Modular Mechatronics Infrastructure for Robotic Planetary Exploration Assets in a Field Operation Scenario

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Abstract

In 2021 the Modular Mechatronics Infrastructure (MMI) was introduced as a solution to reduce weight, costs, and development time in robotic planetary missions. With standardized interfaces and multi-functional elements, this modular approach is planned to be used more often in sustainable exploration activities on the Moon and Mars. The German multi-robot research project "Autonomous Robotic Networks to Help Modern Societies (ARCHES)" has explored this concept with the use of various collaborative robotic assets which have their capabilities extended by the MMI. Different scientific payloads, engineering infrastructure modules, and specific purpose tools can be integrated to and manipulated by a robotic arm and a standardized electromechanical docking-interface. Throughout the MMI's design and implementation phase the performed preliminary tests confirmed that the different systems of the robotic cooperative team such as the Docking Interface System (DIS), the Power Management System (PMS), and the Data Communication System (DCS) functioned successfully. During the summer of 2022 a Demonstration Mission on Mount Etna (Sicily, Italy) was carried out as part of the ARCHES Project. This field scenario allowed the validation of the robotics systems in an analogue harsh environment and the confirmation of enhanced operations with the application of this modular method. Among the numerous activities performed in this volcanic terrain there are the efficient assembling of the Low Frequency Array (LOFAR) network, the energy-saving and reduced complexity of a detached Laser Induced Breakdown Spectroscopy (LIBS) module, and the uninterrupted powered operation between modules when switching between different power sources. The field data collected during this analogue campaign provided important outcomes for the modular robotics application. Modular and autonomous robots certainly benefit from their versatility, reusability, less complex systems, reduced requirements for space qualification, and lower risks for the mission. These characteristics will ensure that long duration and complex robotic planetary endeavours are not as challenging as they used to be in the past.
Keywords: mechatronics, robotics, modularity, exploration, operations

1. Introduction

The implementation of the modular approach in robotics has started a few decades ago with the development of the cellular robotics (CEBOT) from Fukuda and Kawauchi [1]. However, it has become more relevant in the present years with the flourishment of robotic systems beyond the manufacturing sites. Different industries such as the medical, logistics or consumers appliances have realized that with modularity it is possible to reduce costs, improve interoperability and the coordination of different systems [2]. The recent publication of the ISO 22166-1 [3] which specifies the guidelines for modular design and integration of robotic modules in several environments is a solid indication of this trend. This is not different for space application. The Global Exploration Roadmap (GER) [4] has pointed out the importance of the standardization of interfaces and modular architectures in human and robotic exploration missions. Likewise, the Section Five of the Artemis Accords on Interoperability foresees common exploration infrastructure and standards [5]. With more actors working simultaneously on the lunar surface, this strategy appears as a natural solution to ensure sustainability. This is similar to what has already occurred on Earth in the Oil & Gas industry or the Mining sector: different companies and heterogenous systems in the same project led to standardized interfaces and common systems.

Following this tendency and looking towards the future of space exploration, the ARCHES project has the modularity in the core of its structure. This philosophy has provided versatility to the robotic team with the inclusion of the Modular Mechatronics Infrastructure

(MMI) which can extend the capabilities of the robotic units with modular scientific payloads, standardized interfaces, and specific-purpose tools.

This paper goes beyond the design and implementation of the MMI. It shows the validation and testing of the robotic systems in a planetary analogue environment with all its possible challenges.

The aim of this work is to reinforce the benefits of the MMI presented previously in [6] and to show the test and validation phase of the mechatronics infrastructure applied to robotic planetary exploration in a space analogue environment.

This paper presents:

- The related work on robotic modularity in planetary robotics, the modular design approach and the Verification and Validation processes
- A short overview of the ARCHES Demonstration mission
- A summary of the Modular Mechatronics Infrastructure (MMI)
- The tests and validation of the robotic assets carried out during the ARCHES Demo mission
- A short discussion about the tests results and the validation process
- A conclusion with a look towards the future

2. Related Work

In this section, the related work on modularity in planetary robotics, modular design approach, and verification and validation in field robotics are presented.

2.1 Modularity in Planetary Robotics

In the manuscript presented in IAC 21 [6], a series of modular robot units designed for planetary exploration were introduced.

The Scarab prospector rover [7] with the ability to reorganize different scientific payloads on its chassis. The six-legged cargo robot ATHLETE [8] with the capability to turn its limbs into manipulators. The multi-robot cooperation projects LUNARES [9] and IMPERA [10] able to collect soil samples but lacking a docking interface for manipulation. The RIMRES [11] which made great advancements with the standardization of systems and the inclusion of an electromechanical interface to interconnect different payloads. ROBEX [12] which had the development of a standardized docking system for manipulation, few scientific payload modules to be deployed in the field, and the cooperation among the Light Weight Rovers (LRUs). Finally, the ARCHES [13] which enhanced the ROBEX concept with the inclusion of several robots in the network, the standardization of mechanical and electrical interfaces, and the development of a modular mechatronics infrastructure to allow data and power transferring among the robotic assets.

