SIMULATING AN EXTRATERRESTRIAL ENVIRONMENT FOR ROBOTIC SPACE EXPLORATION: THE METERON SUPVIS-JUSTIN TELEROBOTIC EXPERIMENT AND THE SOLEX PROVING GROUND

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ABSTRACT

This paper presents the on-going development for the Supvis-Justin experiment lead by DLR, together with ESA, planned for 2016. It is part of the ESA initiated Meteron telerobotics experiment suite aimed to study different forms of telerobotics solutions for space applications. Supvis-Justin studies the user interface design, and supervised autonomy aspects of telerobotics, as well as teleoperated tasks for a humanoid robot by teleoperating a dexterous robot on earth (located at DLR) from the International Space Station (ISS) with the use of a tablet PC. In addition to giving an overview of the Supvis-Justin experiment, this paper focuses on the development of a simulated extraterrestrial planetary environment to be constructed at DLR. The *SOL*ar Farm *EX*perimental Space Robotics Validation (Solex) environment aims to help collect relevant data to improve future space robotic mission designs. The Solex environment, which simulates a solar farm built on an extraterrestrial site, is intended to be equipped with modular components for the testing of visual, electrical, and mechanical robot-environment interaction. Furthermore, local intelligence built into the Solex environment, together with modular components enables flexible reconfiguration. This provides the possibility for a holistic investigative catalog of space robotic tasks in an extraterrestrial environment. Current progress of the development and testing for Supvis-Justin and Solex, as well as the steps going forward, are also presented.

Key words: Supervised Autonomy; Space Telerobotics; Humanoid Robots; Testing and Validation Environment; Intuitive GUI Design; Tablet PC Based Human-Robot Interface.

1. INTRODUCTION: EXPLORING SPACE WITH TELEROBOTICS

Multi-purpose End-To-End Robotic Operations Network (Meteron) is a suite of experiments initiated by the European Space Agency (ESA) with partners German Aerospace Center (DLR), National Aeronautics and Space Administration (NASA) of the USA, and the Russian Federal Space Agency (Roscosmos) [1]. Its main goal is to explore different space telerobotics concepts, using a variety of communication links with different latencies and bandwidth specifications.

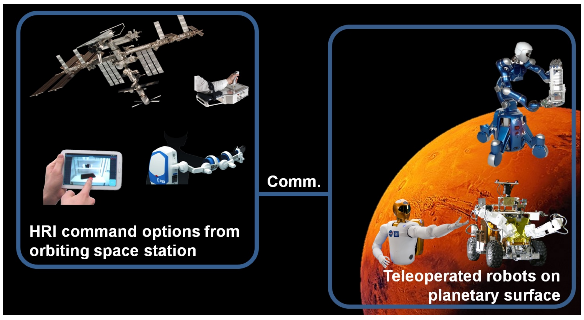

Figure 1. Space Telerobotics with the Meteron experiment suite. Target robots and rovers such as the NASA/GM Robonaut, DLR Rollin' Justin, and ESA Eurobot on earth can be commanded from different HMI devices including haptic input devices (e.g. force reflection joystick and exoskeleton), as well as notebook or tablet PCs. Communication links between the earth and the ISS of different latencies, jitter, and bandwidth will be utilized.

Teleoperating the robot for extraterrestrial exploration allows the operator to remain at a safe distance from the humanly unreachable, and dangerous environment. For the Meteron experiments, rovers and service robots would be deployed on earth, in different simulated space and planetary scenarios to perform a catalog of tasks. The target robot would be commanded from the International Space Station (ISS), through the use of different human-robot interface (HRI) options, ranging from laptop and tablet PCs, to force reflection joystick, and exoskeleton. Fig. 1 gives a concept overview of the Meteron experiment suite.

Two forms of telerobotic commands would be studied in the Meteron experiment suite. One is full haptic feedback telepresence, which requires low latency communication links coupled with haptic capable robots and HMI. Second is supervised autonomy, which uses high-level abstract commands to communicate complex tasks to the robot. This style of telerobotics depends on the local intelligence of the robot to carry out decision making and processing on site. Supervised autonomy can significantly reduce the workload, and improve task success rate of the human-robot team [2], and tolerate significantly higher communication latencies, where multi-second delays can be coped with [3].

