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Mechanical design of a modular experiment carrier for a terrestrial analog demo mission and its potential for future space exploration

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Abstract

The ROBEX (Robotic Exploration under Extreme Conditions) alliance formed by the German Helmholtz Association has the aim to find and use areas of overlapping competencies between institutions involved with the exploration of deep sea and space environment. To demonstrate the developed systems and technologies two test campaigns are conducted, one for the deep sea in the area of Svalbard, Norway and one on the volcano Mt. Etna in Sicily, Italy as an Moon environment analog test ground.

The objective of the volcano mission is to demonstrate seismic experiments built-up and conducted autonomously by robotic elements. It shall serve as scientific benchmark to validate concepts reproducing and extending experiments from the Apollo program and at the same time demonstrate robotic capabilities to do so without direct human interaction. The overall test infrastructure consisting of a stationary lander, a mobile element and instrument carriers has been developed within the ROBEX alliance. The modular instrument carrier, referred to as Remote Unit (RU), is deployed and positioned by a robotic system and supplies the payload, in this case the seismometer, with power, data-handling and communication. It also provides mechanical interfaces to the lander and a grapple interface for robotic handling. The RU's primary structure is a differential carbon-fiber-reinforced-plastic (CFRP) framework with a dedicated payload and bus compartment. Two types of RUs have been developed: one basic version that complies with a mass limitation of 3 kg (RU3) and one extended version of 10 kg (RU10). While the basic version has a fixed seismometer as well as limited lifetime due to the lack of photovoltaics, the extended version is equipped with a self-levelling seismometer, photovoltaics and an inductive power/data interface for unit charging and telemetry/telecommand (TT&C). Both designs use the identical main structure to meet the envisaged modularity approach.

Even though the hardware was never meant to enter the space environment, the design approach for the units was always driven by principles which could be functional under space conditions while respecting the peculiarities and the financial framework of this terrestrial demonstration. This paper presents the functionalities of the RU with a special focus on the overall configuration, structural concept as well as included mechanisms. Moreover, starting with the baseline design for the terrestrial application, it analyses the differences and derives necessary changes and modifications to further develop the system towards a usage in an actual Moon mission.

Keywords: ROBEX, Remote Unit, Moon, Robotic, Payload, Structure

Acronyms/Abbreviations

ALSEP	Apollo Lunar Surface Experiments Package
CFRP	Carbo-fibre-reinforced-plastic
COTS	Commercial off-the-shelf
DLR	German Aerospace Center
EGSE	Electronic Ground Support Equipment
ESD	Electrostatic Discharge
GPS	Global Positioning System
HD	High Density
I-SYS	Inductive Transfer System
MLI	Multilayer insulation
MR	Mission Requirement
ROBEX	Robotic Exploration under Extreme Environments
RTG	Radioisotopic Thermoelectric Generator
RU	Remote Unit
SR	System Requirement
TID	Total Ionizing Dose
TT&C	Telemetry & Telecommand

1. Introduction

From the beginning of crewed expedition to the Moon with Apollo 11, sensor packets to operate on the Moon's surface for scientific longterm data collection were always part of the payload handled by the astronauts. They brought deeper insight into the Moon's environment and internal composition in many ways. From Apollo 12 on, the sensor packets referred to as Apollo Lunar Surface Experiments Package (ALSEP) consisted of several individually wired units for communication and data handling, power supply using a Radioisotopic Thermoelectric Generator (RTG) and sensors. For Apollo 12 these payloads summed up to an overall mass of more than 85 kg including 25 kg for the Central Station and 19.6 kg for the RTG [1]. One specific experiment of that time has been selected to be the role model for the reference payload in the course of the ROBEX (Robotic Exploration under Extreme Conditions) Moon-analog demo mission: a seismometer network subsequently deployed throughout the Apollo missions to measure ground discplacements and seismic events. Back then it was the task of the astronauts to unload, deploy, setup and level the units and activate the measurements manually.

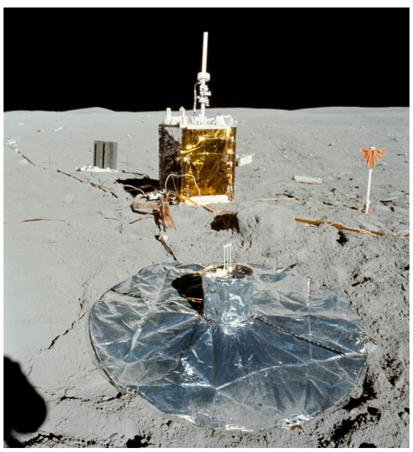

Fig. 1. Apollo Lunar Surface Experiments Package with Passive Seismic Experiment as deployed during Apollo 16. [2]

The aim of the ROBEX demo mission is to demonstrate current robotic capabilities by replacing the human by autonomously operating and interacting systems under harsh environment conditions. The demo mission took place on the active vulcano Mount Etna, Sicily (Italy), which was chosen as a moon analog environment due to its seismic activities and was performed in a campaign of about one month duration from June to July 2017. The overall mission scenario and first findings are explained in detail in [3].

