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The Robot as an Avatar or Co-worker? An Investigation of the Different Teleoperation Modalities through the KONTUR-2 and METERON SUPVIS Justin Space Telerobotic Missions

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Abstract

The continuing advancement in telerobotics is garnering increasing interest for space applications. Telerobotics enables the operator to interact with distant and harsh environments not reachable by most humans today. Depending on the suitability to the task, robots may be employed as an avatar (e.g. physical extension of the user), or a co-worker to be supervised by the operator. This paper examines these different concepts through the lens of two space telerobotic missions: KONTUR-2, and METERON SUPVIS Justin. As a joint mission of German Aerospace Center (DLR) and Roscosmos, KONTUR-2 aims to study the effectiveness of force-feedback telepresence. A two degrees-of-freedom force reflection joystick was deployed to the International Space Station (ISS) to allow the astronauts to command, among others, DLR's humanoid robot Space Justin, to perform different dexterous tasks including grasping of objects, and haptically interacting with a person on Earth. Commanding the robot through this form of telepresence, the operator in orbit can feel the surrounding as experienced by the robot on Earth. This capability allows future scientists to perform extraterrestrial exploration by seeing and touching through the body of the robot. METERON SUPVIS Justin, on the other hand, aims to study the use of the robot as a co-worker. Developed by DLR and ESA, the astronauts on board the ISS are provided with a tablet computer to command Rollin' Justin, a robot similar to the one utilized in KONTUR-2. Using task level command through an intuitive tablet computer user interface together with the robot's reasoning ability, a collaboration is formed between the human supervisor and robotic co-worker to carry out tasks in the robot's surrounding. The supervised autonomy based teleoperation significantly relieves the operator's work load by delegating low-level control to the robot. It extends the astronaut's effective operating time, and gives the possibility for an astronaut to command a fleet of robots to perform larger tasks. This paper examines the performance of no fewer than nine astronauts and cosmonauts on board the ISS teleoperating robots on Earth over four years (2015-2018). The aim is to investigate the suitability of different telerobotics modalities for different tasks in the planetary surface environments. Criteria such as teleoperation range, robot capability (e.g. local intelligence, dexterity), task complexity, and interaction with the environment shall be discussed. We also consider the future of telerobotic systems that may fuse these command modalities to give the astronaut a full spectrum of possibilities for intuitive and effective robot command.

Keywords: Space robotics, Telepresence, Robot avatar, Robot coworker, Telerobotics, Command modalities.

1. Introduction

As the human race continues the exploration into far reaches of space, we are faced with increasingly hazardous environments for the astronaut. One way to alleviate this challenge is through the deployment of robots to assist the crew. The robot’s intelligence and adaptability to new tasks sets it apart from other active and passive tools available to the astronaut.

However, the astronaut remains the most important and commanding member of the human-robot team in space. Telerobotic solutions enables robots to be commanded by the astronaut through different modalities, as avatars or as coworkers in more dangerous environments. We envision the human crew in orbit around a celestial body to command robots on the surface. This would keep the astronauts in relative safety, yet reduce the communication delay as compared to that between the robots and human operators on earth. With advancements in user interface (UI) and robot capabilities, the robots should become increasingly useful tools for the astronauts, becoming either an extension of their physical presence on the surface, or work load-sharing coworkers for large-scale missions.

The key to effectively utilize these robots', often complex, functionality, lies in effective and suitable user interfaces. More specifically, they should provide the most relevant feedback to the astronaut for the task at hand, in an easily understandable/digestible fashion, both physically and mentally.

In this paper, we investigate the effectiveness and suitability of command modalities through the lens of two recently completed space telerobtics experiments: KONTUR-2 [1] and METERON SUPVIS Justin [2].

KONTUR-2 examines the command of robots as avatars through the employment of haptic feedback. On the other hand, with the command concept of supervised autonomy, SUPVIS Justin utilizes the robot's reasoning capability and local intelligence to be commanded via intuitive task level command through a tablet PC.

Both missions utilize the International Space Station (ISS) as the orbiting spacecraft, from where the astronaut and cosmonaut crew can command robots on Earth. In other words, the Earth serves as the celestial body to be explored in our scenarios.