DLR joins the Meteron project with over two decades of experience in space telerobotics missions, starting with the Rotex experiment to explore the possibilities of teleoperated robotic grasping of objects in micro-gravity [4]. With multi-second delays in the communication between the human operator on the ground, and robot on the space shuttle, it required sufficient local intelligence for the robot to carry out this highly dexterous task. In this respect, Rotex has served well as a starting point for supervised autonomy experiment we intend to carry out in Meteron. The ROKVISS experiment that followed, in turn, explored telepresence control of a robotic arm mounted on the outside of the Russian Zvezda module of the ISS. [5] A real-time communication link between the ground station at DLR allowed to full haptic feedback control of the robotic arm in space through a force reflection joystick on earth. Extending on the success of ROKVISS, the force reflection joystick has been redesigned for deployment on the ISS in the Kontur-2 project by DLR and Roscosmos. The upmass is planned for 2015.

DLR's participation in Meteron gives us an opportunity to contribute and build upon the knowledge gained from our previous space missions to the space robotics community. One theme that is currently being investigated in the field space telerobotics is the use humanoid robots for space applications. A humanoid robot is inherently more similar in form and kinematics to the human teleoperator. This feature makes the humanoid robot a uniquely suitable target for an immersing telepresence experience, as well supervised autonomy. NASA's Robonaut [6] is a prime example of a humanoid robot designed for space deployment. Similarly, DLR's extensive experience with humanoid robots [7] [8] has helped tremendously in our effort to design different experiment objectives to maximize a robot's relevant functionality in space teleoperation, whether with telepresence or supervised autonomy.

This paper presents the on-going design and development of the experimental architecture for the Supvis-Justin supervised autonomy [9] [3] experiment, to be ready for a mission currently slated for 2016. An overview is given on the space-to-ground experiment architecture, as well as the robotics technology implemented for Supvis-Justin.

A key to gathering meaningful robot performance data comes into focus in this paper, through the introduction

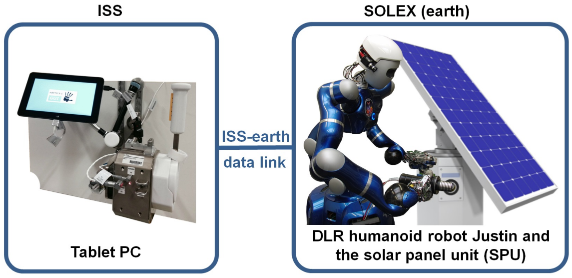

Figure 2. Meteron Supvis-Justin Concept. An astronaut, on the ISS in orbit, teleoperates the dexterous humanoid robot DLR Rollin' Justin on the planetary surface, using a tablet PC with abstract task level commands. The communication link is expected to be higher bandwidth (up to multi-Mbit/s), but with high latency of up to multi-second round trip).

of the *SOL*ar Farm *EX*perimental Space Robotics Validation (Solex) environment, which is being specifically designed to help elucidate different robots' capability to affect different objects and devices in the extraterrestrial setting. In order to systematically understand how well a robot can perform different tasks, a well-designed proving ground is required. Solex's main purpose is to serve this function.

The remaining of the paper is organized as follows: Sec. 2 provides an overview of experiment architecture and design of Supvis-Justin. Sec. 3 discusses the design concept of the Solex environment, as well as the robotic tasks it aims to help investigate. Sec. 4 gives a status report of the on-going Solex development. Finally, Sec. 5 provides Supvis-Justin's outlook going forward.

