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Deployment of the SOLEX Environment for Analog Space Telerobotics Validation

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Abstract

Lunar and planetary surface operations and eventual colonization are gaining increasing interest in the space community exemplified by ESA's Lunar Village Initiative. Consequently, larger and more complex infrastructure would be necessary to support these endeavors. As the assembly, repair, and maintenance tasks grow in correspondence to the infrastructure, robotic teams can serve as viable solution to meeting these needs. In order to test and verify the robotic capabilities necessary for surface operations, analog proving grounds on earth should be designed to simulate surface assets that should be operated by the deployed robots. This paper presents DLR's effort to develop one of such proving grounds: the SOLar farm EXperimental (SOLEX) environment, equipped with a wide array of assets expected in a surface habitat. First utilized for the METERON SUPVIS Justin space-to-ground telerobotic experiment in 2017-2018, it is continuously being further developed with the aim of supporting the validation and verification of different modalities of future space robotic operations.

Keywords: Analog proving ground, Space robotics, Telerobotics, Human-robot collaboration, Orbit-to-surface teleoperation, METERON SUPVIS Justin

Acronyms/Abbreviations

Communication and Power Interface (CPI), Computation Unit (CU), Data Interface Probe (DIP), Data Interface Socket (DIS), Degrees Of Freedom (DOF), European Space Agency (ESA), German Aerospace Center (DLR), International Space Station (ISS), Light Weight Robot (LWR), Multi-purpose End-To-End Robotic Operation Network (METERON), User Interface (UI), Payload Exchange Plug (PEP), Payload Exchange Socket (PES), Smart Payload Unit (SPU), SOLar farm EXperimental (SOLEX)

1. Introduction

For decades, the human race has continued the exploration of our solar system. One of our goals is the colonization of Moon and Mars. Such missions will be characterized by highly demanding tasks to cope with the harsh conditions for both humans and equipment. Effective operation concepts are vital to successfully establishing habitats on the remote surfaces.

Ensuring the safety and the functionality of these assets is crucial to the success of future crewed missions. In addition, due to the hazardous environments, monitoring and maintenance tasks of the growing infrastructures are becoming increasingly complex and laborious for the astronauts. Because of this, robotic coworkers are envisioned to support the astronauts in taking over routine work at these structures. The development and testing of such robots need to take the special characteristics of their future deployment environment into account.

Therefore, the Martian *SOLar farm EXperimental (SOLEX)* environment was specifically developed for the purpose of validation and verification of highly complex telerobotic systems for such extraterrestrial surface missions. It was first envisioned for DLR and ESA's METERON SUPVIS Justin experiment [22], which studied the use case of an astronaut onboard the *International Space Station (ISS)* teleoperating a surface-based humanoid robot as co-worker. The SOLEX environment differs from other proving ground concepts in that it is tailored to testing novel robotic capabilities. As future habitats will include more mechanical, electronic, and software components, such devices are incorporated into the SOLEX environment to better reflect future space habitat conditions. A modular approach ensures that components and interfaces can be added to test new systems and concepts. In 2017 and 2018, the SOLEX environment played a key role in three 4-hours ISS-to-ground teleoperation sessions performed by five ESA and NASA astronauts.

The remainder of this paper is organized as follows: Section 2 summarizes the space robotics background of this work. Extending on this, we present the requirements identified for the analog environment presented in this paper in Section 3. The implementation of the requirements in SOLEX is described in Section 4. In Section 5 is the first use of SOLEX for a space-telerobotics experiment described. The discussion of our findings is presented in Section 6. Finally, Section 7 closes out this paper with our conclusions.

2. Space Telerobotics Background

Future robotic systems deployed to space will support astronauts in more and more critical tasks in- and outside the spaceship as well as in space or even on extraterrestrial surfaces. Commanding and interacting with theses robots will be an everyday task of the crew that needs to be intuitive, low-workload, and effective.

One approach to meet these telerobotics challenges is the utilization of directly coupled command modalities between a *User Interface (UI)* and a robot [1]. The DLR space experiment Rotex in 1993 first demonstrated this possibility between an Earth-bound UI and a robotic arm-gripper system onboard space shuttle Columbia [2]. ROKVISS [3], and KONTUR-2 [4] advanced further by implementing immersive force-coupled telepresence between Earth and the ISS. The Canadarm [5] on board the ISS can be teleoperated at the joint and Cartesian level and continues to play a vital role in ISS operations.

