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On Realizing Multi-Robot Command through Extending the Knowledge Driven Teleoperation Approach

Peter Schmaus*[a], Daniel Leidner[a], Thomas Krueger[b], Jessica Grenouilleau[b], Aaron Pereira[a], Adrian S. Bauer[a], Nicolai Bechtel[a], Samuel Bustamante Gomez[a], Anne Köpken[a], Florian Lay[a], Marco Sewtz[a], Nesrine Batti[a], Edmundo Ferreira[b], Emiel den Exter[b], Ralph Bayer[a], Benedikt Pleintinger[a], Roman Holderried[a], Pedro Pavelski[a], Neal Y. Lii[a]

[a] *Robotics Mechatronics Center (RMC), Institute of Robotics and Mechatronics, German Aerospace Center (DLR), Münchener Straße, 82234 Weßling, Germany, peter.schmaus@dlr.de*
[b] *European Space Agency (ESA), Keplerlaan 1, Noordwijk 2201 AZ, The Netherlands*
[*] Corresponding Author

Abstract

Future crewed planetary missions will strongly depend on the support of crew-assistance robots for setup and inspection of critical assets, such as return vehicles, before and after crew arrival. To efficiently accomplish a high variety of tasks, we envision the use of a heterogeneous team of robots to be commanded on various levels of autonomy. This work presents an intuitive and versatile command concept for such robot teams using a multi-modal Robot Command Terminal (RCT) on board a crewed vessel. We employ an object-centered prior knowledge management that stores the information on how to deal with objects around the robot. This includes knowledge on detecting, reasoning on, and interacting with the objects. The latter is organized in the form of Action Templates (ATs), which allow for hybrid planning of a task, i.e. reasoning on the symbolic and the geometric level to verify the feasibility and find a suitable parameterization of the involved actions. Furthermore, by also treating the robots as objects, robot-specific skillsets can easily be integrated by embedding the skills in ATs. A Multi-Robot World State Representation (MRWSR) is used to instantiate actual objects and their properties. The decentralized synchronization of the MRWSR of multiple robots supports task execution when communication between all participants cannot be guaranteed. To account for robot-specific perception properties, information is stored independently for each robot, and shared among all participants. This enables continuous robot- and command-specific decision on which information to use to accomplish a task. A Mission Control instance allows to tune the available command possibilities to account for specific users, robots, or scenarios. The operator uses an RCT to command robots based on the object-based knowledge representation, whereas the MRWSR serves as a robot-agnostic interface to the planetary assets. The selection of a robot to be commanded serves as top-level filter for the available commands. A second filter layer is applied by selecting an object instance. These filters reduce the multitude of available commands to an amount that is meaningful and handleable for the operator. Robot-specific direct teleoperation skills are accessible via their respective AT, and can be mapped dynamically to available input devices. Using AT-specific parameters provided by the robot for each input device allows a robot-agnostic usage, as well as different control modes e.g. velocity, model-mediated, or domain-based passivity control based on the current communication characteristics. The concept will be evaluated on board the ISS within the Surface Avatar experiments.

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

Acronyms/Abbreviations

AT - Action Template
DLR - German Aerospace Center
DOF - Degree Of Freedom
ESA - European Space Agency
ESTEC - European Space research & TEchnology Centre
GUI - Graphical User Interface
HRI - Human Robot Interface
ISS - International Space Station
MRWSR - Multi-Robot World State Representation
PDDL - Planning Domain Definition Language
RCT - Robot Command Terminal

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 explo-

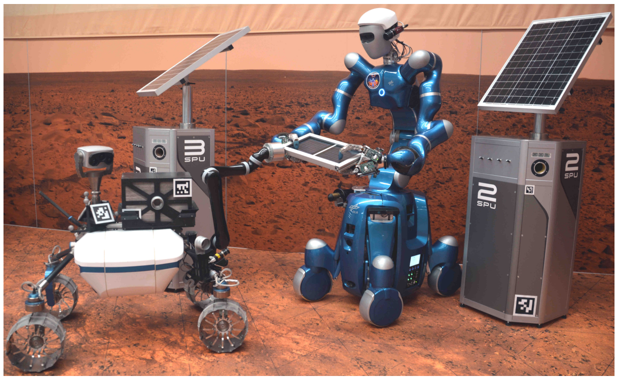

Fig. 1. A robotic team consisting of DLR's humanoid service robot Rollin' Justin and DLR's planetary exploration rover LRU in a simulated martian environment.