2. SUPVIS JUSTIN: SUPERVISED AUTONOMY WITH A HUMANOID ROBOT FROM SPACE

Meteron Supvis-Justin [3], shown in Fig. 2, is spearheaded by the Institute of Robotics and Mechatronics at DLR (DLR-RM), together with the ESA Telerobotics and

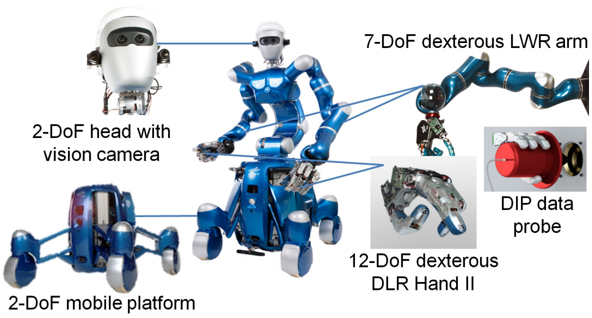

Figure 3. Dexterous mobile humanoid robot for planetary surface tasks: DLR's Rollin' Justin. The highly dexterous capability is shown here by its fully sensorized arms and hands, multiple vision system mounted in the head, a mobile platform capable of coping with uneven terrain, and overall high degrees of freedom.

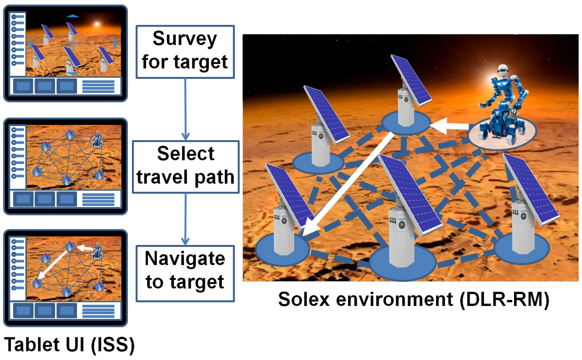

Figure 4. Supvis-Justin experiment protocol 1 and 3: Survey and navigation tasks. The astronaut commands Rollin' Justin to perform environment survey, travel path selection, and navigation to target in the Solex environment located on earth at DLR. Snapshots of objects and surroundings of interest can be taken with Justin's head-mounted camera for further analysis [3].

Haptics Laboratory. It aims to study the task capability for a dexterous humanoid robot on a planetary surface, as commanded from a space station (e.g. ISS) in orbit, using only a single tablet PC. A Dell Latitude 10 tablet PC running Windows 8 has been upmassed with ESA's ATV-5 in July 2014 to the ISS for the Meteron Haptics-1 experiment [10] [11]. A new GUI software will be uploaded to this tablet PC for Supvis-Justin.

Our intended robotic tasks include survey, navigation, inspection, and maintenance. These tasks will be performed on a solar farm located on a simulated extraterrestrial planet surface. Using a communication link between the ISS and the earth, with delays of up to 10 seconds, real-time telepresence would not be possible. Instead, in Supvis-Justin, abstract task-level commands are locally processed and executed by the robot. The robot works together with the tablet PC operator on the ISS in the fashion of a co-worker, rather than a remote electromechanical extension of the astronaut. Furthermore, previous studies have shown that by delegating to the robot through task-space commands, the operator's workload is significantly reduced [2].

An intuitive user interface (UI) is designed to ensure a space mission compliant software that can help the astronaut to communicate and delegate complex tasks to the robot on the planetary surface [12]. As the robot in the Supvis-Justin experiment is teleoperated by humans, the familiarity of the human operator with a humanoid robot's kinematic form may help the operator adapt, immerse, or work together with it. Supvis-Justin hopes to understand a humanoid robot's capability in a space scenario, DLRs dexterous humanoid robot, Rollin Justin, will be utilized to carry out the experiment. Equipped with a head with stereo vision capability, two dexterous arms and hands, mounted on a mobile platform, totaling 51 degrees of freedom (43 in the upper body, and eight in the mobile platform) [7], Rollin' Justin is suited for a wide variety of tasks that a robot may face in an extraterrestrial environment. Rollin' Justin is shown in Fig. 3.