Based on the NASA framework for modular assembly systems [14], it was show that the Modular Mechatronics Infrastructure (MMI) was vital for the high level of standardization, versatility and maintainability of the ARCHES robotic assets.

2.2 Modular Design Approach

The Modular Design Approach was introduced in the CLAWAR project [15] with the purpose to create an open modularity philosophy which would serve both the R&D community and the Industry. This joint effort had the intention to find common tools and standards which facilitate the development of robotic systems.

As presented in the works of Virk [16], Norman [17] and the ISO 22166-1[3], the modular design process can be structuralized with the use of diagrams which include the main modules and the key interfaces linking them. In this way, the designed robotic system becomes very clear to manufacturers and developers. The block diagram consists of an input and an output side with five different channels represented by the interfaces which link one module to the other. These links are: the interface to the environment, the mechanical linkage, the data and communication specifications, the power supply requirements, the security protection, and the safety limits. The generic module is represented on Fig. 1(a) and a simplified example of an application is shown on Fig.1(b). In this example the robot grasps an object with the initial sensor information of the distance, the processing of the data in the microcontroller (μC) and finally with the motor generating a torque on the gripper to grasp the object.

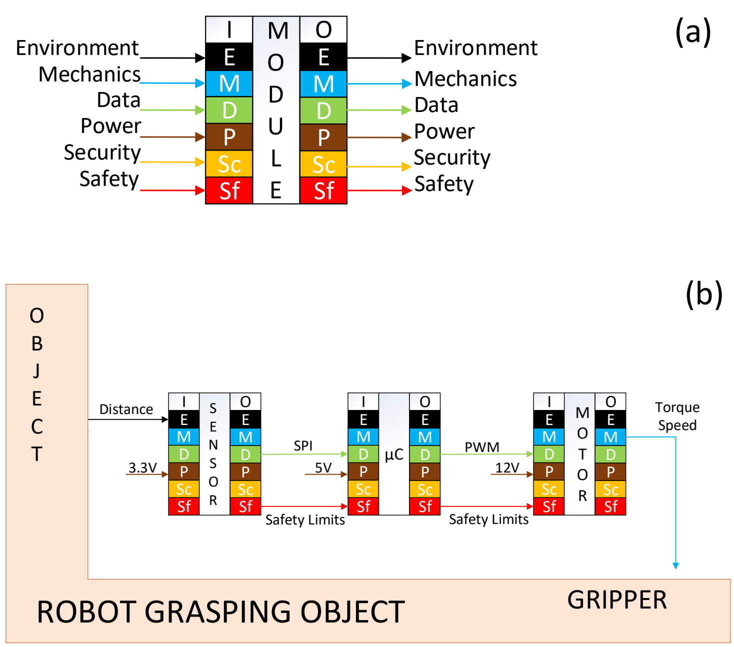

Fig. 1. Modularity Design Approach presented in the ISO 22166-1. (a) Generic Module with interfaces. (b) Example of robotic grasping object with a gripper

2.3 Verification and Validation in Field Robotics

The Verification and Validation (V&V) process it is a critical part of the development of robotic systems. It not only ensures that the requirements and specifications of a system are in conformance but also assess whether this system matches its target application.

In [18] the V&V process for the Mars Science Laboratory (MSL) Entry, Descending, and Landing (EDL) system was presented. Among a few V&V approaches, this highly complex system utilized the event-tree-based approach in which the sequence of hierarchical events and conditions are enumerated and analyzed for the successful execution of the system.

The V-Model [19] [20], which is extensively applied in the industry and space domain, has several dynamic iterations to confirm the V&V execution. The VDI 2206 Standard [20] highlights that several macro-cycles might occur to increase the maturity of the system. This approach is foreseen as the V&V method in [21] with the recognition of robotic and autonomous systems complexity in planetary robotics.

Although the ARCHES robotic assets did not pass through the qualification process for space application, simplified versions of the event-three approach and the V-Model were utilized during the development phase and the field demonstration campaign. This ensured that the robotic systems were fully functional and performed accordingly to the mission requirements. The tests carried out on the terrain of the Mount Etna represent an additional macro-cycle on the V-Model and increase the maturity level of the ARCHES robotic systems.

3. ARCHES Demonstration Mission

The ARCHES [13] [22] demonstration mission was carried out in the summer of 2022 on Mount Etna in Sicily, Italy. Three scientific exploration scenarios took place in this lunar analogue test site: Geological Mission I, Geological Mission II, and LOFAR [23] Demonstration Mission.

The Geological Mission I represented a scenario in which the Lunar Gateway [24] is not present and therefore robots with autonomous functionalities are operated from Earth. This shared autonomy mode allows scientists and operators to interact with the robots taking crucial decisions such as the definition of geological targets. However, simple machine-based decisions such as navigation on the terrain and obstacle avoidance are taken locally by the robot. The tasks performed were the rock collection, the soil sampling, and the elemental analysis of rocks with LIBS [25]. The network of robots in this scenario included the drone ARDEA [26] which scouts the terrain, the LRU1 [27] which inspects geological targets with its ScienceCam [12], and the LRU2 [27] [28] which can manipulate several payload modules and collect geological samples from the terrain with the use of its robotic arm.

