TOWARD SCALABLE INTUITIVE TELEOPERATION OF ROBOTS FOR SPACE DEPLOYMENT WITH THE METERON SUPVIS JUSTIN EXPERIMENT

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ABSTRACT

This paper presents the complete preparation and preliminary findings through user studies and astronaut training, for METERON SUPVIS Justin, a supervised autonomy space telerobotics experiment. Astronauts on board the International Space Station shall command a complex humanoid robot as a coworker to perform navigation, service, and repair tasks in a simulated Martian solar farm experimental environment on Earth through a tablet PC graphical user interface (GUI). The GUI is designed to be powerful, yet intuitive to use, with features such as dynamically update relevant information and robot commands, as well as intuitive user guidance functionality. The robot coworker, in turn, can utilize its local intelligence to reason and execute the commanded tasks. Preliminary findings from the user studies and astronaut training are presented and discussed. Finally, a series of multiple SUPVIS Justin experiment sessions between the ISS and the ground are planned to beginning during ISS expedition 52/53 in 2017, extending through to 2018.

Key words: Telerobotics; Telerobotics Technology; Intuitive User Interface; Supervised Autonomy; Robot Coworker; Robot Intelligence.

1. INTRODUCTION

Space robotic and telerobotic solutions have proven their success in extending our ability to explore farther into our solar system, exemplified by numerous Lunar, and Mars rovers designed and launched by several national and international space agencies. They have also enabled critical space construction and repair tasks, as shown by the Canadarm series [1] on board the space shuttle and the International Space Station (ISS).

As robots grow increasingly capable and consequently more complex, the ability to command these robots effectively to extract their full capability becomes more urgent. This is particular true with space telerobotics, where the user (often an astronaut) must command a complex robot to perform challenging mission critical tasks. This paper presents the work being carried out by the German Aerospace Center (DLR) and the European Space Agency (ESA) toward enabling a robust scalable telerobotics solution for space deployment.

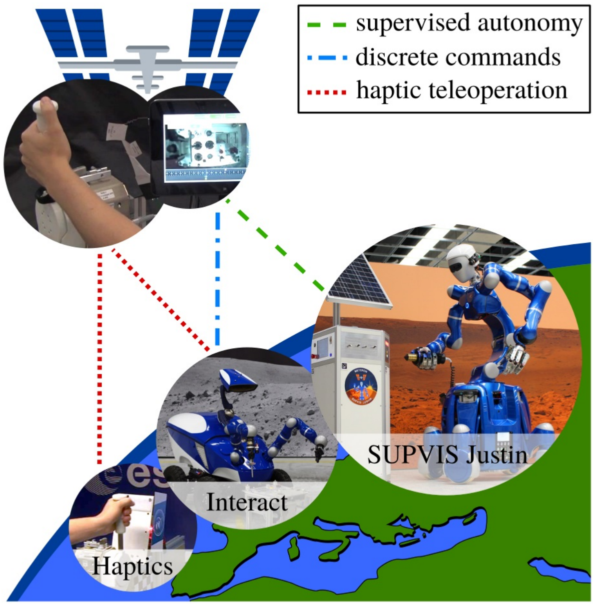

Figure 1. From telepresence to supervised autonomy: the different modes of telerobotics in METERON[2]. One of the goals of METERON is to explore different modalities of teleoperation. In the Haptics series, a one degree-of-freedom (DOF) joystick is used for telepresence with haptic force feedback. In the SUPVIS series, the robot is controlled through a notebook or tablet PC interface at the task level. A mixture of both modalities is also explored in the Interact experiment.