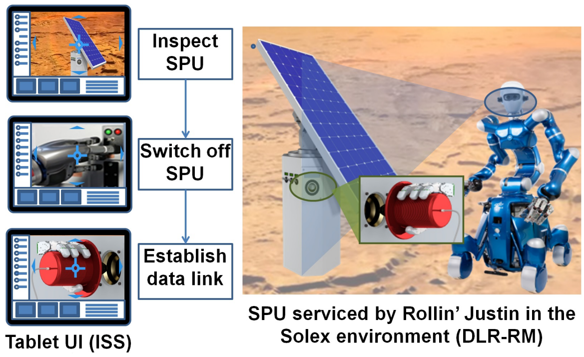

Figure 5. Supvis-Justin Protocol 2: SPU inspection and maintenance tasks. Once the robot reaches a target destination such as a defective SPU, the tablet UI guides the astronaut to command the robot, by visualizing the current state of the robot and the progress of the protocol. Different tasks such as shut down, reboot, and SPU data collection, for SPU system diagnostics can be performed [3].

Supvis-Justin includes three experimental protocols to examine different aspects of supervised autonomy in space telerobotics, including the UI's usability and effectiveness, as well as a robot's ability to carry out different tasks in extraterrestrial environments. The protocol description is visualized on demand as part of the UI to intuitively guide the astronaut without the need for a paper protocol [13], as shown in Fig. 4 and 5. The UI is designed to give the user a deterministic command sequence options, such that the astronaut would always be a known state while teleoperating the robot.

Experiment protocols 1 and 3 aim to study the ability of a mobile robot to survey and navigate in the environment it works in. Utilizing its head mounted visual sensors, the robot can survey the surrounding environment, and record any object or event of interest. The robot would then be commanded to navigate around the terrain to reach a target destination, using a route segment sequence selected by the astronaut on the tablet UI. As the scenario for Supvis-Justin is robot maintenance of a solar farm, the target destination would be a defective Solar Panel Unit (SPU) (discussed in more detail in Sec. 3). Should a travel plan fail, the failure would be reported to the operating astronaut, and a new course of action can be taken. This may include the planning of a new route, or recording images of the location where the travel failure occurred, as unknown obstacles may be in a particular route segment, which would require further attention. A concept illustration of Protocols 1 and 3 are shown in Fig. 4.

Protocol 2 commences after the robot reaches a target defective SPU. An extraterrestrial solar farm should be remotely operated during normal conditions. The likely situation when a robot would be deployed to service a SPU should be only due to unforeseen defects or major maintenance. This would call for the robot to inspect the SPU, and establish a communication link, via a Data Interface Probe (discussed in more detail in Sec. 3) for

