IAC-21-A3.1.7.x64007

Design and Implementation of a Modular Mechatronics Infrastructure for Robotic Planetary Exploration Assets

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Abstract

Traditionally, the robotic systems which aim to explore other celestial bodies include all instruments and tools necessary for the mission. This makes them unique developments. Usually, they are heavy, complex, costly and do not provide any interchangeable parts that could be replaced in the event of permanent failure. However, for future missions, agencies, institutes and commercial companies are developing robotics systems based on the concept of modular robotics. This new strategy becomes critical for planetary exploration because it is able to reduce load, costs and development time. In the German multi robot research project, ''Autonomous Robotic Networks to Help Modern Societies (ARCHES)", led by the German Aerospace Center (DLR), this modern design methodology is followed. Cooperation among robots and modularity are the core of its structure. These characteristics are present in the collaboration between the rovers and the uncrewed aerial vehicle (UAV) during navigation tasks, or when the Lightweight Rover Unit (LRU) interacts with changeable manipulator tools and payload boxes through its robotic arm and its standardized electromechanical interface. Examples of these modules include scientific packages, power supply systems, communication and data acquisition architectures, soil sample storage units, and specific purpose end-effectors. The focus of this work is in the design and implementation of a mechatronics infrastructure (MI) which encompasses the docking interface, the payload modules, and the power and data management electronics board inside each box. These three elements are essential for the extension of the capabilities of the rover and the enhancement of the robotics systems according to the tasks to be performed. This will ensure that robots can cooperate with each other either in scientific missions or in the construction and maintenance of large structures. The MI's hardware and software developed in this project will be tested and validated in the ARCHES demonstration mission on Mount Etna, Sicily, in Italy between 13th June and 9th July 2022. Finally, it is important to highlight that modularity and standardization were considered at all levels of the infrastructure. From the robotics systems to the internal architecture of each payload module, these concepts can provide versatility and reliability to the cooperative robotic network. This will improve the problem-solving capabilities of robots performing complex tasks in future planetary exploration missions.
Keywords: mechatronics, robotics, modularity, exploration

1. Introduction

Mobile robots designed for planetary exploration have transformed the human perception of the Solar System. The discoveries and scientific contributions made on past missions to other celestial bodies are unquestionably remarkable and important. However, they faced significant challenges such as the weight limitation, high costs, lack of interchangeable parts and long development time. Although these limitations did not impact the success of these endeavours, they will become more relevant in future missions. The desired sustainable human and robotic presence on the Moon and Mars indicates the need of a well-developed infrastructure including habitats, power grids and mining facilities. This is highlighted in the Global Exploration Roadmap (GER) [1] which presents a set of six sustainability principles. One of them is the principle of *Capability Evolution and Interoperability* which foresees the use of common interfaces and modular architectures in human and robotic exploration missions. Likewise, the Mechatronics Infrastructure (MI) introduced in this work allows robot units capabilities to be extended and enhanced with modular scientific payloads, standardized interfaces and tools. In addition, the modularization and standardization in space robotics can benefit "NewSpace" [2] companies which are the new actors in the space economy. They can quickly start their projects with a simplified infrastructure and later expand upon it with the inclusion of more complex scientific instruments. According to the German Ministry of Economy and Energy (BMWi) [3], this approach which values speed as much as technology will ensure the survival of NewSpace companies in such a competitive environment.

The aim of this work is to demonstrate the development of a mechatronics infrastructure applied to robotic planetary exploration and how it benefits many space actors in future sustainable planetary missions.

This paper presents:

- The related work on robotic modularity for planetary exploration
- A brief introduction of the ARCHES Demonstration mission
- The Mechatronics Infrastructure (MI) design with the detailed description of its all the key elements
- The integration and preliminary tests carried out during the development of the MI
- A short discussion about the preliminary tests results and the integration process
- A conclusion with a look towards the future

2. Related Work

In this section, the related work on robotic modularity for planetary exploration is presented.

With the focus on modularity within the robot, the technical team who developed Scarab prospector rover [4] opted for a single unit robot which has the ability to rearrange different scientific payloads on its chassis. Although this gives some flexibility and certain level of modularity to the rover, the absence of a robotic arm, standardized interfaces, scalable modules and a robotic team limits the rover's scientific operations in the terrain.

Another relevant project with reconfigurable and scalable features is shown in [5]. ATHLETE is a heavy six-legged cargo robot which can dock to another unit expanding its payload capacity. It can also have its limbs converted into manipulators and has considerable advantages in mobility. However, its heavy weight, large size, and only-mechanical docking capability constrain it to cargo tasks rather than scientific and maintenance activities.

With a multi-robot cooperation approach, LUNARES [6] and IMPERA [7] demonstrated the interaction between a mobile rover and scout robots. While their soil sample collection tasks worked well, there is lack of a developed docking interface for manipulation, multi-payload modules, and a mechatronics infrastructure for power and data exchange.

The RIMRES project [8] made further advancements from [6] and [7] with the inclusion of a standardized Power Management System (PMS) for each payload carrier, and an electromechanical interface able to interconnect different modules. While this concept has similarities to ARCHES, its payloads are limited to a battery module and a simulated science payload module with a camera. In addition, the electronics embedded in the payload carriers mainly accounts for power management. The local data communication features are limited.

