GLEX-2012.01.2.4x12180

THE HUMAN EXPLORATION TELEROBOTICS PROJECT

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The purpose of the Human Exploration Telerobotics (HET) project is to demonstrate how advanced remotely operated robots can increase the performance, reduce the cost, and improve the success of human exploration missions. To do this, we are using the International Space Station (ISS) as a laboratory to test new telerobotic systems, modes of control, and operational concepts. In this paper, we first provide the context and motivation for HET. We then describe the three telerobotic systems currently used by the project, initial testing, and results to date.

I. INTRODUCTION

I.I. Telerobotics for human exploration

For more than a half-century, humans have been learning to live and work in space. Since 1961, the majority of human spaceflight missions have focused on Earth orbit, in spacecraft (the Space Shuttle, Soyuz, etc) and on space stations (Mir, Skylab, and the International Space Station). In the 1960s and 1970s, the Apollo missions took humans to the Moon and brought us in contact with several sites on the lunar surface.

During this same time, robotic spacecraft (Pioneer, Voyager, etc.), robotic landers (Surveyor, Viking, Phoenix, etc.), and planetary rovers (Lunakhod, Sojourner, Spirit and Opportunity) have been used to explore the outer solar system. Robots have flown over, landed, and roamed across planetary surfaces, collecting scientific data from distant worlds.

As we look to the future, however, it is clear that the paths of human and robotic space exploration will increasingly intersect. Future human missions to the Moon, Mars, and other destinations offer many new opportunities for exploration. But, crew time will always be in short supply, consumables (e.g., oxygen) will always be limited, and some work will not be feasible (or productive) for astronauts to do manually.

Remotely operated robots can complement human explorers. Telerobots can perform work under remote supervision by humans from a space station, spacecraft, habitat, or even from Earth. Telerobots, particularly semi-autonomous systems, can increase the performance and productivity of human space exploration by carrying out work that is routine and highly repetitive. Telerobots can also perform work that is beyond human capability and perform work ahead of humans (e.g., scouting) that help prepare for future manned activity and missions.

I.II. Developing and testing advanced telerobots

Integrating telerobots into human space exploration raises several important questions. What system configurations are effective? Which modes of operation are most appropriate? When is it appropriate to rely (or not) on telerobots? What technical gaps, risk factors, and other concerns need to be addressed?

To answer these questions, the NASA Human Exploration Telerobotics (HET) project is developing and testing a variety of telerobotic systems, which can be operated by ground controllers on Earth and by astronauts in space [1]. Our primary objective is to study how advanced, remotely operated robots can increase the performance, reduce the costs, and improve the likelihood of success of human space exploration.

Our work is motivated by the need to reduce risk by demonstrating and proving systems for future missions. The results of HET will inform the development of new design reference missions (DRMs) and architectures. These mission concepts will allow NASA to consider conducting joint human-robot exploration of new destinations of interest. HET will also help NASA advance the state-of-the-art in robotic autonomy, human-robot interaction, robotic assistance, and space robot design.

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I.III. Mission infusion targets

Because HET focuses on telerobotics in support of human space exploration, the primary beneficiary and recipient of HET technology and capabilities is the NASA Human Exploration and Operations Mission Directorate (HEOMD). Consequently, the targeted infusion points for HET technology include current HEOMD missions, such as the International Space Station (ISS), and future missions to the Moon, Mars or Near-Earth Objects (NEOs).

Today, astronauts on the ISS not only conduct science activities, but they also perform a variety of tasks required for ISS housekeeping and system maintenance. The remote monitoring and operation of many ISS systems by ground control has become an accepted practice for certain ISS tasks during the past decade. In terms of robots, these tasks are limited to coarse positioning maneuvers of external payloads/structures using manipulator arms.

However, other types of robots (human-scale manipulators, free-flyers, etc.) offer significant potential to perform a greater variety of tasks. These tasks include tedious, highly repetitive or long-duration work, such as conducting surveys, taking sensor readings or conducting routine maintenance. Thus, one area of emphasis for HET is to demonstrate ground-controlled operations of the Robonaut 2 (R2) dexterous humanoid robot and the Smart SPHERES free-flyer for a range of intra-vehicular activity (IVA) work.