The Geological Mission II represented a scenario in which the Lunar Gateway is already on orbit and with human presence. In this scenario the use of advanced telerobotic concept such as high-fidelity tele-operative control with visual and haptic feedback is possible. The geological tasks were performed by the ESA Interact rover [29] which collected rocks on the terrain with its manipulator and the DLR Scout Rovers [30] which explored the terrain and served as communication relay to the Interact rover.

The LOFAR Demonstration Mission represented a scenario in which a low frequency radio antenna array is deployed on the lunar surface to explore the deep of the universe. On Mount Etna, a set of four LOFAR antennas and three reference antennas were deployed by the LRU2 while LRU1 and ARDEA supported with the localization. The deployment of the antennas was performed after seven power supply payload modules were positioned on the terrain. The antennas were stacked on top of each power supply box to have their operation autonomy extended.

The RODIN mock-up lander was part of all three scenarios. It acted as base station and global landmark for all robots.

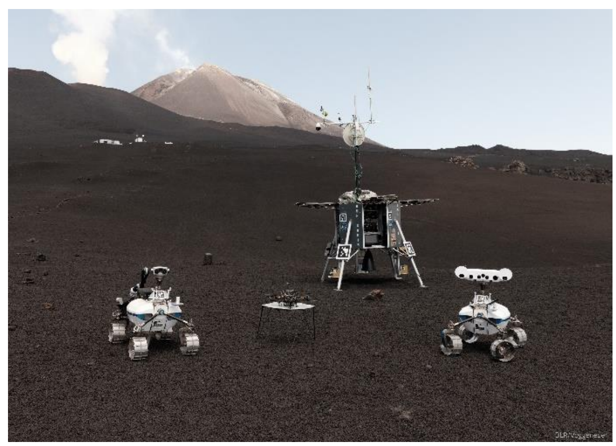

Fig. 2. Robotic Assets for ARCHES Demonstration Mission

4. Modular Mechatronics Infrastructure

The Modular Mechatronics Infrastructure (MMI) consist of the ENVICON Docking Interface System (DIS), the payload modules, the specific-use tools, and the power and data management electronics board. With the MMI, the heterogeneous robots are able to take geological measurements, manipulate objects in the field, improve their navigation and communication, and maintain the set of payload modules deployed on the terrain.

4.1 ENVICON Docking Interface System

The ENVICON Docking Interface System (DIS) [28] encompasses an active and a passive coupling partner. The active coupling partner is a spring-loaded system which can latch the male passive coupling partner mounted on the surface of the payload modules or the specific-purpose tools. This system is an essential part of the modular structure of the LRU2. With the ENVICON DIS the rover is able to manipulate the several modules and tools to accomplish its tasks inside each mission scenario.

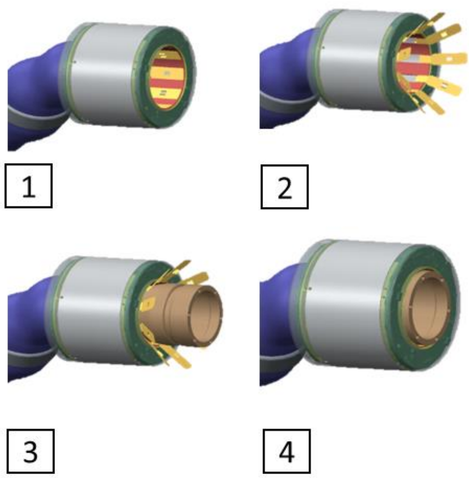

Fig. 3. ENVICON Docking System. The Active Coupling partner latches the Passive Coupling partner.

The docking execution can be expressed according to the standard modular design diagram introduced in the ISO 22166-1, as shown on Fig. 4. The Power Management System (PMS) receives the 24 V on the power interface from the robotic arm, converted it (in 5 V & 7.2 V) and distribute it through the several modules. The Data Communication System (DCS) receive input commands via Bluetooth, RS485 or USB in the data interface and connects to the microcontroller (µC) which will generate the PWM signal to operate the Motor module. It will output through the mechanical interface a torque which will open up the latching springs and dock to the payload module. The same operation can be executed via a User Interface (UI) with its buttons and LEDs. The Sensor module can get inputs of distance and angle through the environment interface and support the docking execution with precision.

