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Introduction to Surface Avatar: the First Heterogeneous Robotic Team to be Commanded with Scalable Autonomy from the ISS

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Abstract

Robotics is vital to the continued development toward Lunar and Martian exploration, in-situ resource utilization, and surface infrastructure construction. Large-scale extra-terrestrial missions will require teams of robots with different, complementary capabilities, together with a powerful, intuitive user interface for effective commanding. We introduce Surface Avatar, the newest ISS-to-Earth telerobotic experiment series, to be conducted in 2022-2024. Spearheaded by DLR, together with ESA, Surface Avatar builds on expertise on commanding robots with different levels of autonomy from our past telerobotic experiments: Kontur-2, Haptics, Interact, SUPVIS Justin, and Analog-1. A team of four heterogeneous robots in a multi-site analog environment at DLR are at the command of a crew member on the ISS. The team has a humanoid robot for dexterous object handling, construction and maintenance; a rover for long traverses and sample acquisition; a quadrupedal robot for scouting and exploring difficult terrains; and a lander with robotic arm for component delivery and sample stowage. The crew's command terminal is multimodal, with an intuitive graphical user interface, 3-DOF joystick, and 7-DOF input device with force-feedback. The autonomy of any robot can be scaled up and down depending on the task and the astronaut's preference: acting as an avatar of the crew in haptically-coupled telepresence, or receiving task-level commands like an intelligent co-worker. Through crew performing collaborative tasks in exploration and construction scenarios, we hope to gain insight into how to optimally command robots in a future space mission. This paper presents findings from the first preliminary session in June 2022, and discusses the way forward in the planned experiment sessions.

Keywords: Space Teleoperation, Robotic Team Collaboration, Scalable Autonomy, Multimodal User Interface, Supervised Autonomy, Telepresence

Acronyms/Abbreviations

ARCHES	Autonomous Robotic Networks to Help Modern Societies Project
Col-CC	Columbus Control Centre
DLR	German Aerospace Center
DLR-RM	DLR Institute of Robotics and Mechatronics
DOF	Degree(s) of Freedom
EAC	European Astronaut Centre
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
GSOC	German Space Operations Center
GUI	Graphical User Interface
ISS	International Space Station
METERON	Multi-Purpose End-To-End Robotic Operation Network
MPCC	Multi Purpose Computer and Communication
MUSA	MUlti-Site Analog Environment

RCT	Robot Command Terminal
ROKVISS	RObotics Components Verification on the ISS
ROTEX	RObot Technology EXperiment (on Spacelab D2-Mission)
SOLEX	SOLar EXperimental Environment
SPU	Smart Payload Unit
TDPC	Time Domain Passivity Control
TDRSS	Tracking and Data Relay Satellite System

1. Introduction

Robotics is an increasingly integral part of current and future missions to the Moon and Mars. The Perseverance mission to Mars landed an exploration robotic team of a rover and a helicopter scout [1]. Robotic teams are also planned for the upcoming Artemis mission in the return of humans to the Moon [2]. Similarly, the Moon Village, proposed by European Space Agency (ESA), also envisions the utilization of robots for tasks such as the construction and maintenance of a Moon base [3].

Fig. 1 gives a vision of a system for robot teleoperation between the Earth, surface of the celestial body (e.g. Moon or Mars), and the spacecraft or station in between. In our previous development of this vision [4], the robotic team is primarily teleoperated from an orbiting spacecraft, supported by a ground support team on Earth. In this updated vision, we have extended the teleoperation to include a direct link from Earth to the robotic team on the surface for some scenarios. This is particularly possible in cislunar missions such as Artemis, where data communication round trip between the Earth and Moon can be under 3 seconds. With the addition of the planned Lunar Gateway [5], we would be able to teleoperate in cislunar space with new advances in teleoperation approaches [6, 7].