The ROBEX [9] project was the precursor of ARCHES. With the development of the Light Weight Rover Unit (LRU), the manipulation capabilities and the electromechanical docking interface, it explored the concept of robots deploying and maintaining scientific modules in the field. ARCHES enhanced this concept with the addition of other robot units in the cooperative team, several scientific payload carriers and tools, the standardization of interfaces, and the creation of a mechatronics infrastructure capable of transferring data and power among modules or between payload carrier and rover.

Finally, the analysis of the robotic assets presented in this section observed the NASA framework for modular assembly systems [10] which defines the modularity attributes as standardization, versatility and maintainability. Thus, the assessment on the number of standardized interfaces and modules, the variety of functionalities and modular levels, scalability, reconfigurability, serviceability, and repairability can provide which is the impact on sustainability for future robotic exploration missions.

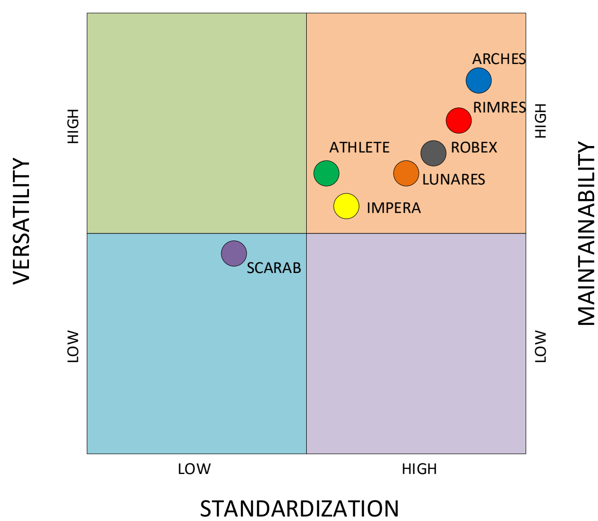

Fig. 1. Modularity Qualitative Assessment based on NASA Framework for Modular Assembly Systems [11]

The mechatronics infrastructure (MI) developed in ARCHES has a high level of modularity characteristics (Fig.1) which places ARCHES robotic assets in the forefront of modular robotics for planetary exploration.

3. ARCHES Demonstration Mission

The ARCHES [12] demonstration mission is planned to happen in the summer of 2022 on Mount Etna in Sicily, Italy. A set of scientific exploration scenarios will take place in this test site with the performance of scientific activities such as the radio-astronomical instruments (LOFAR) deployment [13], the elemental analysis of rocks and soil with LIBS, the rock type identification with the ScienceCam [9], and the geological samples collection. These tasks are performed by a heterogeneous and autonomous robotic team, which includes two LRUs and one UAV. While the drone ARDEA [14] scouts the terrain, the LRU1 [15] inspect geological targets with its science camera. The LRU2 [15] [16] with its robotic arm collects rock and soil samples, and manipulates several payload modules. A mock-up lander is also part of the demonstration mission. It acts as base station and global landmark for all robots.

Fig. 2. Robotic Assets for ARCHES Demonstration Mission [17]

4. Mechatronics Infrastructure Design

The Mechatronics Infrastructure (MI) includes the ENVICON Docking Interface System, the payload modules, and the power and data management electronics board. These key elements allow the autonomous robots to manipulate objects in the field, take important geological measurements, enhance their navigation and communication, and maintain the infrastructure deployed on the terrain.

4.1 ENVICON Docking Interface System

The ENVICON Docking Interface System [16] has an active and a passive coupling partner. It was developed for the ROBEX project and enhanced in ARCHES. This interface ensures the connection between the robotic arm and any payload module or tool. The original version was able to mechanically connect to the passive coupling partners on the boxes. The upgraded version includes an electrical interface which can transfer power and data from the manipulator’s end-effector to the payload module or between two modules.

4.1.1 Active Coupling Partner

The Active Coupling Partner is a spring-loaded system which can latch the passive male coupling partner mounted on the surface of the payload carriers or on the bottom of the end-effector tools. This cylindrical structure has an outer diameter of 102 mm, an inner diameter of 60 mm, and length of 80 mm. Its total weight is 450 grams and its mating force exceeds the payload module weight (3 Kg). With a symmetric geometry, it provides a wider zone to capture the passive coupling partner increasing the tolerance during the docking process. This robustness benefits mobile robots operating in unknown and extreme environments [16].

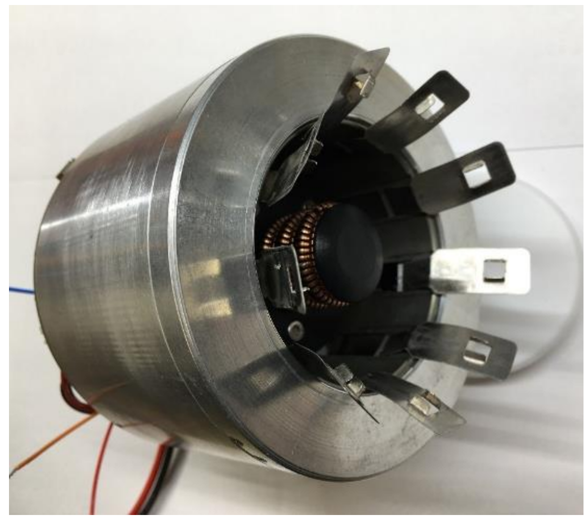

Fig. 3. Active Coupling Partner with spring elements opened-up.