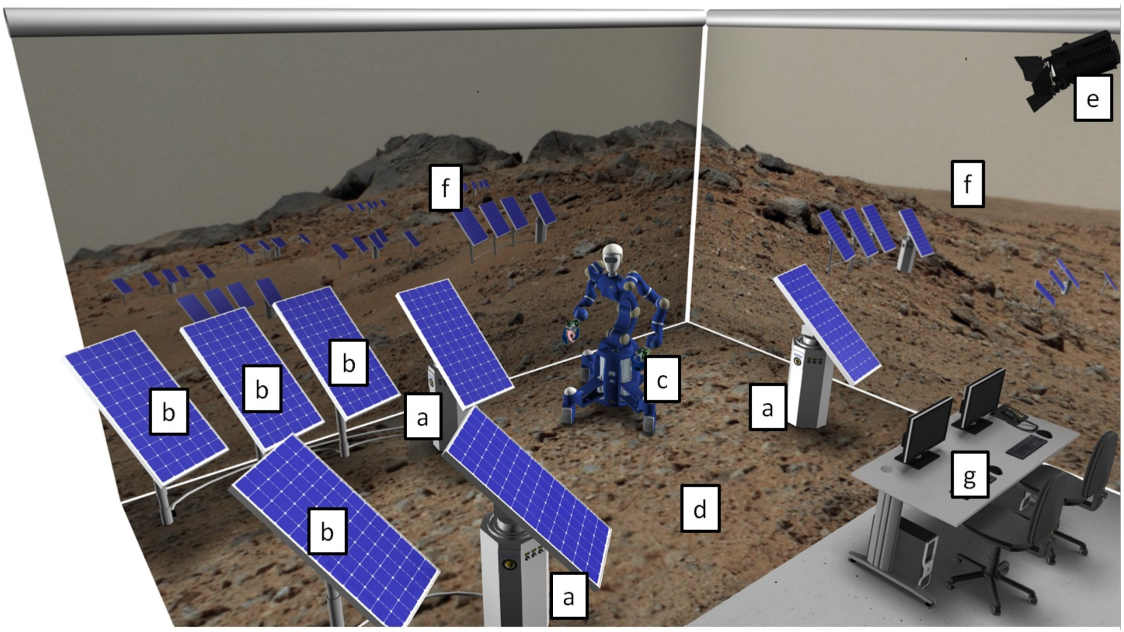

Figure 6. Concept illustration of the Solex environment. A fleet of SPUs with modular smart bases (a) and slave solar cells (b) are installed in the Solex environment to be serviced by DLR's humanoid mobile robot, Rollin' Justin (c). The simulated planetary surface (d) allows the testing of the robot's ability to navigate through uneven terrains. A simulated sun-light source (e) provides the necessary illumination for the solar cells. To round out the Solex environment, virtual planetary scenery canvas (f) surrounds the experimental setup to provide extra realism. The Solex control station (g), located next to the simulated planetary environment, monitors and controls the complete system. The control station would be camouflaged during the experiment for improved realism.

data transfer, software updates, and system check/reboot. The robot should also be able to manipulate appropriate switches and dials to get the SPU to a safe and desired state to commence further service and repair. A concept illustration of Protocols 2 is shown in Fig. 5.

3. SOLEX ROBOT TASK VALIDATION ENVIRONMENT CONCEPT

In order to provide a viable, flexible, and realistic validation proving ground for a high-dexterity mobile robot such as Rollin' Justin for the study of extraterrestrial tasks, the Solex environment is being developed and constructed at DLR in Oberpfaffenhofen.

An illustration of the Solex concept is shown in Fig. 6, which gives an overview of the key components integrated into the environment. For a sustainable space colony in the future, a self-sustaining power source is necessary. The Solex environment simulates a solar farm installed on a planetary surface to serve this purpose.

A fleet of modular Solar Panel Units (SPU) forms the basis of the Solex environment. Each SPU consists of a smart base capable of servicing multiple slave devices, as shown in Fig. 7. The smart base is equipped with an embedded PC to control and monitor the slave solar panels. A modular reconfigurable instrument panel on the SPU smart base is implemented with LED displays and switches to be surveilled and manipulated by the service robot for inspection, service, and maintenance tasks. In addition, a Data Probe Receptor (DPR) data port is designed to allow Justin to establish wired data link with the SPU to perform data extraction, reboot, and software/firmware updates. The Data Interface Probe (DIP), shown in Fig. 10 has been developed to be carried by Justin to plug into the DPR. With local intelligence and modular component design, we can quickly tailor the SPU to more experiment concepts in the future.

The Solex environment will be covered in a simulated Mars terrain to help study the humanoid robots ability to navigate between SPUs and base station in different terrain conditions with different gradients and surface textures. Artificial light sources are equipped for the Solex environment to provide the ability to simulate the light conditions on different planets for image processing studies. The Solex control station, located next to the simulated extraterrestrial environment, serves to monitor and command the entire system, while the robot is commanded from space.

One aspect of interest in the Solex environment development is the design of tools and devices to maximize a robots capability in the space environment. For example, careful design considerations for the DIP and DPR, in particular, have been catalogued, including appropriate device size with respect to the robot, geometry for robust probe mating, data pinout order for electrically safe docking, etc. Inspired by the command/service to lunar module docking mechanism for the NASA Apollo lunar