NASA and its international partners have numerous on-going initiatives, both independent and joint, to develop the frameworks and architectures required for future space exploration to destinations beyond Low-Earth Orbit (LEO) [2][3]. During transit to, or in orbit of, these destinations, robots can perform work that is beyond human capability, such as operating in dangerous environments and performing tasks that require great force. Thus, a second area of emphasis for HET is to demonstrate crew-centric operations of R2 and Smart SPHERES for various simulated extra-vehicular activity (EVA) work.

Finally, in almost all cases, these frameworks for future missions include the use of manned orbiting spacecraft as a supplement to human surface presence. Many of these frameworks hypothesize that having crew remotely operate robots from orbit is an effective and productive means for performing exploration. Similar recommendations for operating robots from orbit were contained in the 2009 Augustine report, as part of the "Flexible Path" option [2]. Thus, a third area of emphasis for HET is to demonstrate crew control of a surface telerobotic system to characterize and validate the feasibility of this operational concept.

Table 1 summarizes the mission infusion targets for the telerobotic systems (and the associated concept of operation) being developed and tested by HET.

System	Concept of operation	Target mission
Robonaut 2	Ground-control	ISS
Robonaut 2	Crew-centric	ISS, Moon, Mars, and NEO
Smart SPHERES	Ground-control	ISS
Smart SPHERES	Crew-centric	ISS, Moon, Mars, and NEO
Surface Telerobot	Crew-centric	Moon, Mars, and NEO

Table 1. Mission infusion targets for HET

I.IV. Concepts of operation

Historically, NASA has used different concepts of operation for human and robotic missions [4]. Human missions (Apollo, Space Shuttle, and ISS) have all been conducted with near-continuous communication (data and voice) and minimal delay (i.e., less than a few seconds). In these missions, astronauts and mission control work together as an integrated team, performing tasks and resolving problems in real-time.

Robotic missions have traditionally centered on the use of carefully scripted and validated command sequences, which are intermittently uplinked by mission control to the robot for independent execution [5]. As a consequence, robots have had to function independently for long periods of time without communication to mission control.

Future human exploration missions, however, will need to combine aspects from both concepts of operations. These missions will need to consider operational constraints due to location (in-space or on-surface), communication link characteristics (bandwidth, latency, quality of service, and availability), and varied timelines (strategic, tactical, and execution). All of these constraints will vary throughout the course of a mission or campaign.

In addition, during human missions, astronauts generally work to a schedule that consists of many varied activities, most of which are planned (scheduled) in advance. Thus, whenever crew is required to perform telerobotic operations, particularly unplanned interventions, they will have to switch tasks. Consequently, it is important to understand how such task switching affects human-robot operations performance as well as crew efficiency and productivity.

In HET, therefore, we are studying two concepts of operations: *ground-control ops* and *crew-centric ops*. For both concepts, we are testing a variety of robot types and configurations, user interfaces and modes of control, and human-robot teaming.

I.V. Ground-control ops

With *ground-control ops*, an Earth-based team performs planning, operations, and analysis of robot task execution. The ground control team may take various forms, but generally consists of a primary robot operations team supported by "backroom" teams (science, robot engineering, etc.)

The *central* question we are addressing with ground control operations is: *How can robots in space be safely and effectively operated from Earth to enable more productive human exploration?* In other words, under what operational conditions and scenarios can robots be controlled by ground control to improve how crew explore and work in space?

Since crew time is always at a premium in space, the best use of telerobotics *may* be as a means to off-load mundane, repetitive, and routine work from astronauts to ground control. This would then enable crew to focus more of their time on tasks that require human cognition, dexterity, or involvement.

I.VI. Crew-centric ops testing

With *crew-centric ops*, the crew performs planning, operations, contingency handling and analysis. Ground control may support crew on an intermittent and/or time-delayed basis. This concept of operations is appropriate when conditions (orbital geometry, time-delay, etc.) make it impractical, or inefficient, for ground control to remotely operate robots.

The *central* question we are addressing with crew-centric operations is: *When is it worthwhile for astronauts to remotely operate surface robots from a flight vehicle during a human exploration mission?* In other words, under what operational conditions and scenarios is it advantageous for crew to control a robot from a flight vehicle, habitat, etc., rather than a ground control team located on Earth?