ration 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." The document further details the use of robots for accessing "the surface of the Moon (with the European Large Logistics Lander) and the long-term revisit of Mars". Therefore 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 limited in bandwidth or contain delay or jitter. Therefore the use of an intelligent robotic co-worker is envisioned which provides 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 (i) an extension of the object-based knowledge management allowing for the integration of traditional skill-based robotic systems, (ii) an approach for a shared knowledge base between robots, and (iii) a concept for a scalable autonomy user interface for robotic teams.

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 multi-robot commanding in Section 3. Section 4 gives an outlook on the upcoming steps for on orbit evaluation of the system and transfer of the findings to terrestrial applications.

2. Related work

The first work by DLR on crewed command of surface robots was done in 2015-2017 together with Roscosmos in the Kontur-2 project [4][5]. In a series of experiments a 2-Degree-Of-Freedom (DOF) force-feedback joystick in the Russian segment of the ISS has been used to telepresently command a robot located in Germany. The experiments used a direct station-to-ground communication link with low latency. Due to the direct S-Band communication, an experiment session was limited to a duration of 8-10 minutes while a direct communication between the ISS and the ground antennas could be established. 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 used 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 semiautonomous 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 tool, as done in the previous experiments, 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 the 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 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 expands the investigations on the use of force-feedback telepresence from a microgravity environment by upmassing 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. 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.

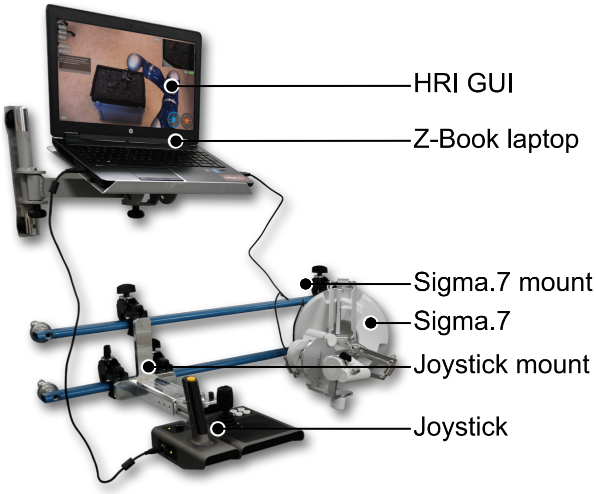

Fig. 2. Robot Command Terminal as upmassed to the ISS for orbit-to-ground robot command in the METERON ANALOG-1 experiment. The terminal consists of a laptop displaying the Graphical User Interface, a 3-Degree-of-Freedom Joystick, and a 7-Degree-of-Freedom haptic feedback device Sigma.7.

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. Furthermore we extend the scope of robot commanding to the management of a team of heterogeneous robots.

3. Teleoperation Concept

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 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. Furthermore, we outline the extensions needed to use the proposed system with a team of heterogeneous robots and present an approach for an intuitive scalable autonomy HRI.

3.1 Knowledge Management

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. Because 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.

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. 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 done 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, like 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 symbolic reasoning is used to determine all actions that are currently feasible for the robot. The resulting list of available actions can be used to command the robot in a supervisory way. As the number of commands can be quite extensive, context- and operator-specific filters are needed to realize an effective HRI.

The focus of the described object-centered knowledge management system lies on interactions with the objects in the environment of the robot. This systems works fine for all scenarios where the robot manipulates prior known objects but has limitations when it comes to unknown or unstructured environments. We therefore enabled the integration of robotic skills 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 resulting in a seamless integration of traditional skill-centered systems into the object-centered domain.