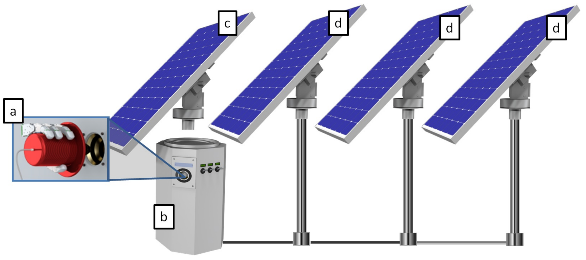

Figure 7. Solar Panel Unit (SPU) concept illustration. The DIP-DPR data interface (a), mounted on the SPU smart base, allows the servicing robot to perform data upload/download, software update, and maintenance functions. In addition, the modular SPU smart base (b) is equipped with an on-board PC for local intelligence, and modular panels with LED displays and mechanical switches to examine robot inspection and manipulation tasks. Each SPU can be installed with multiple solar cell slaves, either a top mounted slave solar panel (c), or auxiliary slave solar panel (d) via a side-mounted cable cluster.

landing missions [14]. The tapered shape of the DIP's tool tip, helps the Cartesian and object level impedance controller [15] of the robot to guide the insertion of the DIP into the DPR, coping with the robot's position estimation errors [16]. This enables the humanoid robot to manipulate a data probe to securely and repeatably establish data link with the SPU in the harsh environment and limited robot dexterity in supervised autonomy mode.

4. CURRENT DEVELOPMENT STATUS OF SUPVIS-JUSTIN AND THE SOLEX ENVIRONMENT

Supervised autonomy based teleoperation research has been underway for several years at DLR. Rollin' Justin is capable of performing a variety of dexterous tasks, as commanded by a tablet PC with an intuitive UI, as shown in Fig. 8. The graphical user interface (GUI) utilizes a ring menu, which updates according to the tasks and events that has occurred. This ensures that the operator would be clearly directed to the possible task/event option available in the current state for the object of interest [12]. The GUI will be completely redesigned in compliance with space mission standards developed for the Meteron Haptics-1 experiment [17]. The robot in turn utilizes hybrid reasoning with symbolic and geometric planning to perform the commanded task [18] [9].

For the design and implementation of the Solex environment, the SPU design and testing is currently underway. Using modular rapid prototype construction, the smart base mock up has been constructed to help clarify and meet the packaging requirements for the PC, power management, energy conversion and storage, as well as slave device specific components. The smart base mock has also proven to be valuable in the robot ergonomics design criteria investigation, particularly for the accessibility and visibility to different data and mechanical interface locations. The first set of mechanical flip switches and a LED display panel are also implemented. The smart base mock up is shown in Fig. 9.

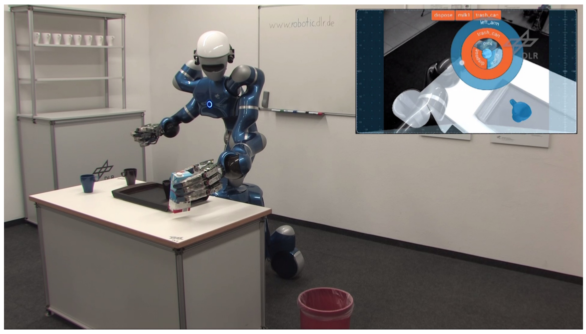

Figure 8. Teleoperating Rollin' Justin with supervised autonomy. DLR has developed the capability to command a complex humanoid robot to perform object manipulation tasks with a tablet PC (screen shot on the upper right corner). The live ring menu on the tablet PC helps direct the operator to the feasible next steps in the robot's task [12]. This approach will be applied to the experiment protocols of Supvis-Justin, using a space qualified user interface layout.

The DIP/DPR prototype design has already been through several revisions at the time of this publication, and further iterations are planned. The tapered DIP tool tip design can be seen in Fig. 10. Fig. 11 shows a sequence view of the DIP being inserted into the DPR on the SPU by Justin. The guiding effect by the tapered tip design can be seen to compensate for the robot's small, but noticeable position estimation error. Through a series of DIP insertion test campaign, excellent success rate has been observed, demonstrating highly repeatable robust connection. The current DIP/DPR design provides a physical layer that accepts Ethernet data communication and power/energy loading. In addition, A variety of different mechanical switches are currently being tested for robot manipulation capabilities. Specifications, procurement, and/or design for other key components for the Solex environment including the simulated terrain, artificial sun light, SPU electronics and firmware, etc. are also underway.