Another possibility is the use of intelligent robots as co-workers that are able to operate with various degrees of autonomy to ease the mental and physical workload of the astronauts [6]. Rather than direct teleoperation, the human plays the role of a supervisor to manage the robot and command tasks which will automatically be executed by the remote unit. Therefore the astronaut is able to concentrate on more challenging work rather than mundane repetitive tasks. Furthermore, by delegating lower level tasks to the robotic asset, requirements for continuous communication availability and short delay becomes less necessary.

Humanoid robotic assets have also gained increasing interest in space deployment in recent years, such as the Robonaut 2 [7] and FEDOR [8]. Furthermore, increasingly autonomous systems for exploration missions, such as Curiosity on Mars [9] and the Yutu rover on the Moon [10], have already been successfully tested.

For the investigation of these topics for future space-robotics missions, ESA initiated the *Multi-purpose End-To-End Robotic Operation Network (METERON)* experiment suite to test new and advanced concepts for human-robot-interaction [11]. To validate different orbit-to-ground robotic teleoperation concepts, several experiments have been conducted both on-board the ISS, as well as ISS-to-Earth. These include the haptic telepresence in the HAPTICS experiments [12] [13], to supervised robots in the SUPVIS experiments [14][15], and mixed-modality teleoperation of the INTERACT experiment [16].

As the UI concepts and robotic assets grow increasingly complex and capable, a proving ground for validating and verifying these systems' capabilities and safety also becomes increasingly apparent.

In order to achieve realistic results, close-to-reality analog testing grounds are needed. Two approaches include the usage of natural locations on earth such as the volcanic areas of Mount Aetna [17] and Lanzarote [18], or the use of artificial environments such as ESA's LUNA facility, which includes an indoor habitat as well as a lunar surface site [19]. Their main purpose is to replicate the geomechanical properties of extra-terrestrial soil. In cases where the compensation of Earths gravitation is required, testing grounds under water [20] and micro-gravity flights can be employed [21].

Existing analog testing sites often focus on the simulation of the remote environment to evaluate the hardware of systems which should be deployed in future space missions. In this paper, we present our approach to an analog environment to test teleoperation approaches for sophisticated robotic manipulation tasks in an immersive setting.

3. Analog Proving Ground Requirements

The aim of a proving ground is to approximate the intended future lunar and planetary sites as closely as possible to aid the development and validation of surface operations. The SOLEX environment differs from other proving grounds in its focus on aspects of robotic tasks and human-robot collaboration foreseen on the surface. Furthermore, as increasingly complex infrastructure would be expected in these sites, effective simulation of these devices and components is also a key criterion.

3.1. Modular design for expansion and rapid deployment

In order to meet the needs of rapid deployment for the (sometimes) rigorous scheduling of mission planning, and continuous addition of new capability, a modular approach should be taken for the design of the SOLEX environment. This would enable quick replacements of peripherals and components. On-board processing would also make it possible to accommodate new components and combinations. As a result, new robotic tasks and operation scenarios can be easily designed and tested in the SOLEX environment. Furthermore, to ensure seamless integration with the existing robotic software tool chain, compatibility of the system software of all components in SOLEX environment should be ensured.

3.2. Full functional interface concept

For the testing of a variety of robot tasks to be carried out on the extraterrestrial surface, interactions of different natures must be examined, including mechanical, electronic, as well as software/data interface. The testing site should be able to help facilitate the evaluation of robotic mechanical handling and manipulation of known components and devices, as well as unknown objects such as surface samples. Furthermore, for habitat building and assembly, robotic capabilities for electronic and software services would become increasingly necessary. The proving ground should accommodate these robotic task scenarios. Finally, for the robotic system development team to be able to study the effectiveness of robot operations the interaction between the robot and the surface assets should be recorded within the devices and components in the SOLEX environment. This would provide a holistic view of the actions carried out when investigated in conjunction with data from the robot and operator video and audio recordings.

3.3. Ground control for scenario management and system monitoring

An increasingly wide array of robotic tasks is expected to be tested for future missions and new robotic systems. In addition, astronaut crews are given strictly enforced time schedules for every task. To help cope with these concerns, a ground control station would become necessary to manage and monitor all the experimental scenarios.

The ground control station also serves as the communication relay between the astronaut and the proving ground operators in orbit-to-ground telerobotic test cases. Communication links should be incorporated between ground control, surface assets (e.g, devices and components), and the operator UI, either in orbit or on ground. Through these communication links, the ground control can, quickly and easily, configure and record different test scenarios to meet the aforementioned strict astronaut crew timeline.