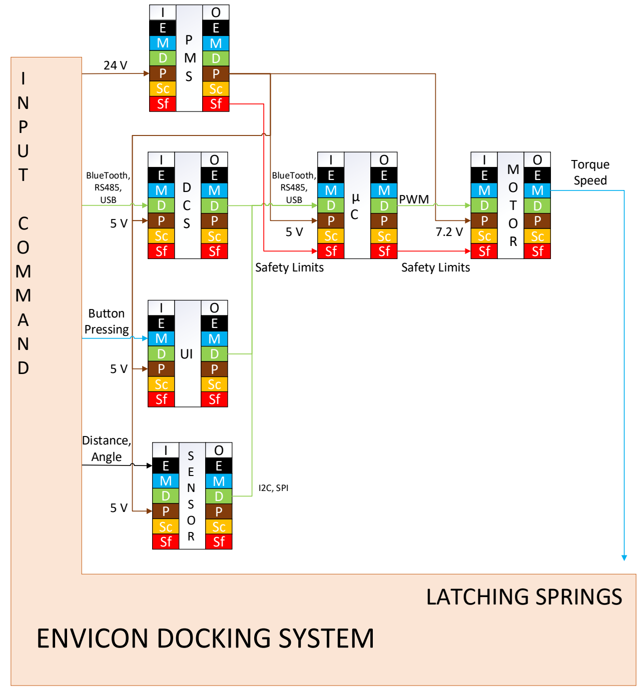

Fig. 4. ENVICON Docking System Modular Design Diagram based on ISO 22166-1.

4.2 Payload Box Infrastructure Management System (PBIMS)

The PBIMS (Fig. 5) is a modular electronic board with the purpose of distributing the power and handling the data communication to the internal components of the payload module or the external parts in the network. One portion of the board is dedicated to the Power Management System (PMS) which includes a power path controller and the Power Electronics. The second portion is dedicated to the Data Communication System (DCS) which manages the communication from internal sensors to the external network through six different data buses. All systems are controlled by an ARM® Cortex®-M3 microcontroller.

The power distribution control to enable or disable a specific power bus can be described according to the ISO 22166-1 standard modular design as illustrated in Fig. 6. The PMS has an input voltage of 24-28 V from the battery pack or the robotic arm (power interface) and proceeds with the power distribution to several modules. The DCS receives an input command via Bluetooth, RS485 or USB in the data interface. It connects to the microcontroller (µC) which will send a digital high/low voltage signal (data interface) back to the PMS - represented in Fig. 6 as Power Electronics (PELEC) as an internal module of the PMS for better readability of the diagram. The PMS will finally switch ON/OFF the power bus channel through the operation of the MOSFET switch.

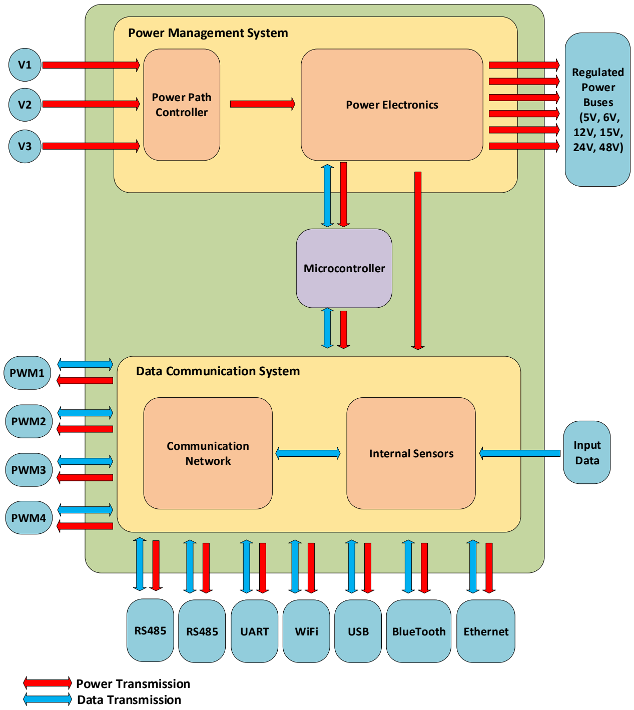

Fig. 5. PBIMS Diagram [6].

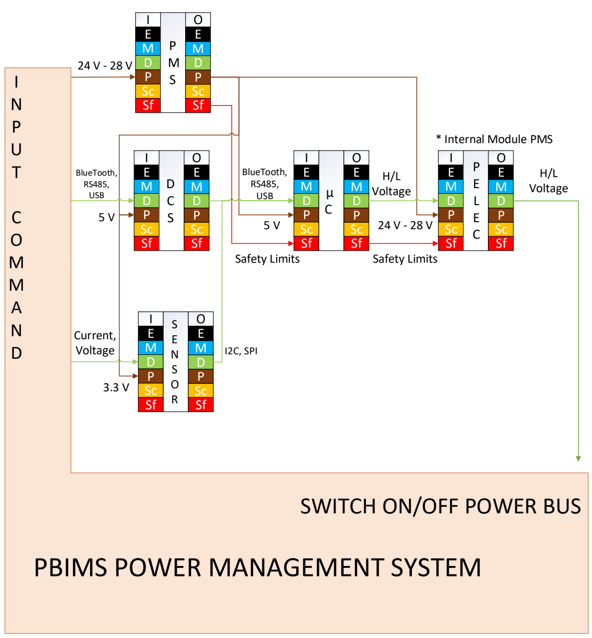

Fig. 6. PBIMS Power Management System Modular Design Diagram based on ISO 22166-1.