In this paper we present the current status of the planned SUPVIS Justin experiment to teleoperate a humanoid robot on Earth from the ISS. SUPVIS Justin is a part of the METERON (Multi-purpose End-To-End Robotic Operation Network), experiment suite initiated by ESA to study viable telerobotic solutions. Figure 1 shows the some different modalities of teleoperation being explored in the METERON experiment suite, from real-time, haptic telepresence with the likes of the Haptics series [3] [4] to task level command using supervisory control of the SUPVIS series [5] [6] [7] [8] . Hybrid teleoperation of mixing real-time haptic telepresence and task level commands to optimize the teleoperation effectiveness, as explored in the METERON Interact experiment [9], further offer great potential for high complexity and unexpected mission scenarios where low level human-in-the-loop may only be called upon sporadically.

For the SUPVIS Justin experiment, we are developing the robot supervisory control in the form of supervised autonomy. The robot is treated as a coworker for the astronaut on the planetary surface as opposed to a physical tool extension, which can be more effectively realized with telepresence. The robot is designed to have more local intelligence, with the ability to perform reasoning to plan and execute a given task [10]. The tablet PC user interface (UI) is incorporated with dynamically updated elements to provide the astronaut with the relevant information and command [11]. This UI would serve as the communication gateway between the astronaut and the robot, where the astronaut can command and receive task execution feedback from the robot.

In the SUPVIS Justin experiment, the astronaut is tasked with commanding a humanoid robot to perform a catalog of tasks including survey, navigation, and repairs in a simulated Martian solar farm environment designed and implemented at DLR as part of the ground segment. In particular, the hardware and software repairs and updates can be carried out with mechanical manipulation, and electrical and data interface by the robot. The aim is to explore the ability of teleoperating a humanoid robot through an intuitive GUI on a tablet PC using supervised autonomy. A high level concept illustration is shown in Figure 2. As identified by the International Space Exploration Coordination Group (ISECG), a teleopration modality gap is still present between full telepresence and autonomy in space robotics. The supervised autonomy concept is a versatile possibility to bridge this gap. Commands are given to the robot at the abstract, (sub)task package level for the robot to execute with its own algorithms. With this approach, time delays in communication can be effectively handled, as the robot would carry out the commanded task, and remain in a safe state throughout. The success (or failure) of the task execution are communicated to the astronaut at the end of each execution.

The remainder of this paper is organized into five sections. Section 2 gives an overview of past related work in space robotics with special attention paid to teleoperation. Section 3 details the development of the key components of SUPVIS Justin on the humanoid robot, GUI, and the experimental environment. These are integrated into the SUPVIS Justin experiment protocol, which is briefly described in Section 4. Section 5 describes the tests conducted so far with ground users as well as astronaut training sessions, and discusses our preliminary findings. Finally, Section 6 draws the relevant conclusions of this paper, looks toward the upcoming ISS to ground experiment sessions, and provides an outlook of SUPVIS Justin and beyond.

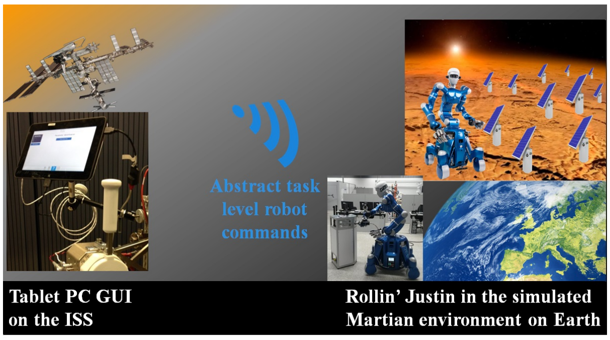

Figure 2. Illustration of the basic METERON SUPVIS Justin command concept[7]. The astronaut on-board the ISS is tasked with commanding a humanoid robot on the planetary surface with a tablet PC in a supervised autonomy fashion. The astronaut and the robot communicate on a abstract task level, which relies on the robot's own intelligence to carry out commanded task packages. The robot in turn communicates the available robot tasks dynamically to the astronaut on the tablet PC. The SUPVIS Justin concept should reduce the astronauts workload on commanding the robot, as it does not require the full attention of the user through out the entire operation. Task level robot cooperation is also robust against communication delays and jitters due to the distance and disturbances between the astronaut and the robot.