Furthermore, effective operation, and *teleoperation*, of these robotic teams are gaining importance, with the deployment of these increasingly capable and complex robotic assets. The robots may be commanded at the task level as intelligent co-workers with supervised autonomy, or as avatars closely coupled to the human operator with direct teleoperation or haptic telepresence. Previous studies discussed the suitability of these different input modalities and levels of autonomy [4]. Astronaut feedback has shown a desire to have both command modalities at their disposal to cope with different tasks and (particularly unforeseen) situations. A multimodal interface or UI [8] would be able help fulfill this requirement. Fig. 2 shows our concept for such a UI design. Equipped with dexterous tactile input devices, visual and audio interfaces, such a multimodal UI would be able to incorporate scalable autonomy that can seamlessly switch between different command modalities, thus providing the space crew and operator the array of possibilities to command a robotic team when, and how, they desire.

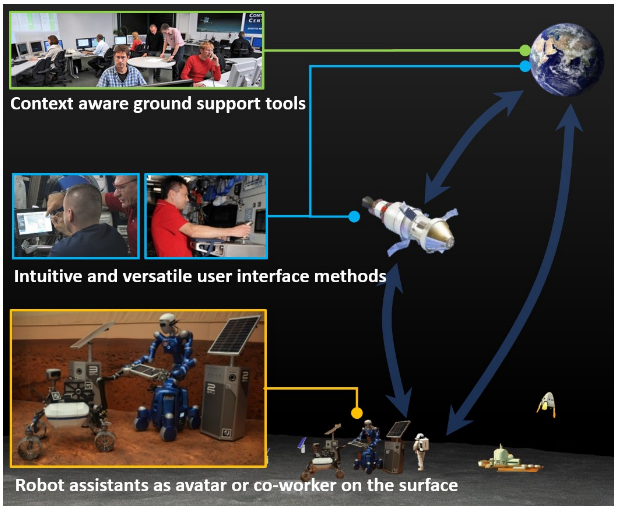


Fig. 1. Vision of a robotic team on a celestial surface, teleoperated from Earth and an orbiting spacecraft. With new advances in telecommand modalities such as supervised autonomy and telepresence to handle longer communication time delays, we can now extend earlier space telerobotic concepts [4] to consider a fully multimodal UI from Earth as well as the orbiting spacecraft.

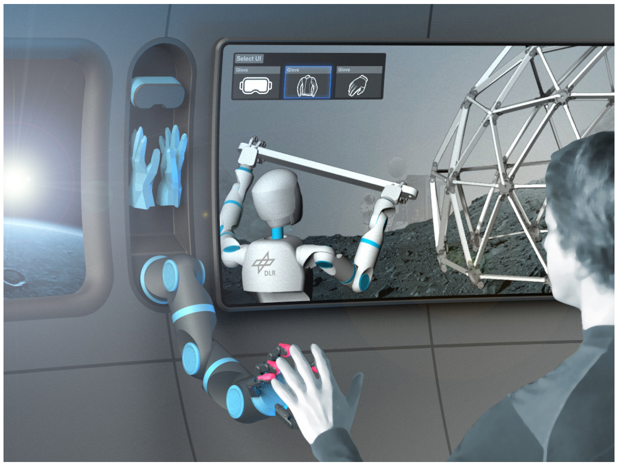


Fig. 2. Concept of a highly immersive and intuitive multimodal UI console to enable scalable autonomy teleoperation. Combining the use of different inputs such as visual, tactile, audio, and text, together with task-level commands, the operator can command a team of robots as avatars or intelligent co-workers as required by the tasks and situations at hand.

The Surface Avatar telerobotic mission, led by the German Aerospace Center (DLR) with partner ESA, aims to develop and investigate the technology needed for teleoperating a heterogeneous robotic team with scalable autonomy. Five experiment sessions are planned between the International Space Station (ISS) and Earth at DLR Institute of Robotics and Mechatronics (DLR-RM) and German Space Operations Center (GSOC) in 2022-2024.