3.2 Knowledge Sharing

In our previous work, we have demonstrated that storing the information on the current state of the objects in the environment of the robot in a world state representation is a good approach for organizing the understanding of the robot for its environment. This component contains all instantiations of objects described in the knowledge base together with their symbolic and geometric state that is used by the hybrid reasoning system.

For the use with a robotic team, we propose modifications to the existing world state representation resulting in the updated Multi-Robot World State Representation (MRWSR). In order to account for robot-specific perception properties, each information on an object in the MRWSR is stored independently for each robot and is shared among all participants. This allows the robotic systems to implement individualized confidence and trust mechanisms that can be used to enhance the autonomy and make the task execution more robust. For example, a robot may choose to disregard the most recent localization result of an object if the observant robot is far away and the localization accuracy is not sufficient for a manipulation task. But the robot may choose to consider the same observation for navigation tasks where the localization precision requirements are lower. In addition to this, the MRWSR allows to merge object instance information of different participants in order to improve the information quality. This information fusion can be done through e.g. Extended Kalman or Particle Filters. The information sharing as proposed for the MRWSR allows robots with limited perceptive capabilities to profit from their robotic teammates observations and thus be more versatile to use.

For synchronizing the information within the MRWSR, we propose a decentralized system where each


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: 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. 3. Preliminary version of the Graphical User Interface of the Robot Command Terminal. The highlight on the object in the center visualizes the localization result of the robot. The widget on the top right is used to select a robot for commanding. Actual robot commands can be selected in the list on the right after choosing which object to manipulate. Teleoperation modes are available in the bottom right widget.

robot runs its own instance of the MRWSR. This allows the robots to use the system in environments where a stable communication between all participants cannot be guaranteed. A synchronization and propagation of information is done as soon as a communication link can be reestablished.

3.3 Knowledge Driven Teleoperation

We are using the MRWSR for robot-agnostic access to the robotic team. Because all information is synchronized among the systems, it doesn't matter to which MRWSR to connect. By this, the robotic team that can be commanded consists of all currently reachable robots and may vary as robots enter and/or leave the area of connectivity. A widget in the GUI lets the astronaut choose which robot to command.

The METERON SUPVIS Justin experiments showed that the knowledge of the robot can be used as a basis for an intuitive HRI. We demonstrated that a common ground for understanding the environment of the robot can be achieved by displaying a live video feed from the cameras of the robot that is augmented with information of the current world state of the robot. The video augmentation is done by highlighting the objects of the MRWSR using CAD renderings as illustrated in Figure 3. These highlights allow the astronaut to easily assess the quality of localization and sensor calibration by reviewing the match of the edges of virtual and actual object. As the autonomy of the robot is used for low-level safeguarding, the augmented video is sufficient for robot operation with low cognitive effort for the astronaut.

The augmented objects in the video stream can also be used to provide access to the available robot commands. Theses commands are determined by the respective robot using the symbolic reasoning as described in Section 3.1. As all of the available commands are originating from the object-centered knowledge management system, it is straight forward to bind them to the object instances they are manipulating. By selecting the highlight of an object the astronaut wants the robot to interact with in the GUI, the list of bounded commands is shown. This approach limits the information displayed to the astronaut to context-specific relevant information. By default, the available commands for the current robot object are shown to allow the astronauts direct access to skill-like commands, e.g. ”look around” or ”drive around”.

Some of the available commands may provide a set of parameters for tuning the effects of the command execution, e.g. the target for driving around. Therefore, the robot first evaluates possible parameter ranges. Afterwards, the astronauts selects the desired value using sliders, drop-down lists or text fields. By implementing command-specific parameterization views, the specification can be made more intuitive by e.g. showing an overlay of the currently specified target position on the video.

Telepresence modalities are integrated into the HRI concept by adding enabling and disabling commands for each teleoperation mode to the robot object. The different teleoperation modes, e.g. for camera or manipulator movement, are using a locking mechanism in the symbolic state of the robot to disable autonomous task execution while being active. This prevents the astronaut from issuing commands while teleoperating because the direct command might interfere with the autonomous command execution. After leaving the teleoperation mode, autonomous commands are available again.

