Extending the Knowledge Driven Approach for Scalable Autonomy Teleoperation of a Robotic Avatar

Peter Schmaus
German Aerospace Center (DLR)
Wessling, Germany
Peter.Schmaus@dlr.de

Adrian Bauer
German Aerospace Center (DLR)
Wessling, Germany
Adrian.Bauer@dlr.de

Nicolai Bechtel
German Aerospace Center (DLR)
Wessling, Germany
Nicolai.Bechtel@dlr.de

Maximilian Denninger
German Aerospace Center (DLR)
Wessling, Germany
Maximilian.Denninger@dlr.de

Anne Köpken
German Aerospace Center (DLR)
Wessling, Germany
Anne.Koepken@dlr.de

Florian Lay
German Aerospace Center (DLR)
Wessling, Germany
Florian.Lay@dlr.de

Florian Schmidt
German Aerospace Center (DLR)
Wessling, Germany
Florian.Schmidt@dlr.de

Marco Sewtz
German Aerospace Center (DLR)
Wessling, Germany
Marco.Sewtz@dlr.de

Thomas Krüger
European Space Agency (ESA)
Noordwijk, The Netherlands
Thomas.Krueger@esa.int

Daniel Leidner
German Aerospace Center (DLR)
Wessling, Germany
Daniel.Leidner@dlr.de

Aaron Pereira
German Aerospace Center (DLR)
Wessling, Germany
Aaron.Pereira@dlr.de

Neal Y. Lii
German Aerospace Center (DLR)
Wessling, Germany
Neal.Lii@dlr.de

***Abstract*— Crewed missions to celestial bodies such as Moon and Mars are in the focus of an increasing number of space agencies. Precautions to ensure a safe landing of the crew on the extraterrestrial surface, as well as reliable infrastructure on the remote location, for bringing the crew back home are key considerations for mission planning. The European Space Agency (ESA) identified in its Terrae Novae 2030+ roadmap, that robots are needed as precursors and scouts to ensure the success of such missions. An important role these robots will play, is the support of the astronaut crew in orbit to carry out scientific work, and ultimately ensuring nominal operation of the support infrastructure for astronauts on the surface. The METERON SUPVIS Justin ISS experiments demonstrated that supervised autonomy robot command can be used for executing inspection, maintenance and installation tasks using a robotic co-worker on the planetary surface. The knowledge driven approach utilized in the experiments only reached its limits when situations arise that were not anticipated by the mission design. In deep space scenarios, the astronauts must be able to overcome these limitations. An approach towards more direct command of a robot was demonstrated in the METERON ANALOG-1 ISS experiment. In this technical demonstration, an astronaut used haptic telepresence to command a robotic avatar on the surface to execute sampling tasks. In this work, we propose a system that combines supervised autonomy and telepresence by extending the knowledge driven approach. The knowledge management is based on organizing the prior knowledge of the robot in an object-centered context. Action Templates are used to define the knowledge on the handling of the objects on a symbolic and geometric level. This robot-agnostic system can be used for supervisory command of any robotic coworker. By integrating the robot itself as an object into the object-centered domain, robot-specific skills and (tele-)operation modes can be injected into the existing knowledge management system by formulating respective Action Templates. In order to efficiently use advanced teleoperation modes, such as haptic telepresence, a variety of input devices are integrated into the proposed system. This work shows how the integration of these devices is realized in a way that is agnostic to the input devices and operation modes. The proposed system is evaluated in the Surface Avatar ISS experiment. This work shows how the system is integrated into a Robot Command Terminal featuring a 3-Degree-of-Freedom Joystick and a 7-Degree-of-Freedom haptic input device in the Columbus module of the ISS. In the preliminary experiment sessions of Surface Avatar, two astronauts on orbit took command of the humanoid service robot Rollin' Justin in Germany. This work presents and discusses the results of these ISS-to-ground sessions and derives requirements for extending the scalable autonomy system for the use with a heterogeneous robotic team.**

978-1-6654-9032-0/23/$31.00 ©2023 IEEE

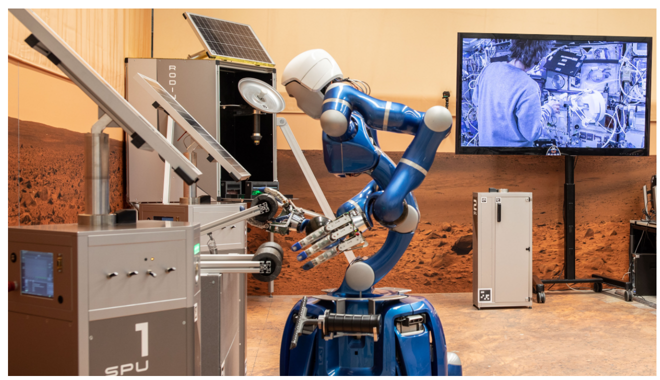


Figure 1. During the first Surface Avatar preliminary experiment session in June 2022, DLR's humanoid robot Rollin' Justin was teleoperated from the International Space Station (ISS). The display in the back shows ESA astronaut Samantha Cristoforetti testing force-reflection teleoperation.

Table of Contents

1. INTRODUCTION

As humankind makes its way back to the Moon and then to Mars, the *European Space Agency (ESA)* formulates its goals in the Terrae Novae 2030+ strategy roadmap [1]: "The mission of the Terrae Novae exploration programme is to lead Europe's human journey into the Solar System using robots as precursors and scouts, and to return the benefits of exploration back to society." It further details the use of robots for accessing the surface of the Moon with the European *Large Logistics Lander (L3)* and long-term (re)visits of Mars. To meet this challenge, ESA plans to develop new robotic techniques, together with human-assisted robotic instruments.

These robots will be located on the surface of the celestial bodies in order to provide support to the astronauts in exploring the environment, running scientific experiments, and setting up and maintaining infrastructure, as depicted in Figure 1. As increasing communication delays render it impossible to directly teleoperate the robots in a traditional way, autonomous capabilities of the robots move into focus. In order to reduce the communication delays, and allow for more efficient robotic operation, the systems will be commanded from astronauts on board an orbiting spacecraft paving the way for crewed landings on the surface.

The difficulties of the microgravity environment in addition to the mental load of operating a spacecraft make it important to limit the astronaut utilization for robot commanding. Furthermore, the communication link to the surface robots may be hindered by limited bandwidth, delay, and jitter. Therefore the use of an intelligent robotic co-worker is envisioned to provide autonomous functionality. In situations where the robot's autonomy reaches its limits, the astronaut should be able to use the system as an avatar in the remote location using teleoperation methods that are tolerant to challenging communication channel characteristics. The astronaut must always be able to scale the autonomy of the robot in order to account for the current situation and personal preferences.