Its power consumption is relatively low with 1.5 W in standby condition and up to 3 W when the motors are in operation. Its mechanical components are basically the rigid structure, the spring elements, the driving unit, the frame, and the cover. They were designed to provide the most reliable and stable docking process considering the analogue mission scenarios and the manipulation tasks to be performed. Its electronic infrastructure is shown in Fig.4. The 24V DC coming from the robotic manipulator are converted into 5V and 7.2V in the Power Management System. The motor drives controlled by the microcontroller operate two motors which lift a cylindrical platform with nine metal spring elements distributed along the inner circumference. These elements open up in a funnel-shaped capturing zone with high misalignment tolerance. The microcontroller also manages the Communication Network with several data communication buses, the internal sensors, and the user interface. The user interface is particularly important because it provides visual feedback to the operator regarding the outcome of the docking process. While green light indicates a successful docking, red light shows the unsuccessful connection resulted from a potential misalignment. In this undesired event, the robotic arm will reinitiate the process aiming the positive result.

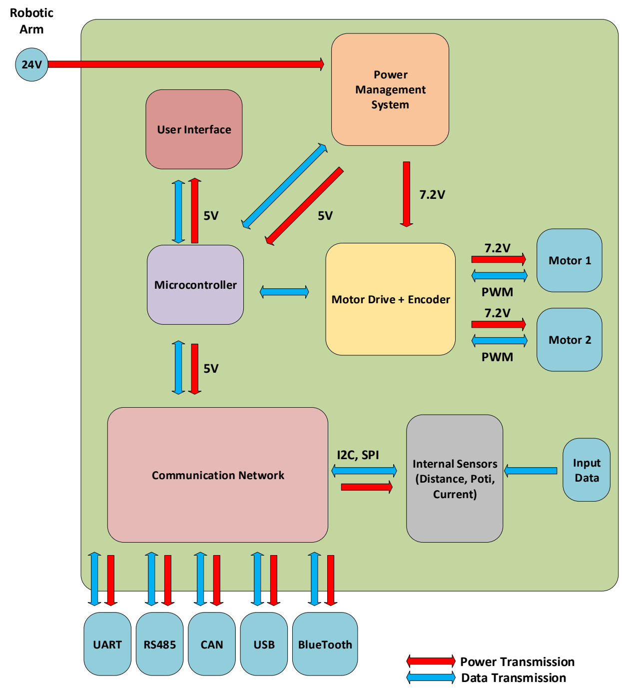

Fig. 4. Active Coupling Partner Electronics Diagram

4.1.2 Passive Coupling Partner

The Passive Coupling Partner is a mechanical part designed for docking purposes. The passive male coupling partner (a) is mounted on the front and/or top of the payload modules. It enables the connection with the LRU2 arm or to another module which has a passive female coupling partner (b) on the bottom. With this configuration, the robotic arm can manipulate the payload carriers and stack them on top of each other. The geometry of each passive coupling partner facilitates the latching and locking process.

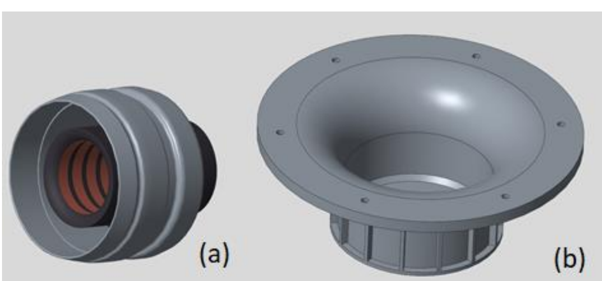

Fig. 5. (a) Passive Male Coupling Partner. (b) Passive Female Coupling Partner.

4.1.3 Electrical Interface

The Electrical Interface has the purpose of exchanging power and data. It has a male and a female counterpart which mate to each other during the docking process. They have three copper-beryllium electrical ring-shaped contacts which can handle up to 100 W without significant warming and 10 to 100 MBps of data transfer depending on the data communication bus.

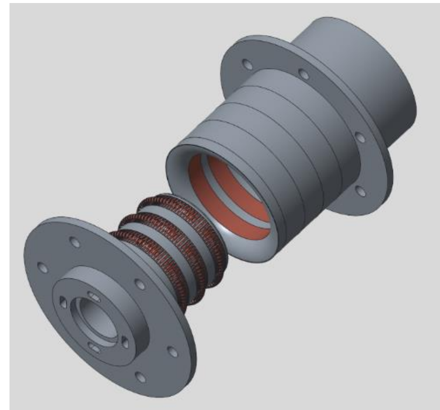

Fig. 6. Electrical Interface

4.2 Payload Box Infrastructure Management System (PBIMS)

The PBIMS is a modular electronic board which manages the power distribution and data communication to the internal consumers within the payload box or external parts in the network. As shown in the diagram (Fig.7), the Power Management System (PMS) is on its top part. It encompasses the Power Path Controller and the Power Electronics. While the former can select three different power supply sources in a prioritized order, the latter has several DC-DC voltage converter modules connected to two high side switches which can activate/toggle each power bus individually. This modular design for the DC-DC converters allows the rapid rearrangement of the PBIMS for different tasks. It also provides variable output voltages as well as flexible current and power. Another benefit is the possibility of removing modules which are not needed to make the electronic board lighter. In the lower part of the diagram, there is the Data Communication System (DCS) which handles the data from internal sensors and the communication network with six different data buses. The sensors gather essential information about the environment, the module's orientation in space, and their distance from the target. The diversity in data communication buses facilitates the integration to several scientific instruments which use commercial off-the-shelf (COTS) components. Both the PMS and the DCS are controlled by an ARM® Cortex®-M3 microcontroller.

