsystems in RIMRES. Note that the combination Rover-Manipulator is static in the current setup and here illustrates a theoretic modularization. Otherwise, the table shows the range of reconfiguration the system is capable of. A principle possibility that is crossed out in the table is a connection of two rovers: One rover could connect to another rover with its manipulation interface to one of the four payload-bays of the other rover.

[3] Relative Interferometric Position Sensor

	Rover	Scout	Manipulator	Payload-Item
Rover	✗	✓	✓	✓
Scout	✓	✗	✓	✓
Manipulator	✓	✓	✗	✓
Payload-Item	✓	✓	✓	✓

Table 1. Possible combinations of subsystems in RIMRES. In principle it would be also possible to connect the manipulator of one rover to a payload-bay of another rover.

4 Software Foundation for a Reconfigurable System

The challenges involved in order to support a reconfigurable team of robots are manifold. Various fields of research tackle individual problems which arise simultaneously in an application such as the RIMRES project. The key characteristics of the overall robotic team in RIMRES are distribution, modularity and reconfigurability. In addition, the team of robots is heterogeneous and uses a modular hardware design, thus adding complexity by introducing a selection of configurations where only a subset of these configurations can be active at the same time.

Reconfiguration properties have to be considered not only in the hardware design, but require support by the controlling software layers which eventually have to take advantage of the reconfiguration capabilities, e.g. by using (re)planning. The usefulness of reconfiguration capabilities can best be shown in an error scenario where a team of robots uses reconfiguration and redundancy in the overall system in order to compensate for hardware fault or temporarily unavailable resources.

As already mentioned a system control station at the lunar surface represents the focal point for the communication of the robotic team, regarding the link to the mission control. This architecture introduces a centralized control approach in the first place. However, to achieve robustness a distributed setup has been selected for the robotic team to decrease the impact of a single-point of failure.

The project RIMRES embeds ESA's Functional Reference Model [12] [13] as general architecture model with the three layer of subsystem control (Level A), task control (Level B) and mission control (Level C). In the following we describe our approach towards a robust subsystem control level (Level A), which is designed to allow for mission success in different operation modes: (1) manual operation: the team of robots is driven by given action sequences that are forwarded by the mission control center to achieve certain objective (2) semi-autonomous operation: the mission control relies on complex task sequences to achieve a mission objective, or to reconfigure systems to compensate for errors (3) autonomous operation: mission control or system control fails to operate or cannot communicate with the robotic team - the architecture allows for self-organization of the robotic team, either to continue with the still known objectives or to reestablish communication with the mission control.

We target the challenges from two different perspectives: the intra-robot and inter-robot perspective.

4.1 Intra-robot architecture

The intra-robot perspective deals with the individual robot. The software stack applied on a single robot in RIMRES is mainly based on Rock[4] which itself is based on Orocos. Rock uses a model-based approach to create an infrastructure of software components. Designing a system with Rock has proven to be useful not only for the RIMRES project, but for multiple others in our institute which try to solve complex tasks.

Components are software modules that have dedicated input and output ports and perform specific tasks. Components represent the lowest level of granularity in the software stack and are specialized to fulfill a specific task. Using a managing component - the so-called supervision - multiple components can be put together to form a network, so-called compositions. These compositions can support complex tasks and by creating them in an 'on-demand' fashion allows to reflect hardware modularity in the software layer. A single component can be combined in multiple compositions. This not only fosters reuse of components but represents also reconfigurability on the software level. Additionally, the supervision evaluates if there is a need for a component to run and thus also represents a resource-saving mean. Figure 4 outlines the basic setup of our component network.

While some generic tools such as the supervision can contribute to reconfiguration capabilities, individual component design does as well. The 'TelemetryProvider' serves here as an example for a generic packaging component to support reconfiguration of the sensor data stream towards the mission control station. Acquiring sensor data and also forwarding to the mission control center might be costly in terms of resources such as processing power and energy. In addition the concurrent communication of images might be even not be feasible regarding communication bandwidth. Thus, mission control has to define and activate the sensors such as a camera which it wants images from. Images are provided in a common internal data-type. On request, sensors will be activated and the output data stream is dynamically attached to the TelemetryProvider component which itself internally converts images to a target format (as expected by the system

[4] Robot Construction Kit, `http://www.rock-robotics.org/`

control station) and outputs a generic telemetry container package. This container package is then forwarded to the system control station, where it is unwrapped and split into the sensor specific packets. The use of the generic packaging component allows us to aggregate sensor data in a dynamic fashion and improves reconfiguration capabilities on the software side.