In addition, these two missions utilize the same type of DLR dexterous humanoid robot, which provides a rare opportunity to examine the performance of different command modalities, and different task objectives using the same robot design, thus providing a more accurate comparison of the telerobotic command concepts.

Our aim, ultimately, is to provide the astronaut crew in orbit with a system to effectively and easily command robots on the surface of the celestial body as illustrated in Fig. 1.

By examining the astronauts' and cosmonauts' interaction with the robotic assets, as well as their feedback after the experiments, we hope to distill a path forward to assemble human-robot teams to realize extended space exploration and large-scale space habitat and colony building in the future.

This paper is organized as follows: Section 2 provides the background of space robotics, particularly telerobotics that precede KONTUR-2 and METERON SUPVIS Justin. Sections 3 and 4 give overviews of KONTUR2 and SUPVIS Justin, respectively. This is followed by the presentation of key results in Section 5, and discussion of our findings in Section 6. Finally, Sections 7 close out this paper with our conclusions.

2. Background

Robotics has played a significant role in space missions since the space race of the 20th century, and continues to be a key part of the roadmap for space exploration [3] [4]. Unlike the ISS, future space outposts, such as the proposed Deep Space Gateway, may be uncrewed for significant amounts of time [5]. (Tele)robotic solutions provide the possibility to continue experiments and other tasks, which have been carried out by human crew members until now.

The Lunokhod program of the Soviet Union successfully landed two remotely commanded robotic lunar rovers in the 1970s to explore the moon with various sensors as their payloads [6]. Robotics, and in particular, teleobotics, have continued to play an increasing role in space exploration ever since. Continuing down the line of lunar exploration, the Chinese National Space Administration (CNSA) launched the Yutu rover in 2013, which remained operational until July 2016 [7]. Starting in 2003, NASA has landed the Spirit, Opportunity, and Curiosity rovers [8] [9] on Mars, bringing invaluable scientific data from our neighboring planet. Due to the distance from the operator on Earth, there are significant communication time delays of several seconds to tens of minutes between the operator on Earth and the rover. In some earlier rover designs, this can limit the rover command to rigidly programmed tasks with long lead time, or potentially dangerous (to the rover) open loop commands.

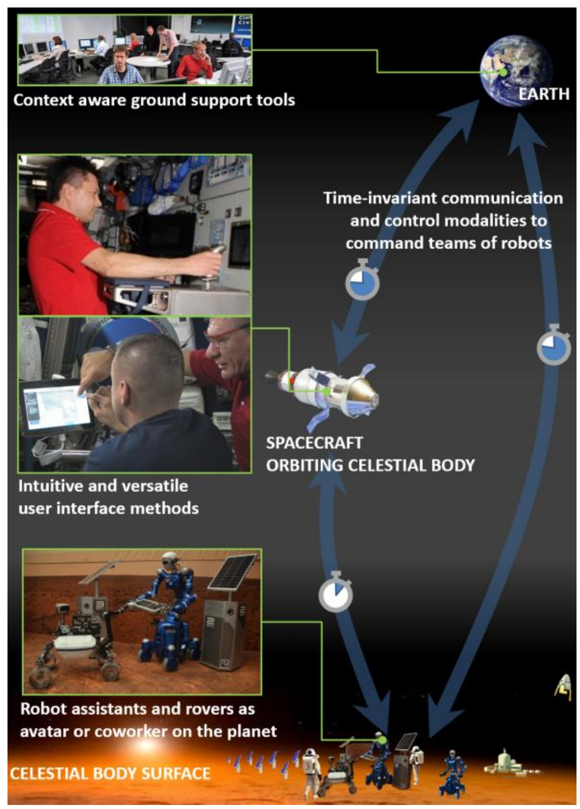

Fig. 1. Vision and key components for space telerobotics. We envision teams of robots on the planet or lunar surface, and the human crew in orbit, working together to enable more immersive exploration experience, and large-scale construction of habitat on site on the surface

Commanding a robot in close proximity would drastically reduce the communication time delay, and enable a significantly more interactive astronaut-robot relationship. This helps the researchers stay within their cognitive window, which is necessary for maintaining their awareness in the iterative scientific process. This is especially desirable for carrying out scientific work. [10].