4. SOLEX Analog Test Ground

The SOLEX environment has been designed as an analog testing ground to validate human-robot collaboration concepts. The development of the environment's functionality was oriented on the needs of the METERON SUPVIS Justin space-to-ground telerobotics experiment, which evaluated a supervised autonomy approach to robot commanding [22]. The basic layout simulates a solar farm on Mars, which is maintained by DLR's humanoid robot Rollin' Justin [23] on site. The focus of SOLEX lies on testing a variety of telerobotic approaches with realistic tasks in an immersive environment rather than simulating correct geomechanical properties of a remote planet. Although originally designed for validation of supervised autonomy telecommand user interfaces, the SOLEX environment can be used as proving ground for any form of robotic operation, from open loop command, haptically coupled telepresence to full autonomy.

4.1. Environment layout

The SOLEX environment layout accounts for a maximum of modularity and accessibility to provide a testing site that can easily be used for a variety of different experiments. Because of this, one of the lab walls is made of a set of moveable panels which can be easily rearranged to change the size of the testing site. The walls and the floor of the indoor laboratory setup are covered with Mars-lookalike textures taken from past Mars missions to achieve a realistic and immersive experience for the teleoperating astronauts.

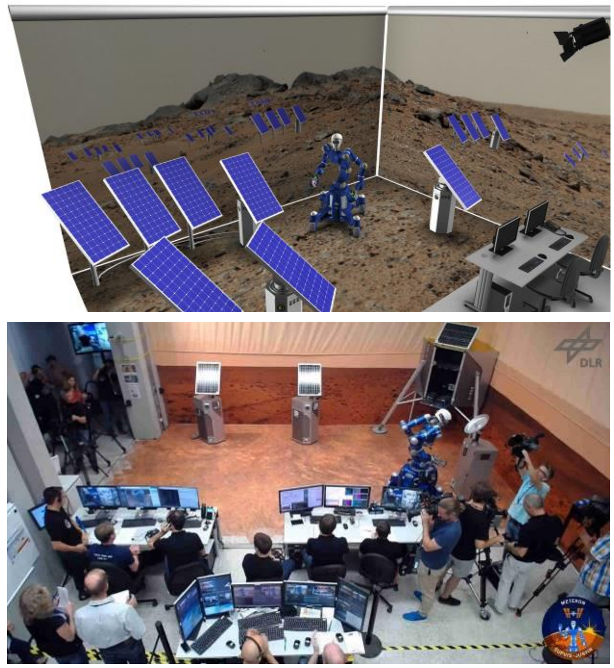

Fig. 1. An early SOLEX environment concept (top), and the actual implementations of the robot proving ground and ground control station (bottom).

To allow for effective operation and supervision of the experiments, a set of workstations is located right next to the testing site. Especially the on-ground development of the robotic skillset needed for autonomous operations profits form the small distance to the robot. This makes SOLEX a holistic site for robotic development, testing, and operation.

A multi-purpose media ceiling allows the mounting of arbitrary equipment as e.g. cameras for recording of experiment sessions, printed canvasses for laboratory separation, and an additional light source for realistic solar farm simulation.

The last version of SOLEX testing site is shown in Fig. 1. This setup has been used in August 2018 during the final SUPVIS Justin experiment session with the astronaut Alexander Gerst commanding the robot from on board the ISS. It contains multiple solar panels, a lander model, and Rollin' Justin maintaining the assets.

4.2. Robot data and electrical connectivity

The maintainability of assets of space missions comes with the increasing interest for on-orbit servicing more and more into the focus of the space robotics community. Future infrastructure on celestial bodies will therefore be designed to be maintained by robots. In order for a robot to perform data-readout or transfer tasks, or even charge its batteries on an external solar array, an interface needs to be provided that allows the robot to mechatronically connect to the assets.

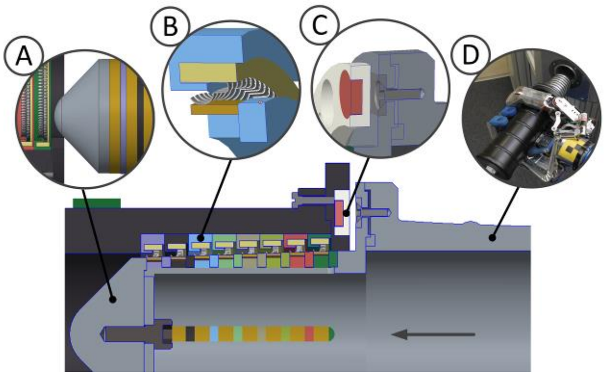

Fig. 2. Cross section of exemplary CPI configuration highlighting key features: A. Replaceable tip, B. Modular spring-loaded contact rings with Isolating ring holder, C. Magnetic retaining mechanism, D. Configuration as a tool for a humanoid robot.