Both the robotic aspect and the environment of course have a big impact on the requirements of how a payload platform has to look like. For this purpose an instrument carrier to house the seismic sensors has been designed in the frame of the ROBEX project to provide the necessary resources for the payload but also interfaces to both the stationary system (Lander) and the mobility unit (Rover). The developed payload platform is referred to as Remote Unit (RU) and is the central element of this paper. The mission architecture contains four RU's to meet the scientific requirements. They are implemented in two different versions: one with an maximum allowed mass of 3 kg (RU3) for direct interaction with the Rover and one with an increased upper mass limit of 10 kg (RU10) to demonstrate the full capability of such a payload platform. Starting from a global system overview describing the main components and requirements leading to the final system design, the paper focusses on the mechanical design of the structure, mechanisms, interfaces and the overall configuration of the platform. From this description an assessment will be given on how this design may be changend and improved for actual planetery exploration missions.

2. System Overview

2.1 Requirements and Design Constraints

The top-level system and mission requirements with direct impact on the RU's mechanical design are listed in Table 1. Additional design constraints and guidelines are collected in Table 2.

Table 1. Requirements for Remote Unit mechanical design

ID	System Requirement
SR-01	The RU as a standalone device shall provide all resources (as power, data, communication, structure) to operate the payload.
SR-02	The basic RU shall have an overall system mass of less than 3 kg.
SR-03	The extended RU shall have an overall system mass of less than 10 kg.
SR-04	The RU main body shall have an outer envelope of 340x240x200 mm.
SR-05	In stowed configuration, no elements (except mechanical interfaces to the Lander and Rover) shall protrude the outer envelope.
SR-06	The RU design shall be compatible with the environment conditions of the selected test side.
ID	**Mission Requirement**
MR-01	The overall mission architecture shall consist of four active RU's: three basic RU3s and one extended RU10.
MR-02	The RU shall be stored within the Lander's payload bays.
MR-03	The RU shall be deployed by robotic manipulation.

Table 2: Design constraints for Remote Unit

ID	Constraint
C-01	To demonstrate modularity, the two RU versions shall share the same hardware to the maximum possible extent.
C-02	Space qualified / qualifiable technologies and concepts should be selected preferably.

2.2 System Concept

The selected RU concept to meet the identified requirements and constraints consists of a few key elements, which will be described from a mechanical point of view in detail in the subsequent chapter. All components shall be accommodated inside a lightweight primary structure, supporting docking interfaces both for the lander and the rover system. The payload and the avionics are separated as two units in dedicated housings and accommodated in different compartments of the primary structure, allowing for different payload setups. Components which would exceed the allowed volume shall be deployed after robotic handling. Electronic interfaces to the lander and for EGSE are placed externally onto the primary structure to be accessible during operations. The two RU versions shall re-use the same mechanical components, while being open for different payloads and for additional features in the case of the extended RU10.

3. Mechanical Design

3.1 Structure Design

The two main mechanical elements of the RU are the CFRP primary structure and the common Electronic Box housing. As the two positions have the biggest share of the overall mass, they are optimized to be as lightweight as possible, while still meeting the described requirements and design considerations. The technical solutions are described in the following.

3.1.1 CFRP Primary Structure

The primary structure of the RUs is a CFRP framework in a differential design. It is orientated on the MASCOT primary structure in its principle to strengthen dedicated load paths. The MASCOT structure is designed for a minimum mass while providing sufficient strength and stiffness. The ROBEX RU structure on the other hand is designed with a higher focus on production time and cost as well as robustness for easy handling.

The loading conditions are oriented on the earth driven experiment. Those are introduced by earth's gravity and additional accelerations during the robotic manipulation. Infect the driving load case is the robotic manipulation under earth's gravity. The bearing loads at the lander are lower than a real space probe would encounter because potential launch loads are not taken into account.

As the accelerations during robotic handling are low an inert acceleration of 1.5 g is considered in all three axes. This is simulated with the RU fixed at the docking Interface to the landing module and with the RU fixed at the grapple. Using a max strain criterion this leads to factors of safety above 2.3.

The actual driving criterion is the structural stiffness. To avoid interaction with the robotic movement a minimum natural frequency of 5 Hz is chosen. This required some additional stiffening of the structure at the interface to the grapple. With this measure the lowest natural frequency ended at 7.5Hz (c.f. Fig. 2).