Such telerobotic systems have been developed for different purpose over the last two to three decades. In the Robot Technology Experiment on Spacelab D2-Mission (ROTEX), predictive simulation and local autonomy of the robot to compensate for the signal delay were employed to teleoperate a robotic arm and end effector to capture a free-floating object in microgravity [11]. Different versions of the Canadarm, first deployed on the space shuttle, then the ISS, have been a vital part of the station. It is used to carry out a wide array of duties include capture, repair, docking, and inspection [12]. Different command modalities can be used by the astronaut on board the ISS, including individual joint rate, end effector control, and automatic trajectory command. Manual command can be done by Cartesian movement of an arbitrary command frame using two hand controllers (translation/ rotation).

To study the deployment of a haptically coupled telerobotic system in orbit, German Aerospace Center (DLR) and Roscosmos jointly carried out the Robotic Component Verification on the ISS (ROKVISS) experiments from 2005 to 2010. A 2-degree of freedom (DOF) robot was upmassed and installed outside the Russian Zvezda segment of the ISS. Each joint is equipped with torque sensors, which enabled it to sense forces when the robot's fingertip comes into contact with the environment. The robot is controlled via a 2-DOF force reflection joystick located at DLR's Oberpfaffenhofen site in Germany [13].

ROKVISS provided the first space telerobotic system with the possibility of haptic interaction in the space environment using the robot. This paved the way to operating a robot, with telepresence, as an immersive avatar for a human operator. The technology has since been utilized in the KONTUR-2 [1] experiment to enable orbit-to-surface telepresence, which is discussed in detail in the rest of this paper.

Another multi-agency orbit-to-ground telerobotic study is the Multi-purpose End-To-End Robotic Operation Network (METERON) experiment suite. Initiated by ESA with partners NASA, Roscomos, and DLR, METERON investigates technologies to enable telerobotics in space. With several completed and on-going experiments, METERON aims to study human-robot interactions, and operational issues [14] [15].

METERON SUPVIS Justin, which is also discussed in detail in this paper, is part of the METERON experiment suite.

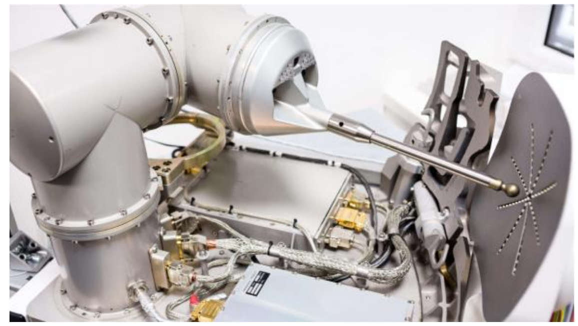

Fig. 2. The ROKVISS robot. A metal fingertip can be seen tracing through the LED grid on the specially designed task board to help study the effectiveness of telepresence in microgravity.

3. KONTUR-2: Teleoperating a robot as an avatar

Telepresence with haptic feedback allows the human operator to interact with distant environment through a robotic avatar. In 2015-2016, DLR, Roscosmos, the Russian State Scientific Center for Robotics and Technical Cybernetics (RTC), RSC Energia, and the Gagarin Research and Test Cosmonaut Training Center (GCTC) carried out the KONTUR-2 project to explore this form of robotic teleoperation in space. A space qualified 2-DOF force reflection joystick was upmassed to the ISS to command different dexterous robots on Earth [1].

3.1 On-surface assets

Two robotic assets at DLR Oberpfaffenhofen, Germany, were commanded from the ISS in KONTUR-2. One was the aforementioned ROKVISS robot, as shown in Fig. 2. With torque sensors implemented at each of its two active joints, the robot can sense the forces acting on it while it interacts with the environment with its metal fingertip [13]. A task board with various geometric profiles and LED guidance provides the environment to help study the command of the robot with telepresence.

Fig. 3. DLR humanoid robot space Justin.

To interact with more complex material and environments, DLR humanoid robot Space Justin (shown in Fig. 3) was also commanded from the ISS. Space Justin is equipped with two dexterous arms and hands, as well as a pan-tilt head and adjustable torso [16]. Similar to the ROKVISS robot, the arms and hands are also equipped with torque sensors. In addition, the head is equipped with cameras to survey the robot's environment.

