RIMRES: A Project Summary

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Extended Abstract

I. INTRODUCTION

The Moon has been a subject of interest of space agencies, being seen as a candidate to establish a permanent outpost in space [1]. However, in order to reach this goal with reasonable efforts, the utilization of local resources which are available on the Moon is an essential requirement. The access to water-ice is of main interest, since it would provide a local source for oxygen and hydrogen, and thus make a costly transport of breathable air and fuel from earth dispensable.

The formation of water-ice on the Moon can be explained from different mechanisms [2], e.g. reactions of sunwind particles with locally present oxides which can be found in Moon regolith. Further theories explain the presence of water-ice with out-gassing of the Moon's core, or consider meteoroids or comets as possible carriers. Meanwhile, the missing atmosphere and exposure to the sun leads to evaporation and thus a reduction of water-ice on the lunar surface. This leads to the conclusion that water-ice can be only present in so-called cold traps, permanently shadowed polar regions, and LCROSS mission [3] successfully provided evidences for the presence of water-ice in these regions.

In order to allow for a direct, local examination and exploration of polar regions, more complex and technological challenging missions are required. These missions will comprise a higher risk than remote sensing missions – commonly the deployment of mobile robotic systems is considered which need to be capable of locomotion in demanding crater regions [4]. Despite a higher operational risk, such missions provide a high scientific value, since they will allow a thorough exploration of the polar regions of the Moon, e.g. to analyse the presence of volatile matter and distribution of this matter [5].

Motivated by these requirements and building upon experiences gained in LUNARES [6], the project RIMRES has developed a modular, reconfigurable, heterogeneous multi-robot system to serve as a terrestrial demonstrator for lunar crater exploration missions. The capability of reconfiguration is one of the essential design aspects of the project RIMRES leading to a flexible approach to (re)use of available resources. This reconfigurability can be exploited for nominal operation and in conditions of failure, and provides a means to increase the system's overall efficiency while still maintaining redundancies.

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II. RIMRES

This paper presents the results of the project RIMRES and discusses the core achievements in the areas of hardware as well as in software. As a baseline for the development in RIMRES the following main requirements have been derived from a mission scenario: 1) a scout robot specialized on locomotion in crater regions, i.e. locomotion in steep terrain and allowing for sample extraction 2) a wheeled rover to provide an energy efficient transport over long distances for the legged scout, e.g. to a crater rim 3) an electro-mechanical interface to allow a modular design of the multi-robot system, so that subsystems can be interconnected 4) design of immobile so-called payload-items to serve as general purpose containers which can host scientific equipment and can be dynamically combined to form subsystems, and 5) a robotic arm to allow manipulation of payload-items and exploitation of modularity by reconfiguration.

The main outcomes of the hardware development process are the leg-wheeled rover Sherpa (Sherpa: Expandable Rover for Planetary Applications), the six-legged robot CREX (CRater EXplorer), and battery and camera payload-items.

Figures 6,8 and 2 illustrate the development results. To allow for reconfiguration, each of these systems is at least equipped with one standardized electro-mechanical interface (EMI).

In section III we will describe the development details of the EMI. Since the interface design is essential for the reconfigurability of the overall system, we describe it with a higher level of details than the other hardware systems. Sherpa will be described in section IV, CREX in section V and finally the payload-items in section VI.

Subsequent to the presentation of the achievements of hardware design and low-level control, we illustrate the software architecture in section VII. Requirements for control and operation are explained in section VIII.

The design of the multi-robot system has been validated with typical task sequences executed by each of the robotic systems and an overall realistic mission sequence involving ground-based control. This approach allowed verification of the main reconfiguration capabilities and will be described in section IX. Section X will summarize the results and gives an outlook on future activities.

III. RECONFIGURATION USING THE ELECTRO-MECHANICAL-INTERFACE

The EMI is the key element in RIMRES regarding reconfigurability. It allows to connect (sub)systems, so that they can share power, can communicate, and provide mechanical linkage.

The main components of this interface are:

- a passive male and active passive female interface to allow for mechanical connection
- embedded electronics to enable
  - communication
  - energy management
  - control of subsystem functions, e.g. locking mechanical interface or illumination using embedded LEDs
- a μ-PC-system [1] to allow application of the software framework including camera control to allow for visual servoing

An iterative design process has been applied for the development of the EMI, and further strategies to provide mechanical locking and guidance for the coupling of two payload-items have been evaluated. The development process resulted in a final design which consists of an actively driven female interface to lock the central connection pin of the male interface as illustrated in Fig. 1 and 2.