This paper presents the concepts and current development of Surface Avatar, as well as some early findings from the first ISS-to-Earth telerobotic session. The rest of this paper is organized as follows: Sec. 2 discusses the related work in space telerobotics. Sec. 3 details the experiment design and setup, followed by the ISS experiment schedule and key goals of each session in Sec. 4. Our early findings from the first preliminary session are discussed in Sec. 5. Finally, the conclusion to this paper and outlook for Surface Avatar is presented in Sec. 6.

2. Related work

Telerobotics has been developed and applied to space exploration for several decades. RObot Technology EXperiment (on Spacelab D2-Mission) (ROTEX) was carried out on board space shuttle Columbia (STS-55) in 1993. It demonstrated the feasibility of teleoperated robotic capturing of free-floating object in micro-gravity. The robotic arm deployed on board Columbia was commanded from Earth over multi-second time delays. To cope with this, local intelligence was implemented on the robot to assist the operator on ground to locate and capture the object [9]. This was also an early development of combining different levels of autonomy in space telerobotics. Several versions of the Canadarm have been deployed on board space shuttles and the ISS for a wide variety of duties [10, 11]. Originally designed to be commanded in joint space, other teleoperation modes, such as Cartesian space, were added in later development.

Haptic telepresence has been studied in a rigorous series of force-reflection ISS-Earth telerobotic experiments. The RObotics Components Verification on the ISS (ROKVISS) experiment first demonstrated this from Earth to space in 2005, by commanding a 2-Degree(s) of Freedom (DOF) robotic arm mounted on the exterior of the ISS with a 2-DOF force-reflection joystick on ground over a direct point-to-point S-band communication link [12, 13]. This was followed by several experiments in the reverse direction in 2014-2016, with the force-reflection UI on board the ISS used to command a robotic asset on Earth. A 1-DOF joystick was developed for ESA's Haptics and Interact experiments in the Multi-Purpose End-To-End Robotic Operation Network (METERON) experiment suite [14] to realize telepresence with Earth over Ku-band [15, 16]. in the Kontur-2 experiment, DLR developed a 2-DOF joystick to command several high-dexterity robotic assets (individually) [17].

Supervised autonomy was first investigated in METERON SUPVIS Justin in 2017-2018 by DLR and ESA. A tablet-PC deployed on the ISS with a Graphical User Interface (GUI) program was used to command a complex humanoid robot, at the task level, as an intelligent co-worker on ground [6, 18, 19]. As mentioned in Sec. 1, this spurred a discussion of the suitability of supervised autonomy or telepresence for telerobotics in space, concluding with the realization that both are needed to cover different mission scenarios [4].

This pointed to a future of scalable autonomy, which integrates different command styles (e.g. direct open-loop, telepresence, supervised autonomy) into a multi-modal UI console. A first demonstration of this concept was performed in Analog-1 in 2019 [7, 20]. A UI console, referred to as the Robot Command Terminal (RCT), equipped with a GUI on a notebook PC, an open-loop joystick, and a 7-DOF Force Dimension sigma.7 [21] force-reflection input device, was utilized to command a rover to navigate and retrieve samples in a test environment. This was further tested in an analog surface environment on Mount Etna in 2022 during the DLR-led Autonomous Robotic Networks to Help Modern Societies Project (ARCHES) mission [22, 23]. Improved autonomy features such as waypoint driving were introduced with maps and automated rock detection and picking as alternatives to the original low-level commanding [24], enabling a pilot test of the scalable autonomy concept.

Multi-robot collaboration has also been investigated and deployed for space exploration in recent years. The aforementioned ARCHES mission brought a team of dissimilar robots, including rovers, a drone, and a lander, to operate collaboratively on Mount Etna [23, 25]. Also mentioned in Sec. 1 was NASA's on-going Perseverance mission on Mars, which uses a scout helicopter, Ingenuity, to assist the rover, Perseverance [1].