The PBIMS can also be extended with the connection of additional support boards which enhance its capabilities and adaptability to several systems. A clear example is the integration to the BATMAN board in the Power supply payload module which is introduced in the subsection 4.3.4. Here, the PBIMS can exchange data with a local Battery Management system (BMS) through this extension.

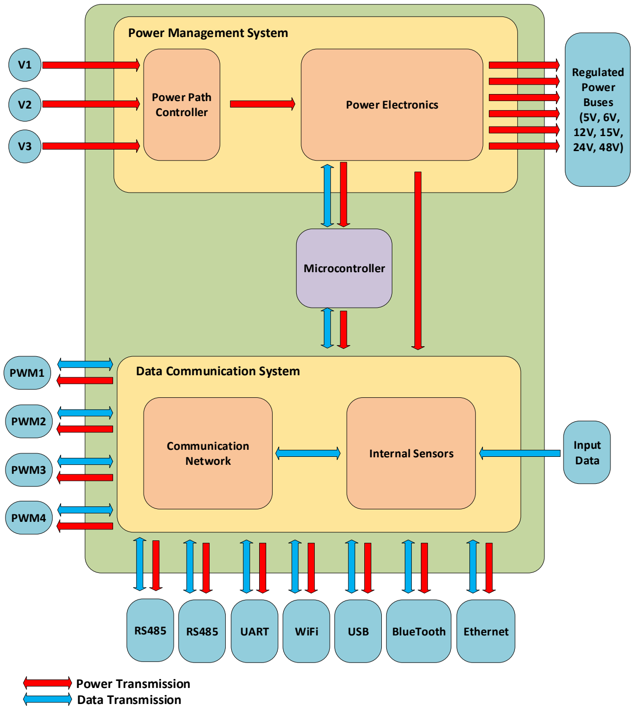

Fig. 7. PBIMS Diagram

4.3 Scientific and Engineering Payload Modules

The payload carrier is a standardized carbon fiber container with dimensions of 340 mm x 200 mm x 237 mm and maximum weight of 3 Kg. It can accommodate scientific instruments or operational support devices in about 85% from its total volume (16000 cm^3). The main scientific modules and engineering payload carriers designed for the ARCHES demonstration mission are presented as follows.

4.3.1 Soil Sample Container

The Soil Sample Container is an open module with six separated slots which can receive rocks and soil samples collected during geological tasks. Although the first version has no electronics embedded to it, the standardized parts allow future versions to be upgraded with the PBIMS, load cells, sensors and actuators.

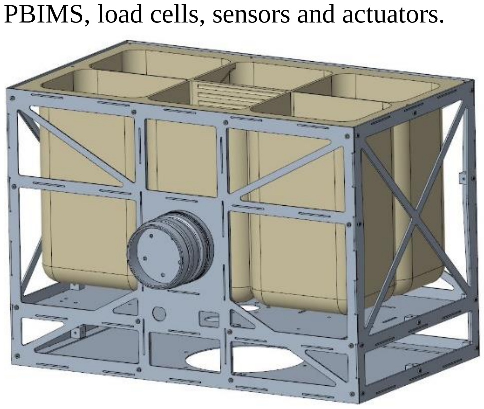

Fig. 8. Soil Sample Container

4.3.2 Radio Communication and Low Frequency Radio Array (LOFAR) Payload modules

The LOFAR [13] payload module is used as proof of concept for a novel radio-localization system developed at the DLR Institute of Communications and Navigation. Low frequency radio arrays on the far side of the moon are envisioned for radio-astronomy, and precise location information of spatially widely separated antenna elements is mandatory. The architecture makes use of the modular framing and the PBIMS (Fig.9). The radio communication, positioning and timing system (Fig.10) consists of an Intel-NUC board as central processing unit and a software-defined radio from Ettus Research. An additional software-defined radio for low RF frequencies and a foldable antenna are used to receive and store raw data for LOFAR post-processing. In the final demonstration the aim is the radio-localization accuracy. Hence, a low-cost Ublox GNSS-RTK receiver is integrated, as well as an additional radio communication system to offload LOFAR samples to the lander and the control room for processing. Most hardware is software re-configurable to support modularity, e.g., the LOFAR signal acquisition can be flexibly set to different RF frequencies, bandwidths, and snapshot lengths. Four fully equipped LOFAR payload modules and three without the low frequency SDR (as radio-localization anchors) will be used in the final demonstration.