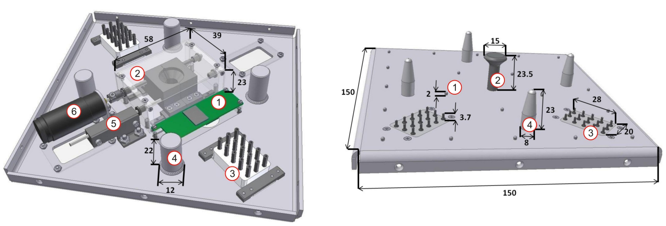

Fig. 1. CAD drawing of the electro-mechanical interface: bottom/female interface (left) and top/male interface (right).

In addition, to establish communication between two payload-items different contact options have been considered, resulting in the final application of spring-mounted contact pins with crown-shaped heads (to deal with dust accumulation) on the male interface. The following elements of payload-items have been initially developed independently, i.e. using separate electronic layouts: communication interface, mechanical linkage and control of the mechanical interface, illumination and energy management. After each design reached a sufficient level of maturity, the designs have been merged into a single one. The development of the EMI has been described in detail in [7], [8], [9].

[1]Gumstix Overo Fire

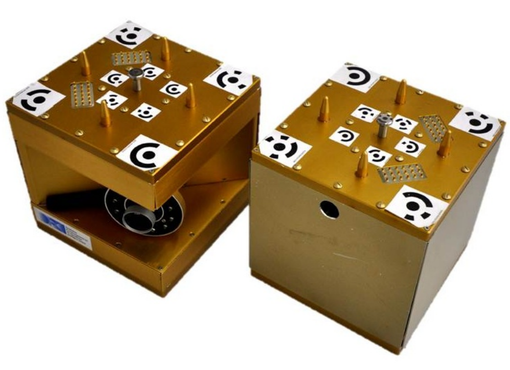

Fig. 2. Two payload-items: a camera payload-item on the left hand side and a battery payload-item on the right. Both are equipped with visual markers on top to allow for visual servoing as part of stacking procedures.

A. *Requirements and Design*

The requirements listed in Table III-A were considered to assure a secure mechanical and electrical connection, and have been met within the project [8]. In an experimental series, an unaffected opening of the latch was possible with up to 60 kg load on the central pin in vertical orientation. In tilted orientations of up to 30° loads of up to 40 kg were tested. The mechanical guidance of the system tolerates single Degree of Freedom (DOF) misalignments of ± 6 and $\pm 7^\circ$, respectively. The lateral play in connected state is negligible, while rotational play is present but within the tolerances of the electrical contact pins. The design of the interface allows docking and stacking in four orientations, and the latch mechanism only consumes energy, when actuated.

For experiments, dust accumulations have been simulated which exceeded by far the anticipated contamination in operation which could be handled by the EMI. The whole latch mechanism and the complete top interface were covered with fine grained basalt (granular size from 0.7 mm to 1.3 mm and from 0.02 mm to 0.2 mm). Electric connection and mechanical function of the latch mechanism were still operative despite the extreme pollution.

In [7] we describe experiments transferring up to 200 W of continuous electric energy via one pair of pins in the EMI. After two minutes a stable temperature around 75°C was reached. After ten minutes the experiment was completed. In the current version of the EMI we use contact blocks with 18 instead of 15 pins and doubled the power connection pin. In principle, this allows an application of higher energy rates, but up to now this feature was never required. Apart from that, the module electronics are currently configured to limit the current flow with a maximum of 10 A.

1) Power Management System: Figure 3 displays the architecture of the Power Management System (PMS) that is part of each EMI in the system. Despite the heterogeneity of the systems that employ a EMI, the PMS is homogeneous in all systems. The main part of the PMS is the power bus with three switches (A, B, C) that are controlled by the micro controller of the module electronics.

With the power switches it is possible to disconnect from a power source or to actively switch between a top, a bottom, and an internal power source (if available). Thus, energetically dead items can be "awakened" when a power source is stacked to one of the top or bottom interfaces. Though, current is routed through an increasing number of MOSFET-switches when the stack size is increasing (see Figure 3), experimental validation showed, that the power loss is marginal [9]: with 48 V applied and a constant current of 1 A (2 A) is lead from top interface to bottom interface, the power loss is at 0.04% (0.08%).

Different modes for power switching are available [9]: (1) hard deliberate: direct change of the connected power

TABLE I

REQUIREMENTS FOR THE EMI DESIGN

Mechanical Connection	The latch mechanism has to be able to payloads and CREX.
Electrical Connection	Minimal play to ensure a reliable electrical connection.
Mechanical Guidance	The interface should provide guidance to tolerate (small) initial pose errors.
90°-Steps Docking	Support of docking in 90°-steps of orientation to reduce the handling complexity.
Form Factor	The interface is limited to the quadratic size of a payload-item's ground plate (150 mm x 150 mm). The height of the EMI itself has to be kept to a minimum to allow maximum space for module components.
Energy Efficiency	The latch should not consume energy in closed or opened state.
Dust-Resistance	The latch mechanism needs to work in dusty environments and prevent dust from entering into the module.
Contact Probes	The contact probes actually have to realize the electrical connection for energy and data transfer. Since dust is one of the major concerns, the heads of the contact probes should cope with that.
Energy Bus	The EMI has to withstand currents to supply the actuators of the rover by battery payload-items.
Data Transmission	Allow local and global communication across a network of EMIs.