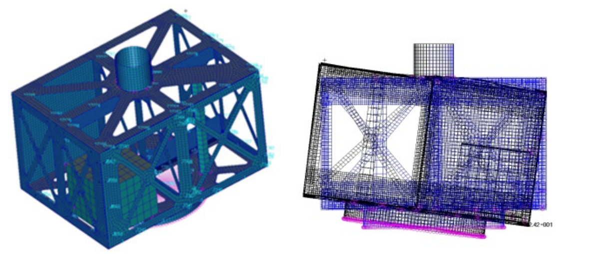

Fig. 2. Finite Element model of the remote unit and displacement at the lowest natural frequency of 7.5Hz

The RU structure is based on flat plate with 6 layers of Style 887 fabric in a quasi-isotropic layup. The matrix is from Araldite LY 556 with the hardener Aradur HY 906 and the accelerator DY 070.

The cured flat plates are machined into the shapes of the different walls. To connect the walls angles are produced. The original design favoured bolted connections for quick production and flexibility. As it became clearer, what flexibility is actually needed for

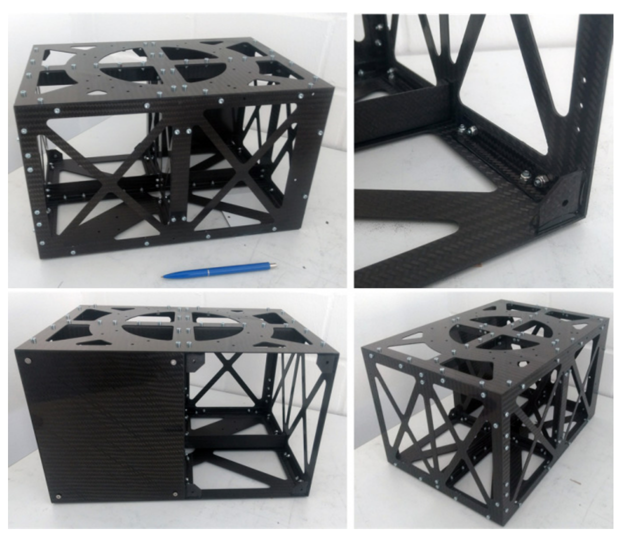

Fig. 3. Multi-view of the Remote Unit`s CFRP primary structure

integration, it was decided to permanently glue most of the angles to the adjacent walls. The originally placed holes proved to be very useful. The fixation during the curing process was easily done with screws and as the integration and concepts moved forward some holes where used to connect additional parts (c.f. Fig. 3). The reduction in strength due to the hole is uncritical for the use in the demo mission.

3.1.2 Electronic Box Housing

The central avionic elements of the RU are grouped within one single compartment, referred to as Electronic Box (E-Box). The electronic stack consists of six boards following the PC-104 standard, two of them commercial off-the-shelf Cubesat components (i.e. batteries and power control & distribution unit) plus in-house developments for data-handling, communication and interfacing tailored especially for this application. The design of the E-Box housing has its heritage in the DLR Gossamer project [4], where it was used inside the Boom and Sail Deployment Unit. The rectangular aluminium box uses a configuration of six side panels, where each of it is directly attached to the adjoining neighbour panel by screws without the need of an additional common frame. For electrical connections, the box provides accesses on two sides: one parallel to the electronic boards for direct connection to the surface mounted connectors of the interface board (Fig. 4, (1)) and one plug sheet orthogonally to it for additionally required connectors (Fig. 4, (2)). The later one is used for E-Box-internal wired connectors and for that reserves enough clearance for the connector feedthroughs and the harness by the help of a spacer frame, see (Fig. 4, (3)). For the RU3, this panel accommodates the connectors for debugging and the seismometer, which for the RU10 are supplemented with two HD D-Sub connectors for the photovoltaic harness.

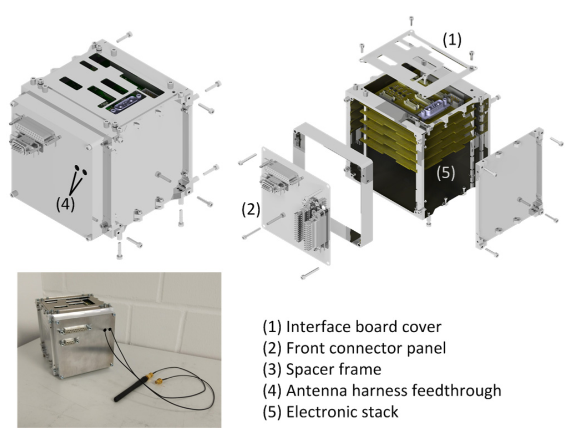

Fig. 4. Mechanical design of the Remote Unit's electronic box housing

The original design had to be modified for ROBEX in height, as the number of required boards increased from four to six. The required height was derived from the stack layout of the RU10, as it uses a battery with higher capacity resulting in an increased stack height compared to the RU3. By that, the housing could be used for both units without additional design changes. Contrarily, for mass savings it was possible to reduce the wall thickness of all panels by 50 % to 1 mm due to less severe environment and load conditions. The designs allows for (de-)integration of the electronic stack by simply removing the front connector panel. The E-Box housing fits inside an envelope of 144x125x115 mm³, is manufactured from Aluminium 7075 and has a mass of only 0.297 kg (excluding connectors and electronic stack).