This work builds on our prior work on a knowledge driven approach for effective teleoperation of an intelligent service robot [2] and exploring planet geology through force-feedback telemanipulation from an orbiting spacecraft [3]. The contribution of this work is an extension of the object-based knowledge management allowing for the integration of scalable autonomy teleoperation.

The remainder of this work is structured as follows: Section 2 summarizes the prior work of orbit-to-ground robot commanding done by the German Aerospace Center (DLR) and ESA. Subsequently we detail our concept for knowledge driven scalable autonomy teleoperation in Section 3 and present the implementation detail in Section 4. The first results of the presented system in an on orbit experiment are described in Section 5. Section 6 gives an outlook on the upcoming steps for extension and further evaluation of the system and the transfer of the findings to terrestrial applications.

2. RELATED WORK

In 2015-2017, astronauts in orbit commandes several robots on Earth in DLR and Roscosmos's Kontur-2 project [4][5]. In a series of experiments, a 2-*Degree-Of-Freedom (DOF)* force-reflection joystick in the Russian Svezda module of the ISS was used to command robots located in Germany and Russia with telepresence. The experiments used a direct station-to-ground communication link with low latency. Due to the direct point-to-point S-Band communication, an experiment session was limited to a duration of 8-10 minutes while a communication link between the ISS and the ground antennas could be established. On the other hand, thanks to the direct communication between space and ground, a short communication roundtrip of about 20ms could be achieved for crisp force reflection performance. The project demonstrated in various experiment sessions with different cosmonauts that direct telepresent robot command from a microgravity environment using a force-feedback device is possible and allows the crew to interact with unmodelled rigid objects in a remote environment using a robotic avatar.

In the ESA-initiated *Multi-Purpose End-To-End Robotic Operation Network (METERON)* project, ESA, DLR, NASA, and Roscosmos investigated the operation and relevant technology of space telerobotics [6]. The METERON HAPTICS experiments focused on the investigation of astronaut perception of force-feedback in a microgravity environment [7][8]. In these experiments, ESA deployed a 1-DOF force-feedback joystick together with a tablet computer inside the Columbus module of the ISS. The on board setup has been used to do various studies with different astronauts on the perception of force and the telepresent command of a ground robot via a communication link with a latency of 800+ ms. Building on the experiences of this prior work, the METERON Interact experiment supplemented the teleoperation with semi-autonomous navigation capabilities of the ground robot. These capabilities were communicated to the astronaut operator by the use of virtual assistance markers in the Graphical User Interface (GUI) lowering the mental effort while approaching the manipulation target object. The astronaut on board the ISS could then execute a sub-millimeter precision peg-in-hole task using a robotic rover located at the *European Space research and TEchnology Centre (ESTEC)* [9].

During the METERON SUPVIS-E and SUPVIS-M experiments, ESA investigated the use of supervisory robot command [10] for optimizing the workload balance between the robot and astronaut. Predefined task-level commands allowed the robot to execute parts of the mission scenario autonomously. The astronaut could then select the commands and monitor the execution in the METERON Operations Software GUI installed on a laptop computer [11]. The experiments showed that the use of supervisory command allows for efficient robot command even in scenarios where the communication link between astronaut and robot is very limited in terms of delay, bandwidth, or jitter.

In the METERON SUPVIS Justin experiment, the focus is shifted from using the remote robotic system as a direct extension of the user, to treating the robot as a coworker of the astronaut [12][13]. DLR's Rollin' Justin robot provided intelligent features such as autonomous object detection, reasoning, and action execution needed for such a use [14][15]. An intuitive GUI installed on the tablet computer upmassed to the ISS for the METERON HAPTICS experiments, allowed the astronaut to select robot actions which Justin would autonomously execute [16]. The available actions are context-specifically updated by the robot so that only actions which are currently reasonable are displayed in a *Graphical User Interface (GUI)*. A mission control component allows further scenario-specific filtering of available actions in order to provide ground support to the astronaut. By showing the live video feed of the robot in the GUI and overlaying it with information on the currently detected objects, the astronauts

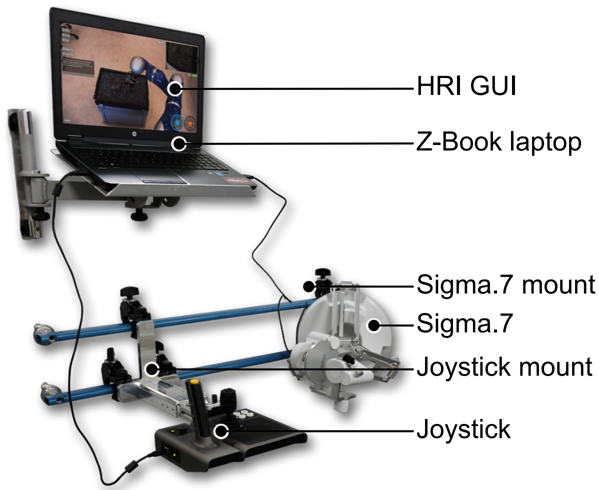


Figure 2. Robot Command Terminal as upmassed to the ISS for orbit-to-ground robot command in the METERON ANALOG-1 experiment. The terminal consists of a laptop displaying the Graphical User Interface, a 3-Degree-of-Freedom Joystick, and a 7-Degree-of-Freedom haptic feedback device sigma.7.

on board the ISS could correctly assess the situation on the ground and perform a variety of survey and maintenance task in a simulated martian environment [17]. METERON SUPVIS Justin demonstrated that a supervised autonomy system can be used to provide intuitive robot command to even untrained crew allowing for efficient crew and robot utilization in structured environments [2].

The METERON ANALOG-1 experiment expanded the investigations of robot command *User Interface (UI)* with the upmass of a new *Robot Command Terminal (RCT)* to the ISS. The RCT, depicted in Figure 2, consists of a laptop computer for displaying a GUI, a 3-DOF joystick with a set of buttons, and a 7-DOF force-feedback haptic input device sigma.7 of Force Dimension. During the experiment, a robotic rover at ESTEC has been commanded to do navigation tasks using open-loop teleoperation and rock sampling tasks using force-feedback teleoperation [3]. The experiment demonstrated that a tele-exploration scenario can be successfully executed via haptic telemanipulation using a limited communication channel with 800 ms delay. The developed control method ensures stability at high delay without reduction in speed or loss of positioning accuracy.

In this work, we extend the previous findings on supervised autonomy teleoperation from METERON SUPVIS Justin and force-feedback telepresence from METERON ANALOG-1. We outline a system for scalable autonomy robot command that allows the astronaut operator to context-specifically decide on which level of autonomy to command the remote robot.