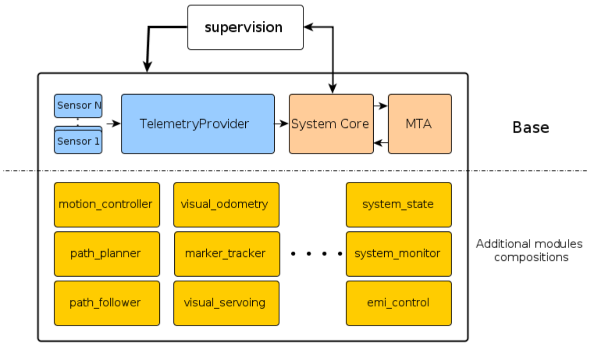

Figure 4. Schematic of the component architecture showing the structure of base elements such as the 'System Core' which performs communication protocol validation and mediates between the system control center and supervision.

4.2 Inter-robot architecture

For the inter-robot challenges we take advantage of the experience which exists in the multi-agent community. FIPA[5] has brought up a number of standards that have been applied mainly in the domain of software agents. We try to widen the field of application and use elements of the abstract architecture described by FIPA to build up our inter-robot infrastructure. We implemented the bit-efficient message standard of FIPA and use the idea of so-called message transport services (labeled MTA in Fig. 4). Each robotic system, i.e. Sherpa, CREX and payload-item has a local message transport service. All local services connect to a network and effectively create a message bus. Each message transport service announces its existence on the network using the zeroconf solution Avahi. This mechanism enables the message transport services to dynamically find each other in a network and can be also used for other components (or services) to announce their presence. This allows us to handle dynamically appearing or disappearing components and fulfills a specific requirement we have regarding modules which can be build during the mission and should be available and visible to other modules after powering up. This mechanism comes with an additional benefit: appearing and disappearing systems due to communication losses, power down or similar can be detected in the network.

In the current context we use this setup to create a dynamic communication network between all participating robots, which are able to communicate via FIPA messages (which take any type of messages as payload).

[5] Foundation of Intelligent Physical Agents

4.3 Modularization and Heterogenity

As already mentioned the supervision represents a major contribution towards reconfiguration. Yet, in the first place our general development approach (and the one of Rock) outputs highly modularized software, which allows to reuse components to a large extend within the overall system. Modularization starts by designing low-level drivers that will be embedded into the Orocos modules, e.g. to control the EMI a dedicated (framework-independent) driver has been developed along with a corresponding (framework-specific) Orocos module. The Orocos module exposes the EMI functionality and allows to be used withing the supervision. Modularization continues regarding robot capabilities. While there is common functionality for all systems, e.g. to create our communication infrastructure, specific skills per system exist. At supervision level we using a hierarchical structure which allows to bundle functionalities respectively and minimize the effect of heterogenity. This structuring allows us to run the same basic software stack on Sherpa, CREX, and all payload items in RIMRES. While still some configuration and optimization has to be performed to account for lower system resources on the payload items or for CREX, we achieve a common high-level software framework for the robotic team in RIMRES.

4.4 Configuration and optimization

We use the Orocos framework as a basis for our components and as such we can use full capabilities of the system. Still, careful management is required for the setup of a large component network since the configuration space is quite large. First of all, every component can either run with a fixed period to evaluate data on its port and trigger some activities, or it can be event driven i.e. trigger as soon as data is available on a specific port. This setup cannot be mixed at the current stage, but the period setting allows for an optimal usage of resources or in case of an uninformed usage can also create unwanted delays in the communication flow.

5 Conclusion and Future Work

This paper presents the state of the RIMRES project. Within this project, a novel approach of tightly cooperating heterogeneous robotic systems is pursued. Reconfiguration of the subsystems themselves and the overall system by combining the single subsystems is considered in the design phase and enables a wide range of actions to be taken in cases of failure, and a high adaptability to terrains that should be covered in planetary exploration. Reconfigurability and modularity can be found on different levels of the overall system.

The main pieces of hardware and control software are now available, the next phase of the project includes intensive experimentation and validation of the systems.

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