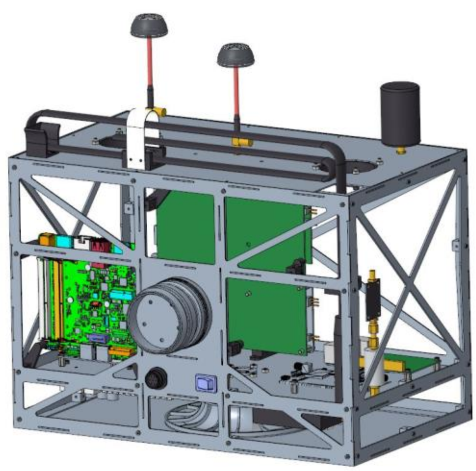

Fig. 9. Radio Communication LOFAR Module

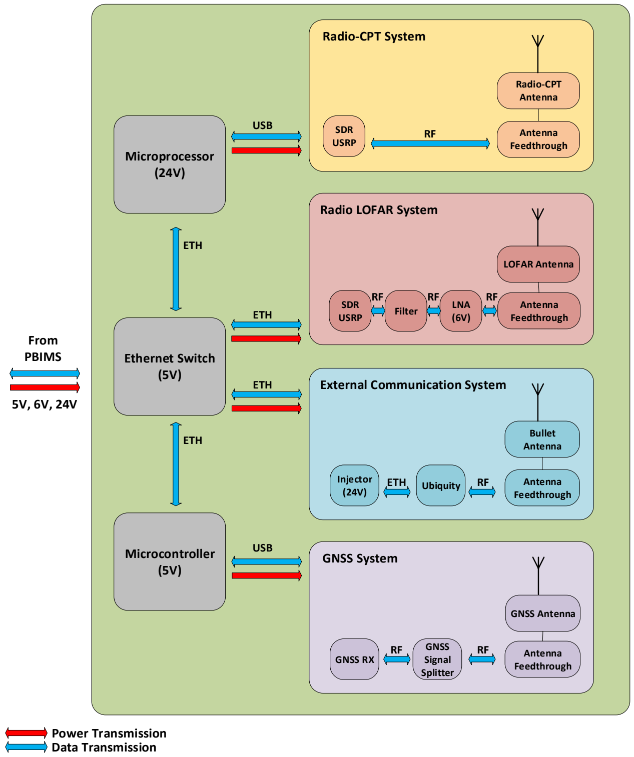

Fig.10. RC-LOFAR Diagram

4.3.3 Laser-Induced Breakdown Spectroscopy (LIBS) Payload module

The laser-induced breakdown spectroscopy (LIBS) module performs elemental analysis of rocks and soils. The instrument weighs about 1 kg and occupies only a small part of the volume of the standardized payload carrier (Fig.11). A Nd:YAG laser with 8 mJ and 6 ns pulses at 1064 nm is used to create the micro plasma that is analyzed from 550−770 nm. With a moving mirror, the instrument scans along an arc over the surface in close distance from the payload carrier which is positioned by a 75 mm long mechanical spacer. A single board computer (Fig.12) manages data acquisition and distributes the LIBS data to the rover network. The camera is used for visual target inspection while the LEDs for target illumination and laser power indication.

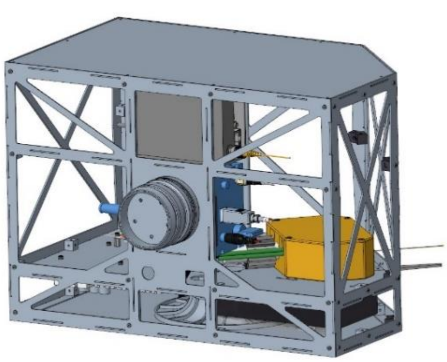
Fig. 11. LIBS Module

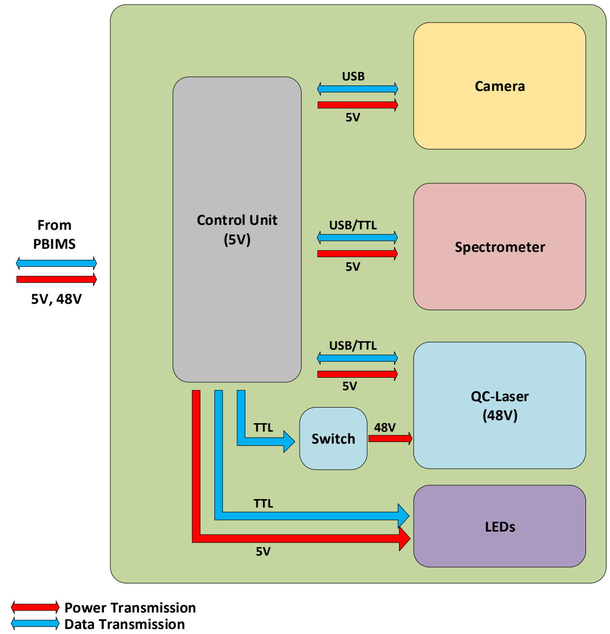

Fig. 12. LIBS Diagram

4.3.4 Power Supply Payload module

The Power Supply Payload module provides additional power to other payload carriers when they are stacked to it. With a battery capacity of 400 Wh, it can add up eight extra hours for a 50 W nominal consumption. This is a full day of operations in the analogue mission in the field.

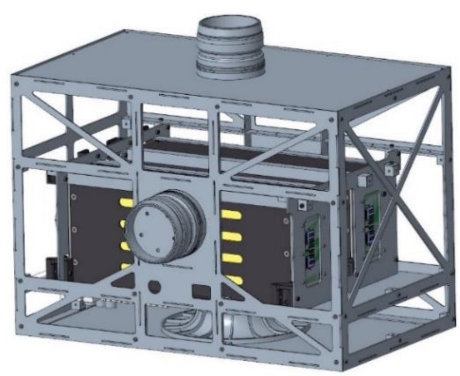
Fig. 13. Power Supply Module

The following diagram (Fig.14) shows the interconnection between the electronic components inside the module. Each battery pack comes with a local Battery Management System (BMS) which can deliver important battery information such as its remaining capacity. The BATMAN electronics makes the data interface between the local BMS and the PBIMS. Finally, the PBIMS gathers all the information and manages the power and data distribution to the external network.