3.2 Orbit-to-surface communication

The KONTUR-2 experiment utilized a point-to-point communication architecture. As shown in Fig. 4, an S-band antenna on board the ISS is used to establish data link with a ground station, located in Weilheim, Germany, 30 km from the location of the ground robotic assets.

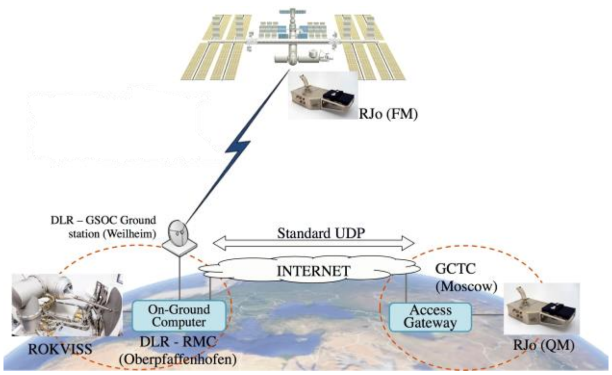

Fig. 4. The S-band space-to-ground communication architecture of KONTUR-2 [17].

The direct link between the ISS and the ground node provided low communication latencies of 20-30 msec roundtrip. However, the data link can only be established when the ISS orbit is over the horizon of the ground station. This resulted in the availability of about 10 minutes during a 90-minute ISS orbit. The space-to-ground link has an uplink and downlink bandwidth of 256 Kbit/sec and 4 Mbit/sec, respectively. For more information on the communication performance, please refer to Table. 1.

Table 1. Key orbit-to-ground communication specifications.

	KONTUR-2	SUPVIS Justin
Format	Point-to-point	Via TDRS
Frequency/Band	S-band	K_u band
Uplink	256 Kbit/sec	10 Mbit/sec max
Downlink	4 Mbit/sec	10 Mbit/sec max
Communication roundtrip	20-30 ms	~820 ms
Availability	10 minutes per 90-minute ISS orbit (during direct fly-over)	Continuous link theoretically possible

3.3 On-orbit asset: user interface design

To enable an immersive robot command experience, DLR developed and space qualified a force reflection joystick known as the *Raumfahrttauglicher Joystick* (RJo, meaning Space-qualified Joystick), as shown in Fig. 5. In addition to angular position sensing through hall sensors and encoders, each DOF is actuated with a brushless DC motor to provide force reflection to the user [1].

Fig. 5. The KONTUR-2 2-DOF force reflection joystick.

One of the major challenges for enabling haptic feedback telepresence is the treatment of package loss and jitter factors. This was realized through the implementation of passivity, and the Time Delay Power Network (TDPN) concept [17].

Voice and video streaming were implemented on the S-band link for verbal communication between the cosmonaut and the ground team, as well as to provide visual feedback from the robot to the astronaut, and the ISS activities to ground.

Fig. 6. KONTUR-2 joystick on board the ISS. Russian cosmonaut Oleg Kononenko can be seen operating the joystick. He is able to survey the environment on ground through the robot's camera. A voice link is also implemented for voice communication between the cosmonaut and the ground team [1].

3.4 Experiment design, tasks and objectives

Five cosmonauts participated in KONTUR-2. Three carried out ISS on-board studies using a local simulation, two other crew members were tasked with commanding the ROKVISS robot and Space Justin to perform a variety of dexterous tasks over 10-minute sessions throughout 2015 and 2016. The KONTUR-2 joystick can be seen on board the Russian Zwezda Module of the ISS in Fig. 6.

To examine the ability to interact with complex rigid geometries, the cosmonauts were tasked with commanding the ROKVISS robot to trace different physical geometric profiles. In addition, experiments were also conducted to follow the light patterns on a LED grid.

For interaction with deformable or stochastic environments, the ISS crew commanded space Justin to perform different dexterous tasks. This included the grasping and manipulation of an inflated beach ball, as well as performing hand shakes with humans on the ground using the robot as an avatar, as shown in Fig. 7.

Fig. 7. Human on Earth interacting with a cosmonaut in orbit via a robot avatar, DLR's Space Justin.

4. METERON SUPVIS Justin: Supervising robots as co-workers

Led by DLR and ESA, METERON SUPVIS Justin examines the concept of supervised autonomy as a form of commanding robots [2]. With this form of robotic teleoperation, the robot is treated as a co-worker, utilizing the robot's intelligence to plan and execute low level tasks. The astronaut serves as the supervisor to the robots, providing high level commands, and checking the status and progress of the commanded tasks.