2. RELATED WORK

Telerobotics in space applications has seen great progress in the past few decades. As mentioned in Section 1, the Canadarm series has been deployed on the space shuttle, and continues to be a vital part of the ISS [1]. The first humanoid robot, Robonaut 2, developed by NASA and General Motors, has also been deployed on the ISS [12]. The humanoid form is of particular interest for telerobotics as it offers the most intuitive form factor as the avatar for the human operator, which can in turn reduce training time and improve teleoperation effectiveness.

Other telerobotic systems such as the ROKVISS experiment have also shown great promise in providing long distance (Earth to ISS) real-time haptic telepresence. In this five-year long experiment jointly conducted by DLR, Roscosmos, RTC, and RSC Energia, a 2-DOF robot with force-torque sensors at each joint was mounted on the outside of the Russian segment Zvesda module of the ISS, and controlled from ground using a 2-DOF force reflection joystick [13]. The same concept has been put in reverse with the on-going KONTUR-2 experiment, in which the joystick is deployed on board the ISS to control several dexterous robots on the ground. With a 4-channels architecture controller with guaranteed stability [14] through passivity and the Time Delay Power Network, hatpic telemanipulation have be successfully achieved in several experiment sessions [15].

These system the current state-of-the-art in real-time haptic force feedback telerobotics. They provide the user with the best immersion performance, having the robot acting as an extension of the user in distance. However, such systems require short time delays of well under 1 sec. communication round trip. This could prove to be unfeasible in more stringent communication conditions due to distance (for example, Earth-Moon communication round trip is around 3 sec.), or disturbances in the communication infrastructure that can cause undesirable jitter. In addition, full immersion telepresence requires a high mental, and sometimes physical, workload, which reduces the effective astronaut teleoperation time. Research has been underway in recent years to reduce the teleoperation workload by delegating some of the tasks to the robot. With the TaskMan concept, in which the user commands the robot through gestures, rather than joint level command, the robot is effectively commanded in task space. Furthermore, by delegating completed tasks for the robot to maintain, the user is relieved of significant workload, while achieving greatly improved telemanipulation performance[16]. With supervised autonomy, the task space command concept advances further forward in by using higher levels of autonomy of the robot with more advanced reasoning and task execution capabilities, in combination with an interactive UI [10]. The supervised autonomy concept also serves as the basis for SUPVIS Justin's mode of teleoperation. The UI can be implemented on a Tablet PC, or in a new form factor of the smartwatch. Given the ease of to carry, particularly of the smartwatch, the astronaut can have available a mode of communicating with the robot(s) at all times [17].

3. KEY TECHNOLOGY DEVELOPMENTS FOR SUPVIS JUSTIN

To realize the SUPVIS Justin experiments, several key technology components have to be in place and integrated, namely, the deployment of a humanoid robot capable of reasoning and abstract task execution, a powerful, yet intuitive, tablet GUI to command Justin, an experimental environment that simulates realistic planetary conditions, and is able to measure the robot task performance, and the ISS to ground Ku-band communication link.

3.1. Rollin' Justin and robot reasoning

Rollin' Justin, as shown in Figure 3, is DLR's high dexterity humanoid robot [18] to be deployed for SUPVIS Justin. It is equipped with two 7 DOF DLR Light Weight Robot (LWR) III [19] arms, and DLR II hands [20], a 1-DOF torso, 2-DOF head equipped with an assortment of camera options, and an 8-DOF mobile platform capable of navigating Justin through uneven terrain. Commanding such a complex robot can be cause a significant workload for the astronaut.