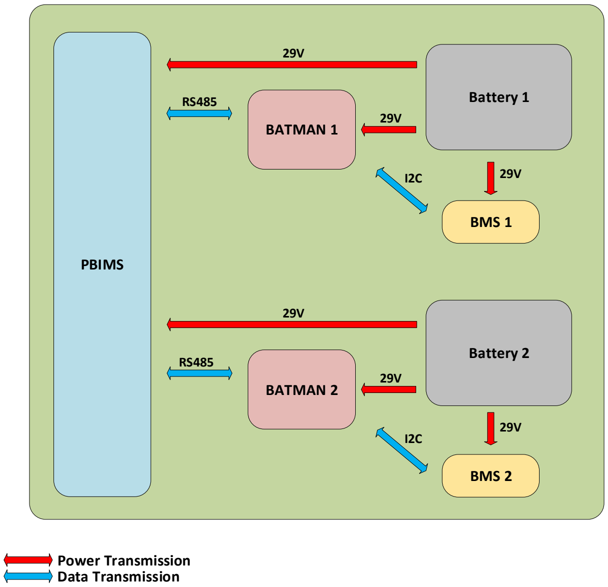

Fig. 14. Power Supply Payload Module Diagram

4.3.5 Wi-Fi Repeater Payload module

The Wi-Fi Repeater Payload module is an essential element to enhance the WLAN network in the field. Depending only on the Wi-Fi router located in the mock-up lander, both LRUs and ARDEA will be limited to a 200 m communication range. With the deployment of Wi-Fi repeaters in the field the communication range can have its value doubled.

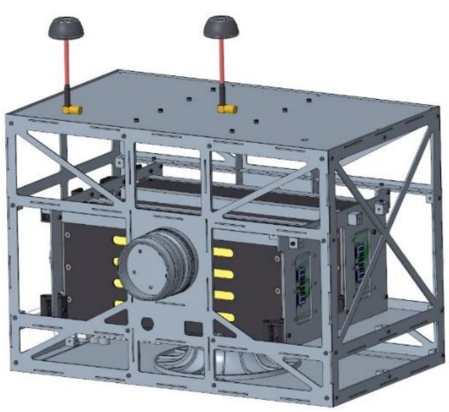

Fig. 15. Wi-Fi Repeater Module

The diagram (Fig.16) presents the main components used in this module and how they interact with the PBIMS for power and data exchange.

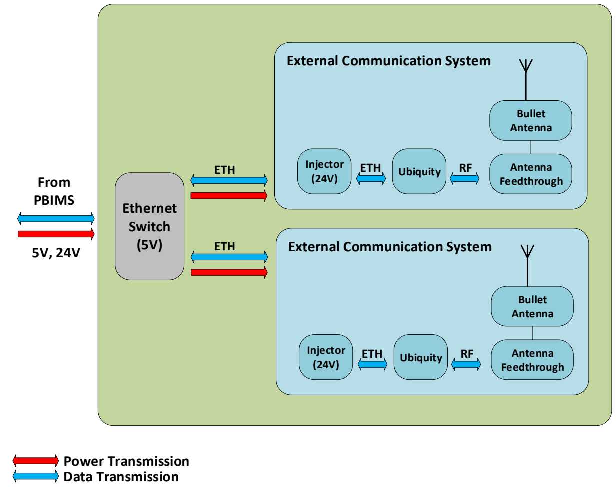

Fig. 16. WiFi Repeater Payload Box Diagram

4.4 Specific Purpose tools

Besides the payload containers, the robotic manipulator's end-effector can attach to several tools through the ENVICON docking interface system. These tools are attached to the body of the LRU2 and can be quickly accessed when needed.

The Scoop (a) is an aluminium tool used to collect soil samples from the terrain. These samples will be placed in the Soil Sample Container. The Segregation Tool (b) is utilized to separate a rock from each other when they are aggregated in a pile. This will facilitate the rock grasping task from the hand. The Karlsruhe Institute of Technology (KIT) Hand tool (c) is a prosthetic five-finger hand designed for grasping different rocks in the terrain. It has two motors actuating ten degrees of freedom. Its cylindrical grasp force is 24.2 N, its hook grasp is 120 N and the hand closing time of 1.3 s [18].