3. Knowledge Driven Teleoperation Concept

The time of the astronauts is one of the most valuable resources in space missions. The dexterity, adaptability, and ingenuity of humans are unmatched by mechatronic systems. Nevertheless, robotic coworkers should be deployed to support the astronauts wherever possible to ensure mission success, and allow the astronauts to maximize their scientific output. Ideally, the astronauts would assign tasks to the autonomous robots, and only need to intervene in robotic operations when the autonomy of the system fails. This makes the actual robot commanding a side task of the astronaut, which is executed in parallel with their actual work with an intuitive command process requiring a low cognitive load. In our previous work, we presented and evaluated a concept for a *Human Robot Interface (HRI)* that utilizes the intelligence of the robot to provide such an intuitive interface to the operator. This section gives an overview of core elements of the system and proposes extensions that allow to not only command the robot on a supervisory level, but to integrate haptic telemanipulation modalities in order to create a scalable autonomy HRI.

Knowledge Representation

Our previous work has shown that organizing the knowledge of the robot in an object-centered context is advantageous for robot operation [15] and supervisory command [16][2]. Storing the information about the objects and manipulation instructions with the objects, allows for straight-forward management of the knowledge base of the robot. As all the information for specific use-cases can easily be found by analyzing the task and identifying the associated objects, scenario-specific modifications can be done even without full awareness of the knowledge of the robot that is not connected to the task at hand. By using an inheritance mechanism, general object properties are specified on a parent level while the description of more specific object details and manipulation instructions is done in the individual children objects. This allows for rapid changing of objects or introduction of similar objects into the knowledge base by reusing prior knowledge of the robot.

Interaction Representation

Action Templates (ATs) organize the knowledge on the handling of the objects in a robot-agnostic way by separating the information into a symbolic header and a geometric body [15]. The symbolic header describes the action in *Planning Domain Definition Language (PDDL)*. It describes the parameters, preconditions, and effects of each action. This information is then used by a symbolic planner to create a possible sequence of ATs to achieve a desired goal state. The geometric body defines the process model for interacting with the object and grounds the intended action to the physical robot. Therefore a sequence of operations is defined that describe the actual movement of the robot executing the AT. Because the operations themselves are robot-agnostic and realized by the actual robots, each robot that implements all the operations in a geometric body of an AT can execute the underlying manipulation.

The planning of the actions is carried out in a hybrid approach: First, a symbolic planner reasons on a symbolic level using the symbolic headers in order to determine a sequence of ATs that reaches a desired goal state. Afterwards a geometric planner uses robot-provided planning modules, such as motion or grasp planners, to generate robot-specific execution plans based on the geometric body of each AT of the symbolically planned sequence. In the case that the planning fails, the system first tests for geometric alternatives (geometric backtracking) and then different symbolic solutions (symbolic backtracking).

The geometric execution plan generated by the hybrid planning algorithm can be directly executed by the robot. The described system reaches its limits in dynamic environments or when anomalies occur during the execution because the transition of the symbolic properties can no longer be guaranteed when deviating from the plan. As a result, all symbolic properties need to be manually updated by an expert when an action execution failed while the autonomous recognition of the symbolic properties is subject to future work [18]. Nevertheless, with METERON SUPVIS Justin, we demonstrated that the system is well suited to supervised autonomy command of a robot with limited autonomy, as long as the operator is in the loop to manage and evaluate the action execution and robot perception.

Knowledge Driven Scalable Autonomy

The focus of the described object-centered knowledge management system lies on interactions with the objects in the environment of the robot. This systems functions well in all scenarios where a robot manipulates known objects, but cannot effectively work with unknown or unstructured environments. We propose to extend the knowledge driven approach for such situations, in order to allow the command of the robot on a lower level of autonomy, e.g. direct control or telepresence. Such a system would allow for scaling the autonomy of the commanded robot depending on the current context and requirements of the operator.

We integrate the robot-centric functions needed for operating the robot on the lower levels of autonomy, into the object-centered domain by treating the robot itself as an object in the knowledge management system. This allows us to create an AT for each robotic skill or function that we want to access for knowledge driven teleoperation. The geometric body of the ATs is used to plan executions of the robot-centric functions of the underlying system, which can be accompanied by safeguarding mechanisms for robust execution. The symbolic header of the ATs is used to make sure the robot is a symbolically safe state to execute the action. Further more, the symbolic properties of objects in the environment of the robot that may be changed by the directly commanded robot actions are invalidated in order to trigger an reevaluation before continuing autonomous operation. Adding the status of the robot (e.g. controller mode, localization accuracy, etc.) as symbolic properties of the robot object allows us to keep track of the current operation mode of the robot in the symbolic domain. This information can then be used by the symbolic planning algorithm to autonomously transition between the different autonomy layers of the scalable autonomy system by sequencing the ATs accordingly. The described system enables us to seamlessly integrate traditional skill-centered systems into the object-centered domain.

Of special interest for a scalable autonomy system is the integration of direct teleoperation of the robot. We integrated three operation modes: discrete, open loop, and closed loop force-reflection teleoperation. For direct teleoperation, the operator specifies a target configuration or pose of the robotic system that is then autonomously reached by the robot. The specification of the target is done by parameterizing the underlying AT. The hybrid reasoning system plans the required robot movements before the command is executed in a safe manner. We evaluated the viability of such a system in the METERON SUPVIS Justin experiments. Open loop teleoperation requires an additional communication channel between the UI and the robot for transmitting a stream of commands. The command stream can be populated by different UI devices depending on the requirements of the selected teleoperation mode, e.g. a GUI slider can be used for rotating the robot to a target orientation or a joystick can be used to command a camera's pan/tilt unit. The underlying AT defines which class of input devices are supported for each teleoperation mode and delivers a parameter set for configuring how the command stream is generated in its response. As such, arbitrary input devices can be added to the system by just implementing a corresponding parameter handler. The actual mapping of the UI commands to robot movements is done on the robot side separating the UI and teleoperation controller development. Closed loop teleoperation adds a feedback channel to the open loop system. Although live video feeds may be sufficient for closing the loop for the crew in some scenarios, we extend the system to allow for force-feedback teleoperation. This can be especially beneficial when interacting with unknown environments or for preventing the operator from unintentionally damaging the robot or its environment. The configuration of the input devices, e.g. a force reflection joystick, or an exoskeleton, is done analogously to open loop teleoperation.

Context Specific Command Generation

A symbolic planning algorithm is used to determine all actions that are currently feasible for the robot. These actions depend on the current symbolic state of the environment and the capabilities of the robotic system. As the symbolic planning algorithm is able to plan AT sequences for reaching arbitrary symbolic goal states, the amount of generated commands can be extensive. Because of that we filter the generated commands in order to limit the cognitive load for the operator. Therefore a Mission Control utility is used by mission and task specialists that allows to define and update filters and manage context specific filter sets. An example of a task for such a filter would be the removing of physical object interaction commands when the mission of the operator is to navigate to a remote target location. Using this approach, the generated commands that are available to the operator are limited to a manageable amount.