To ease this workload, the robot functions as coworker by taking over some of the cognitive workload with its own intelligence, utilizing hybrid reasoning [10] to help plan and execute the commanded task. As such, the astronaut is not required to provide every detail of the robot's trajectory to complete a simple motion. Instead, the command takes the simple intuitive form of task packages with easy-to-understand terms such as "shut down device", or "navigate to target". Furthermore, Justin can be updated with additional relevant functionality for the tasks at hand. This capability enables great potential for scalability of functionality. Finally, a context-aware mission control concept ensures that only the safe and relevant actions are provided to the astronaut [21]. They are sent to the tablet PC GUI to be described in the next section.

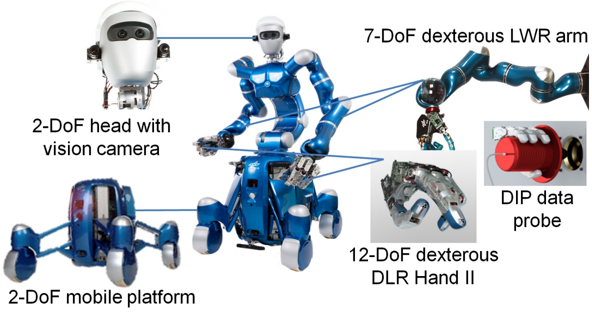

Figure 3. DLR humanoid robot Rollin' Justin [7]. With 51 total active DOF in the head, torso, arms, hands, and mobile platform [18], as well as a data interface probe (DIP), Rollin' Justin is a high capability, high complexity humanoid robot. It's local intelligence is capable or reasoning to help plan and execute a commanded task.

3.2. Designing a user interface for supervised autonomy in space

Given the limited space in the ISS, size of any item is at a premium. On the other hand, commanding complex robots to perform complex tasks, even with the aid of supervised autonomy, requires the exchange of a significant amount of information through the GUI. The key to a successful UI design for the ISS is to pack relevant information in a timely manner, while maintaining usability by not flooding the user with unnecessary information.

The SUPVIS Justin tablet PC application is developed based on the ESA Telerobotics lab's GUI design for the METERON Haptics and Interact experiments. Therefore, they share the same look and feel. For SUPVIS Justin, we further developed context specific and safe robot functions for the current task, such that only the relevant commands and information are displayed at all times [11]. Figure 4 gives an example of the GUI layout. The large amount of information made available can be seen in the figure and its caption.

Furthermore, the UI is designed with intuitive user guidance functionality. With the camera view in the UI, the operator sees through the robots vision which is augmented by the objects known to the robot. To interact with an object, the user simply has to click on the object in the camera view. A set of available and relevant robot commands is then displayed to the operator. This constitutes a vital step forward toward a powerful, yet in-

Figure 4. An example of the SUPVIS Justin GUI layout. Maximizing information while making it manageable by the user through dynamic status and available command updates. 1: live status of the connectivity to the robot on the ground. 2: progress of the protocol and the instructions for the current tasks. 3: main viewing area of the GUI. In this figure, the camera view is shown, which displays the view as seen by the robot's camera. This is the sole source of visual information of the location and object the astronaut can work with through the robot. An orange overlay of the object in view can be seen, which represents the robot's estimation of the location of the actual object. The user may click on the overlay to interact with the object with the robot. 4: view selector buttons to switch between different views such as map view or camera view. 5: dynamic robot command area. relevant and safe robot commands are populated here by mission control to ensure the astronaut not to command dangerous and faulty tasks. 6: buttons to access manual of the experiment or to log out of the application. 7: stop button to stop the experiment protocol at any time.

tuitive UI for telerobotics. By keeping the UI simple to use, it can be foreseen to scale up the robot commanding task of one GUI device to command a team of robots. In the space environment, where the number of astronaut is scarce, this can be a great advantage.