4.3 Scientific and Engineering Payload Modules

The payload module is a 340 mm x 200 mm x 237 mm standard carbon fiber container which can carry scientific instruments or support engineering infrastructure to the ARCHES network [6]. The four scientific-type modules are the LIBS box, the Radio Localization box, the LOFAR box, and the Geological Sample container. The two support-infrastructure-type modules are the Power Supply box and the WLAN-repeater box. Fig. 7 illustrates the diverse types of payload boxes utilized in the ARCHES Demo mission.

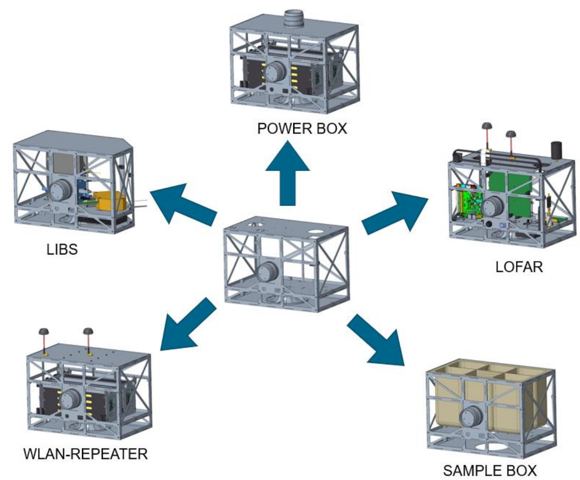

Fig. 7. Set of scientific and engineering Payload Modules

4.4 Specific Purpose tools

The specific purpose tools are attached to the body of LRU2, can be quickly accessed by the robotic arm, and connected to its end-effector docking interface. The three different tools are essential for the geological tasks performed during the ARCHES Demo mission. The Karlsruhe Institute of Technology (KIT) Hand tool [31] is a prosthetic five-finger hand designed for grasping different rocks in the terrain. The Segregation tool helps to segregate rocks which are in a pile. This facilitates the grasping task of the KIT hand. Finally, the Shovel is a simple aluminium tool used to collect soil samples from the terrain.

Fig. 8. Specific purpose tools

5. Field Test and Validation

During the ARCHES Demonstration Mission, the Modular Mechatronics Infrastructure (MMI) was verified and validated which led to an additional layer in its maturity level. If the preliminary tests carried out during the design and development phase proved the functionality of the system, now the MMI demonstrated its robustness and versatility in a harsh environment such as the volcanic terrain of the Mount Etna. The several processes verified and validated are presented as follows.

5.1 Docking Process

The sequence of events for the Docking Process are as the following simplified event-tree-based diagram (Fig. 9). This task breakdown method facilitates the verification and validation (V&V) of this subsystem since the performance can be checked in intermediary steps of the entire Docking task. In an event of failure, a rapid troubleshooting process can be applied and the system can be fixed and improved. The manipulation system autonomy ensures that the robot restarts the docking process in case one of the events is not successful. This procedure will be repeated until a successful attempt is achieved or there is a hardware failure in which human intervention is needed.

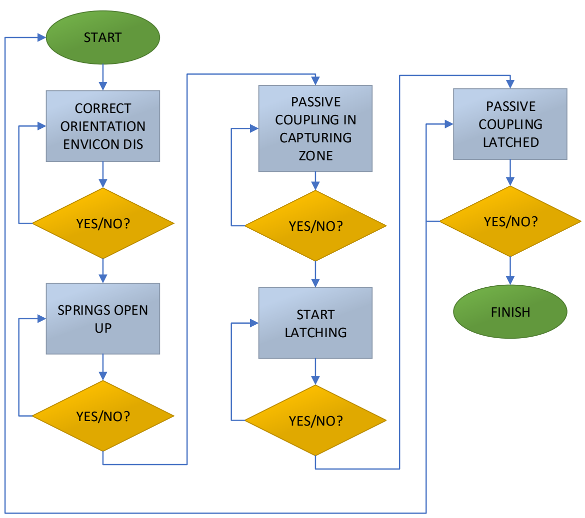

Fig. 9. Simplified Docking task event-tree-based diagram for the V&V process during the ARCHES Demo Mission.

The flow control software RAFCON [32] provides a feature which can log the activities performed by the LRU with the breakdown of the steps within a certain task. Hence, it was possible to track the amount of docking processes carried out during the four weeks of demonstration mission. Table 1 shows the success rate considering the preparation, demo mission and experiment phases. As presented, in a total of 17 days and nearly 200 docking processes, the docking success rate was of 95%. However, it is important to highlight that failures are often related to software issues rather than mechanical. They are usually caused by the inaccurate orientation of the robotic arm or the wrong load data set of the manipulator during impedance control. Once a docking failure is detected by the LRU, it recalculates the motion path and repeats the docking process until it obtains a success. This means that an unsuccessful docking does not compromise the execution of the task, it just adds a few more seconds in the process.