In this mission, the human-robot team is tasked with handling of known objects, as would more likely be the case for working in a planetary surface habitat scenario, where upmassed assets would be maintained, repaired, or assembled. As a result, models of the known objects can be made available to the robot on the surface, easing its computational work load. Supervisory command concept of a different style has also been investigated with NASA's humanoid robot Robonaut, with the robot on board the ISS [18].

4.1 On-surface assets

Similar to KONTUR-2, SUPVIS Justin also utilized the DLR humanoid robot Justin. In addition to the upper body, Rollin' Justin [19] as deployed for SUPVIS Justin includes a mobile platform for navigation, and is able to carry an assortment of electronic and mechanical tools to carry out different tasks. An illustration detailing Rollin' Justin's features is shown in Fig. 8.

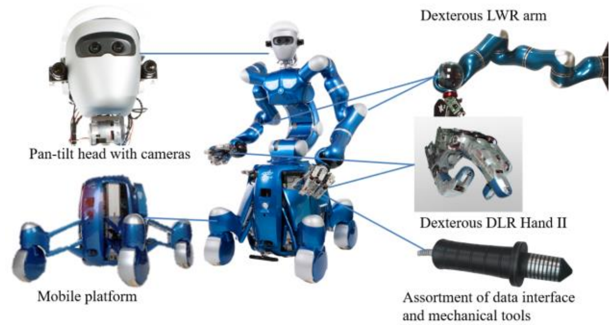

Fig. 8. DLR humanoid robot Rollin' Justin, as configured for METERON SUPVIS Justin.

To function autonomously in a complex environment in a safe fashion, the robot is implemented with enhanced whole-body control to enable compliant interaction with its environment [20]. To teleoperate Justin with supervised autonomy, the robot is implemented with reasoning and planning capability. This is realized with the concept of Action Templates. For each known object, an Action Template provides the properties and preconditions for each action that can be performed on the object, as well as the geometric procedure to carry out each action. By joining a series of Action Templates, the robot can plan and execute complex tasks, as commanded by the astronaut [21] [22].

Fig. 9. The Simulated SOLar Farm EXperimental (Solex) environment. An assortment of smart payload units (SPU) and lander can be seen to be serviced, repaired, and installed by the robot Rollin' Justin

To examine the human-robot team's ability to handle planetary surface tasks, the Simulated SOLar Farm EXperimental (Solex) environment was developed with a range of components to be expected in a future Martian habitat [23]. The Solex environment has been continuously updated to accommodate more complex robotic tasks throughout the life cycle of the METERON SUPVIS Justin experiments. The most recent setup includes solar panels mounted on smart payload units (SPU), antenna receivers, and a lander unit, as shown in Fig. 9.

4.2 Orbit-to-surface communication

The data communication between the ISS and ground is provided on the K_u-band via a team of Tracking and Data Relay Satellites (TDRS), as shown in Fig. 10. The TDRS relays data from the ISS to the ground station in the U.S.A., which is then linked to Europe via Internet. Comparing to the point-to-point S-band link of KONTUR-2, the large sum of gateways and distances introduces a larger time delay in the communication. On the other hand, as the ISS and ground can theoretically be linked continuously with minimal interruptions, we are able to carry out longer teleoperation sessions, lasting several hours. For more information on the communication performance, please refer to Table 1.

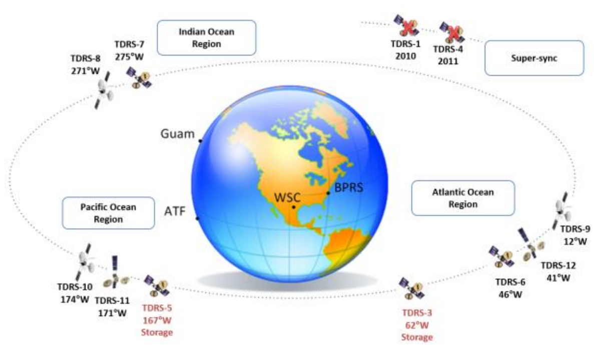

Fig. 10. Tracking and Data Relay Satellites (TDRS) that enables ISS-to-ground communication for METERON SUPVIS Justin [24].