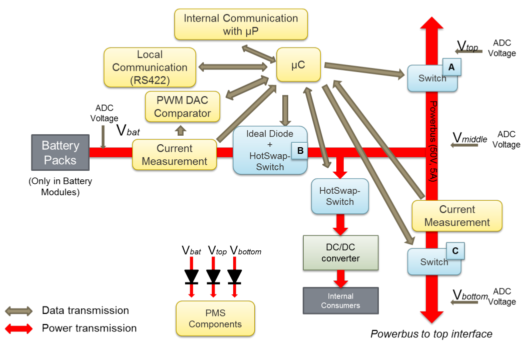

Fig. 3. Schematic of the power management system (present in each EMI).

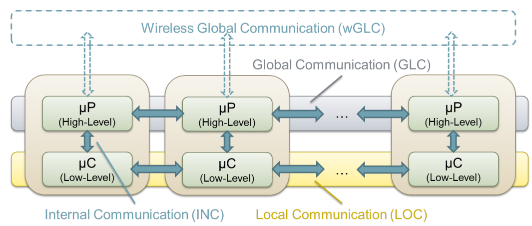

Fig. 5. Three levels of inter module communication: μP refers to a μ-PC, while μC to a low-level μ controller. Wireless inter-robot and wired intra-robot global communication (GLC) and low-level local communication (LOC). Additionally the internal communication of each module/EMI introduces a bridge between LOC and GLC.

source, (2) soft deliberate: change from high voltage power source to lower voltage power source, and (3) hardware: cutting power line in case of over currents.

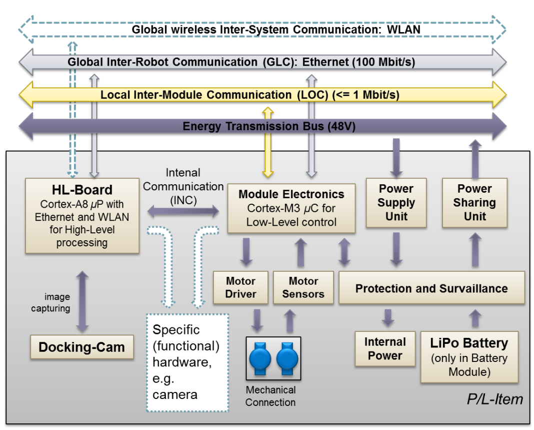

Fig. 4. Power management and communication in/via the EMI

2) Communication Concept: The EMI and therewith all modules[2] in RIMRES provide various possibilities to communicate with other nodes of the modular system. Apart from global inter- and intra-robot communication via Wireless LAN (WLAN) and Ethernet, a local, low-power communication via RS-422 is available. Figure 5 illustrates the three levels of communication. The control concept introduces a redundancy for routing high-level commands to the hardware-driver of an EMI. As long as one of the μ-PC-systems in a module stack is available, commands can be forwarded through local communication to the appropriate EMI, e.g. to open a latch. Fig. 4 and 5 illustrate components of an EMI and the EMI's communication concept.

Based on the local communication-protocol, topology information gathering and distribution is implemented. Each interface periodically sends registration frames to neighbor nodes. A registration frame contains basic information about the emitting EMI, e.g. the ID and the type of module the EMI is part of. Receiving EMIs add their own ID and information before forwarding the topology-list. In this way, a complete topology of physical connected modules is gradually built up. In case of a split up of parts of the stack, the information update is distributed in the two new stacks originating from the two EMIs that constitute the new boundaries of the respective systems.

IV. ROVER: SHERPA

The rover Sherpa is the the only system of RIMRES capable of payload-item manipulation. In addition to this

[2]i.e. mobile systems and immobile payload-items; in other words: each subsystem equipped with an EMI

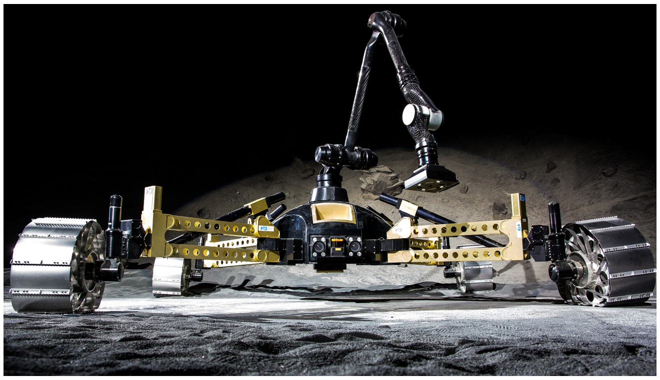

Fig. 6. The planetary rover Sherpa in a flat stance configuration of its active locomotion platform.

specialty it represents the highest technology integration density of a system in RIMRES. Sherpa is depicted in Fig. 6 – the design of the locomotion platform has been described in detail in [10].