The enabling command of each teleoperation mode returns a specification on how the teleoperation command channel should be configured. The configuration depends on the hardware to be teleoperated and which command mode to use, e.g. direct (velocity) command, model-mediated control, or domain-based passivity control. This information is used by the HRI to assign a virtual or physical input device to the current teleoperation mode. For the use with the RCT developed for METERON ANALOG-1 as described in Section 2, the 3-DOF joystick and the 7-DOF Sigma.7 are possible input devices.

Integrating the telepresence modes into the knowledge driven HRI approach provides a variety of benefits: The intelligence of the robot can be used to context-specifically tune teleoperation properties, e.g. limit the movement speed when being close to obstacles. Using command parameterization, the astronaut can be given

Fig. 4. Development setup of the Robot Command Terminal with a preliminary version of the User Interface as used for commanding Rollin' Justin in a simulated martian environment at DLR.

some freedom to optimize the underlying controllers for the current task, e.g. by changing the force scaling of haptic telepresence. Furthermore, the mission-specific customization of available commands done in the mission control component, allows to enable and/or disable teleoperation modes depending on the current situation and/or operator. Moreover, communication channel characteristics - e.g. bandwidth limitations, high delay, package loss, or jitter - can be used to customize allowed teleoperation modes or even restrict the use of modes with a relatively high demand on the communication link, e.g. haptic telepresence.

4. Future Work

The proposed knowledge driven teleoperation HRI has been integrated on a system similar to the RCT developed for METERON ANALOG-1 as depicted in Figure 4. We will evaluate the system with an extensive user study in order to optimize the system for the use with meaningful space-related inspection, maintenance, and sampling tasks. First, we will evaluate the system using only one robotic system to be commanded and then add more robotic teammates subsequently.

The system is then evaluated in DLR and ESA's Surface Avatar orbit-to-ground ISS experiments. During the experiment sessions, astronauts on board the ISS will use the RCT to command Rollin' Justin and a heterogeneous team of robots to execute a variety of tasks [18]. Preliminary ISS sessions in 2022 focus on the evaluation of the concept for the use with only Rollin' Justin as surface robot. The first actual Surface Avatar experiment session with a robotic team on ground is currently scheduled for the first half of 2023.

The findings of this work are transferred to terrestrial applications in the SMiLE2gether project. In this project, we plan to 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.

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References

[1] European Space Agency (ESA), "Terrae Novae 2030+ Strategy Roadmap." `https://esamultimedia.esa.int/docs/HRE/Terrae_Novae_2030+strategy_roadmap.pdf`. June 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*, pp. 1–17, 2017.

[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*, pp. 13–22, Springer, 2016.

[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*, pp. 318–324, IEEE, 2015.

[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*, pp. 27–52, Springer, 2017.

[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] N. Y. Lii, P. Schmaus, D. Leidner, T. Krüger, J. Grenouilleau, A. Pereira, A. Giuliano, A. S. Bauer, A. Köpken, F. Lay, M. Sewtz, N. Bechtel, S. Bustamante Gomez, P. Lehner, S. Bustamante Gomez, M. Denninger, W. Friedl, J. Butterfass, E. Ferreira, A. Gherghescu, T. Chupin, E. den Exter, L. Gerdes, M. Panzirsch, H. Singh, R. Balachandran, T. Hulin, T. Gumpert, A. Schmidt, D. Seidel, M. Hermann, M. Maier, R. Burger, F. Schmidt, B. Weber, R. Bayer, B. Pleintinger, R. Holderried, P. Pavelski, A. Wedler, S. von Dombrowski, H. Maurer, M. Görner, T. Wüsthoff, S. Bertone, T. Müller, G. Söllner, C. Ehrhardt, L. Brunetti, L. Holl, M. Bévan, R. Muehlbauer, G. Visentin, and A. Albu-Schäffer, "Introduction to Surface Avatar: the First Heterogeneous Robotic Team to be Commanded with Scalable Autonomy from the ISS," in *Proceedings of the 73rd International Astronautical Congress (IAC)*, International Astronautical Federation, September 2022.