3. ISS-to-Earth telerobotic team experiment design and setup

3.1 Multimodal Robot Command Terminal on the ISS

The multimodal UI is deployed on board the ISS with the RCT, first upmassed in the aforementioned Analog-1. Fig. 3 shows its installation in the Columbus Module during Surface Avatar's first preliminary session. The 3-DOF RCT joystick allows roll, pitch and yaw inputs, and is equipped with six additional programmable buttons, as well as an enable button which additionally acts as a dead man's switch. The sigma.7 has 6-DOF movement and an additional pincer DOF, all enabled with force-reflection functionality. This is particularly useful for telepresence operation of robotic arms with grippers for object grasping.

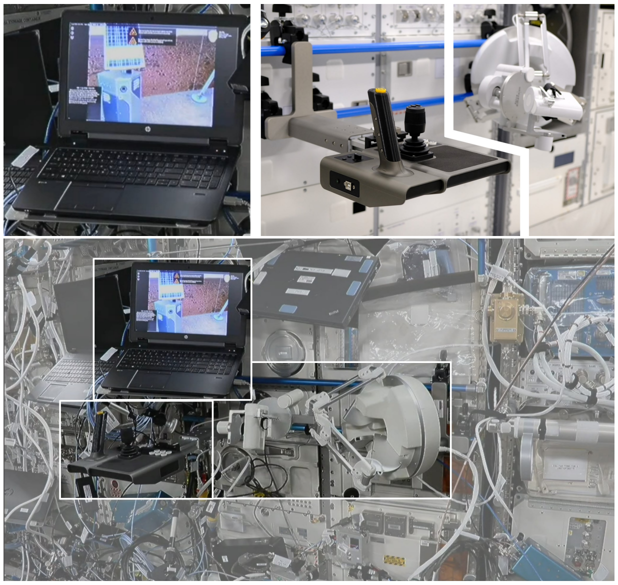
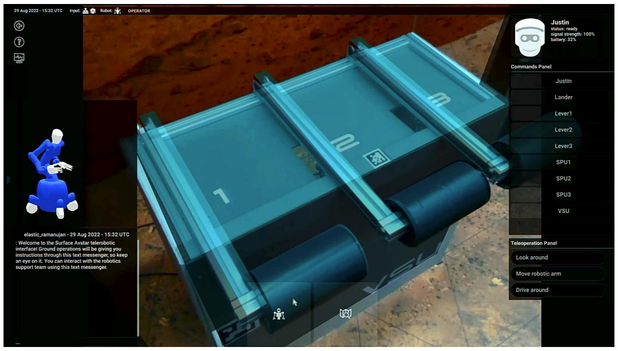


Fig. 3. The multimodal UI Robot Command Terminal (RCT) of Surface Avatar. A notebook computer with a GUI program **(top left)**, an open-loop joystick **(top center)**, and a force-reflection sigma.7 input device **(top right)** [20], give the crew the possibility to command a team of robots with different command modalities with scalable autonomy. The system as installed on board the ISS for the first preliminary session **(bottom)**.

The RCT notebook computer is an ISS standard issue HP ZBook. The GUI program deployed on the notebook is developed to serve as a command center of the RCT to manage all of the input devices, as well as providing a wide array of visual, textual information, and command possibilities. Fig. 4 gives an example view of a recent version of the GUI. The crew can communicate with the ground control team via a text messenger to supplement the standard ISS voice loop communication. A robot pose viewer gives the crew better awareness of the robot currently being commanded. A main viewer shows the camera view as seen by the robot's camera. Augmented reality geometric overlays display the robot's localization of the objects in its surrounding. As the robot can be used as an intelligent co-worker, a dynamically populated menu of relevant task-level commands enables effective supervised autonomy. In addition to being able to drive the rover with the joystick, map-based navigation may also be used to reach points of interest.

Effectively bringing a large amount of capability into the GUI, while maintaining intuitiveness and ease-of-use, is of great importance for commanding an increasingly complex robotic team. More details on the knowledge-driven command concepts used in the GUI design can be found in [26].