3.3. The Solex environment and SPU

The SOLar Farm EXperimental (Solex) environment, shown in Figure 5, is developed to provide a realistic Martian solar farm environment for the purpose of space robotics performance testing and validation[8]. It is designed with Martian scenery and terrain to give a close approximation of the Martian environment for the robot to navigate through. A fleet of Solar Panel Units (SPUs) are placed in the Solex environment for the robot to perform mechanical manipulation tasks on different forms of switches and mechanisms, as well as electronic data interface using the DIP. With mechanical and electronic interface available, the robot can perform a wide range of maintenance and repair tasks.

The SPU, as shown in Figure 6, uses modular design to enable quick and easy exchanges of components to facilitate a wide array of robot task experiments. Each SPU is equipped with a Smart Base to monitor and control each component. This enables the SPU to record the actions performed by the robot from the perspective of the manipulated object, which helps obtain a fuller picture and understanding of the conducted experiment, thus eliminating faulty interpretation of the task execution on the environment or the serviced and repaired device.

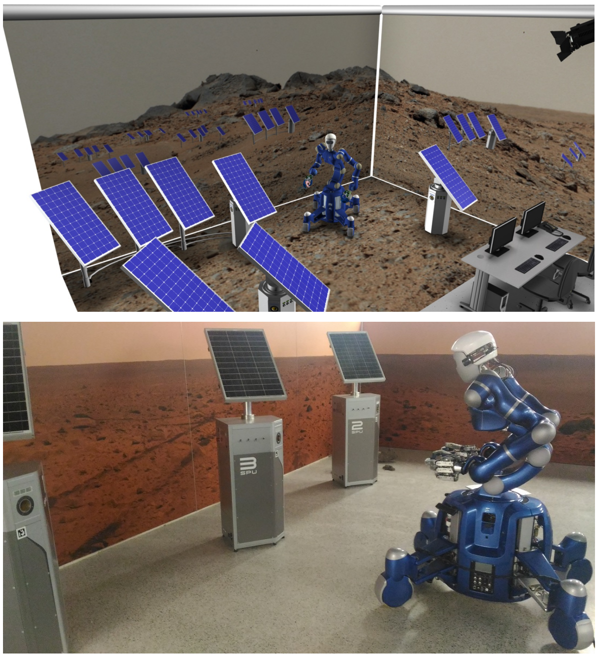

Figure 5. Solex concept and realization. Top: the Solex environment concept. It is envisioned to simulated a solar farm on the Martian surface. It is equipped with solar panel units (SPUs) to be serviced and maintained by the robot Rollin' Justin. Simulated Martian terrain are to be implemented. Life-size Martian surface photographs printed on large surfaces surround the Solex environment to give the astronaut a more realistic feel of commanding a robot on Mars. Bottom: the Solex environment under construction. In the photo shown, the Solex environment is near completion, with the SPUs in place, and Martian surface image surrounding the Solex environment. The simulated Martian terrain is not yet installed in this photo.

3.4. ISS-Earth communication

For the communication link between the tablet PC on the ISS and the robot on the ground, SUPVIS Justin employs the Multi Protocol Communication Controller (MPCC) over the Ku-band, which was also used in METERON Interact [9]. The data is relayed between a team of Tracking and Data Relay Satellites (TDRS) in orbit relays data between the Earth and the ISS, as shown in Figure 7. With full satellite coverage around the Earth, loss of signal (LOS) can be theoretically completely avoided through the ISS's entire orbit time. However, short LOS (about 5 minutes) do occur during most ISS orbits. Due to the multiple gateways the data must go through, the round

Figure 6. The Solar Panel Unit (SPU). Left: the front of the SPU. A variety of modular mechanical switches located on the Smart Base can be quickly exchanged to help examine the robot's manipulation performance. (Center) the view of the electronic components in the Smart Base of the SPU. An industrial PC (shown in the pulled-out drawer) enables it to record all actions, mechanical and electrical, as performed by the robot to help better evaluate the real performance of robot's actions. The smart base can be equipped with different electronics to support different accessories attached via a quick-change adapter on the top side of the Smart Base, such as the solar panel used for the SUPVIS Justin experiment. (Right) touch screen display on the Smart Base. A touch screen on the side of the Smart Base of the SPU allow the operator to command the robot to make easy changes to system settings and read information on the state of the SPU.