The system's suspension platform consists of four wheeled legs, each offering 6 DOF leading to an overall 24 DOF suspension system. This suspension system can adapt to changing surface conditions using different locomotion modes, e.g. using posture adaptation to dynamically adapt the body height, to apply inch worming, or even to use walking patterns to traverse short distances on terrain unsuitable for wheeled driving. In general, the active suspension platform allows to develop a broad spectrum of locomotion modes in order to provide an autonomous terrain-based selection of locomotion modes in future applications.

In addition to the locomotion platform, Sherpa is equipped with a manipulator which is centrally mounted on the main body. The manipulator has been primarily designed for manipulation of payload-items, but also to support locomotion. In order to find an optimal solution of link length and manipulator design evolutionary computation has been used [11].

The main manipulation tasks are: 1) handling of payload-items in order to create stacks of payload-items which form new subsystem, 2) handling of CREX, e.g. for lifting of the lander (cf. Fig. 7), and 3) inspection of Sherpa using the camera in the manipulator's interface. Using the manipulator for handling CREX has the additional benefit, that CREX could be used as a six-fingered hand.

We have shown that the manipulator is also strong enough to support locomotion and can be used as an additional leg at least in a tripod stand of Sherpa (cf. video evidence [12]). This behavior has been tested in a standalone fashion and was not embedded into an autonomous navigation task, but it opens new directions for developing advanced locomotion strategies.

Sherpa is built using different modules and it uses an internally distributed computing system, i.e. while the high-level software framework is hosted on a PC system (Mini-ITX), Sherpa also comprises two μ-PC systems - one in the manipulator's interface and another in the bottom interface

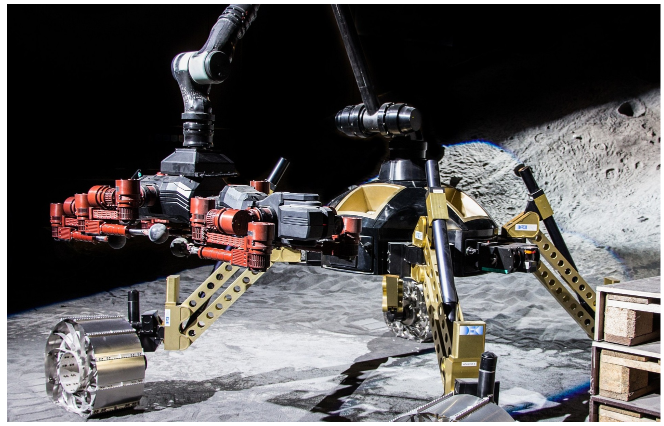

Fig. 7. Sherpa lifting CREX using its manipulator.

TABLE II
KEY SHERPA

Description	Value
Body height (min/max)	-189 / +711 mm
Footprint (quadratic)	2100 - 2500 mm
Mass (incl. manipulator)	$\approx$ 160 kg
Manipulator mass	25 kg
Manipulator length	1955 mm
Manipulator max. static load (stretched out DOF5)	183 N
Manipulator max. static load (gravity aligned DOF5)	537 N

to enable control and access for the interface cameras. In addition, to control the locomotion platform an FPGA-based controller board has been deployed running the micro kernel M.O.N.S.T.E.R [13].

One of the main motivations for reconfiguration and creating a monolithic system from CREX and Sherpa is a better exploitation of system resources, i.e. efficiency. CREX has been specifically built to explore crater regions and thus can traverse difficult terrains - this also means it can easily cover planar surfaces. Yet, a wheel based transport will be more efficient for long distance travel and attaching CREX to Sherpa allows to take advantage of this.

Clearly, the main requirements for the system design are related to locomotion. Flexible wheels add to this and have been designed to improve traction and locomotion. They represent a good means to ground adaptation for fields of small rubble, and their current design is basis for future improvements such as additional sensory and active wheel adaptation, e.g. control of the stiffness, to react to different terrains. This way the wheel represents a placeholder for an additional intelligent subsystem similar to the ones advocated in [14].

The main hardware characteristics of Sherpa are listed in Table II.

V. Scout: CREX

CREX has been selected as scout in RIMRES and is specialized to explore lunar crater regions. The fully assembled system is depicted in Fig. 8.