It is often the case that astronauts within a crew vehicle can remotely operate the same robots that are normally operated by ground control. This concept of operations is appropriate in three situations: (1) poor, delayed, or intermittent communication prevents ground control from performing the task; (2) the crew's physical presence is critical to performing the task; or (3) local operations significantly outperforms remote operations (e.g., number of command cycles).

I.VII. International Space Station as a testbed

HET makes extensive use of the ISS for testing. Although using the ISS is complex (particularly in terms of certification and scheduling), the ISS is the only facility available for performing high fidelity, integrated simulations of future deep-space human missions. In particular, ISS testing is the only way to confirm that all significant environmental conditions, operational constraints, and other factors are replicated.

Ground-based simulators (laboratory tests, outdoor testbeds, etc.) lack fidelity in many areas, including:

- Effect of micro-gravity on crew (this affects sensorimotor performance, etc.)
- Effect of long-duration stay in space on crew (this affects cognition, proficiency levels, etc.)
- Crew activities, workload, and other sources of in-flight stress
- Flight vehicle constraints (including micro-gravity workspace, crew displays, etc.)
- Operational complexity (particularly coordination with ground control, scheduling, etc.

The HET systems and activities on ISS are classified as ISS payloads (experiments), and as such, must follow the ISS payload process. This process nominally requires an 18-month lead-time to allow completion and compliance with:

- Payload agreements that provide activity requirements for ISS and supporting facilities
- Safety certification for both the launch vehicle (for hardware up-mass) and ISS operations
- Verification of hardware and software interface requirements to the launch vehicle and ISS
- Development/delivery of engineering documents
- Development of crew procedures and training
- Scheduling of crew activity and resources

II. ROBONAUT 2

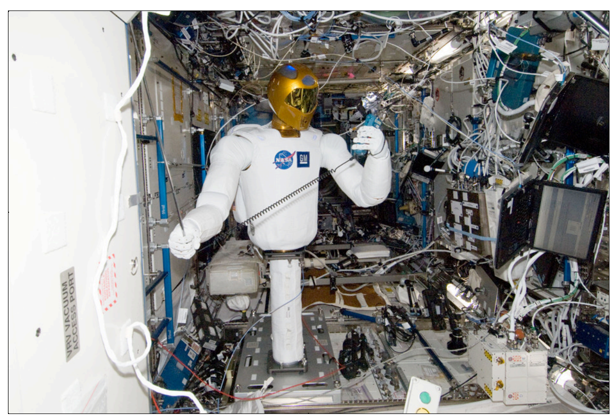

Figure 1. Robonaut 2 (R2) is the first humanoid robot in space (NASA ISS030-E-148273).

II.I. System description

Robonaut 2 (R2), as shown in Figure 1, is the first humanoid robot in space [6]. R2 is the latest result of a long-term effort to develop robots that can safely operate near humans and can perform significant work using the same hardware and interfaces (connectors, switches, etc.) used by astronauts. R2 is designed to have manipulation capabilities similar to suited astronauts. Modularity is prevalent throughout the hardware and software design along with layered approaches for sensing and control.

R2 has 42 independent degrees-of-freedom (DOFs) and over 350 sensors. R2 has two 7-DOF arms, two 12-DOF hands, a 3-DOF neck and a single DOF waist, which make use of 50 actuators with collocated, low-level joint controllers embedded throughout. The system also integrates built-in computing and power conversion inside its backpack and torso.

R2, like its predecessor, Robonaut 1 (R1) [7], uses brushless DC motors, harmonic drive gear reductions, and electromagnetic brakes in the robot's human-scale, 5-DOF upper arms. The use of *series elastic actuators*, however, differentiates R2 from previous designs. Developed initially with legged robots in mind, series elastic actuators provide improved shock tolerance, beneficial energy storage capacity, and a means for accurate and stable force control [8].

The R2 hand and forearm are designed to improve upon the approximation of human hand capabilities achieved by R1 [9]. The five fingered, 12-DOF hand and the forearm, which houses two wrist DOFs, is a modular, extremely dexterous, standalone end-effector. The R2 thumb has one more joint than the R1 thumb allowing a much wider range of grasps. The thumb and primary fingers can achieve dexterous grasps. When these are combined with the ring and little fingers, the hand can form a full range of power/tool grasps and has the capability to manipulate a large set of EVA tools, conventional hand tools, and soft goods (Figure 2).

Figure 2. Manipulating soft goods.