Table 1. ENVICON Docking Process Performance Rate

	Period (days)	**Success (n)**	**Success (%)**	**Failure* (n)**	**Failure* (%)**
Preparation	10	150	96	7	4
Demo Mission	4	13	93	1	7
Experiment	3	11	92	1	8
Total	17	174	95	9	5

**Failure rate due to software processes. Reattempt ensured the task was completed successfully.*

5.2 Stacking Payload Modules

The Stacking Process can be decomposed in the chain of events illustrated in Fig. 10. This is part of the V&V method and each step can be checked individually. First the LRU2 get the pose of Box1 on the ground, then dock to the Box2 on its back. The robotic arm moves Box2 above Box1 and then stacks it (on top of Box1). If the stack task is successful, the process is finished. Otherwise, the robot can restart it from the beginning and reattempt to complete the task.

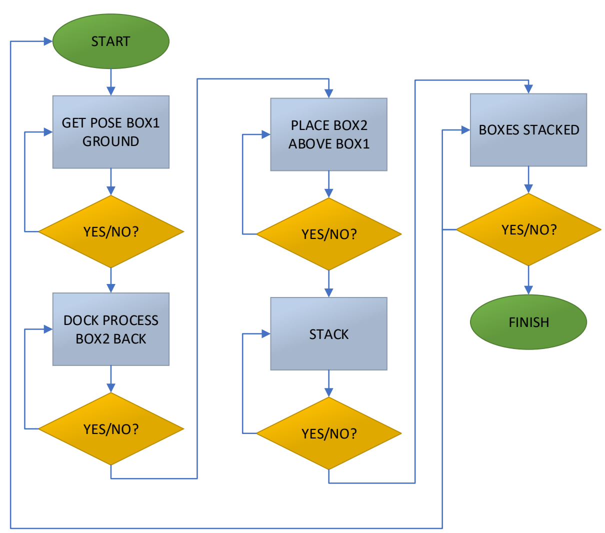

Fig. 10. Simplified Stacking task event-tree-based diagram for the V&V process during the ARCHES Demo Mission.

Fig. 11 shows this sequence with actual photos of the experiment on Mount Etna. It is possible to see that the execution is carried out flawlessly. Although in [6] the system was pushed to operate within linear and angle tolerances (20mm offset and 20 degrees inclination), in the ARCHES Demo mission a flat area was selected rather than challenging slopes. This represents a choice that offers less risk to the mission. The switching time between power sources of top and bottom modules remained in the magnitude of 2 μs as observed in the design and implementation phase.

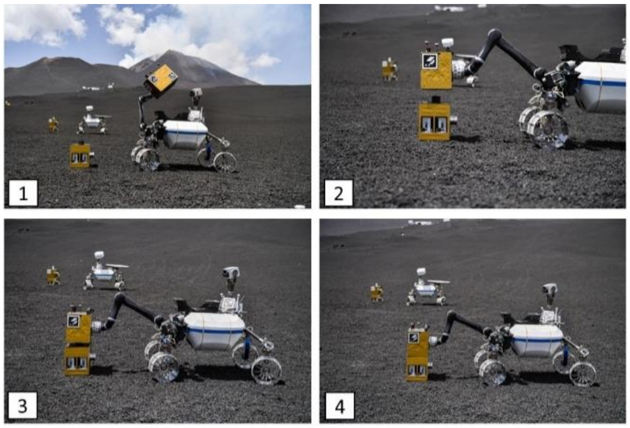

Fig. 11. LRU-2 stacking RC-LOFAR payload boxes on top of the Power Supply box.

5.3 Soil Sample Collection with shovelling tool

The soil sample collection task follows the sequence of events which starts with the connection of the shovel to the LRU2 robotic arm (Fig. 12.1), then the movement of the arm to the target (Fig. 12.2), the collection of the soil sample (Fig. 12.3), and is finalized with the delivery of the sample to the container (Fig. 12.4).

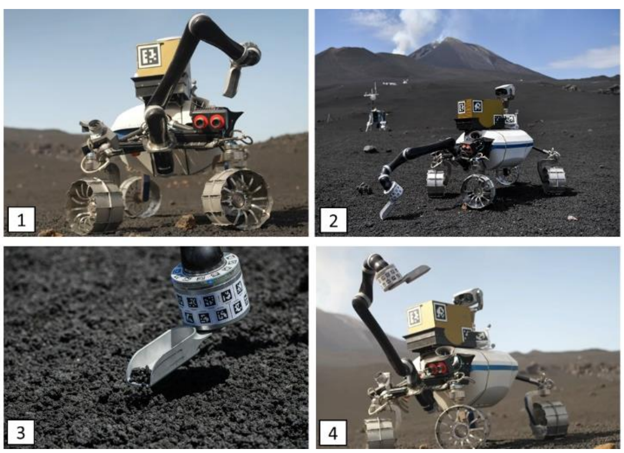

Fig. 12. LRU2 with the Shovelling tool collecting volcanic soil sample

Regarding the manipulation system (ENVICON Docking Interface and LRU2 robotic arm) power management, the related power data was logged via the RAFCON tracking capability. Fig. 13 presents a low power consumption (around 8 W) which is below the threshold of 25 W for nominal manipulation operations.