3.2 Mechanisms

The RUs had very strict requirements on the allowed volume they may use during stowed configuration inside the lander's payload bays. They did not allow for any parts protruding the assigned volume of the RUs primary structure. At the same time, it was required to accommodate a monopole whip antenna with a good antenna pattern as well as a large solar generator on top of the structure. In order to deploy these two elements after robotic handling, two different mechanisms were implemented. Both are based on the same functional principle of a spring loaded hinge in combination with a thermal knife as release. The thermal knife is a simple heater element, in this case a ceramic resistor, which, when powered, melts a tether securing the hinge and thus releases the pre-loaded spring and the stored torques to bring the hinge's moving part to the open position.

3.2.1 Antenna Deployment

For an optimal reception of the WiFi and GPS signal, the two antennas need to be located on-top of the RU, outside the primary structure. To meet this while respecting the maximum allowed envelope in stowed configuration, an antenna deployment mechanism has been designed following the principle explained above. The two antennas are mounted on the moving part of the custom-made spring-loaded hinge, which uses a 430 Nmm double torsion spring. The hinge is mounted on the backside of a CFRP base plate with a long hole cut-out for the antennas.

The resistor holder has a simple geometry, optimized for 3D printing, providing the accommodation of the small ceramic resistor, shielding of all other components against the punctually very high temperatures and guidance of the nylon tether to be reliably in contact with the resistor.

The antenna deployment assembly was designed as one integral unit to be easy to dismount and refurbish without the necessity to open the RU`s structure. As the structure was designed and manufactured before the final selection of the antennas and the design of the mechanism, this was especially challenging due to the limited available cut-out area inside the CFRP primary structure, which may be used for the antenna assembly. For this reason, the footprint of the hinge and also the resistor holder had to be optimized accordingly (c.f. Fig. 5). The selection of the right combination of resistance and nylon tether diameter has been done in several tests, using different heating elements and nylon wires from 0.3 to 0.5 mm diameter under consideration of geometrical and functional requirements. The final design uses a small 10 Ω ceramic resistor, which powered with 8 V from the E-Box, melts a tether of 0.3 mm diameter reliably in less than 2 seconds.

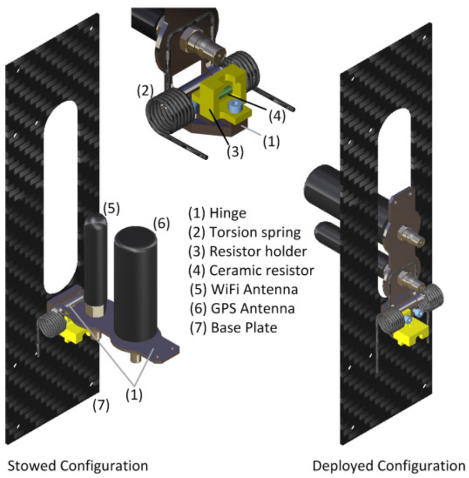

Fig. 5. Design and elements of the Remote Unit's antenna deployment mechanism

3.2.2 Photovoltaic Deployment

The extended RU version (RU 10) is equipped with photovoltaics to recharge the batteries and extend the unit's operational life time. To optimize the available surface for solar cells, the unit includes one deployable panel, which almost doubles the top surface area, taking up the biggest share of power generation. The mechanism to release and deploy the panel uses the same elements as the antenna deployment, with adaptations w.r.t. to required opening torques and panel dimensions. The overall mechanism consists of two spring-loaded hinges and two thermal knife release mechanisms for redundancy. The hinges are scaled-up versions of the antenna hinge and use two double torsion springs each (c.f. Fig. 6).

Even though one of these springs per hinge should have been enough to open the panel, the decision to increase the torque by doubling the number of springs became necessary as the mechanisms showed to be

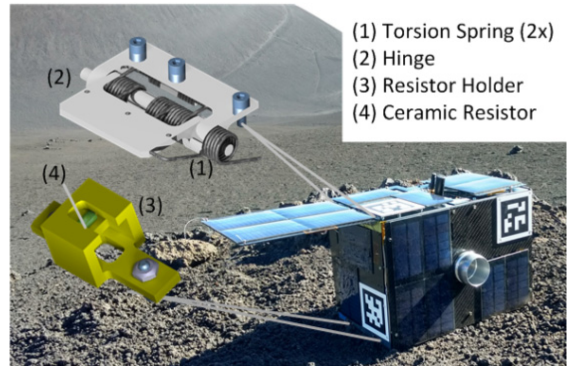

Fig. 6. RU 10 with deployed photovoltaic panel during Etna test campaign including the main elements of deployment mechanism.

sensible against dust and wearing-out of the springs especially under the harsh environment of the field test. The resistor holders for the thermal-knife releases are mounted internally against the primary structure and are equipped with a 21 Ω ceramic resistor each. The two resistors are connected in parallel to the 8 V power supply, so that the current through each of the resistors are the same as for the antenna deployment. The high preload of the mechanism made an increase in tether diameter to 0.5 mm necessary. The time to melt the tether and release the deployment under this setup took between 5 and 10 seconds, depending on the test environment and temperature.