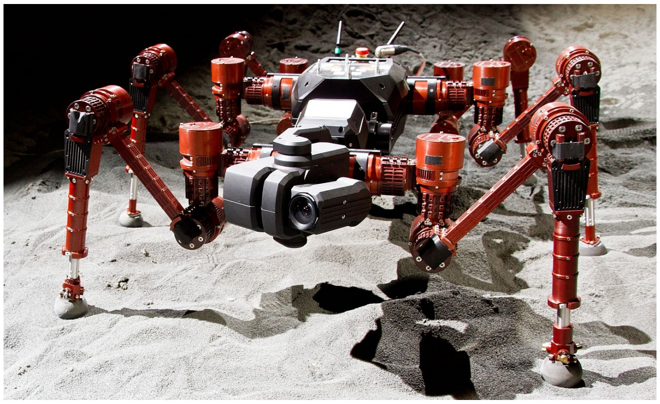

Fig. 8. The six-legged walking robot CREX which acts as scout in the aspired mission scenario of RIMRES.

In the planning phase of the project the reuse and extension of the eight-legged Scorpion as used in LUNARES had been considered. Eventually though, it became clear that the application of a SpaceClimber [15] based system would be a better approach, so that CREX is now a further modified and based on previous experience improved version of SpaceClimber. While the external design was only mildly adapted, main modifications had to be performed to allow reconfiguration of CREX to form a monolithic system with Sherpa: the EMI has been added to the back of CREX and new electronics have been added to control this interface. Furthermore, the electronic design has been reiterated along with the mechanical design of the joints.

The locomotion system of the six-legged CREX has been built using identical actuators to construct legs with four DOF, i.e. the actuators represent modularity at the hardware level and each leg a subsystem. CREX is split into a main body and a front body – a body joint allows lifting the front body including the sensor head with respect to the main body. Overall, CREX offers 25 DOF which can be used for locomotion and manipulation purposes. Manipulation can be performed using a reconfigurable leg with a gripper attached to the lower leg. However, an actual application of manipulation and also using the additional body joint is part of future work.

To allow CREX to navigate autonomously, its sensor head comprising a laserscanner and a monocular camera – the sensor head is able to pan. Similarly to Sherpa, CREX hosts a distributed control system, i.e. the high-level software framework runs on a Pico-ITX mounted in the front body compartment, while the motion control resides on an FPGA-board in the main body.

The main characteristics of CREX are listed in Table III.

TABLE III
KEY CHARACTERISTICS OF CREX

Description	Value
Body height	150 mm - 400 mm
Body shift (front-back / lateral)	±150 mm / ±50 mm
Dimensions in standard pose [L×W×H]	850 × 1000 × 220 mm^3
Dimensions body only (inkl. sensor head) [L×W×H]	895 × 208 × 165 mm^3
Leg length (front / middle / back)	640 / 650 / 640 mm
Mass (incl. battery pack)	27 kg

VI. Payload-Items

Payload-items allow to either to construct independent (immobile) subsystems or to extent existing mobile systems such as Sherpa or CREX. This kind of modularity creates high flexibility for space missions. Systems can exchange these modular components, e.g. when a battery is running low, and mission operators can more easily react to science alerts, i.e. unanticipated finding suggesting an immediate experiment/system deployment. Furthermore, additional and new types of payload-items can be shipped after a mission has started in order to extend the range of equipment or for placing new experiments.

The application of payload-items and experiments in RIMRES focuses on two payload-item types: camera and battery as depicted in Fig. 2. The battery payload-item serves primarily as an energy supply for other payload-items, but it can also serve as an additional power source for CREX and Sherpa. Currently, the battery payload-item is the only payload-item that can operate independently. All other payload-items will need to be connected to a power source. Currently, a single battery payload-item has a power capacity of 2400 mAh, which could be extended to 4800 mAh if needed.

The camera payload-item represents only one out of many options to design a scientific unit, e.g. a sensor / measuring device. All payload-items comprise a μ-PC to run the high-level software framework. This means, that all systems in RIMRES rely on the same software basis for communication and high-level control. In the case of the camera payload-item it means controlling the specifically mounted camera, i.e. controlling parameters and alignments. All payload-items have a camera embedded in their interface (cf. Fig. 1 item 1), so that stacking can benefit from visual servoing capabilities if required. Clearly, the payload-items have limited processing capabilities and in practice the camera processing and image transfer allowed frame rates around 2 Hz – full image transfer required.

Evaluations in the project have shown that for a real mission each payload-item should have an internal power supply. While the functionality is available in RIMRES electronic design will have to be adapted, i.e. battery payload-item specific functionality will have to be merged into the general payload-item design. Sherpa uses the so-called stacking to combine multiple payload-items leading to dynamically created subsystems. Similarly, the transfer of payload-items between two mobile system can be considered – the same manipulation problem compared to attaching a payload-item which has already deployed on the ground surface. The stacking procedure can rely on previously taught positions, e.g. when manipulation is solely performed using the well defined payload-bays at Sherpa main body. Alternatively, for the transfer to a system with previously undefined relative position visual servoing will be necessary. Markers have been added to the male interface as illustrated in Fig. 2, so that visual servoing can be applied. Using the corresponding camera images of the female interface during the stacking to extract the marker positions allows for a visual servoing approach.