4. Implementation

In order to realize a scalable autonomy UI, we extend the knowledge driven system described in [2] to support the teleoperation modes that are provided by the robot as described in Section 3. As the robot itself provides the different operation modes, e.g. autonomy or haptic feedback teleoperation, and makes them accessible in the object-centric domain using ATs, an effective mechanism for switching between the different modes is of special interest.

To switch between robot operation modes, the robot publishes and provides a list of possible command modes for the crew to enable. The underlying AT provides possible operation modes as parameter options from which the operator can select the desired mode. When then enabling command is issued by the operator, the selected mode is transmitted to the robot together with the chosen UI device and a user id, as depicted in Figure 3. The robot then creates a user session with a unique session ID in which the requested operation mode is active. In order for the UI to send the correct commands, the robot sends back a session id together with the configuration parameters of the desired UI device. The UI applies these parameters and starts publishing a stream of commands. By accompanying the commands with the session id, it is ensured that the correct device configuration is used. For closed loop teleoperation modes, the UI subscribes the stream of feedback data that is published by the robot. The session id is also used here for making sure the feedback is correctly configured. Using the session id for

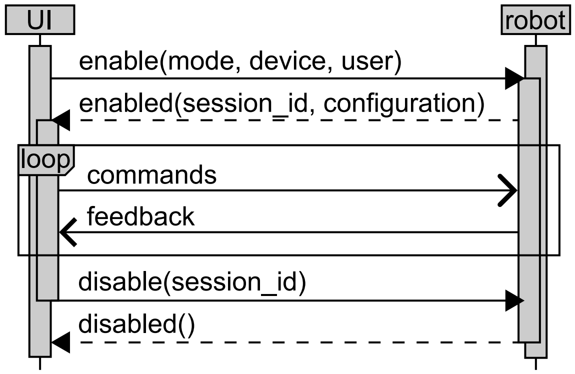


Figure 3. Sequence diagram for explicitly switching between robot operation modes for scalable autonomy.

safeguarding the status of the command and feedback data streams if of special importance in setups with high delays when synchronizing UI and robot is not trivial. By issuing the command for disabling the current operation mode, the operator releases the user session on the robot and brings it back into the default autonomy mode.

The described method of explicit switching between operation modes allows to directly integrate the scalable autonomy operation modes into the knowledge driven UI presented in [2], as the mode enabling and disabling commands are handled in the same way as the other object related commands. The only necessary extension to the system is the implementation of the parameter handlers for configuring the input devices to publish the correct commands.

A limitation of this concept is that switching between the different operation modes needs to be done manually and thus can be time consuming. This is especially true for systems with a high communication latency between the UI and robot as common in orbit-to-ground robot command. To address this, a seamless mode switching method has been implemented which drastically reduces the time required for mode switching.

The design goal for the seamless operation mode switching method is to reduce the time on mode switches by reducing the actual UI-to-robot communication. This is accomplished by pre-mapping the available operation modes to command the robot to the available UI devices, which is defined by an AT. The command is parameterized with all available devices of the UI and the id of the user, as depicted in Figure 4. Similar to the explicit mode switching, a user session is created by the robot. In contrast to the previous mode switching method, this session is not specific to one operation mode but a set of possible combinations of operation modes with different UI devices (e.g. joystick, force-reflection teleoperation, or supervisory command) is created. Each of these operation mode configurations consists of a session ID, the targeted UI device, and the device-specific configuration parameters. The generated operation modes set is then sent to the UI, where the operator can select any mode at any time. Selecting a mode applies the mode-specific configuration parameters to the UI device and initializes the commanding on the UI side without any communication to the robot required. The command stream published by the UI contains the session id of the selected operation mode allowing the robot to seamlessly execute the required mode transition without further time delay. The robots user session can be terminated by releasing the command of the robot.

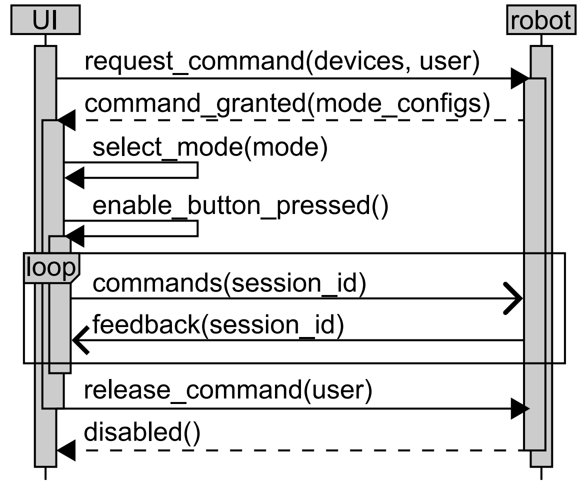


Figure 4. Sequence diagram for seamless switching between robot operation modes for scalable autonomy.

In order to improve the reliability of the system, we added an enable button that must be kept pressed while teleoperating the robot. There are some advantages of using the enable button:

1. The robot can always transition into its default autonomy state while the enable button is not pressed where supervisory command can be continued.
2. The operator always needs to used both hands when teleoperating the robot: one hand pressing the enable button while the other hand uses the current UI device. This is useful for avoiding unintended robot commanding and makes sure the operator is focused to the task.
3. For use in micro gravity, the enable button can be attached to a handle that the astronaut can hold onto during operation to prevent floating away.

The seamless switching method introduces an additional UI widget, which serves to

- provide all possible operation modes
- select a desired operation mode
- display the current operation mode

Although this feature may require slightly more familiarization time for the operators, it brings two key advantages. First is operator situational awareness of the current robot operation mode, which ensure safe and correct robot operation. Second is the near-instant operation mode switching, which can significantly reduce waiting time and operator work load.

Going up a level of operation mode switching, and expanded scalable autonomy, the UI design gives the operator to command similar tasks through different ways. Two examples are the look around and drive around functions. For looking around, the operator may choose to command the robot to point its head at a desired direction to be executed by the robot using the GUI's scroll function coupled with a cross-hair in camera view, or using the joystick to directly pan and tilt the camera view. For moving around the robot's environment, the operator is given an assortment of navigation possibilities in the GUI such as the use of a map, or selection of a desired target. Similar to the look around command, the operator can also use the joystick to traverse and rotate the robot's pose.