The *Communication and Power Interface (CPI)* implements a modular concept for electrical connections of arbitrary devices. The interface design comprises the following key features (see Fig. 2):

- **(A)** The tip of the interface plug is replaceable. It provides the possibility to add-on enhanced functions such as locking mechanisms, proximity sensors, or drivetrain connections (e.g. for a motorized positioning of the solar panels). In the basic concept a simple cone-shaped tip has been used to achieve robust and repeatable insertions, even in the event of positioning errors. It has been used throughout the METERON SUPVIS Justin experiments.
- **(B)** The contact ring modules of the interface socket and plug can be assembled pairwise according to the desired amount of connections. Even full duplex (100 Mbit/s) Ethernet links are possible. Each module comprises a plastic ring which acts as a spacer, electrical insulator and as connection ring holder. In order to provide an oxidation free contact surface with a low electrical resistance, the copper rings have been improved with a gold coating. In addition the interface socket ring module is equipped with contact springs. It achieves a full rotational and centered contact and is robust against dirt particles.
- **(C)** The magnetic retaining mechanism supports the electronic connection by keeping the contact in place after the insertion process is completed. Furthermore, the necessary magnetic release force can be measured by the robot during the disassembly task thus proving a clear indicator on when the connection has been released. It is also possible to adjust the force by changing the amount and/or strength of magnets in the socket.
- **(D)** The CPI is able to be physically connected for electrical and data access by the surface robot. Consequently, the connector plug is integrated into the robotic tool to be carried and used by the robot.

The CPI has been used in SOLEX to establish connections between Justin and the solar farm assets to read-out status data and install firmware updates. In addition to that, another configuration of the CPI has been used to connect solar panel modules to an energy collection basis station.

In order to demonstrate a variety of robotic assembly tasks, a special focus of SOLEX lied on the design of components that can be manipulated by Rollin' Justin and, at least part, make use of the CPI.

4.3. Modules for robotic assembly

Experiment-specific hardware was encapsulated in modules that can be switched out on demand. These *Computation Units (CUs)* are used as subsystems inside the SOLEX assets. A small and lightweight design allows the robot to perform maintenance and assembly tasks. Each CU enables the astronaut to assess its current status by means of visual information provided by LED lightning (see Table 1).

Table 1. Computation Unit System Status LED Modes

LED Mode	**System State**
Pulsing - Green	Nominal
Blinking – Red	Failure
Single Blinking - Blue, Green	Storage
Rotating - Blue	Recovery
Switched off	Not connected

For the METERON SUPVIS Justin experiments, we used mockup CU's stripped down to the LED status feedback functionality. Printed circuit board models have been visibly integrated at the side and the top of the housing to achieve the imitation of an actual computer module. Some highlights of the mock-up units are highlighted in Fig. 3:

- **(A)** In order to reach a visual differentiation of damaged and nominal CUs, the damaged CU was equipped with a wireless controllable miniature fog-machine and fans to optimize the airstream to the outer environment. Furthermore, the skin of the CU has been prepared with burn marks.

(B) A magnetic holding mechanism has been designed to support Justin with the pick and place tasks. The CU is plugged in an associated interface socket.

(C) Each CU contains several RGB LED stripes to display different system states (see Table 1).

(D) An ergonomically-shaped grip with a top-bulge ensures a robust and non-slip grasp of the robotic hand. Embedded illuminated stripes facilitate the recognition of the units in dark surroundings by the astronaut.

Fig. 3. Computation Units with main features A: wireless controllable miniature fog-machine, B: magnetic holding mechanism, C: RGB LED stripes for visual illustration of system states, D: Ergonomically-shaped grip with embedded illuminated stripes.

Another module developed for robotic manipulation is a satellite dish that can be mounted on the SOLEX assets. Lightweight materials such as carbon fibre and plastic are utilized for the design of the components to help reduce payload. For connecting the satellite dish to the basis asset, we used a module-specific configuration of the CPI.

Providing this set of modules in SOLEX allows us to run a variety of different assembly, swap-out, and repair tasks.

4.4. Lander

A mock-up planetary lander has been added to SOLEX to increase the experiment scenario plausibility as the infrastructure components need to be delivered somehow. Furthermore, the lander provides stowage for the modules not yet installed in/on the assets of the environment.

A total of up to six CUs are stowed on a tray inside the cargo bay of the lander. A satellite dish unit is located above the CU-tray.

In future extensions, the lander can be equipped with more components either for assembly or for direct use with the robot, as e.g. tools for maintenance.

As the lander functions merely as a module-stowage, the real work in SOLEX is done by assets set-up around the lander. This simulates the future setup of a research site near a landing spacecraft to avoid contamination of science results due to influences of the landers propulsion system.