The primary operator interface for the robot is a custom R2 Graphical User Interface (R2 GUI), which permits the user to build up command sequences using simple reusable control blocks (Figure 3). The R2 GUI can save, edit, and execute sequences. The command sequences can include conditional sections, which enable the robot to use its sensor data to adjust its approach to a task. The R2 GUI also includes data displays for monitoring robot health, status and collecting data for later analysis.

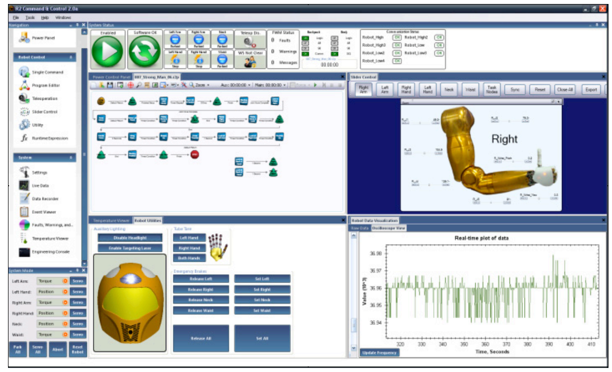

Figure 3. R2 Graphical User Interface (R2 GUI).

II.II. ISS deployment

R2 was flown to the ISS aboard the STS-133 Space Shuttle flight in February 2011. The path from laboratory prototype to flight involved hardware modifications to meet radiation hazards and the addition of thermal management systems to prevent overheating in non-convective environments.

After R2's arrival and installation on the ISS, ground controllers and astronauts powered on the robot for the first time on August 22, 2011. This initial "power soak" activity allowed evaluation of the robot after its journey into space. R2 remained powered for 2.2 hours while ground control collected data to verify the health of the robot and to assess thermal trending in the micro-gravity environment.

Following the "power soak", a series of checkouts was performed with R2 over the next several months (Figure 4). This sequence included sensor checkout, control gain tuning, initial free-space motions and the performance of proof-of-concept tasks.

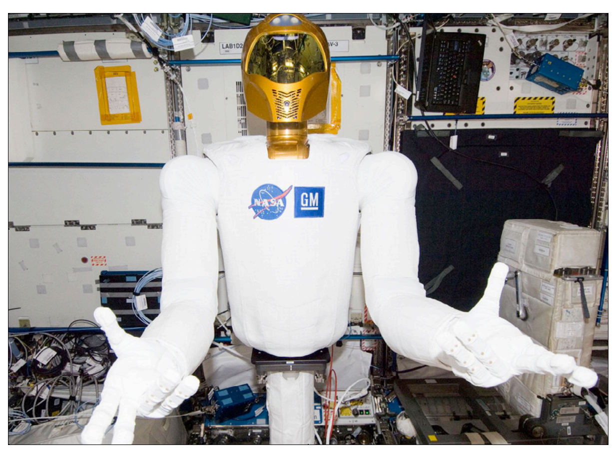

Figure 4. The initial R2 on-orbit activities focused on checkout: verifying sensors and controller gains (NASA ISS029-E-039211).

A key part of sensor checkout was to verify R2's force sensing system. This system includes four 6-DOF sensors, one in each forearm and one in each shoulder. These sensors monitor R2's limb forces and are critical for operation. R2 will autonomously stop motion and "safe" itself if these sensors experience readings beyond pre-specified limits. On September 1, 2011, ISS astronauts verified proper functioning of the force sensors during the "Checkout 1" activity.

The next checkout activity focused on determining control gains. In order for R2's joint actuators to operate properly in space, it was necessary to determine control loop gains through experimentation. Thus, an astronaut commanded R2 to sequentially maneuver each upper arm joint, one at a time, while automatically adjusting control gains through repetitive motions. The performance data acquired through this process enabled appropriate gains to be determined.

II.III. Ground-control ops tests

R2's on-orbit operations are performed in accordance with the ISS "payload" (experiment) process [10]. The Payloads Operations Integration Center (POIC) located at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama manages all payload operations. Prior to any on-orbit activity, crew procedures, documentation of flight rules, and software files have to be prepared. In addition, crew training is performed for each specific activity [10].

During ground-control ops, the R2 ground control team monitors real-time activities from the ISS Mission Control Center (MCC) at the NASA Johnson Space Center (JSC) in Houston, Texas. The R2 ground control team consists of three roles: *Operator, Task,* and *Lead* (Figure 5).