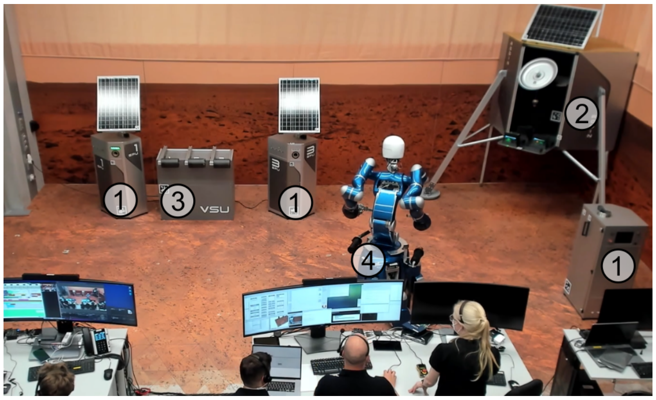


Figure 5. View of the SOLEX environment as used in the preliminary sessions of Surface Avatar including (1) Smart Payload Units, (2) Lander mockup, (3) Variable Stiffness Unit, and (4) Rollin' Justin robot

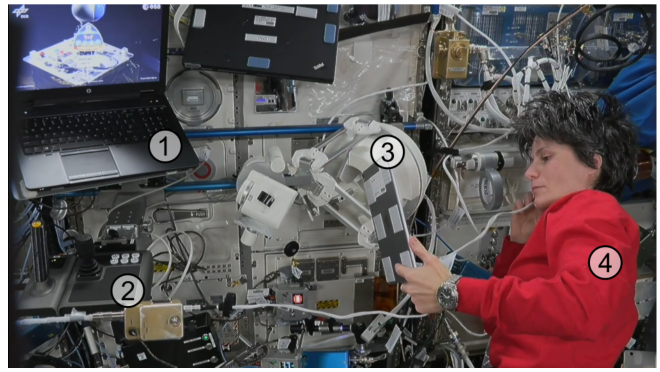


Figure 6. Surface Avatar Robot Command Terminal setup on board the ISS including (1) HP ZBook laptop computer running the Surface Avatar GUI, (2) custom open-loop joystick, (3) Force Dimension sigma.7 force-reflection device, and (4) ESA astronaut Samantha Cristoforetti setting up the system

5. SPACE-TO-GROUND EXPERIMENT

The Surface Avatar space telerobotics experiment investigates the use of a scalable autonomy HRI for commanding a team of heterogeneous surface robots from an orbiting spacecraft. The goal of the experiment is to demonstrate the operational readiness of such a system for future crewed missions to Moon and Mars. In order to obtain realistic assessments of the system in a micro gravity environment, we use the ISS as an analogue site for a future space vessel and set up a team of service, exploration, and scouting robots in an analogue surface environment on Earth. The series of three orbit-to-ground experiment sessions is led by DLR with partner ESA. Two preliminary experiment sessions, in 2022, are used to evaluate the on-orbit setup and test the communication link and scalable autonomy UI concepts. In the next two years, they will be followed by three prime sessions, which shall pair the on-orbit UI with an increasingly large, capable, and complex, robotic team.

Setup

For the initial evaluation in the preliminary experiment sessions of Surface Avatar, the *SOLar farm EXperimental space robotics validation (SOLEX)* environment is used that has been used in the METERON SUPVIS Justin experiments [17]. This facility is set up at the *Robotics and Mechatronics Center (RMC)* in DLR Oberpfaffenhofen, Germany, for realistic testing of needed capabilities of future service robots for planetary deployment as well as the usability of the utilized HRI [12]. An overview of the setup is depicted in Figure 5. The targets for the servicing tasks of the robots is a fleet of three *Smart Payload Units (SPUs)* which are equipped with an internal computer, a variety of environmental sensors, an LED panel, and battery packs for energy independence. A set of mechanical switches, a capacitive touchscreen, and a *Data Interface Probe (DIP)* can be used by the service robot to interface with the SPU. In order to simulate realistic infrastructure that is set up on a remote planetary surface, the SPUs are equipped with internal and external connector sockets which allow for scenario specific equipment of the units with solar panels, antennas, or computation units. A planetary lander mockup, used for component stowage for complex maintenance or infrastructure construction scenarios, completes the SOLEX setup.

In the preliminary sessions of Surface Avatar, only one robot is used instead of the heterogeneous robotic team that is planned for the actual experiment sessions. This allows us compare the tested system with the results of previous experiments, e.g. METERON SUPVIS Justin or ANALOG-1. We deployed DLR's dexterous humanoid service robot *Rollin' Justin* to SOLEX to simulate a future robotic coworker of the astronauts. The robot consists of two DLR LWR arms which are equipped with DLR Hand II endeffectors, an actuated torso with neck and head, and a wheeled platform [14]. All sensors, computers and power supply needed for the robotic operation are integrated into the system to allow for autonomous operation. Time-invariant whole-body control strategies allow the robot compliant and precise interaction with its surrounding [19].

The *Multi-Purpose Computer and Communication (MPCC)* software suite of ESA is used for establishing an IP connection between the HRI payload on board the Columbus module of the ISS and Rollin' Justin in the SOLEX setup on Earth. The MPCC connects the robot to the *Columbus-Control Centre (Col-CC)* at DLR Oberpfaffenhofen, Germany, which is in turn connected to the *Johnson Space Center (JSC)* in Houston, Texas, USA. JSC connects to the *Huntsville Operations Support Center (HOSC)* that operates antennas which provide a K_u-Band data link [20] to the geostationary *Tracking Data Relay Satellite System (TDRSS)* constellation [21], and finally to the ISS. For the Surface Avatar experiment sessions, the MPCC data link provides a bandwidth of 4 Mbit/s up/down with a communication delay of approximately 800 ms, which is sufficient for haptic telepresence as demonstrated in the METERON ANALOG-1 experiments.

The robot commanding is performed using the RCT, upmassed to the ISS for the METERON ANALOG-1 experiment in 2019 [22], which consists a HP ZBook laptop computer sourced from the ISS, a custom joystick, and a force-reflection haptic input device, as depicted in Figure 6. The custom joystick aggregates three components: a 3-DOF open-loop joystick for teleoperation, a set of mechanical buttons for selecting operation modes, and a mechanical enable button on top of a rigid handle that provides the astronaut with an anchor-point in micro gravity when teleoperating a robot. A stable body posture of the astronaut is of special interest when using the commercially available 7-DOF haptic input device Force Dimension sigma.7 for force-reflection teleoperation of a robot. The joystick and sigma.7 are connected to the station laptop where the teleoperation controllers translate the inputs

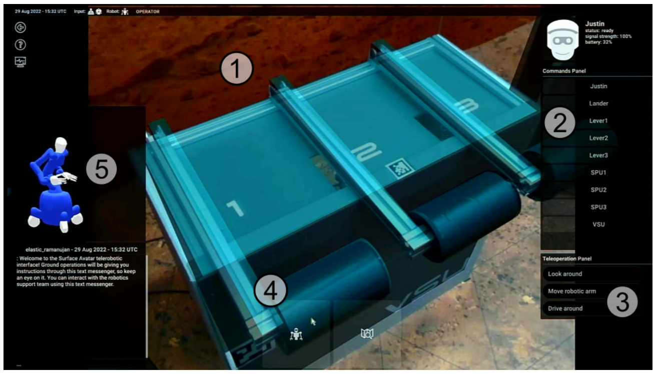


Figure 7. Graphical User Interface used in the preliminary sessions of Surface Avatar including (1) live video stream from the robots' camera, (2) list of available object-centered commands, (3) list of available teleoperation modes, (4) virtual object overlays, and (5) virtual robot viewer

into robot commands and the HRI GUI is displayed. The connection of the RCT to the robot is realized using MPCC via NASA's *Joint Station LAN (JSL)* on the ISS.