3.3 Interfaces

The RU is the actual payload in the scenario and thus has to interact with both the Lander and the Rover. The interfaces are divided into interfaces for mechanical connection plus handling of the RU's and electrical interfaces. EGSE connections are available for preparatory purposes and maintenance, but are out of scope during the mission scenario.

3.3.1 Docking Interfaces

At the beginning of the mission, the four RUs are stored inside the lander's payload bays, two of them connected above each other to the two payload shelves using the Mechanical Docking Ring. The ring is working based on the principle of a bayonet catch, with the difference that the rotary motion to connect or separate the two elements is done by a moving ring inside the active docking interface on the lander side. The RU is equipped with a matching passive counterpart which is being pulled against the active part during locking. Anti-rotation locks prevent the RU from losing its orientation during release. The configuration at the lander and the Mechanical Docking Ring is pictured in Fig. 7.

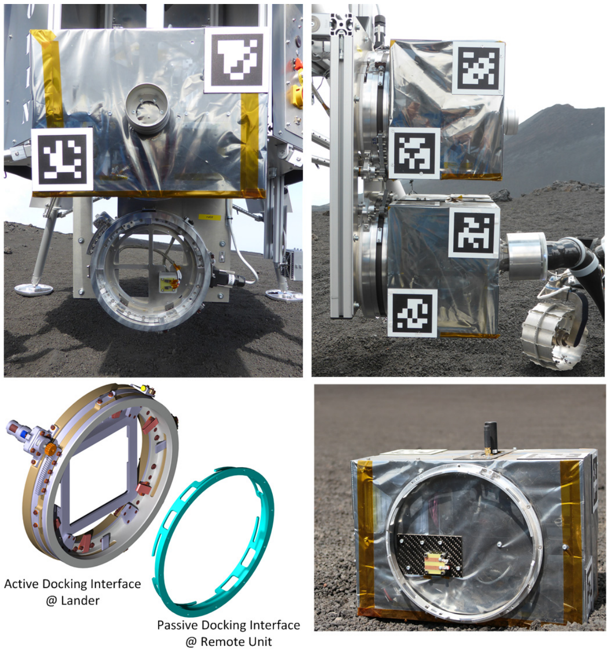

Fig. 7. Remote Unit to Lander docking interface and stowed configuration of RU's on payload rack.

Once the lander opened its solar panels and the payload racks are lowered to a height reachable for the Rover, the RUs wait to be grabbed by the rover's robotic arm. For this purpose, the RUs are equipped with a grapple fixture opposing the Docking Ring. First plans to integrally include the grapple fixture inside the RU's primary structure became obsolete in the course of the design, as it would have forbidden subsequent changes to the design of the grapple, something which needs to be avoided if developing several interacting systems in parallel. The solution was to include a generic adapter flange to which the latest version of the grapple can be externally screwed (c.f. Fig. 8).

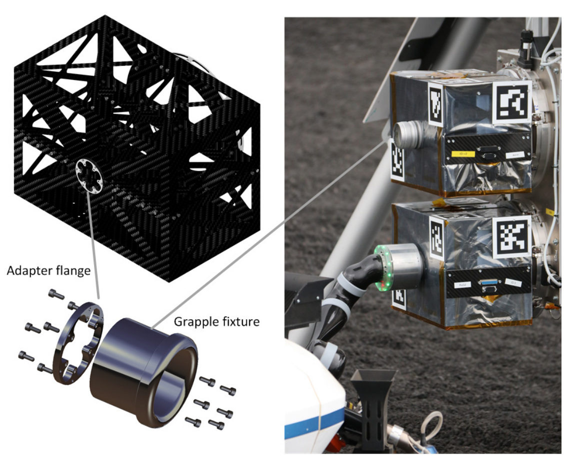

Fig. 8. Passive part of Remote Unit to Rover docking interface.

3.3.2 Power / Data Interface

The mission scenario foresees that the RUs need to be charged and activated by the lander. For this purpose, electrical interfaces are required to connect the two elements.

The extended RU is equipped with an inductive interface, referred to as Inductive Transfer System (I-SYS), which allows for contact-less power transfer of maximum 200 W using three different voltage levels (5 V, 12 V and 24 V) and a half-duplex data transmission with a maximum data-rate of 10 Mbit per second between the RU and the lander. One part of the symmetrical setup has a volume of 150 x 150 x 20 mm³ and has a mass of 0.18 kg. [6]

As mass is a critical design factor for the basic RU version, the RU3 is equipped with a less complex electrical interface consisting of simple but robust contact springs, only allowing for charging and activation of the RU omitting direct data transmission.