4.5. Smart Payload Unit (SPU)

The *Smart Payload Unit (SPU)* is the basis component for the (simulated) experiments in the SOLEX site. Once its set-up, its modular design allows to easily reconfiguring the asset to change its functionality.

A key aspect when designing the SPU was the possibility to rapidly implement enhancements and simple modifications to gradually increase the complexity of robotic maintenance tasks investigated in SOLEX. Another focus of the design has been the co-working maintainability, e.g. to be able to cover in-situ scenarios together with a robot on site.

In order to evaluate the performance of the human-robotic-teaming throughout the METERON SUPVIS-Justin experimental sessions, the SPU provides the possibility to record mechanical, electronical and software interactions on the integrated main computer.

4.5.1. Payloads

Each SPU is reconfigurable to serve different main functions, such as solar energy collection, or communication relay. To mount the corresponding module on the SPU, a *Payload Exchange Socket (PES)* is mounted on the deck plate of the SPU. The PES is a specific configuration of the CPI allowing for transfer of solar power as well as communication data.

To fix the orientation of a payload module, a self-developed locking mechanism allows retaining the turning by a division of 5°. The *Payload Exchange Plug (PEP)* is the corresponding part of the solar panel or the satellite dish fitting inside the PES.

The internal capabilities of the SPU can be extended using CUs. Two of the units can be plugged into a drawer inside the SPU where they can be connected to the main computer. This allows easy updating of the functionality of the SPU and removing of damaged components for inspection and repair.

4.5.2. SPU -Robot connection

To read out the internal status and interact with the firmware of the payload components and the main computer, a central electronic access point has been designed for the SPU. Therefore, we implemented a configuration of the CPI allowing full Ethernet support and integrated the *Data Interface Socket (DIS)* to the front panel of the SPU.

The DIS Panel was extended with an RGB-LED system status bar allowing for a variety of visual feedback. It has been used to indicate nominal operation by solid green, a failure state by red blinking and a critical unknown error by short red and yellow flashing.

The DIS allows to directly access to Ethernet interface of the main computer. Hence it allows reading or writing data, such as the SPU status, the payload status, or flashing new firmware.

4.5.3. External command interfaces

In order for an astronaut on-site to read-out status reports or change parameters of the software, a resistive touchscreen was integrated on the back of the SPU, as depicted in Fig. 4. It shows the current status of the SPU and all of the connected modules. Located right next to the touchscreen, two USB-Ports, and a VGA-Port allow easily connecting commercial of-the-shelf hardware for maintenance and feature upgrades.

Fig. 4. Backside of SPU with touch screen for data analysis, two USB-Ports, one VGA-Port, a reset button and an emergency stop.

In case the touchscreen is malfunctioning, some of the most important settings of the SPU can be accessed via a modular panel on the side of the SPU frame. It is equipped with mechanical switches allowing the robot to directly interact with different components of the SPU for e.g. emergency switch-off or manual unlocking of installed payload modules. The modular setup allows reconfiguring the panel to add on further input modalities for future experiments or SPU upgrades.

4.5.4. Internal infrastructure

After several experimental sessions and accompanying extensions, the infrastructure as shown in Fig. 5 has proven suitable for our requirements on modularity and reconfigurability. For the SPU infrastructure a self-sufficient power management and wireless network interface is realized. It enables a cableless utilization which makes the SOLEX environment more realistic.

The first SPU version was equipped with an industrial computer, which can be useful for data storage and data evaluation of the smart payload unit. Also the SPU interaction tasks during the experiment can be monitored and recorded onboard the computer.

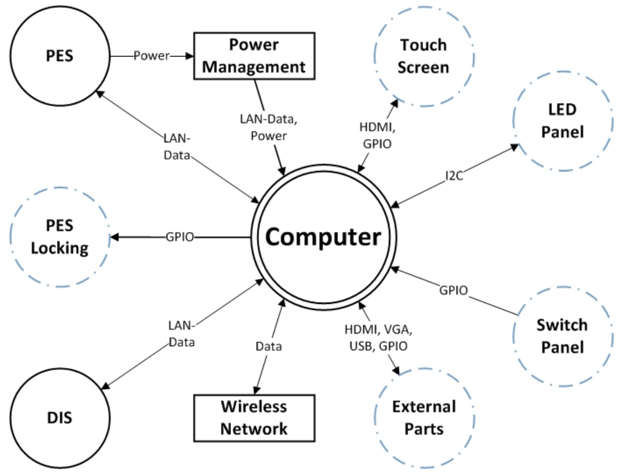

Fig. 5. Internal SPU infrastructure with interaction modules connected to the computer and communication direction shown with named arrows. Black circles are robot used interfaces. Blue dash dotted circles are human and robot usable interfaces. Black rectangles show the power management and wireless network interface.