5. OUTLOOK AND FUTURE WORK

This paper presented our work in progress for the Meteron Supvis-Justin supervised autonomy telerobotics experiment. Through Supvis-Justin, we hope to further our knowledge in intuitive teleoperation of a dexterous humanoid robot for extraterrestrial exploration by utilizing supervised autonomy. The Solex environment, on the other hand, shall provide a systematic proving ground to proposed space teleoperation concepts. The continuing testing and development of the Supvis-Justin experiment, along with Solex environment, are vigorously moving ahead. We expect to learn more lessons throughout this process, in implementing supervised autonomy, as well

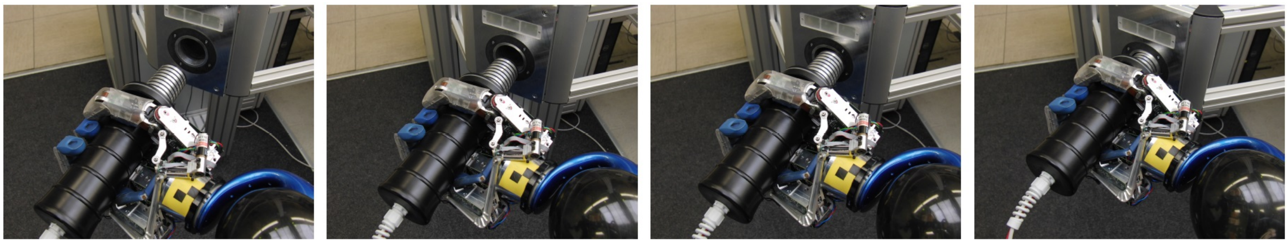

Figure 11. Sequence of the DIP being plugged into the DPR on the SPU. Note the geometry of the tip of the DIP accounting for position estimation error by allowing for a gliding-in action.

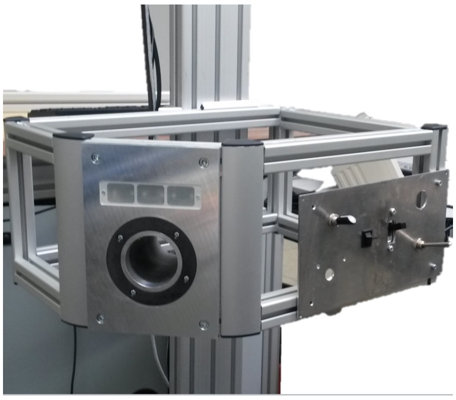

Figure 9. SPU smart base ergonomics and packaging under development. The geometry of the smart base is tailored to the workspace of the service robot, similar to ergonomic design practice for human operated devices. The DPR socket, located at the corner, is robustly reachable by Justin's DIP. An LED display panel, located above the DPR, shows the status of the SPU. Flip switches of different form factors are also implemented for robot manipulation testing. The smart base has a foot print that can accommodate the on-board PC, energy storage, communication, and power management, and experimental task specific hardware.

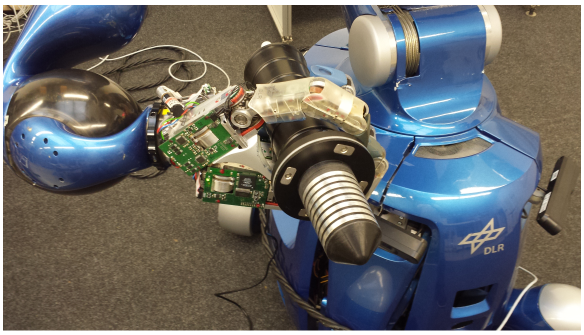

Figure 10. The DIP held by Justin. The DIP is a result of design for the robot's ergonomics and limitations in dexterity. The ergonomic design is demonstrated from the close form fitting to the robot's hand. The tapered tip of the DIP allows for position estimation errors when plugging the DIP into the SPU smart base, by helping it slide/glide into position.

as the design of experimental proving ground, for space telerobotics, well before the mission. Supvis-Justin experiment is currently planned to be carried out in 2016.

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