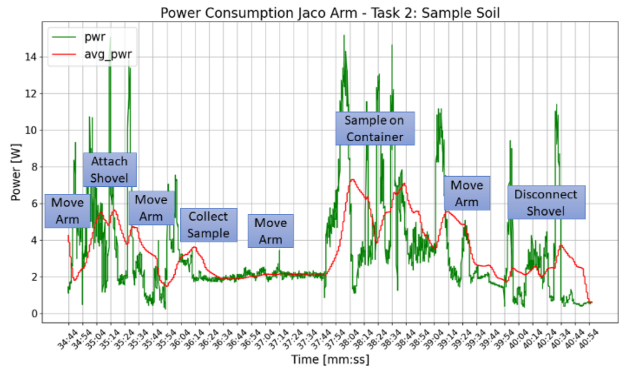

Fig. 13. Power Consumption LRU2 Robotic Arm during the Soil Sample task below nominal consumption (25W)

5.4 Rock Grasping with KIT Hand

The Rock Grasping task was carried out with the following sequence: initial docking of the KIT hand, then the arm is positioned over the selected rock (Fig. 14.1), the KIT hand opens its fingers (Fig. 14.1), the KIT hand grasps the rock (Fig. 14.2), the rock is placed on the container (Fig. 14.3, 14.4).

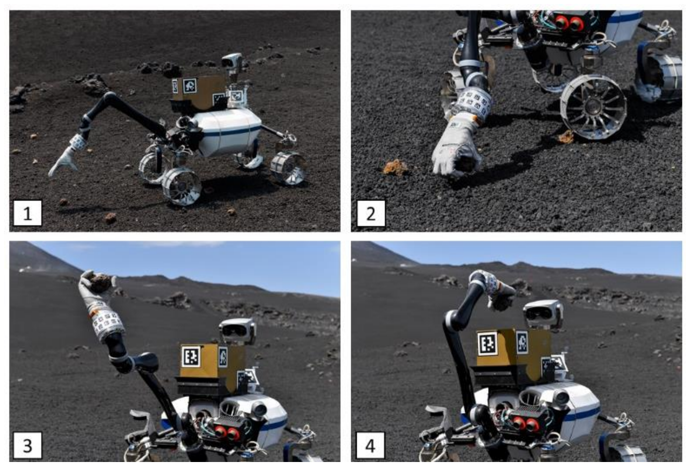

Fig. 14. LRU2 with KIT hand docked grasping a rock and placing it in the container

Considering the power management of the manipulation system (including the ENVICON docking interface and the LRU2 robotic arm), the RAFCON tracking features recorded the power consumption of the LRU2 robotic arm during the 14-minute Grasping Rock task. Fig. 15 shows that this power consumption remains below the 25 W nominal for manipulation operations. The expected peak power is up to 100 W, therefore the few outliers which surpass the nominal threshold are in conformance. In addition, when the data is plotted with a moving mean value of 200 samples, the curve stays below the operational nominal threshold (red graph: avg_pwr).

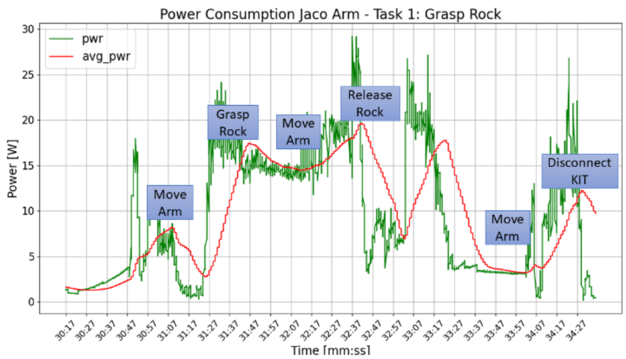

Fig. 15. Power Consumption LRU2 Robotic Arm during the grasping rock task below nominal consumption (25W)

5.5 LIBS Module Manipulation and Operation

The execution of the V&V method with the event-tree-based diagram can also be applied to the LIBS module manipulation and operation. The sequence of events from the identification of the geological target until the acquisition of the spectrum with specific chemical elements are described in Fig.16.

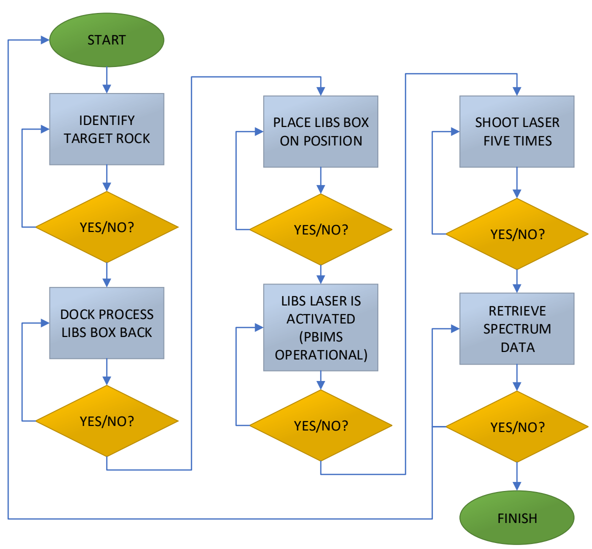

Fig. 16. Simplified LIBS task event-tree-based diagram for the V&V process during the ARCHES Demo Mission.