The *Operator* sits next to the PLUTO (Plug-in-Port Utilization Officer) flight controller since the PLUTO's computer communicates directly to the ISS Space Station Computer (SSC) that is connected to R2. This setup allows the ground control team to monitor all R2 on-orbit activity. On a separate computer, the Operator has the same R2 GUI that is on the SSC and can monitor R2 telemetry. However, the Operator cannot directly control R2.

The *Task* position monitors the mission and task timelines, procedure steps, and assists the Operator during anomalies. The *Lead* position is in charge of the entire activity and handles all real-time communications with various positions at MSFC and with the astronauts.

During each R2 activity, the ground controllers monitor R2's performance by viewing video from fixed cameras in the ISS and from R2's built-in cameras. During times of video *loss of signal* (LOS), all of this on-board video is recorded and then downlinked at a later time.

R2's data and video are transmitted to the ground using the ISS Ku-band system. This presents a challenge when scheduling on-orbit operations because there are occasionally dropouts in Ku-band coverage. During real-time operations, ground controllers constantly monitor the Ku-band coverage and make decisions based on R2's performance using the real-time data and video.

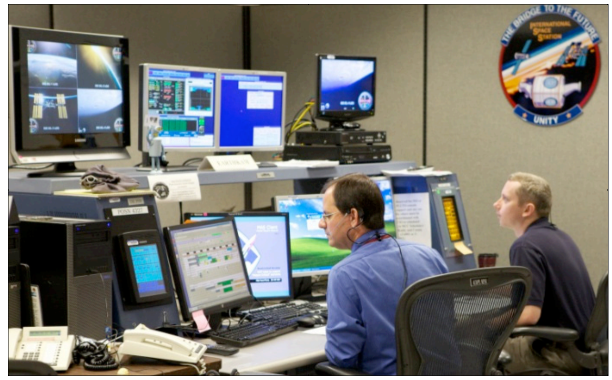

Figure 5. R2 ground controllers at the ISS Mission Control Center, NASA JSC.

II.IV. Crew-centric ops tests

To enable crew to remotely operate R2 in a range of control modes, particularly during EVA, we have developed a full set of teleoperation gear. This gear (Figure 6) was certified for use on ISS and launched on an ISS supply mission in October of 2011.

By mapping human head, arm, hand, and body motions to corresponding R2 robot motions with minimal time delay, astronauts will be able to perform complex and unstructured tasks that cannot currently be performed autonomously. We are planning to conduct a series of crew-centric ops tests with R2 beginning in Fall 2012.

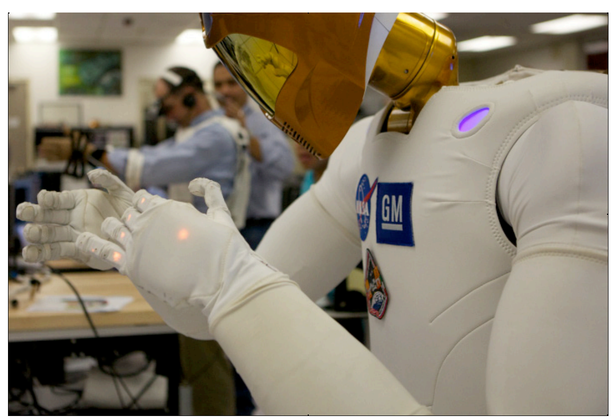

Figure 6. Remotely operating R2 using immersive teleoperation gear. The user wears a head-mounted stereo display and fully instrumented gloves to control R2 motions.

III. SMART SPHERES

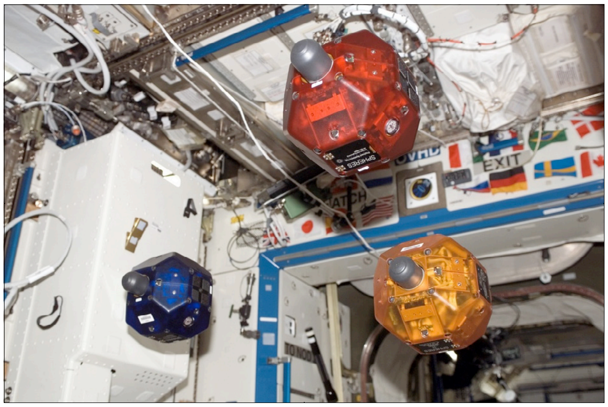

Figure 7. Three SPHERES free-flyers have been on the ISS since 2006. (NASA ISS016-E-014220)