3.4 Configuration

The accommodation of the main components inside the RU was a challenge especially due to the fact that both versions (RU3 and RU10) are supposed to use the exact same primary structure and common main components as e.g. the E-Box and antenna mechanism but with additional add-ons for the more sophisticated RU10 version as e.g. the self-levelling seismometer, inductive interface and photovoltaics. The resulting configurations of both versions are presented in Fig. 9 and Fig. 10 and shall be explained together with its rationale in more detail in this chapter.

The E-Box (1) is connected in the upper corner of the bus compartment to the primary structure using additional spacer elements. It is oriented with the Interface Board facing to the removable cover panel while the Front Connector Panel is oriented towards the payload, to allow for an easy integration and to minimize the internal harness' length.

The position of the antenna mechanism (2) was derived from the attitude of the RU during ground operation with the additional constraint of unobscured volume inside the main volume during the antennas' stowed configuration. For the RU10, the antenna mechanism had to be re-located to the bus compartment, to not interfere with the big self-levelling seismometer.

For external power supply, activation and debugging, two EGSE connectors are required, which are mounted onto a common adapter plate (3) from outside the primary structure directly next to the E-Box.

The fixed seismometer of the RU3 (Fig. 9, (7)) uses a simple cylindrical aluminium-housing to accommodate the geophones and the electronics. The housing is attached together with the tetrahedron accelerometer to the removable cover panel (4) of the

CFRP, which is in contact with the ground during measurements.

The self-levelling seismometer of the RU10 (Fig. 10, (7)) in turn needs to be gimbaled inside the payload compartment to align itself along the gravity vector. Three extendible legs ensure ground contact. Thus, the removable cover plate is omitted in this case.

The umbilical connections for power supply and activation between RUs and lander are different for both versions. The RU3 uses simple contact springs (Fig. 7, Fig. 9, (8)) for the power connection to the 12 V bus of the lander, while the RU10 is equipped with the inductive interface (Fig. 10, (8)) for both power and data transmission. Both solutions are accommodated in the middle of the passive docking ring at the backside of the primary structure.

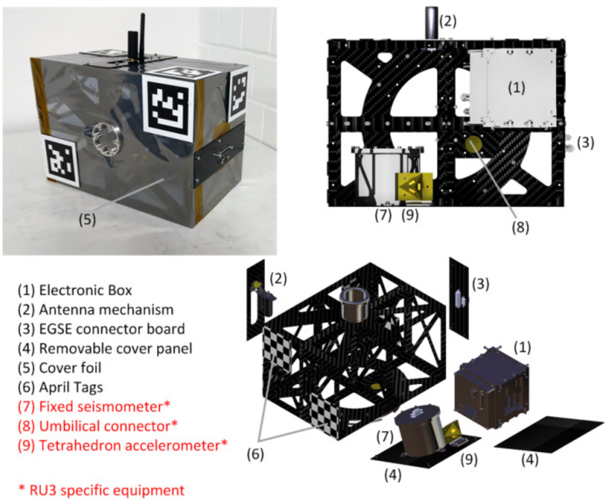

Fig. 9. Configuration of main components inside the RU3.

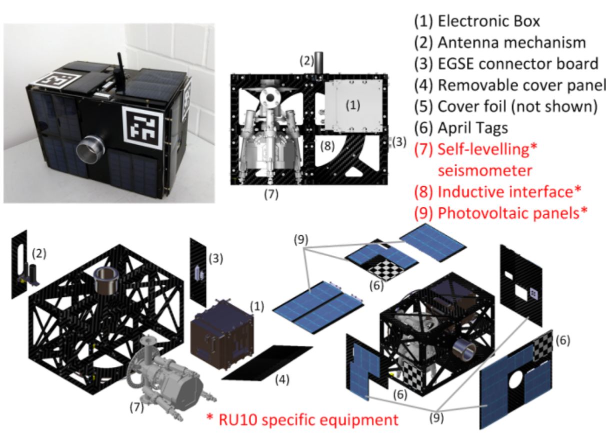

Fig. 10. Configuration of main components inside the RU10 including photovoltaic panels.

Both the RU3 and RU10 are covered using ESD foil (5), mainly for protection against dust and moisture. Additionally, the RU10 is equipped with five surface-mounted solar panels plus one deployable (Fig. 10, (9)). The former ones are mounted with an offset of 8 mm using spacer elements onto the primary structure allowing for sufficient clearance for harness and fastening elements. April Tags (6), which are required by the rover to be able to detect and identify the RU and estimate its pose, are attached to either the primary structure or the solar panels. Seven April Tags are accommodated onto the RU3, while this number had to be reduced for the RU10 to a still sufficient minimum of four, as they are in direct competition with the usable surface for solar cells.

4. Discussion

After the description of the main components and configuration of the two RU versions, an assessment of their strengths and weaknesses will be elaborated in this chapter. Additionally, an outlook is given on how the current design would have to be upgraded to suit the qualification needs for actual moon and planetary exploration.