VII. Software Framework for a Heterogeneous Multi-Robot System

The software framework in RIMRES serves all participating systems, i.e. it represents the basis for high-level control in this multi-robot architecture.

Similarly to modularity of the hardware architecture, we can identify modularity in the software framework. First of all, hardware abstraction is achieved by introducing an appropriate driver layer. This driver layer also includes the mobile locomotion platforms of Sherpa and CREX. To eventually exploit system capabilities each of the mobile systems has its own motion-controller. Especially for Sherpa this will become more significant in the future, when the manipulator will be included into locomotion. The development of the EMI also included the development of a driver that allowed to access low-level information including the topology of components connected via an EMI and controlling functionality such as illumination and opening and closing of a latch. Information about the system topology from the EMI interface can be used in a variety of ways, e.g. to check whether systems have been successfully connected or to infer if certain functionality is available at all in a reconfigured system.

The hardware abstraction layer exposes basic functionality to high-level control, and in RIMRES high-level control is designed following a model-based workflow using Robot Construction Kit (Rock) [16]. Rock is a toolkit which allows a model-based design of software components. It fosters decomposition of functionality and thus a modular layout of software components, leading to a high degree of reusability. Software components in Rock are well-defined Orocos-RTT [17] components, i.e. while the existing task model of Orocos is being used, Rock facilitates generation and usage of such components. Having a standardized model for generation of these components allows to build management infrastructure on top. Rock uses for this purpose the supervision or even more recently the so-called syskit.

Specific functionality, i.e. a capability of a robot will require multiple software components. The software components form a dependency network based on the needs of each capability, i.e. the corresponding information processing chain. Eventually, the supervision is responsible to manage these component networks and prevent conflicting subnetworks to be running at the same time. Such conflicts might arise, e.g. due to different component configurations. These capabilities can be used to create actions which a robot can perform, e.g. in the case of Sherpa one simple action probes the communication while one complex action allows to guide another system into the docking interface based on visual information.

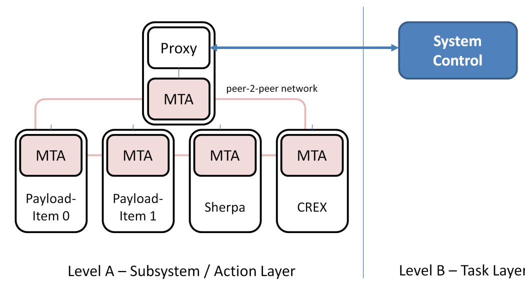

Fig. 9. RIMRES as a distributed system in Layer A of the FRM model

While the software framework has been developed for reusability, each of the systems also required specialization or specific tuning. This means that when components are deployed to the individual systems, this might be done using different configuration parameters, e.g. since the Gumstix has lower processing capabilities, processing visual data will be done at lower frequencies. Dealing with specialization and reusability is also reflected in the design of the supervision. Supervision supports specialization by so-called bundles. Each bundle allows – among other things – to specify component networks and actions relying on these kind of networks. Functionality of bundles can be reused in other bundles, allowing to organize capabilities in a hierarchical fashion.

RIMRES uses a multi-robot system and assumes a fully distributed system. Communication is performed using FIPA messages which allow to perform high-level control, e.g. requesting the execution of a specific action or retrieving a specific configuration object. Each of Sherpa, CREX, and payload-items hosts a software component called Message Transport Agent (MTA). An MTA is responsible for delivering FIPA messages to the local system or forwarding from the local system if requested – this is defined in the FIPA message. All MTAs use a service-discovery mechanism to dynamically find each other and connect to each other. This allows to account for dynamically appearing and disappearing systems.

Using so-called performatives in a FIPA message to describe the element of a speech-act, e.g. request, inform, or failure, allows to validate the flow of communication in the multi-robot system and thus provides a means to validate conformance to communication protocols. Currently, most cases in RIMRES use a request-response protocol, but even this simple protocol takes advantage of the default integration of failure handling available in the conversation monitoring.

VIII. Control Station and System Control

The design of the control architecture in RIMRES relies on ESA's Functional Reference Model (FRM). Fig. 9 illustrates the setup of the distributed system within the implementation of the FRM [18], [19].

In the RIMRES scenario mission control and operators – aka mission layer or Level-C – are ground-based, while a system control – aka task layer of Level B – is assumed to be installed at the lunar surface; the system control station communicates directly with the subsystems, i.e. Sherpa, CREX, and payload-items, and is responsible for controlling the execution of an uploaded mission sequence. The general design using system control is a centralized control approach. Nevertheless, the software architecture of the multi-robot system allows for further extension, including a distributed control approach at subsystem level (Level A). Thus, the architecture in RIMRES has been designed with future improvements in mind – specifically scenarios where subsystems will work more independently and with a higher degree of autonomy. Such situations can easily occur when communication to the system control station is temporarily not available and to guarantee mission success local communication and coordination of the systems has to be used.