The computer was missing easy access to additional interfaces like GPIO or I^2C bus which is useful for adding new hardware components to increase the complexity of the SPU interacting scenarios. Thanks to the modular design, the computer was replaced by a Raspberry PI 3B with several preinstalled interfaces like the GPIO headers, the mentioned bus system and a wireless network interface allowing easier connection to the SPU. In order to allow low-level command and monitoring of all hardware and software components, the operating system is Linux based. SPI and I^2C interfaces are used to connect extension boards like the LED panel. Several GPIO ports are available and have been used for simple integration of external components such as mechanical switches on the side panel and the PES locking mechanism. Latter is manually controllable via the reconfigurable switch panel.

By using the wireless network of the computer, the internal status and data can be read out, changed and validated from the mission control center e.g. to adjust the experimental scenarios without the need of a physical cable connection.

The touch panel and co-located connection ports (see Fig. 4) were integrated into the infrastructure by directly wiring to the internal computer. Hence external devices like a keyboard, mouse or an external screen can easily be connected if needed to trace down problems in the system if needed.

The DIS is connected to the Ethernet interface of the internal computer. Hence it allows direct interaction with the computer for e.g. reading the actual SPU status or flashing a new firmware of the SPU.

The PES is also connected to the internal network allowing simple integration of the SPU payload into the overall system. As the network interface is not suited for directly connecting the solar panel payload to the internal power management, we extended the PES to allow such a connection. The realized power management consists of a battery, electronics for wired operation, and a charge controller for solar powered charging. The charge controller is connected to the main computer allowing for power and charging status monitoring which has been used to validate the solar panel scenarios during the experiments.

Fig. 6. SPU equipped with solar panel (left) or satellite dish payload providing the key functionalities: A. Fully functional solar panel payload B. PES locking mechanism, C. Modular switch panel, D. Satellite dish payload, E. CPI panel, F. CU payload drawers.

4.5.5. Functionality

The latest iteration of the SPU as depicted in Fig. 6 can either be equipped with a solar panel payload module or a satellite dish payload module. The key features of the asset are summarized as follows:

- **(A)** The SPU setup comprises a fully functional and 360° rotational solar panel payload module, which can easily be swapped on into the systems power management architecture. Therefore the PEP on the solar panel structure and the PES on the deck plate of the SPU is used as described in section 4.5.1. The solar panel powers the SPU and can charge the internal battery. Possible servicing tasks are e.g. reorienting, or cleaning the panel for optimizing the power output.
- **(B)** The position of the top mounted payload module can be retained by a division of 5°, e.g. for cleaning the solar panel, through the PES locking mechanism. A solenoid is used to move or release a spring-loaded safety pin into the corresponding notch of the payload module plug.
- **(C)** The modular switch panel on the side of the SPU frame allows interaction with different components of the SPU using mechanical switches. The modular setup allows adding on further input modalities for future experiments or SPU upgrades.
- **(D)** The model of a satellite dish is used to simulate sophisticated robotic assembly task. It can be connected to the PES on the top of the SPU as replacement of the solar panel payload module. Full rotation of the antenna allows simulating reorientation tasks with the aim to optimize data transfer.
- **(E)** The connection of DIP and DIS allows the physical data network connection between Rollin' Justin and the SPUs. The DIS Panel comprises an RGB-LED system status bar allowing for visual indication of the SPUs internal status.
- **(F)** The internal modules of the SPU are accessible via a service door. The electronic components are stored on drawers. Due to the modular design, the drawers can be swapped and therefore allow a rapid reconfiguration of the system.

In the communication relay version of the SPU (shown on the right of Fig. 6), the internal architecture has been replicated through CU payload modules to allow for an advanced robotic component replacement and repair missions.

Fig. 7. Rollin' Justin with attached holster equipped with solar panel cleaning tool (left) and DIP (right).

4.6. Robot toolset

For a full utilization of the SOLEX environment, the co-worker Rollin' Justin is equipped with a toolset comprising the DIP and a cleaning tool for the solar panels depicted in Fig. 7. Both tools are equipped with a handle which is ergonomically designed to fit into the grasping robotic hand [24]. Due to the therefore increased contact surface and the grooves, a robust grasp is achieved. The end stop on the top of the handle ensures a fixed position of the tool when grasped or when the DIP is fully inserted into the DIS. In addition, the concave handle shape supports the gripping process by sliding the robotic hand towards the center of mass.