To provide data connection between the RCT and the robotic team, the Multi Purpose Computer and Communication (MPCC) link [27] is used. It connects the ISS to ground over the Tracking and Data Relay Satellite System (TDRSS), which provides near-continuous communication of up to 8 Mbit/s at a data rountrip of ∼800ms to our experiment sites in Germany. Given the large amount of video and telemetry data being transmitted between space and ground, 4 Mbit/s bandwidth is required for both up- and down-link.



status: ready
signal strength: 100%
battery: 32%

elastic_ramanujan - 29 Aug 2022 - 15:32 UTC
: Welcome to the Surface Avatar telerobotic interface! Ground operations will be giving you instructions through this text messenger, so keep an eye on it. You can interact with the robotics support team using this text messenger.

Fig. 4. An example view of the GUI deployed in the first preliminary ISS session. The Surface Avatar GUI functions as a command center for the ISS crew. Some of the current version's functions include a viewer of the robot's pose, a text messenger with the ground control team, the robot's camera view, selector of input devices (sigma.7 or joystick), map navigation (not shown here), and a dynamically updated menu of task command based on situation and task relevance.

3.2 Heterogeneous robotic team

Our concept incorporates a team of robotic assets with different forms and capabilities to collaborate on larger, more complex tasks over a greater area of coverage. The robotic team, as shown in Fig. 5, shall grow in number in each successive ISS-to-Earth session, with the final team consisting of four robotic assets:

- Rollin' Justin [28, 29]: a mobile dexterous humanoid robot with two arms and articulate hands, suitable for delicate tasks such as fine construction and sample handling;

- Interact Rover [20]: a four-wheel-drive rover with an articulated camera-equipped head, and a robotic, camera-equipped arm and gripper, suitable for long traverses, component transportation, surveying, and sample acquisition;
- Bert [30]: a small quadrupedal scout robot, suitable for exploring tight crevices and challenging terrains;
- Lander equipped with space robotic arm [31]: the lander serves to deliver components to be deployed on the surface, and stow sample containers for return to Earth. The robotic arm, based on DLR's TINA space robotic technology, enables the lander to be an active player in the transfer of these items, and ease the workload of the other members of the robotic team.

Fig. 5. The heterogeneous robotic team of Surface Avatar: a small quadrupedal scout, Bert, **(top left)**, a lander equipped with a space robotic arm **(top right)**, a dexterous humanoid robot, Rollin' Justin **(bottom left)**, and a long-traverse-capable Interact Rover **(bottom right)**.

3.3 Analog experimental environments

In the two preliminary sessions, Rollin' Justin is commanded to perform different tasks in the SOLar EXperimental Environment (SOLEX), which simulates a surface habitat, as shown in Fig. 6 [32]. Located at DLR-RM, it is based on and expanded from the design for METERON SUPVIS Justin, to add more components to help investigate a wider variety of robot actions.

A new MUlti-Site Analog Environment (MUSA) Environment is being developed for the prime sessions to be deployed at GSOC. The MUSA Environment aims to mimic larger mission scenarios. It should help investigate the robotic team's ability, both individually and collectively, to effectively explore and handle a larger area. The layout is specifically designed to incorporate multiple sites with different purposes and accessibilities, such as a lander site, a science site, and scout site. Barriers are introduced to help create physical and visual separations. The concept and layout of the MUSA Environment is shown in Fig. 7