III.I. System description

The Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) are volleyball-sized free-flyers (Figure 7) that have been on the ISS since 2006 [11]. The SPHERES were originally developed by the Massachusetts Institute of Technology as a platform for testing spacecraft guidance, navigation, and control algorithms in micro-gravity. To date, astronauts have conducted more than 30 test sessions with individual and multiple SPHERES to study formation flying, rendezvous, and docking.

Each SPHERES unit is fully self-contained with propulsion, power, computing and navigation equipment. A cold-gas (carbon dioxide) thruster system is used for motion control and DC batteries provide electronic power. For processing, the SPHERES rely on a digital signal processor, which handles all on-board software functions including navigation, device control, and communications. An external ultrasonic, local positioning system provides data to estimate the position and orientation of SPHERES.

HET Smartphone

Because the SPHERES were designed for testing spacecraft control algorithms, they require modification in order to function as telerobots. The original SPHERES lack a high-performance, general-purpose processor for running modern robotics software. In addition, the SPHERES do not have the sensors (e.g., color cameras) commonly used with mobile robots. Finally, the SPHERES do not have a high-bandwidth wireless communications link, which supports IP-based data messaging.

To remedy this, we have added a commercial, Android-based Smartphone (Samsung Nexus-S) as a high-level controller to SPHERES. The HET Smartphone provides SPHERES with a 1 GHz processor (including graphical processing unit), color cameras, additional sensors (temperature, sound, gyroscopes, accelerometers), a touchscreen display, and Wi-Fi networking. For clarity, we refer to the combined Smartphone and SPHERES system as “Smart SPHERES”.

One key advantage of using off-the-shelf consumer devices, such as the HET Smartphone, is that we can very rapidly research and develop new capabilities at a significantly lower cost than with traditional space flight hardware. Moreover, with the rapid evolution of mobile communications technology we can regularly upgrade the computing and sensing capabilities of Smart SPHERES, which will enable increasingly complex robot capabilities.

In order to certify the HET Smartphone for use on ISS, we had to make three modifications to the device. First, to avoid any possible radio frequency interference with ISS, we removed the cellular GSM transmitter chip from the device. Second, to address concerns about the use of lithium-ion batteries on ISS, we developed an external battery pack using AA alkaline batteries. Finally, to capture and contain the display glass in the event of breakage, we covered the touchscreen with Teflon tape.

The HET Smartphone is connected to SPHERES via a custom cable, which connects the Smartphone USB port (in RS-232 serial mode) to the SPHERES hardware expansion port. The Smartphone sends motion commands to the SPHERES and receives low-level telemetry (power, position, etc.) messages across this serial link.

User interface

The Smart SPHERES Workbench (Figure 8) is a robot user interface, which is modeled after the NASA Exploration Ground Data System (xGDS) [15]. The Workbench consists of software services for creating and executing command sequences (robot trajectories, sensor data collection, etc.), displaying telemetry, and monitoring robot activities with 3D graphics.

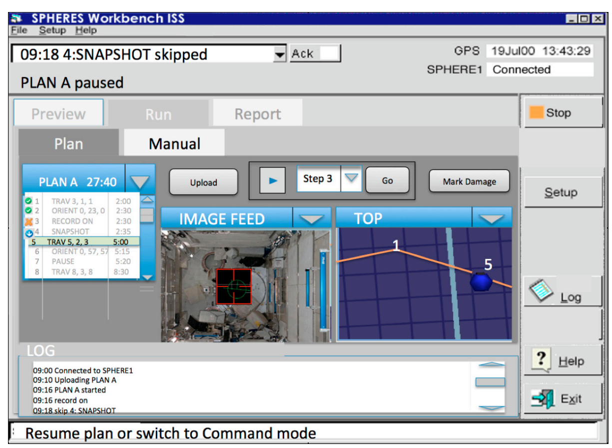

Figure 8. The Smart SPHERES Workbench is used to create and execute robot command sequences.