In order to achieve a robust and repetitive accessibility of the tools and prevent blocking of Rollin' Justin's workspace while unused, a special holster has been developed (see Fig. 7). Two holsters are attached on one side of the robot's mobile platform.

Due to the modular design, the holster enables the stowage of a wide variety of different tools for future experiments.

5. Rapid deployment of the SOLEX environment for METERON SUPVIS Justin

The SOLEX environment was first deployed for an on orbit experiment in METERON SUPVIS Justin [15], led by DLR and partner ESA. The aim of this experiment was to investigate the necessary functionality of a robot co-worker to operate in an eventual planetary surface habitat or colony. Three ISS-to-ground sessions were scheduled in SUPVIS Justin, each different robotic task executions of increasing levels of complexity to help study the performance limits of a space telerobotics system.

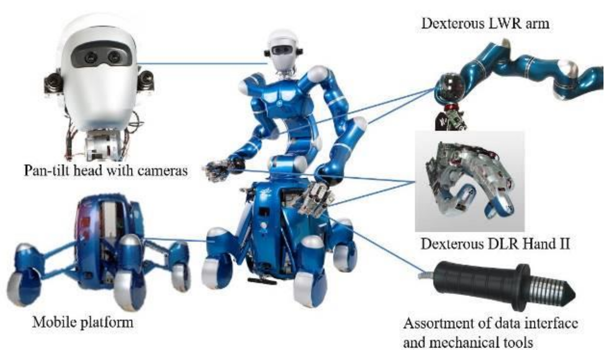

Fig. 8. DLR humanoid Rollin' Justin as deployed in the METERON SUPVIS Justin experiment.

With rapid deployment made possible by the modular design, the SOLEX environment was quickly reconfigured for each of the three experiment sessions at around six months apart. DLR's humanoid robot Rollin' Justin [23], shown in Fig. 8, served as the robot co-worker in the SOLEX environment. A growing number of task execution capabilities were developed for the robot. To be able to test and validated these capabilities was one of the key goals and challenges for the SOLEX environment.

The first session's main aim was the validation of the robot co-worker concept as a mode of teleoperation in the space context [26]. A variety of navigation and inspection tasks were carried out, in which Justin must be commanded to navigate to intended destinations, utilize the DIP to connect to the SPUs in the solar station configuration to perform tasks such as data read-out, software update, and system reset. Fig. 9 shows some of the tasks made possible by the SOLEX environment in Session 1.

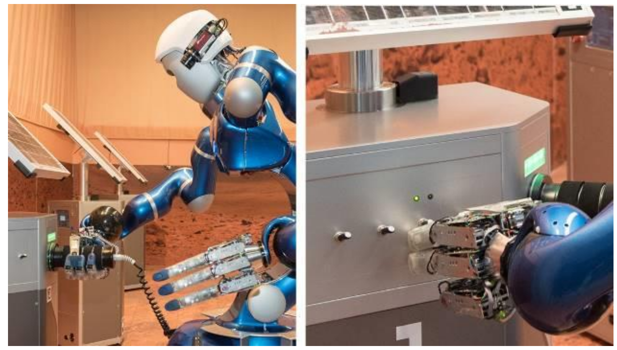

Fig. 9. SPUs with solar panel payload module being serviced by Rollin' Justin in Session 1.

To study teleoperated robotic capability to perform dexterous manipulation for Session 2, the SPUs were upgraded to include a PES payload rotating capability with locking/unlocking functionality. The robot can manually rotate the panel to a desired orientation. Furthermore, a dust/regolith cleaning function for the solar panel was implemented using the cleaning tool as shown in Fig. 10.

Fig. 10. Added functionality for Session 2 for panel rotation (left) and dust/regolith cleaning (right).

Session 3 called for the highest environment complexity for SOLEX to date. The telerobotic system is tested for component retrieval, repair, and assembly. To enable these experimental requirements, the lander with a stowage carrying different components was added, as shown in Fig. 11. The robot may retrieve a component such as the CU or a satellite dish payload module for installation or repair tasks. Furthermore, one SPU was reconfigured to introduce a wide range of object manipulation tasks such as object placement, door opening/closing, and drawer manipulation, necessary for the installation and repair scenario.