The layout of the control architecture in RIMRES has been built on top of the existing infrastructure developed in LUNARES [6]. While main parts of the architecture could be reused, significant extensions had to be made in order to cope for reconfiguration aspects. A mission can be arbitrarily complex if one assumes a dynamic adding of payload-items and payload-capabilities. The current setup of the control station and the system layout is static. This means, that the combination of payload-items that will be used in a mission has to be defined before a mission is started, and only those combinations that have been previously defined, will be usable during a mission.

IX. Performing a Mission Sequence

The general mission outline will be design by human operators and uploaded to the system control station. A mission consists of the execution of tasks by individual subsystems, though task execution is controlled by the system control station. Each task can be decomposed into one or more actions. Therefore, mission execution is tightly controlled by the system control station and only after completing an action successfully, a subsystem will receive a new task.

When outlining a mission, an operator plans for activities of separated systems and also activities of combined systems. Clearly, Sherpa and CREX cannot be operated at the same time as the combined system. Mission planning accounts for this by checking for the correct configuration status. This configuration status can be queried from each of the subsystems represents the topology information retrieved from the EMI.

A. Mission Outline

The final project demonstration showed a mission sequence illustrating the following capabilities of the system:

- application of the manipulator for system inspection
- reconfiguration of CREX and Sherpa
- manual control of CREX and Sherpa
- system requesting for interaction
- locomotion of Sherpa and CREX

The mission starts with the two separate systems CREX and Sherpa. The operator controls CREX in order to walk underneath of Sherpa. Once a position has been reached from where the bottom camera can see CREX' interface markers, the reconfiguration process is prepared and eventually started. Once the target position is reached, CREX uses blind docking to move its male EMI into the corresponding female EMI of Sherpa. After locking the EMI CREX is folded, so that the combined system is ready for travel. Subsequently Sherpa will carry CREX to a designated target position near the crater; Sherpa is controlled by a human operator for this purpose. After reaching its target position, an action is initiated in order to release CREX from Sherpa. The successful release of CREX starts the exploration of the lunar crater.

During the mission the manipulator can be set into taught positions to allow observation. This feature is used for the guided approach of CREX and the docking procedure and illustrates one additional benefit of the manipulator.

B. Operations and Action Details

The reconfiguration of CREX and Sherpa is the most complex action in RIMRES and consists of sequentially executed activities. Among those are:

- calibration of the EMI
- switching LEDs on/off
- querying topology information from the EMI
- changing body pose of CREX
- unfolding and folding CREX

The reconfiguration also involves a visual servoing process, which guides CREX to a taught position, relative from Sherpa's bottom interface. The main controller of this visual servoing process is Sherpa, which performs marker extraction of the images it retrieves from the bottom interface. Following the same process as outlined in [20], pose correction commands are generated.

For the reconfiguration process CREX uses a dedicated low-level behavior, which allows to memorize its configuration before the visual servoing starts. This is required for a safe release, since we assume a similar ground level and currently no sensor information is processed to test on ground contact. Folding and unfolding of CREX is also a predefined action to set CREX into a very compact pose – it is only used when CREX is attached to Sherpa.

The manipulator's EMI comprises a camera which can be used for system inspection or to other observational activities. It thus facilitates teleoperation of CREX, i.e. to guide the system underneath of Sherpa using the observation camera and CREX' head mounted camera.

Sherpa, CREX, and all payload-items use frequent monitoring of telemetry data. Using a rule-based system the status of the telemetry is verified and upon firing of a rule a predefined action is initiated. In the current implementation, a so-called interaction request is sent to the operator.

C. Qualitative Description of the Final Performance

The final project demonstration has been setup like a real mission. Operators were put into an isolated control room and the system were deployed in the simulated lunar crater environment. Mission control and system control station were running on the same physical systems. Additionally, a proxy has been setup to translate between a legacy socket-based communication and the FIPA-based communication of the subsystems.

The general startup procedures of the systems have been automated to main parts. Still, since CREX comprises a locomotion platform that has to be powered and due to some alignment procedure of the legs in the beginning, CREX is initially mounted on a specially designed support structure. Meanwhile, Sherpa does not require power to keep its posture. The startup procedure still involves the powering up of the locomotion platform, the manipulator, the sensors, and eventually starting the high-level software framework.

Once the mobile subsystems are up the system control center connects and verifies the startup configuration, i.e. checking if all configured Level A systems are available and have the correct configuration state. Additionally, the communication channels between system control and subsystems will be probed.

The operator can directly activate and deactivate sensors of the subsystems. For guiding CREX underneath of Sherpa the head camera of CREX is used along with the manipulator's interface camera. Ideally such an approach will be fully automated, since teleoperation under these conditions – limited video information and significant communication delay – is too prone to errors. However, this way we compensated for a not yet implemented autonomous approach and verified teleoperation. The overall setup had not been optimized to achieve high performance throughput of data and subsystems were connected using WLAN standard 802.11g. Overall, the end-to-end communication delay for the camera data from CREX was approximately 2 s.