The display of information and selection of robot commands in the GUI is a new development which extends the supervised autonomy approach used in METERON SUPVIS Justin [2] to scalable autonomy for Surface Avatar. The main components, as depicted in Figure 7, are (1) the live video of the operated robots' camera in the center, (2) a list of available robot commands, and (3) a list of available teleoperation modes. By highlighting objects which were localized by the robot in the video stream, a common ground in the understanding of the environment is established between operator and robot(s) with a low cognitive load for the operator. By selecting an object highlight, the currently available commands for the specific object are displayed. For parameterizing selected commands, specialized parameterization widgets can be used as presented in our previous work [16]. The GUI is extended by a window showing a 3D rendering of the current configuration of the robot that can be used by the operator to get a better understanding of the current situation as the field of view of the cameras is limited.

Preliminary Sessions

Two preliminary ISS-to-ground experiment sessions of Surface Avatar were conducted in 2022 for evaluating the orbital setup and testing the communication link between the RCT on the ISS and Rollin' Justin in SOLEX. The first session focused on the overall setup validation with an HRI system as close as possible to the METERON SUPVIS Justin experiments while still extending it for scalable autonomy. The explicit operation mode switching was utilized for robot command together with object-centered supervisory command. In the second preliminary session, we integrated the seamless operation mode switching approach while keeping the rest of the HRI the same. The two experiment sessions were conducted by different astronauts on board the ISS in June and September 2022 which were both trained on the use of the HRI with explicit mode switching approach prior to their flight. A short checkout session prior to each experiment allowed the astronauts to familiarize with the HRI updates.

Results

Both Surface Avatar preliminary sessions demonstrated the operational readiness of the orbital setup and the newly implemented HRI system by executing three different experiment protocols each.

In the first experiment protocol, both astronauts commanded Rollin' Justin to survey its environment and search for anomalies and unexpected situations. The astronauts used different teleoperation modes for open loop command of the head of the robot to look around and the mobile platform for navigating in SOLEX. Supervisory command was used for autonomously navigating to target positions and taking photo snapshots of anomalies for further review by the ground control team on Earth.

To help us examine the advancement from supervised autonomy to scalable autonomy, we asked our ISS crew to command similar robotic tasks from METERON SUPVIS Justin in Surface Avatar, now with the full-complement of a multi-modal UI.

In the first preliminary session, the astronaut was asked to survey the environment, and conducted of SPU maintenance. For completing the protocol, Rollin' Justin was required to interact with the SPU in order to connect a probe for reading out telemetry data and use the mechanical switches for restarting the device. The astronaut decided to carry out most of the tasks using supervisory command and used teleoperation for aligning the camera.

For the second preliminary session, the astronaut was again asked to survey the environment. This was followed by an infrastructure setup protocol. In this protocol, the astronaut commanded Rollin' Justin to navigate between different assets of SOLEX, pick up an antenna component from the stowage of the lander mockup, and connect it to an SPU. The robot supported the astronaut by providing supervisory commands to execute the protocol tasks so that the astronaut used teleoperation only for looking around and navigation.

In both of these experiments, the crew was given the flexibility to command similar actions, such as looking around, and driving around, as task level commands using the GUI, or with direct joystick command. For looking around, we observed the ISS crew to favor joystick, instead of the GUI, to command of the pan-tilt head to change the view of the robot's camera.

For driving around, the results were more mixed. For the purpose of surveying the environment, the crew preferred to use the joystick to drive and change the pose of the robot. However, once a specific target destination becomes the goal of a robot traverse, the crew would almost exclusively command the robot through the GUI at task level to reach the intended location.

A correlation can be drawn from these preferences: For more exploratory tasks, and situations for gathering more information, the operator would tend toward a more direct (and immersive) fashion of commanding a highly complex, and capable robot. On the other hand, for known targets and actions, the operator would be inclined to delegate more execution to the robot to relief the human work load. These observations of commanding the robot with different modalities echoed our belief of providing the operator with the flexibility to command a robot in the most suitable manner to the task at hand.

With the introduction of force-reflection capability, we also conducted experiments using the sigma.7. In the first preliminary session, a protocol for evaluating the force-reflection haptic telepresence was conducted. The astronaut was asked to identify a stuck lever out of a set of different options. Rollin' Justin supported the astronaut in providing autonomous commands for approaching and grasping the different levers. The lifting of the levers and successful identification of the stuck unit was then done by the astronaut using the sigma.7 to command the arm of the robot.

For second preliminary session, we went a step further with a simulated failure of a probe connection to an SPU. The astronaut was then tasked with using the sigma.7 to teleoperate the arm of the robot to complete the probe connection and read out telemetry data. Not only did this serve as a force-reflection telepresence test, it also served as a successful test run of a teleoperation task where the crew must switch command modes (from task level to telepresence) to complete a task.

The preliminary sessions gave us the opportunity to validate the operation mode switching behavior in realistic on-orbit scenarios. Even though the explicit mode switching that was used in the first preliminary session worked as intended, we got the feedback from the astronaut that the switching is cumbersome and time consuming. We also observed that the waiting time which is caused by the time delay of orbit-to-ground communication risked distracting the astronaut during robot operation. Further more we noticed that the astronaut was not always aware that the currently chosen operation mode had to be disabled again before continuing with supervisory command. Even though this improved during the session, extending the GUI with a good visible operation mode indicator seems reasonable in order to improve the awareness of the astronaut. The seamless mode switching that was used in the second preliminary session already utilized a GUI element displaying the available operation modes and highlighting the current mode. Using this mode switching approach resulted in more and more successive operation mode switches than with the explicit mode switching approach. Also the astronaut feedback was not mentioning a problem with the mode switching anymore.

The successful completion of all experiment protocols was a validation for our approach. By combining supervisory command with telepresence, we reduced the workload for the astronaut and the overall operation time.

6. Conclusion and Outlook

This paper presented the extension of our knowledge driven approach for the use with scalable autonomy teleoperation. By integrating different operation modes, our UI enables the command of remote service robots, both as intelligent coworkers, and avatars from a single unifying console.