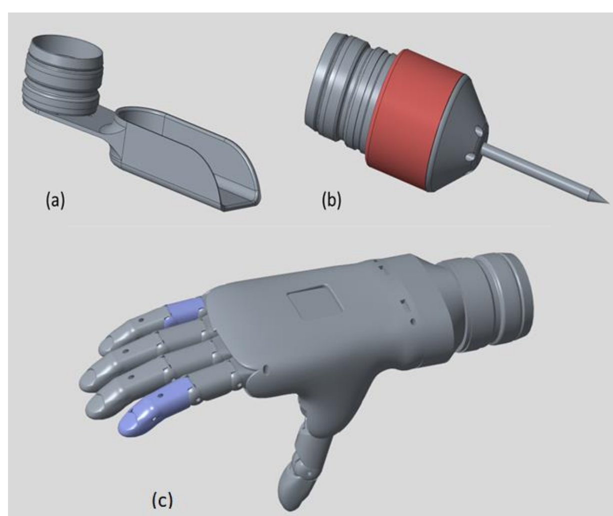

Fig. 17. Specific Purpose Tools. (a) Scoop. (b) Segregation Tool. (c) KIT Hand Tool

4.5 Software Architecture

The Software architecture (Fig.18) highlights its main elements which make the PBIMS and the ENVICON docking Interface system operational. From the hardware to the application level, it is possible to see how the software is built in a modular manner and can be reused in the future. It also shows the multi-function aspect of its elements providing communication, power distribution, and motor control capability.

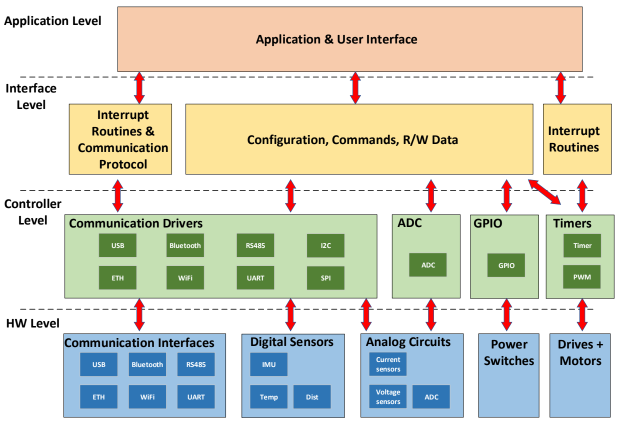

Fig. 18. Software Architecture Diagram

The main functions of the PBIMS' Software are:

- Communication to internal and external networks
- Monitoring current and voltage levels in the PMS
- Monitoring the battery capacity and state through the connection with BATMAN and local BMS
- Controlling power switches in the PMS
- Controlling the servo-motor (antenna deployment)

And concerning the functions for the ENVICON docking system:

- Controlling the motor-drives in the docking process
- Providing correct power distribution in the PMS
- Monitoring current and voltage levels in the PMS
- Providing feedback of the docking outcome through the user interface
- Communication to internal and external networks

5. Integration and Preliminary Tests

During the development of the Mechatronics Infrastructure (MI) several preliminary tests and the integration in the subsystem or the system level were carried out. The experimental results show an efficient power transfer between modules, no hardware faults, and flawless data communication among internal and external parts.

5.1 Integration Subsystem Level

The integration in the subsystem level was implemented to ensure a reliable Power Management System (PMS) and Data Communication System (DCS) within the MI.

The preliminary tests on the PMS confirmed an accurate power distribution with different loads connected to the system. The switching between different power sources occurred with no interruption nor significant voltage drop. The switching time of 2 µs guaranteed continuous operation of all scientific instruments.

The initial tests on the DCS permitted that several communication interfaces and network had their functionality assessed. No interruption nor glitches were observed in the data transferring. From simple sensor data gathering to remote control commands, the results were satisfactory.

5.2 Integration System Level

The integration in the system level was executed with at least two elements of the MI. The tests were performed according to the tasks to be carried out during the demonstration mission.

5.2.1 Stacking Payload Modules

The stacking of payload carriers (Fig.19) tested not only the LRU2 manipulation capabilities, but also the mechanical and electrical interfaces. The LRU2 was able to identify the payload module on the ground through its cameras and to find different path solutions for the stacking task with its manipulator motion planner. To do this autonomously, the flow control software RAFCON [19] was utilized. The stacking between the top and bottom modules tolerates maximum offsets of 15 to 20 mm (in the X and Y axes) as well as angles up to 20 degrees in inclination. The power is continuously transferred to the top payload module with 2 µs switching time when exchanging from the manipulator to the bottom module power source.

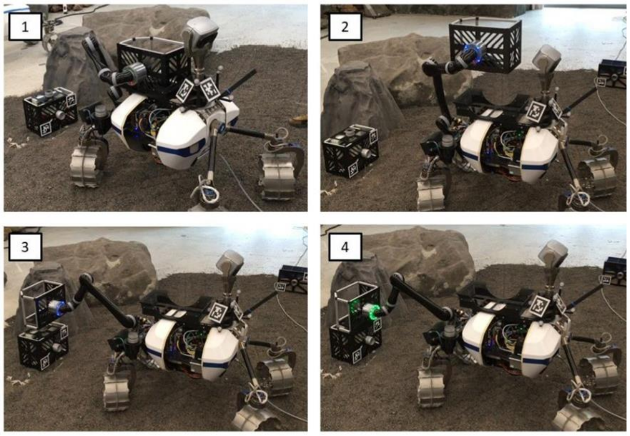

Fig. 19. LRU2 operating during the payload module stacking task.

5.2.2 LRU2 to LIBS Module

The PBIMS was integrated to the LIBS instruments and then the LIBS module was docked to the LRU2 manipulator. The PMS was able to distribute the power accurately and the LIBS data was transferred through the communication network. The peak of power consumption (78 W) was observed when the laser was shot. The sequence of actions (Fig.20) for the LIBS operation is shown as follows.