trip time observed between DLR Oberpfaffenhofen and the ISS is 800-850 msec, which is significantly higher than a direct ISS to ground link such as the S-band link used in the KONTUR-2 of 20-30 msec [15]. However, the S-band link suffers from much higher LOS, with nominal communication availability of around 10 minutes in orbits when the ISS flies by the ground station. Furthermore, as supervised autonomy does not depend on a real-time link, the high availability with low LOS makes it the more desirable communication architecture for SUPVIS Justin. A bandwidth of 1 Mbit up/down has been requested, although more bandwidth is available.

4. EXPERIMENT SCENARIO

With the key technologies discussed in the previous section in place, we are able to fully implement the SUPVIS Justin experiment. One of the main goals is to study telerobotics capability to serve in a planetary colony environment. This differs from exploration missions in that manufactured mechanical and electronic devices would be present in such a scenario. As such, we envision using the tablet PC GUI, as shown in Figure 4, on board the ISS to command Justin on the ground to perform navigation, service, and repair duties on devices in the environment, as shown in Figure 5. Our early findings are presented in the following section.

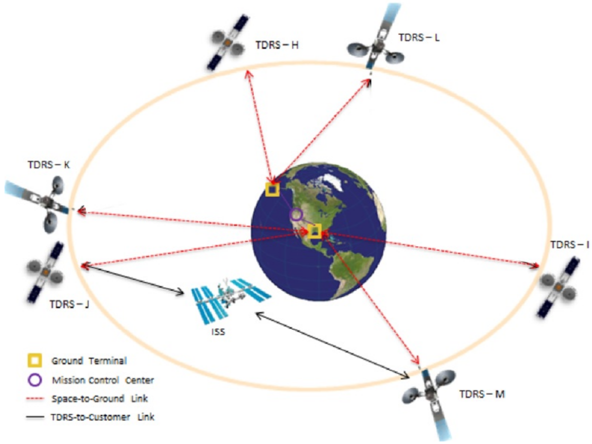

Figure 7. The Communication architecture between ISS and ground for SUPVIS Justin [22]. The team of TDRS satellites serves as the gateway between the ISS and ground. The Tablet PC in the Columbus Module through this array of satellites on the Ku-band using MPCC. A bandwidth of 1 Mbit up/down is assigned for the experiment, with communication round trip of about 800-850 msec.

5. PRELIMINARY FINDINGS

Over 150 test runs of on-ground user studies have been carried out to test the SUPVIS Justin experiment concept. Part of the test campaign has been conducted during the Automatica exhibition in Munich in 2016, as shown in Figure 8. During these protocol runs, the tablet PC was placed in an actual size ISS European segment Columbus module mockup 35 km away from the Solex environment. In order to further approach real ISS to ground conditions, an artificial time delay of 800 msec was injected into the communication. In addition, astronaut training and ground segment simulation have also been performed between DLR Oberpfaffenhofen and the European Astronaut Center (EAC) in Cologne, Germany.

Through the tests we conducted, we noticed a learning curve for the user regarding the supervised autonomy form of teleoperating a robot. This is particularly true with users who are not familiar with the robot's performance limits. We noted the users readjusting workload expectations between full robot autonomy ("I am not sure why am I needed here?"), and full user immersion e.g. telepresence with real time haptic and position feedback ("I have/want to control everything on the robot!"), until reaching the optimal level of human-robot collaboration as afforded by current technology availability. Regarding scalability, users have reflected that the system can be feasible for commanding multiple robots.

As technology improves, the level of abstraction can also be increased, yielding larger autonomous work packages. The robot can also provide more detailed and nuanced feedback to the astronaut to be more effective member of the human-robot-collaboration, albeit with human maintaining the lead role in the working relationship.