The mission sequence was designed with several so-called interaction requests – dedicated breakpoints for the operator to check system status and guarantee the precondition for subsequent actions. As previously mentioned and in addition to these dedicated breakpoints, systems in RIMRES use a rule-based monitoring of their own state. When the system sends an interaction request to an operator, the operator is then in charge of handling the issue. The operator has to actively acknowledge being informed about the request, but is otherwise free to handle or ignore it, e.g. normal joint currents of CREX are temporarily exceeded during the reconfiguration procedure, which is normal for the reconfiguration procedure, so that the operator will be informed, but does not need to take action. Fig. 10 illustrated an operator's view during mission execution.

The execution of the final mission demonstration in RIMRES did run well for main part, but not run completely smoothly. After the successful semi-autonomous docking procedure it was affected by a low-level communication error that prevented to control Sherpa's bottom EMI using high-level commands and operators required direct system access to command the EMI for latch opening and closing. To account for this error, the mission's outline had to be changed and the operator created new mission sequences to adapt to this situation. After uploading the new sequences, the mission continued at a much slower pace but eventually completed successfully.

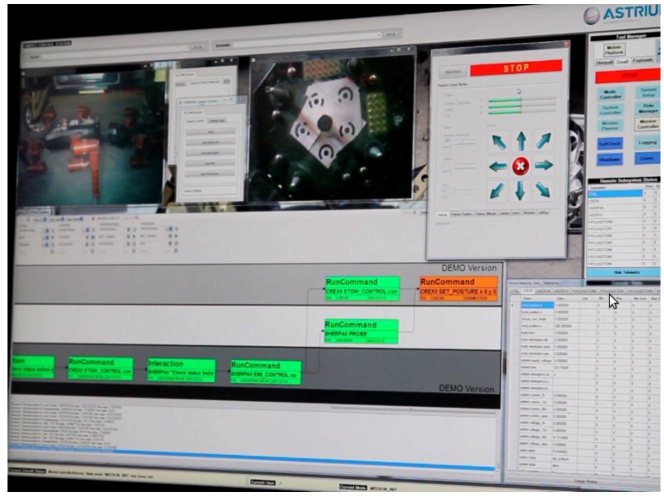

Fig. 10. An operator's view during the docking procedure.

X. Conclusion

The project RIMRES developed a complex, heterogeneous multi-robot system. RIMRES comprises a leg-wheeled rover Sherpa, a six-legged scout CREX and payload-items which can be combined to payloads. The system demonstrates how a lunar exploration mission can benefit from modularity and reconfigurability of the deployed systems. The leg-wheeled rover allows to carry the scout in order to make long distance travel more efficient and safe energy for the legged-locomotion of CREX. At the same time, Sherpa can handle payload-items and creates scientific payloads dynamically, e.g. to react to a science event. The main goal of the team of robots is the exploration of permanently shadowed polar region on the lunar surface and probing of the environment. To achieve the multi-robot system in RIMRES development was performed on a spectrum from low-level hardware to high-level software. At all development levels, the project tried to support a modular approach in order to achieve reusability. The high-level software framework is based on Rock and shows the success of the advocated model-based development approach: the same software foundation applies to Sherpa, CREX, and all payload-items. Additionally, the mission control center and system control center of LUNARES have been significantly revised and extended in this project and now take reconfiguration capabilities and modularity of subsystems into account. This new functionality has successfully been demonstrated in the final milestone, especially during the error handling.

The multi-robot system in RIMRES is – despite its modularity – capable of complex activities: the autonomous docking procedure between CREX and Sherpa is the most complex and cooperative activity implemented. This cooperative activity involves inter-robot communication, electromechanical coupling for reconfiguration, and interaction with a human-supported ground station. Meanwhile, Sherpa's manipulator – specifically developed for the rover – is precise and accurate enough to manipulate payload-items, and at the same time strong enough to support extraordinary locomotion modes involving the manipulator as a fifth leg.

Key to the overall reconfigurability, however, has been the development of the EMI. This interface in combination with a sophisticated power management has proven its functionality and even more its significance for the whole approach. Much of the functionality of RIMRES builds on top of the EMI design, which is thus an enabling but at the same time constraining factor.

Ongoing projects such as IMPERA [21] and future developments building upon the achievement of RIMRES continue to improve multi-robot based exploration. A revision of the EMI and a possible reduction to a single-gender interface will be part of future consideration. Furthermore, since the hardware platform allows for a great range of reconfiguration options, cooperative skills and exploitation of reconfiguration capabilities will be improved. A full exploitation of reconfiguration options will require new approaches to support operators and an increased level of autonomy of participating systems.

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