The chain of events is also illustrated in Fig. 17 with the LRU2 docking to the module (Fig. 17.1), positioning it on target (Fig. 17.2, 17.3) and receiving the spectrum in a graphical user interface (GUI) (Fig. 17.4) on a remote PC connected to LRU2. The PBIMS was crucial here for the power distribution and the data communication. The maximum power consumption observed was in line with the values noted in the development phase [6]: 78 to 80 W when shooting the laser.

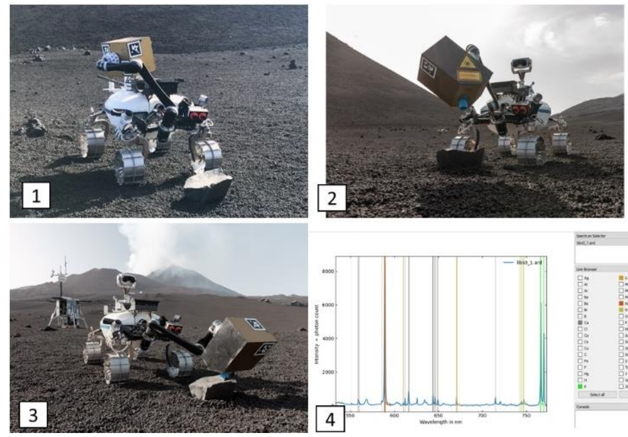

Fig. 17. LIBS experiment in the ARCHES Demo Mission

5.6 RC-LOFAR Module Deployment and Operation

The deployment of the RC-LOFAR modules was carried out autonomously by the LRU2. Since the geometry of the array impacts in the performance of the antennas, this arrangement was supported by LRU1 and ARDEA with the localization and terrain mapping. Besides the correct manipulation of the modules and precise stacking of the boxes, the position where they were deployed was also a goal of this task.

While the ENVICON Docking Interface components were key for the manipulation operations, the PBIMS supported significantly with the power distribution and data communication. The several consumers inside the payload module received their required currents and voltages as expected. The peak power consumption registered was 67 W during the processing of the radio-communication data. The power buses could be accurately power up and toggled with the software implemented in the microcontroller, the local DCS and the external network. Likewise, the antennas were deployed with a remote command. Fig. 18 illustrates the operation of the RC-LOFAR during the night with the attempt to record the Jupiter radio burst signal.

Fig. 18. RC-LOFAR deployed and in operation on Mount Etna during the night.

6. Discussion

The successful tests, verification and validation performed on the ARCHES Demonstration mission confirmed that the robotic assets gained one layer of maturity level being able to operate in the harsh environment of the Mount Etna. The LRU2 accurately manipulated, stacked and deployed the payload modules in the volcanic terrain. The ENVICON docking interface performed nearly 200 docking executions with 95 % of success rate and no hardware faults. The PBIMS provided the requested power to each of the internal consumers inside the payload module and was able to transfer the data flawlessly through the network. The Power Supply modules delivered the additional power to the other payload modules enhancing their autonomy. The LIBS scientific instrument operated accordingly in three different geological targets with the laser shooting and the elemental spectrum acquisition. The RC-LOFAR payload module, after deployment, executed well the localization task and radio-astronomy experiment.

The subsequent step can be the test of MMI components in a different environment or different robotic units. For instance, a subsea version of the ENVICON docking interface is in development and it could be utilized in a marine environment. With robots that can dock to standard payload modules (with scientific instruments), the modular approach would be applied to another robotic network.

In addition, as mentioned in [6], the modular approach facilitates the ARCHES robotic assets' space qualification. It reduces the time compared to standard space qualification with the fairly quick replacement of its parts to space-rated components and materials.

7. Conclusions

This paper presented the test and verification & validation (V&V) of the Modular Mechatronics Infrastructure (MMI) in a Moon-analogue environment during the ARCHES Demonstration mission.

The related work section made a brief summary of the several modular robotic unities introduced in [6] and the high levels of standardization and versatility inherent to the ARCHES robotic assets. It also showed the new concept of the modular design approach in robotics from the ISO 22166-1 with its key interfaces to link different modules. In addition, the V&V processes such as the V-model and the event-tree-based approach were introduced with some examples of its application. Next, an overview of the ARCHES Demonstration mission was presented followed by the main elements of the MMI. The field test and validation section gave an idea on how these elements of the MMI were utilized in several tasks carried out during the ARCHES Demo mission. Finally, the discussion section pointed out how the maturity level of the robotic assets and the MMI was increased after the high performance demonstrated in the field.

In conclusion, there is a clear trend which shows that modularity is going to play an important role in both planetary and Earth service robotics. The implementation of versatile and standardized interfaces in these machines will ensure more sustainable planetary missions and less complex systems on Earth. This will allow different actors to operate together and technologies to be upgraded in the future with less effort. The ARCHES MMI, tested and validated in the field, is a valid solution for this increasing demand. It was demonstrated that it provided the right degree of modularity to the ARCHES robotic team which accomplished all the scientific tasks successfully.

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