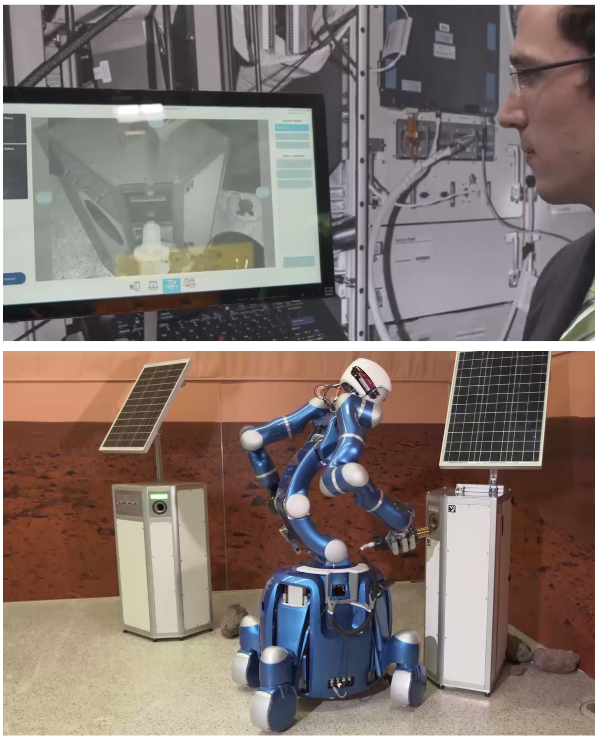

Figure 8. A preliminary test campaign in 2016. In this test campaign, the robot Justin is located 35 km away from the user, which provided the first simulation of true telecommand from a distance. Top: a user commanding Justin from an ISS Columbus Module mockup with the supervised autonomy tablet GUI. Bottom: Justin carrying out an SPU maintenance task in the Solex environment located at DLR Oberpfaffenhofen.

One interesting observation made during training and simulation sessions wars the users' realization the robot is intelligent, and it knows how to perform a task. This is a cross-over point for us to see the user recognizing the robot as a coworker, rather than just a complex tool. A consequence is that detailed descriptions of each task becomes redundant, and allows the protocol description to be short. This should be a welcomed feature to astronauts working with bulky documentations for each experiment. Equally importantly, it can greatly improve work efficiency on board the ISS.

We find that the supervised autonomy concept deployed in SUPVIS Justin shows great potential for scalability. By delegating (sub)task packages to the robot on-site, thus relieving the astronaut of every minute detail of each robot task, he/she can command a team of robots in future missions to perform larger, more complex tasks. Through the continuing advancements in robot physical (e.g. payload, dexterity) and processing (e.g. perception, reasoning), the level of task abstraction can be increased, which would allow each astronaut to be in charge of increasing numbers robots. This would make large scale planetary projects such as colonization, large scale exploration, and mining more feasible.

The final validation of METERON SUPVIS Justin is planned in the form of multiple successive ISS to ground experiments with iterative experiment design changes to help improve human-robot collaboration performance. The first experiment of SUPVIS Justin is slated for ISS Expedition 52/53 in 2017, and shall continue into 2018. Our aim is for the outcome of this experiment to serve as a benchmark for future space missions with telerobotics deployment.

6. CONCLUSION AND MISSION OUTLOOK

In this paper, we presented the complete preparation of METERON SUPVIS Justin toward ISS to ground experiment. The experiment design and the key technologies developed and incorporated were described and discussed. Through extensive preliminary testing we learned of the performance potential of supervised autonomy based telerobotics. In was particularly interesting to observe the user's learning curve in becoming familiar with the concept of using the robot as an interactive coworker, rather than a tool extension. It was also noted through the user study, that the current design lends itself to scaling up to commanding a team of robots to perform more complex tasks. Finally, the SUPVIS Justin mission is planned to start in ISS Expedition 52/53 in 2017 through to 2018.

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