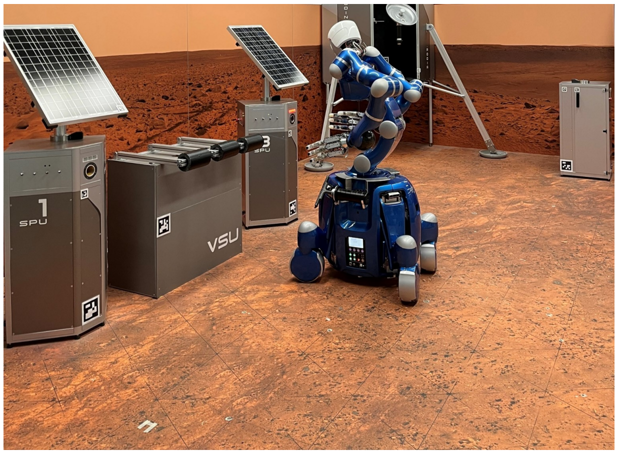


Fig. 6. The analog experimental environment used in the preliminary session. Extending upon the SOLEX environment of the SUPVIS Justin experiment [32], various analog systems expected in a lunar or planetary surface habitat are implemented to help examine robot performance of different tasks.

4. Surface Avatar ISS-to-Earth experiment plans

A total of five ISS-to-Earth telerobotic sessions are planned from 2022 to 2024. The first two preliminary sessions in June and September 2022 serve to check the functionality of the RCT on board the ISS, and the MPCC space-to-ground communication link. Although the main purpose of these two sessions are for system function validation, we are nonetheless using these opportunities to investigate scalable autonomy and multimodal UI design.

The three prime sessions are scheduled to take place in 2023-2024. A multi-robot team will be commanded in these sessions to perform increasingly complex tasks. With each successive sessions, the number of robotic assets incorporated into the team will increase. This should add to the robotic team's capability, but also introduce new challenges of integrating the increasing number of robotic assets to work collaboratively. Furthermore, the RCT must be further developed to enable the ISS crew to efficiently and intuitively teleoperate the robotic assets as

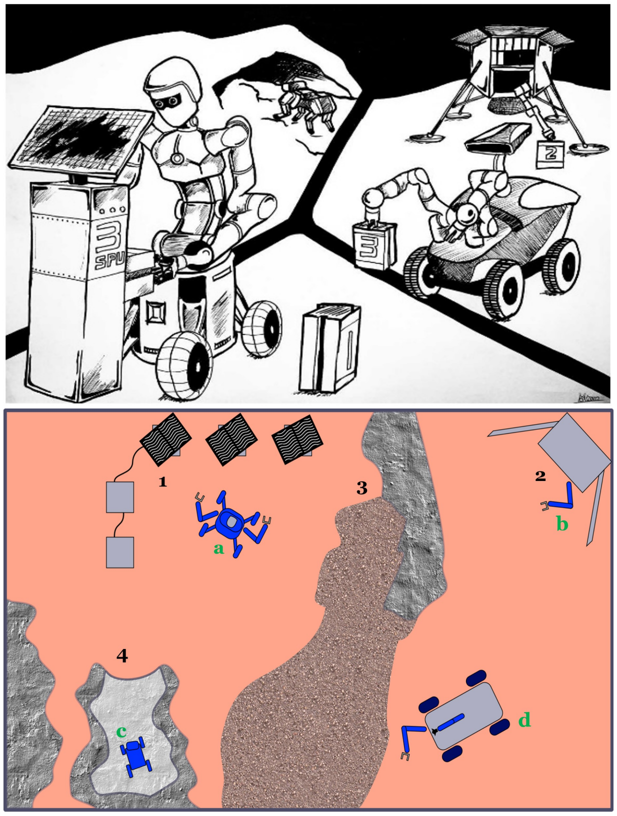


Fig. 7. Concept and layout of the MUlti-Site Analog Environment (MUSA) for the prime ISS sessions of Surface Avatar. Our concept as illustrated here **top**, is to realize a heterogeneous robotic team collaborating in a multi-site surface scenario. The layout of the MUSA environment **bottom** includes (1) a science site , (2) a robotic lander site, (3) barriers to create visual and physical separations, and (4) scouting site with tight crevices or challenging terrain. The robotic assets (a) Rollin' Justin, (b) lander with robotic arm, (c) quadrupedal scout, Bert, and (d) Interact Rover, are also shown.

avatars, intelligent co-workers, and as a team. More details of each of the five ISS-to-Earth experiment sessions can be seen in Table 1.