We evaluated our scalable autonomy system in the preliminary sessions of the Surface Avatar ISS-to-ground space telerobotics experiment. During the two sessions, two astronauts on board the ISS took command of our service robot Rollin' Justin on Earth to perform a variety of inspection, maintenance, and assembly tasks. In order to successfully execute the experiment protocols, the robot has been commanded in a mixture of supervisory, open-loop and closed-loop teleoperation using a multi-modal UI. Having the opportunity to compare performances the same robotic tasks performed in SUPVIS Justin with purely supervisory task commands, with the multi-modal approach in Surface Avatar, we are able to see the operating ISS crew's preference of different command modalities for different natures of robotic tasks. We also found that a seamless switching between operation modes is preferred to an explicit switching approach. Our observations from the ISS-to-Earth experiments so far gave us a first validation of knowledge driven scalable autonomy.

The preliminary sessions demonstrated the readiness of our scalable autonomy system for the upcoming Surface Avatar experiment sessions currently scheduled for 2023 and 2024. Surface Avatar investigates the feasibility of teleoperating a team of heterogeneous robots on a planetary surface from an orbiting space station with a scalable autonomy UI. We will extend the system described in this work to support commanding a team of robots for the upcoming ISS experiments, which will bring us yet another step closer to commanding a fleet of complex heterogeneous robots to perform large scale tasks on the lunar and Martian surface in future missions.

In the spirit to bringing space technology to terrestrial applications on Earth, the scalable autonomy system described this work will be transferred in the SMiLE2gether project. In this project, we will use a modified version of the HRI to command personal service robots in household settings in order to support people in need of care such as physically handicapped or senior citizens.

Acknowledgments

Realizing the Surface Avatar experiments would not have been possible without the support of the German Space Operations Center (GSOC), the Columbus Control Centre (Col-CC), and the European Astronaut Training Centre (EAC). We thank them for the support during experiment preparation, testing, and astronaut training.

This work is partly supported by the Bavarian Ministry of Economic Affairs, Regional Development and Energy, within the project "SMiLE2gether" (LABAY102).

References

[1] European Space Agency (ESA), "Terrae Novae 2030+ Strategy Roadmap," https://esamultimedia.esa.int/docs /HRE/Terrae_Novae_2030+strategy_roadmap.pdf, October 2022.

[2] P. Schmaus, D. Leidner, T. Krüger, R. Bayer, B. Pleintinger, A. Schiele, and N. Y. Lii, "Knowledge Driven Orbit-to-Ground Teleoperation of a Robot Coworker," *IEEE Robotics and Automation Letters*, vol. 5, no. 1, pp. 143–150, 2020.

[3] M. Panzirsch, A. Pereira, H. Singh, B. Weber, E. Ferreira, A. Gherghescu, L. Hann, E. den Exter, F. van der Hulst, L. Gerdes, L. Cencetti, K. Wormnes, J. Grenouilleau, W. Carey, R. Balachandran, T. Hulin, C. Ott, D. Leidner, A. Albu-Schäffer, N. Y. Lii, and T. Krüger, "Exploring planet geology through force-feedback telemanipulation from orbit," *Science Robotics*, vol. 7, no. 65, p. eabl6307, 2022.

[4] J. Artigas, R. Balachandran, C. Riecke, M. Stelzer, B. Weber, J.-H. Ryu, and A. Albu-Schaeffer, "KONTUR-2: Force-Feedback Teleoperation from the International Space Station," in *IEEE International Conference on Robotics and Automation (ICRA)*, 2016.

[5] M. Stelzer, B. M. Steinmetz, P. Birkenkampf, J. Vogel,

B. Brunner, and S. Kühne, "Software Architecture and Design of the Kontur-2 Mission," in *IEEE Aerospace Conference*, 2017, pp. 1–17.

[6] A. Schiele, "METERON - Validating Orbit-to-Ground Telerobotics Operations Technologies," in *11th Symposium on Advanced Space Technologies for Robotics and Automation (ASTRA)*, 2011.

[7] A. Schiele, M. Aiple, T. Krueger, F. van der Hulst, S. Kimmer, J. Smisek, and E. den Exter, "Haptics-1: Preliminary Results from the First Stiffness JND Identification Experiment in Space," in *Proc. of the International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2016, pp. 13–22.

[8] A. Schiele, T. Krüger, S. Kimmer, M. Aiple, J. Rebelo, J. Smisek, E. den Exter, E. Mattheson, A. Hernandez, and F. van der Hulst, "Haptics-2 - A System for Bilateral Control Experiments from Space to Ground via Geosynchronous Satellites," in *IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE, 2016.

[9] A. Schiele, "Towards the Interact Space Experiment: Controlling an Outdoor Robot on Earth's Surface from Space," in *Proc. of the 13th Symposium on Advanced Space Technologies for Robotics and Automation (ASTRA)*, 2015.

[10] M. Sarkarati, M. Merri, K. Nergaard, and P. Steele, "How to plug-in your rover into a space mission to moon or mars," in *Automation, Robotics and Applications (ICARA), 2015 6th International Conference on*. IEEE, 2015, pp. 318–324.

[11] M. Cardone, C. Laroque, M. Sarkarati, K. Nergaard, P. Steele, and S. Martin, "MOE: A System Infrastructure for Robotic Experiments," in *Space Operations: Contributions from the Global Community*. Springer, 2017, pp. 27–52.

[12] N. Y. Lii, A. Schiele, D. Leidner, P. Birkenkampf, R. Bayer, B. Pleintinger, A. Meissner, and B. Andreas, "Simulating an Extraterrestrial Environment for Robotic Space Exploration: the METERON SUPVIS-Justin Telerobotic Experiment and The Solex Proving Ground," in *13th Symposium on Advanced Space Technologies for Robotics and Automation*, Noordwijk, The Netherlands, 2015.

[13] N. Y. Lii, D. Leidner, P. Birkenkampf, B. Pleintinger, B. Bayer, and T. Krueger, "Toward Scalable Intuitive Telecommand of Robots for Space Deployment with METERON SUPVIS Justin," in *Symposium on Advanced Space Technologies for Robotics and Automation*, 2017.

[14] C. Borst, T. Wimbock, F. Schmidt, M. Fuchs, B. Brunner, F. Zacharias, P. R. Giordano, R. Konietschke, W. Sepp *et al.*, "Rollin'Justin - Mobile Platform with Variable Base," in *IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2009.

[15] D. S. Leidner, *Cognitive Reasoning for Compliant Robot Manipulation*. Springer, 2019.

[16] P. Schmaus, D. Leidner, T. Krüger, A. Schiele, B. Pleintinger, R. Bayer, and N. Y. Lii, "Preliminary Insights From the METERON SUPVIS Justin Space-Robotics Experiment," *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 3836–3843, 2018.