4.3 On-orbit asset: user interface design

As robot commanding in future crewed spaceflights should be possible as a side task of the astronaut in parallel to other activities inside the spacecraft, the UI for METERON SUPVIS Justin has been implemented to run on a tablet computer. Even though the small screen size limits the displayed amount of information, the availability on board the ISS, the portability, and the intuitive usability of the device makes it a good choice for robot commanding [25]. Fig. 11 shows the tablet PC deployed in the Columbus Module on board the ISS, and being used to telecommand Rollin' Justin on Earth.

Fig. 11. The intuitive SUPVIS Justin tablet user interface being used by ESA astronaut Alexander Gerst.

Common ground between the astronaut and the robot is established using a high-resolution video feed of the camera of the robot allowing the operator to see through the eyes of the robot. The objects which are known to the robot are overlaid with their respective 3D-models in the video. The object-related robot commands, which are generated using the Action Templates, are provided to the astronaut using an intuitive point-and-click approach.

For the METERON SUPVIS Justin experiment, a HD video camera was deployed on board the ISS for the ground team to observe the astronaut's actions. In addition, voice communication is enabled on the ISS voice loop for verbal communication between the astronaut and the ground team.

Fig. 12. Example layout of the SUPVIS Justin tablet UI.

Therefore, the astronaut first selects the overlay of the object, the robot should manipulate. A list of all currently feasible robot command options - related to the selected object - is then presented to the astronaut. The selected option is autonomously executed by the robot while the astronaut can supervise the execution. This approach effectively simplifies the cognitive-challenging task of teleoperating an advanced robot. Complex robotic tasks can be easily and intuitively commanded by selecting the target object and choosing a command option. An example of the UI design is shown in Fig. 12.

Even though the generation of the list of currently feasible commands already respects the symbolic and geometric status of the robot, the resulting list could be quite comprehensive. Therefore, a Mission Control Center, located on Earth, can context-specifically prune the list to guide the astronaut towards task completion by applying a set of symbolic and geometric filters [26].

4.4 Experiment design, tasks and objectives

Between 2017 and 2018, three 4-hour ISS-to-ground supervised autonomy teleoperation sessions have been carried out by five astronauts. In part based on the performance and feedback of the commanding crew members, each successive session was updated with more complex tasks to examine the performance limit of this telerobotic architecture. Each of the three sessions focused on a key goal, as described below:

- Session 1: System usability validation. This session was designed to validate the supervised autonomy concept for space robotic teleoperation. The robot was commanded to perform data readout, system reboot, as well as survey and navigation tasks.
- Session 2: Dexterous device adjustment and manipulation. Increasing robotic task complexity, session 2 introduced dexterous manipulation tasks such as solar panel readjustment and dust wiping.
- Session 3: Execution of full assembly task. To examine the feasibility of full end-to-end installations, session 3 added tasks that included component retrieval and mechanical assembly.

5. Results

Telerobotic experiments of both KONTUR-2 and METERON SUPVIS Justin have been concluded by 2018.

Overall, KONTUR-2 demonstrated that a multi-DOF force reflection joystick can be paired with different robot formats and complexities. The joystick provided crisp force reflections, which yielded good immersive experience. This is thanks to a combination of short communication time delay (20-30 ms), and the effective time delay handling of the controller implemented for the telepresence system [17]. With longer communication time, the force reflection would tend toward less crisp contact, as observed in other space telepresence experiments [27].

The command of the ROKVISS robot demonstrated the system to be able to provide crisp haptic feedback and deliver precise command to trace a complex geometric profile, and follow a path directed by the implemented LED grid.

The command of Space Justin yielded encouraging results as it was successful in grasping and manipulating of the deformable elastic beach ball. The hand shake between cosmonaut and person on the ground via Space Justin as avatar was also successfully carried out. In addition, both cosmonaut and the person on the ground reported feeling the forces exerted by other party. This also marked the first time that a multi-DOF haptic input device is paired with a multi-DOF robot as an avatar to provide a dexterous sense of physical contact between human users. The experiment successfully demonstrated the task-specific mapping of an input device with only two DOF for the command of a seven DOF robotic arm.