4.1 Strengths and Weaknesses

The RU, even though partly inherited from designs and concepts of existing space projects, is to be seen as a prototype and proof-of-concept of a modular payload carrier for robotic exploration. The ROBEX demo mission together with the preceding test campaign were the first opportunities to assess the advantages and disadvantages of the selected mechanical concept, which, once defined, could not be iterated and optimized as a whole during the ongoing project, as there were too many interdependencies and interfaces to parallel system developments and partners in combination with a tight development and manufacturing timeline.

The primary CFRP framework structure is a good example on how early design decisions can simplify or complicate the accommodation of additional components or design-changes in the subsequent phases and thus to what degree the selected concept supports the envisaged modularity approach.

The general decision to follow the design principle from the MASCOT role-model [5], i.e. two separated compartments for payload and bus components inside a common framework structure, has been suitable for the purpose of ROBEX. It allows for the accommodation of different types of payload independent from the bus components, as demonstrated by the two seismometer variants of RU3 and RU10, and should be maintained for future developments.

The selection of a framework as primary structure in turn, which was mostly driven by the strict mass limitation, had both pros and cons. On the one hand, due to the cut-outs inside the structure it was possible to attach additional smaller components by means of adapter plates quite comfortably from outside the structure (e.g. antenna mechanism, EGSE or umbilical connector) or to upgrade the RU (i.e. photovoltaic panels for RU10) without the necessity to modify the primary structure as such with all the associated drawbacks and additional effort. This advantage has also been supported by the various included boreholes inside the structure, originating from the manufacturing process, which could be re-used for fastening elements. Bigger components, as the self-levelling seismometer, the E-Box or the inductive interface, on the other hand had to be considered already during the design of the primary structure to ensure enough available mounting points with the framework trusses, which partly even had to be optimized accordingly. This prohibited any subsequent design change or upgrade leading to a change in position of interface points for these main components and thus, especially in case of the payload, restricts the modular approach.

The E-Box, as it is designed now, can accommodate stacks of PC-104 boards with a maximum overall stack height of 110 mm for being compatible with the electronic components of the RU10. This, together with the concept of an exchangeable plug sheet for wired connectors, gives some freedom in the design of the electronic stack with all benefits coming from the growing Cubesat community and available COTS components and subsystems. Even though the E-Box housing design in general can be stretched to cope for any further increase in stack height for added boards and features, as demonstrated by the update of the original design of the Gossamer project for ROBEX, it would lead to a modification of the interface points and thus, potentially to an impact on the primary structure and interference with other equipment (e.g. EGSE or umbilical connector panel). This fact can be eased by the explanation that modular concepts still define specific limits to which degree design modification can be allowed (“scalability within boundaries”) [6]. By optimizing the usable volume inside the structure for the E-Box and defining it as standard, systems would have to meet this constraint and design their electronics according to these ranges.

Additionally to these discussions, it can be stated that the concept of one common, easily accessible and removable E-Box showed significant benefits with regard to testing, debugging and integration.

In general, the implementation of two very different RU versions with significantly different total masses and features using one and the same primary structure design, E-Box and ancillary equipment has been successful and has to be seen as a big accomplishment.

The simple concepts of the included mechanisms could prove their functionality also under the harsh environment of the test site. As described in 3.2 especially the Photovoltaic deployment mechanism showed some vulnerability against dust, abrasion and as a result increased friction. Additionally, in the course of the tests and demo mission, the included torsion springs had to be replaced as they showed signs of deformation leading to unsatisfying opening characteristics. The refurbishment of the tether for the release mechanism required some time and experience, but did not impede the overall mission process. One missing feature was a sensor feedback to acknowledge the successful deployment, which led to a manually adjusted activation time.

4.3 Potential for future space exploration missions

The hardware was designed under the constraint to consider only concepts which can theoretically fulfil requirements for space environmental qualification. This means that the RU design could undergo a delta-design in key components to prepare it for the application in future space exploration missions. The required design changes are always depending on the mission’s target. As an example, a potential Moon mission shall be used for a qualitative assessment in the following, which would have to be analysed in detail in following studies.

<u>Launch Loads</u>

As described in 3.1.1, the primary structure has been designed to withstand the loads expected during the terrestrial demo mission, which were mostly defined by static loading conditions from the unit’s own weight in different orientations. A space version would need to survive the loads during launch with extreme accelerations and dynamic loads (vibrations, acoustic, shocks). MASCOT’s CFRP sandwich framework was especially designed to guide the launch loads through the trusses to bearing points in the corners of the structure and from there into the launch interface [5]. MASCOT’s mission will take place on an asteroid *1999 JU3 Ryugu* with only a fraction of gravity compared to terrestrial applications [7], impeding no additional design-driving requirements for the structure. A lunar version of the RU would have to follow a similar approach in optimizing the structure w.r.t. launch conditions. Additionally, even though the Moon has only one-sixth of the Earth’s gravity [8], in comparison to MASCOT, the mission scenario on the Moon’s surface including handling of the rover must be considered for the structural design. It is expected though, that robotic handling loads as experienced during the field test are more critical than they would be on the Moon.