Table 1. Surface Avatar ISS-to-Earth telerobotic sessions

ISS Session	Date	Note
Prelim. 1	06/2022	Test/validation session 1 with Station UI and robot Rollin' Justin
Prelim. 2	09/2022	Test/validation session 2 with Station UI and robot Rollin' Justin
Prime 1	03/2023	Multi-robot team teleoperation with two robotic assets
Prime 2	H2/2023	Multi-robot team teleoperation with three robotic assets
Prime 3	H1/2024	Multi-robot team teleoperation with four robotic assets; execution of end-to-end surface tasks

5. First findings and observations

The first preliminary session was successfully carried out in June, 2022. Over two days, we were able to deploy and confirm the functionality of the RCT on board the ISS. Furthermore, ESA astronaut Samantha Cristoforetti performed three different tasks teleoperating Rollin' Justin.

The first experiment protocol was a navigation and environment survey task, during which the crew was requested to search for anomalies and unexpected situations in Justin's surroundings, and take photo snapshots to send to the ground control team on Earth for further investigation.

This was followed by our benchmark service and maintenance task on a Smart Payload Unit (SPU), first introduced in METERON SUPVIS Justin. Justin was commanded to perform mechanical tasks such as probe insertion and switch flipping, and digital tasks including data readout and software update. Most of the tasks were carried out with task-level commands in supervised autonomy with the GUI.

Nevertheless, unlike SUPVIS Justin, which utilized a tablet computer as the sole UI, and strictly supervised autonomy, in Surface Avatar, the crew was able to use different command modalities provided by the RCT. For example, the crew could command Justin to navigate or look around with Justin's pan-tilt head, either by task-level command in the GUI, or using the joystick. This gave the crew more flexibility to command the robot in a more comfortable and intuitive manner. This was our first foray into scalable autonomy in Surface Avatar.

Force-reflection haptic telepresence was also investigated in two different tasks. One was a stiffness recognition task where the crew was asked to command the robot with the sigma.7 to lift different levers to identify a stuck lever. Cristoforetti was able to determine the correct lever through force reflection. In this task, scalable autonomy is again utilized, with the locating and grasping of each lever commanded at the task level from the GUI, and lifting of the lever performed in telepresence. This reduced the workload and operation time by utilizing the robot both as