In METERON SUPVIS Justin, all three ISS-to-ground supervised autonomy telerobotic sessions were successfully carried out. Six different robotic task scenarios, referred to as experiment protocols, were designed scenarios to be performed by the five participating ISS crew members. All protocol runs through each of the three ISS sessions were successfully completed, some under tight time constraints due to the strict ISS crew time scheduling. A questionnaire was completed by each crew member, along with the option to provide additional feedback.

Through all three sessions, the astronauts consistently rated the supervised autonomy based telerobotic system to be easy to use, and did not pose a significant mental work load. All participating astronauts rated the system and concept to be capable of enabling the crew member to manage a large team of multiple robots. This was a promising finding, pointing supervised autonomy as a viable way to deploy teams of robots to assist astronauts to carry out large scale tasks.

As all experiment protocols were successfully carried out, a comparison cannot be drawn based on success or failure of a given task. However, some observations can be drawn on the crew's acclimatization to commanding the robot. One was the relationship between prior training and task completion time. As expected, crew members with training on ground prior to their mission were noticeably faster in completing the same task. Interestingly, a crew member who had no prior knowledge of the system was recruited spontaneously to perform the protocol. With on-the-fly interactive training by another crew member, the recruited was able to briskly complete the task at hand. We also noted that as the astronauts become more familiar with the system, they grow faster in performing their given tasks. The increases in speed and confidence in the telerobotic system were clearly noticeable in all three sessions.

6. Discussion

KONTUR-2 and METERON SUPVIS Justin each demonstrated the viability of using the robot as a haptically coupled avatar, and an intelligent coworker.

Observing the ability of the KONTUR-2 system's ability to interact with complex objects and humans through the robot, it would be well suited in exploration tasks, and handling of unexpected situations, where the human intelligence and dexterity are utilized for the bulk of the command of the robot's action, down to a low level. Given a sufficiently coupled telepresence system, the robot becomes an extension of the astronaut, superimposing the human onto the robot into its environment.

However, this could be mentally and physically tiring, as remarked by some astronauts. As a result, such system could only be operated for a relatively short amount of time (20-30 minutes), before performance diminishes. For the KONTUR-2 experiment, this was not an issue, as each session provided only about 10 minutes of experiment time, but this issue should nonetheless be addressed for future system.

On the other hand, as the space community moves toward building outposts on the moon and Mars, large scale construction with known components would become increasingly relevant. Such work packages would require long work time and include repetitive tasks. In these scenarios with objects with known/partially known models, the astronaut should be able to depend on the robots' local intelligence to carry out work commanded at the task level, as proposed with the supervised autonomy concept of METERON SUPVIS Justin.

As robotic capabilities, teleoperation modalities and technologies continue to advance, the effectiveness of both styles of teleoperation should also continue to improve. We can foresee future space missions in which most mundane or better-defined tasks can be carried out with supervised autonomy. However, robots should always have the possibility to be utilized as avatars for handling and studying the unknown. Therefore, development of a comprehensive telerobotic system able to adjust the amount of human involvement as desired should be investigated.

An interesting additional observation is on the use of Space Justin and Rollin' Justin. By using similar humanoids for both missions, we also observed the versatility of this format for deployment in a telerobotic system. The level of dexterity, coupled with compliant behavior, and local intelligence, are all keys to an effective robot avatar and co-worker. The human familiarity with this form may also allow the user to immerse with the system more easily. Furthermore, for future surface habitats in which humans are expected to occupy, the humanoid form would also make sharing tasks easier, as the form factors of tools and components would fit both the human and the robot.

7. Conclusion

Through KONTUR-2 and METERON SUPVIS Justin, we have shown that robots can serve as useful tools and assistants for the astronaut. Particularly for the case of orbiting around a celestial body, the proximity between the robot on the surface and the astronaut in orbit provides sufficiently low communication delays for different forms of telerobotic solutions, while keeping the human crew in relative safety from the hazards of the space environment. Particularly for exploring unknown environments, or performing highly complex tasks with high degrees of uncertainties, the robot can be used as an avatar, which allows the human intelligence to take over in these situations and interact directly, and haptically with the task at hand. For large scale tasks and handling of known objects, robots can be used as co-workers with supervised autonomy. The ease of use and low mental work load would allow astronauts to comfortably manage large-scale work packages over long periods of time.

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