[17] R. Bayer, P. Schmaus, M. Pfau, B. Pleintinger, D. Leidner, F. Wappler, A. Maier, T. Krueger, and N. Y. Lii, "Deployment of the SOLEX Environment for Analog Space Telerobotics Validation," in *Proceedings of the 70th International Astronautical Congress (IAC)*. International Astronautical Federation, October 2019.

[18] A. S. Bauer, P. Schmaus, F. Stulp, and D. Leidner, "Probabilistic effect prediction through semantic augmentation and physical simulation," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, 2020, pp. 9278–9284.

[19] A. Dietrich, *Whole-Body Impedance Control of Wheeled Humanoid Robots*, ser. Springer Tracts in Advanced Robotics. Springer International Publishing, 2016.

[20] A. J. Cecil, R. L. Pitts, R. N. Sparks, T. W. Wickline, and D. A. Zoller, "Extending the International Space Station Life and Operability," in *AIAA SpaceOps Conference*, 2012.

[21] J. Teles, M. Samii, and C. Doll, "Overview of TDRSS," *Advances in Space Research*, vol. 16, no. 12, pp. 67–76, 1995.

[22] K. Wormnes, W. Carey, T. Krueger, L. Cencetti, E. Exter, S. Ennis, E. Ferreira, A. Fortunato, L. Gerdes, L. Hann, C. Lombardi, E. Luzzi, S. Martin, M. Massironi, S. Payler, A. Pereira, A. P. Rossi, R. Pozzobon, F. Sauro, and J. Grenouilleau, "ANALOG-1 ISS – The first part of an analogue mission to guide ESA's robotic moon exploration efforts," *Open Astronomy*, vol. 31, pp. 5–14, 01 2022.

BIOGRAPHY

Peter Schmaus *received his M.Sc. Degree in "Robotics, Cognition, Intelligence" from Technical University of Munich, Germany, in 2013. He joined the German Aerospace Center (DLR) Institute of Robotics and Mechatronics in 2011 where he was involved in the ISS-to-ground telerobotics projects Kontur-2, METERON SUPVIS Justin, and became Co-Investigator of the Surface Avatar experiment suite. His main interests lie in Shared Autonomy and effective Human-Robot Interaction.*

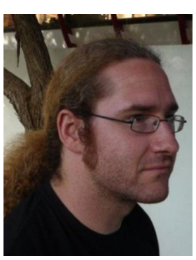
Adrian Bauer *received a Bachelor in Mechanical Engineering in 2012, a Bachelor in Cognitive Sciences in 2015, and a master in Robotics, Cognition, Intelligence from TU Munich in 2018. Currently he is pursuing a PhD in robotics at the German Aerospace Center. His interest is in enabling robotics to generate meaningful symbolic plans in presence of epistemic uncertainty.*

Nicolai Bechtel *received his Master of Science in Computational Engineering from the University of Applied Sciences Munich in 2018. Since then, he has been conducting research in the field of haptics and virtual reality as a research assistant at the Center for Robotics and Mechatronics of the German Aerospace Center (DLR) in Oberpfaffenhofen. His research focuses on haptics, multi-body-dynamic simulations, and development of virtual reality environments. He is currently working on topics such as Model-Based Teleoperation and GUI development involving Augmented Reality.*

Maximilian Denninger *received a Bachelor in Computer Science in 2015, and a master in Robotics, Cognition, Intelligence from TU Munich in 2017. He is currently finishing up his PhD in Computer Vision for robotics at the German Aerospace Center. His interest is in reconstructing and segmenting 3D scenes to better understand a robot's environment.*

Anne Köpken *received a Bachelor in Electrical Engineering from TU Munich in 2019, and a Master in Robotics, Cognition, Intelligence from TU Munich in 2021. She spent one semester at the JSK Laboratory at the University of Tokyo in 2019/20. Currently she is pursuing a PhD in robotics at the German Aerospace Center in Oberpfaffenhofen near Munich. She is interested in enabling robots to cope with unexpected situations and finding ways to prevent and recover from failures.*

Florian S. Lay *received his B.Sc. degree in Engineering Science in 2018, and his M.Sc. in "Robotics, Cognition, Intelligence" in 2020 both from the Technical University of Munich. Since 2020 he is pursuing a PhD in robotics at the German Aerospace Center (DLR). His interests range from symbol grounding and emergence for task and motion planning to multi-robot world representations.*



Florian Schmidt *received his Master of Science degree from the Munich University of Applied Sciences in 2007 (computer graphics and digital image processing). Since then he is with the German Aerospace Center - Institute of Robotics and Mechatronics. In his master thesis he developed a planning system to solve the Rubik's Cube with the humanoid robot Justin. His research interests include task and motion planning, real-time capable software architectures and novel robot programming interfaces.*

Marco Sewtz *received his B.Eng. degree in electrical engineering at the University of Applied Sciences of Munich and his M.Sc. degree at the Technical University of Munich. He works at the Institute for Robotics and Mechatronics at the German Aerospace Center (DLR) as a researcher since 2018. His interests focuses on SLAM and multi-model perception of the environment. Before his current role, he worked as an electrical designer for high-performance processing modules for space hardware at Airbus Defence and Space.*

Aaron Pereira *is a researcher at the German Aerospace Centre (DLR) and a guest researcher at ESA's Human Robot Interaction Lab. His PhD from the TU Munich was in industrial human-robot co-working, and his current research focusses on haptics for dextrous manipulation and teleoperation of robots in space.*

Thomas Krüger *is head of the Human Robot Interaction Lab at ESA. Involved with ESA's haptic experiments since the beginning, Thomas headed the technology development for the ANALOG-1 experiments and is Co-Investigator on Surface Avatar. He received his PhD in Lab Automation from the University of Rostock and worked on wind turbines before joining ESA.*

Daniel Leidner *received his diploma degree in communications engineering in 2010, and his M.Sc. degree in information technology in 2011 with distinction from the Mannheim University of Applied Sciences, Mannheim, Germany. In 2017 he received the Ph.D. degree in artificial intelligence from the University of Bremen, Bremen, Germany. His dissertation was honored with the Georges Giralt PhD Award as well as the Helmholtz Doctoral Prize. He is currently leading the Rollin Justin Team and the Semantic Planning Group at the Institute of Robotics and Mechatronics, German Aerospace Center (DLR), Wessling, Germany. As Co-Investigator of the Surface Avatar experiments, he investigates artificial intelligence in the context of astronaut-robot collaboration.*

Neal Y. Lii *is the domain head of Space Robotic Assistance, and the co-founding head of the Modular Dexterous (Modex) Robotics Laboratory at the German Aerospace Center (DLR). Neal received his BS, MS, and PhD degrees from Purdue University, Stanford University, and University of Cambridge, respectively. He has served as the principal investigator of the ISS-to-Earth telerobotic experiments, Surface Avatar, and METERON SUPVIS Justin. Neal is primarily interested in the use of telerobotics in both space and terrestrial applications.*