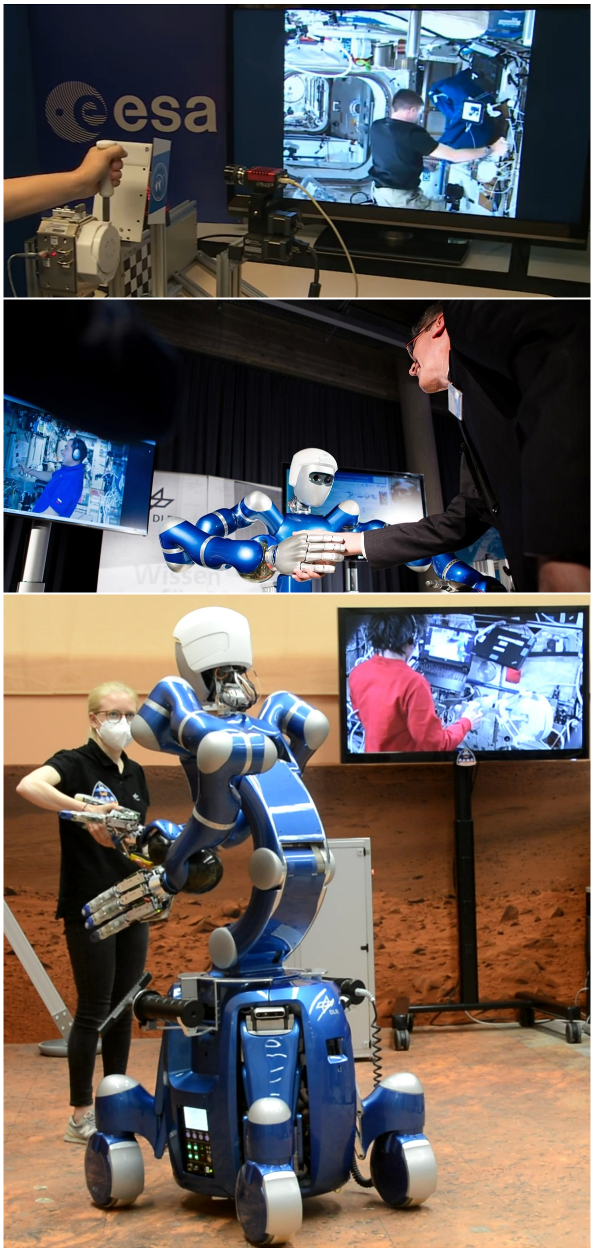


Fig. 8. The continuing advancement in haptic telepresence shown in a handshake. From 1-DOF handshake of Haptics-2 **(top)** [33], to the 2-DOF joystick handshake of Kontur-2 **(middle)** [17], we have further enhanced the telepresence capability in Surface Avatar. We are now able to couple a 7-DOF input device (sigma.7) to the robot (Rollin' Justin) avatar's 21-DOF hand and arm **(bottom)**. The ISS crew can feel the contact forces and motion of the person shaking hands with Justin on Earth in 6-DOF, over a communication network with ∼800 ms time delay.

an intelligent co-worker, and immersive force-reflection coupled avatar in one task.

Finally, an ISS-to-Earth tele-handshake was performed. Surface Avatar continued the advancement in haptic telepresence here. We follow in the footsteps of the 1-DOF-to-1-DOF joystick handshake in Haptics-2, and 2-DOF joystick-to-7-DOF robot arm handshake of Kontur-2. The handshake performed here further raised the dexterity (and complexity) on both the UI side to 7-DOF (six active and one passive), and robot side to 21-DOF (7-DOF for the arm, and 12-DOF for the hand). The haptic telepresence over time delays of ∼800 ms was enabled with Time Domain Passivity Control (TDPC) approaches developed at DLR-RM [7]. Fig. 8 shows the continuing advancement of space haptic telepresence manifested in space-to-ground tele-handshakes.

6. Conclusion and outlook

This paper presents the ISS-to-Earth telerobotic experiment Surface Avatar, led by DLR and partner ESA. The goal is to study the feasibility of teleoperating a team of heterogeneous robots on the lunar and planetary surface from an orbiting space station. In our analog scenario, the ISS acts as the orbiting station, and the Earth as the location for the surface robotic team.

A crew member would use a multimodal UI with direct teleoperation, haptic telepresence, and GUI to command the team of robots. With such a telerobotic system in place, we aim to realize scalable autonomy to allow the crew to command complex and highly capable robotic assets, easily and intuitively.

Having performed the first preliminary ISS-to-Earth session recently, we are able to present some early findings and outcomes from the teleoperation of the humanoid robot, Rollin' Justin, to perform tasks at different levels of immersion and autonomy. The preliminary session also allows us to validate the system readiness of the RCT on board the ISS, as well as the MPCC space-to-ground communication link.

It is planned for Surface Avatar to carry out five ISS-to-Earth telerobotic experiment sessions in total. This includes a second session, and three further prime sessions to conclude in 2024. With each prime session, the heterogeneous robotic team on Earth increases in the number of robotic assets to be incorporated, culminating in a team consisting of a dexterous humanoid robot, a rover, lander with a space robotic arm, and a quadrupedal scout. The robotic tasks shall also grow in complexity to help our investigation of the performance and feasibility of scalable autonomy teleoperation and robotic team collaboration.

Finally, we believe the scalable-autonomy-based telerobotics being developed will prove a valuable contribution to cislunar endeavors such as NASA's Artemis mission and ESA's Moon Village concept, as well as distant planet exploration.

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