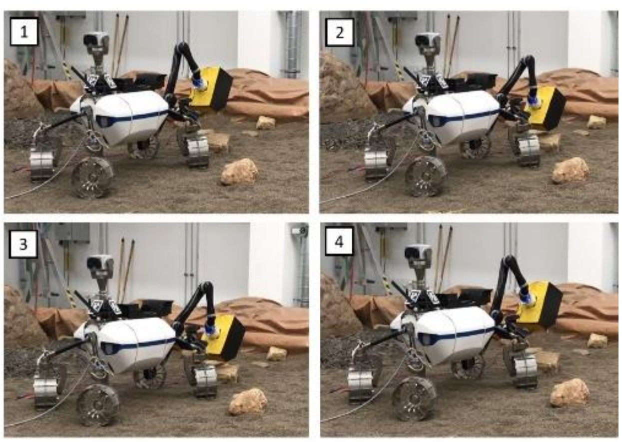

Fig. 20. LRU2 manipulating the LIBS module. (1) LRU2 docks to the LIBS module; (2) The manipulator takes the LIBS module close to the target rock; (3) The laser is shot and data is acquired; (4) LRU2 retracts the manipulator with the LIBS module to original position.

5.2.3 PBIMS to RC-LOFAR Module

The PBIMS was integrated to each RC-LOFAR module (Fig.21). Several load tests were carried out to ensure the proper power distribution to each of the four instruments in the interior of the module. The maximum power observed was 65 W when the RC-LOFAR microprocessor was processing the radio communication data. All the power buses were accurately power up and toggled with the software implemented in the microcontroller, the local DCS and the external network. Similarly, the antenna can be deployed with a remote command.

Fig. 21. Seven RC-LOFAR modules assembled and integrated to the PBIMS in each module.

5.2.4 LRU2 to KIT Hand

The KIT hand is attached to the body of the LRU2. The rover manipulator docks to the hand providing it with power and data communication capability. The coordinated movements of the manipulator and the hand permit the target rock to be grasped. Figure 22 shows the grasping task sequence.

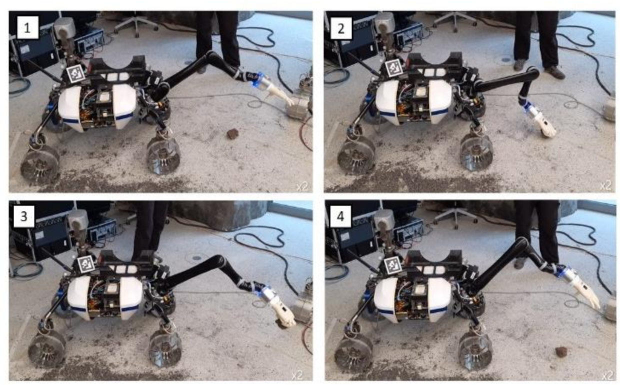

Fig. 22. LRU2 performing the geological task with the KIT hand connected in the manipulator end-effector.

6. Discussion

The successful preliminary tests and integration demonstrated that the ARCHES robotic assets are ready for operation in the field. The LRU2 can accurately manipulate, stack, and deploy payload modules in the terrain. The PBIMS can deliver the requested power for the scientific instruments and distribute the data through the network. The scientific payloads had their functionalities confirmed and were able to make measurements within accepted parameters.

The subsequent step will be the validation of all these systems in the demonstration mission to take place in the summer of 2022 on Mount Etna, Sicily. In this stage, challenges in full system integration, environment conditions and logistics are expected. However, positive results can confirm the benefits of a modular infrastructure for sustainable planetary missions: interoperability across several architectures, multi-partners being able to work together, reducing costs and risks in complex missions [1].

In addition, the modularity approach showed in this work lowers the entry height for the ARCHES robotic assets' space qualification. The modular architecture of each system permits relatively quick replacement of its parts to space-rated components and materials. While this does not qualify the assets immediately to a space mission, it can reduce the time compared to a standard space qualification.

7. Conclusions

This paper presented the design and implementation of a modular Mechatronics Infrastructure (MI) which allows the ARCHES heterogenous robotic team to extend their capabilities in the analogue planetary exploration.

The related work in modular robotics indicated the levels of modularity for several robotic units as well as the ARCHES robotic systems which have a high degree of standardization and versatility. Those high levels were justified with the introduction of the MI design. In that section, implemented standardized interfaces and multi-function modules reinforced the flexibility they can provide to a planetary mission. Next, the integration and preliminary tests section provided an idea of the scientific scenarios planned for the ARCHES demonstration mission. Finally, the discussion section pointed out the current status of the ARCHES robotic assets and had a brief look in the future steps.

In conclusion, the foreseen increased number of planetary exploration activities as well as the rise of new actors in this field will demand flexible and standardized infrastructures to overcome the challenges of long-duration and complex missions. The ARCHES modular MI is certainly the key element to solve this problem with the right degree of modularity provided to robotic teams. Consequently, these ground-breaking modular robotic systems will pave the way to a sustainable planetary exploration in the Solar system.

Acknowledgements

The authors of this work sincerely thank the involved teams in the DLR-RMC, DLR-KN, DLR-OS, and ROBEX & ARCHES projects. Also, Heinrich Gmeiner for his contributions in the development of the ENVICON Docking Interface System. Special thanks to the Helmholtz Association for the support to both ROBEX (under contract number HA-304) and ARCHES (under contract number ZT-0033) works.

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