<u>Radiation</u>

For planetary missions, the most important radiation sources to be considered are cosmic rays, solar energetic particles and secondary protons / neutrons. [9] The concept of a common E-Box is beneficial for protection of sensible bus electronics, as the wall thickness can be adapted for the actual radiation environment. A literature research on space electronic shielding yields to a first conservative estimate for suitable wall thicknesses of approx. 5 mm of aluminium [10]. The mass of the RU E-Box would therefore increase at least by the factor of 5 to ~1.5 kg with additional small design changes to keep the inner volume big enough to accommodate the electronic stack. The optimal shielding thickness has to be selected under consideration of the finally selected electronics. Taking the RU`s EPS board as an example, a radiation level up to 10 kRad (Total Ionizing Dose, TID) [11] can be assumed to be tolerable for COTS components, which comparting with the results of [10] could be achieved by a approx. 3 mm aluminium shielding.

Temperature

The lunar surface temperature varies strongly depending on illumination by the Sun and thermophysical properties of the Regolith. Daytime temperatures vary between almost 400 K at the equator to 200 K at the poles and drops to 120 to 5 K respectively during night-time, while some craters even show temperatures of just 26 K, the coldest temperature known in our solar system [12]. As a reference, the Central Station of the ALSEP used passive elements (insulation/coating, reflectors and radiators) and internal heaters powered by the RTG to keep the temperature within specifications. However, positions in or near craters and slopes were to be avoided to exclude continuous shading and undercooling. As discussed in detail by Ulamec et al. [13], to keep a surface package alive throughout the night-time without the help of RTGs is extremely challenging, especially for small units with limited volume and capabilities. If a submerged setup is forbidden, several measures have to be taken to prepare the RU for a lunar mission. A first step is replacing the cover foil used during the demo mission with Multi-Layer-Insulation (MLI). More difficult to achieve w.r.t. available volume and power is the integration of additional components as external radiator plates (for high daytime temperatures), internal heaters (both for the payload and the E-Box) and heat-capacitors to ensure an appropriate mean temperature.

Power

The ALSEP setup used a RTG to power the modules during their nominal one year lifetime. For programmatic and safety reasons, a nuclear generator may not be applicable, which is why the photovoltaic concept, as included in the RU10 design, shall be considered as baseline to charge the batteries during the daytime. The long Moon nights of up to 14 days [13] without any photovoltaic energy input are a challenge. Batteries with enough capacity to cover these periods would exceed the volume and mass restrictions of the RU. Thus, for longterm operations, the RU needs to include a hibernation mode with minimal power consumption to survive the Moon nights, especially w.r.t. the aforementioned temperature problematic. Alternatively, it would also be conceivable to operate several RUs as common infrastructure, i.e. one unit for avionics and payload plus one exclusively for batteries and photovoltaics.

Mass/Rover interaction

A lot of the structural design decisions were taken to optimize towards the requirement of 3-kg upper total mass to make the RU3 manageable for the Rover (especially for the motors of the manipulator) under Earth's gravity. Under Moon's gravity, the weight of the RUs would be approx. 0.5 kg (RU3) and 1.7 kg (RU10) respectively. Assuming a manipulator with similar capabilities, the total mass of the RU3 could be increased by approx. the factor of six and would still be within specifications. This would have to be optimized in combination with the overall rover design to ensure an acceptable Centre of Gravity for the Rover-RU system in all possible states and configurations during the mission. The allowed extra mass could be used to e.g. upgrade the unit according to the Moon-specific aspects discussed above.

6. Conclusions

The mechanical design and configuration of the Remote Units developed in the course of the ROBEX project has been explained together with their rational originating from the mission scenario or project constraints. The overall design is open to accommodate different payload set-ups and upgrades for the bus components (e.g. additional photovoltaics) while re-using mechanical elements in different versions. This has been demonstrated by the basic and the extended Remote Unit, which proved to be suitable for the application under harsh environments during the space analog demonstration-mission on Mt. Etna, Sicily (Italy). Lessons learned and strengths and weaknesses of the concept and its implementation were discussed to prepare for future activities. Finally, the RU`s suitability for planetary exploration has been investigated with the help of an exemplary Moon application to give a qualitative outlook on necessary adaptations. Especially the long lunar nights could bring the RU to its performance limits w.r.t power generation and thermal control, assuming the same available volume and associated capabilities. Still, the concept is the first of its kind to having been demonstrated in an integrated mission setup involving lander and robotic elements under harsh conditions. Many of its elements are reusable for future planetary exploration, with the design impacts of alternative power / heat sources (as radioisotopes) being planned for detailed investigation in future studies.

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