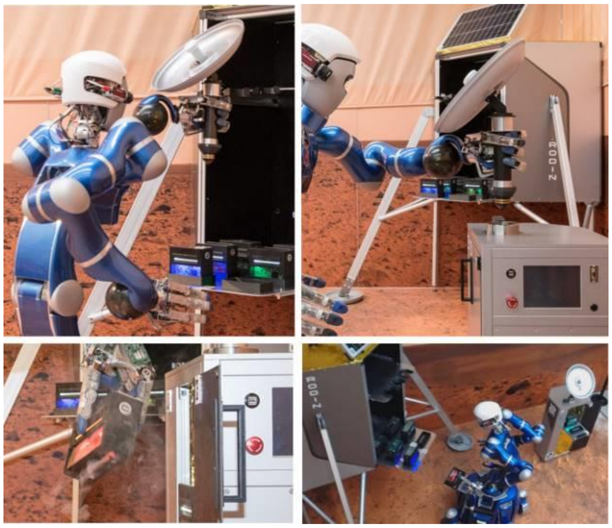

Fig. 11. Lander with stowage compartment (top left) to be used for assembly tasks in SOLEX. An example of satellite dish payload module assembly is shown (top right). Retrieval of defective CU from SPU (bottom left). Returning defective CU to lander (bottom right).

6. Discussion

With METERON SUPVIS Justin's successful ISS-to-Earth telerobotic experiments, the effectiveness of an intelligent robot as a co-worker on a planetary surface habitat for the astronaut was clearly demonstrated and closely investigated [26]. This would not have been possible without the SOLEX environment. As this was the first space telerobotic experiment to utilize this robotic proving ground, conversely, it also helped showcase the usefulness of such a dedicated environment for testing future robotic systems for space deployment.

In particular, the modular approach allowed the METERON SUPVIS Justin team to continuously incorporate different and more complex tasks, Different components could be designed and added in accordance to the robotic capabilities to be tested. From inspection and navigation of Session 1, to dexterous object manipulation of Session 2, culminating in a full repair assembly protocol in Session 3. The increasing level of robotic task complexity with each session is thus far unique to SUPVIS Justin among the METERON experiment suite. With each session no more than six months apart, rapid deployment of new interfaces and components was a necessity, which the modular approach made possible. Particularly noteworthy is the SPU's architecture, which enables the experiment design team to quickly adapt new modular components to be operated by the robot. Furthermore, the on-board computer allows for recording of every action taken by the robot on the SPU, which provides us with a holistic view of the flow of the performed task, when examined together with the robot's, and the ISS crew's action.

The participating ISS crew members were among the first ever to command a highly complex robot such as Rollin' Justin. One of the hopes of the experiment was to gain the crew's confidence in teleoperating robots to perform combinations of intricate tasks. The astronaut performance and feedback afterwards confirmed the operator confidence, as they were all able to perform the assigned tasks successfully within the available time. Furthermore, they all responded that they would be able to command a team of robots for even larger tasks. This is in large part due to the capability and ease-of-use of the supervised autonomy based telerobotic system developed for SUPVIS Justin. However, equally important was the SOLEX environment's wide array of use cases and scenarios, which allowed for the crew to use the robotic asset to its full potential.

Although SUPVIS Justin was an investigation of using the surface robot as a co-worker, we aim to provide astronauts and space operations with different modalities of commanding robotic assets, from robotic co-workers to closely coupled human-robot interactive systems such as force reflection telepresence [6]. With these different command modalities, the teleoperator would be enabled with more avenues to effectively command the robotic assets. In SUPVIS Justin, the SOLEX environment was tailored to a robot working in a known environment, such that it would be able to cope with pre-programmed actions [25]. However, to be effective in unexpected and unknown situations that can arise in any given space mission context, as well as scientific exploration scenarios, the telerobotic system must be carefully verified prior to mission. To enable this, design studies are currently underway to expand the SOLEX environment to provide realistic test scenarios, while accommodating existing and planned robotic technologies and assets.

7. Conclusion

This paper presents the SOLEX analog planetary and lunar surface proving ground developed at DLR. The SOLEX environment and the robotic tools designed for operations with the surface assets forms a new approach to analog experiment and testing, dedicated to the validation and verification of surface habitat robotic tasks. The modular design concept allows rapid integration of new functionalities and components. Furthermore, the SPU incorporates logging capability of mechanical, electronic, and software interactions with its components. Together with the robot's and UI's data logging, as well as video and audio steams of the astronaut's performance, the SOLEX environment enables the space robotic systems development team to gather a complete dataset of the actions taken for each task from different perspectives. This provides a holistic view of the human-robot team execution necessary for future space (tele)robotic system development.

For its first deployment, the SOLEX environment was successfully utilized for the validation of human robot collaboration in the METERON SUPVIS Justin experimental sessions. It enabled the development of various experimental scenarios with different enables the space robotic systems development team to gather a complete dataset of the actions taken for different complexity levels. The goal is to further enhance the functionalities of the SOLEX environment to help serve the testing and verification more future space robotic systems of different operation modalities.

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