The primary mode of control used with Smart SPHERES is "command sequence with interactive monitoring", which is a variant of supervisory control. In addition, Smart SPHERES can be operated in a manual control (direct teleoperation) mode.

Data communications

The data communications architecture for Smart SPHERES is shown in Figure 9. A ground controller in the ISS MCC (at NASA JSC) uses the Smart SPHERES Workbench to generate command sequences for the robot. The command sequences are uplinked, and robot telemetry is downlinked, via the Orbital Communications Adaptor (OCA) LAN and the TDRSS link to ISS. On ISS, the data is routed to/from the HET Smartphone via the OPS LAN and the JSL Wi-Fi.

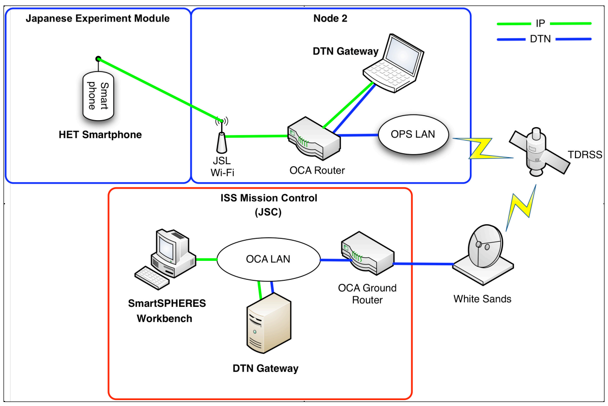

Figure 9. Smart SPHERES data communications

Software architecture

Smart SPHERES uses a service-oriented software architecture, which is inspired by the NASA Ames Service Oriented Robotics Architecture (SORA) [14]. The architecture encapsulates robot functions as a collection of modular services, which can be assembled and configured for different applications using high-performance middleware.

High-level services reside on the HET Smartphone. The *Motion and Action Sequencer* is a simple task executive, which manages command sequence execution. The *Camera* service captures images from the Smartphone color camera. The *On-Screen UI* manages state and diagnostics display on the Smartphone touchscreen. The *WiFi Comms* service is a Robot Application Programming Interface Delegate (RAPID) middleware client (see Section V.I), which receives commands and transmits telemetry. The *SPHERES Comms* service manages serial communication with the SPHERES.

Low-level services reside on the SPHERES. The *Mobility Control* service provides 6-DOF motion control. The *State Server* service manages serial communications with the HET Smartphone, which includes processing mobility (trajectory) commands and transmitting state (power, position, etc.) data.

III.II. ISS deployment

The HET Smartphone was delivered to the ISS by the last Space Shuttle flight (STS-135) in July 2011. The first on-orbit test of Smart SPHERES (Figure 10) took place on November 1, 2011. During this test, the Smartphone was mounted on a SPHERE, which was then commanded to fly a pre-defined trajectory in the Kibo Japanese Experiment Module (JEM). During the flight, we recorded data from a number of Smartphone sensors, including a color camera, accelerometers, gyroscope, and magnetometer. The primary result of this test was successful verification that the Smartphone works well in the ISS environment.

Figure 10. Astronaut Mike Fossum testing Smart SPHERES. The Smartphone is shown in the inset (left). (NASA ISS029-E-036493 / -036497)

III.III. Ground-control ops tests

In August 2012, we will use Smart SPHERES to demonstrate that ground control can perform tasks that require mobile sensors and that would normally required crew. For example, ISS operations require routine systematic surveys of environmental conditions (sound levels, temperature, etc.) to assess safety for habitation. These surveys, however, consume significant amounts of valuable crew time. Similarly, tracking and locating inventory items is a time-consuming crew task, which could possibly be performed by a ground-controlled free-flying robot.

As with R2, ground control operation of Smart SPHERES will be performed from the ISS Mission Control Center at NASA JSC. During operations, the Smart SPHERES (SS) Ops lead will use the Smart SPHERES Workbench on a computer located in the PLUTO Multi-Purpose Support Room (MPSR). All commanding and remote operation of Smart SPHERES on ISS will be performed by the SS Ops lead from this location. The PLUTO flight controller will support Smart SPHERES operations by managing the configuration of ISS computers and ground assets related to the communications link.

To carry out an interior survey, the SS Ops Lead will select an initial survey plan with the Smart SPHERES Workbench, preview execution in simulation, and then upload it to the Smart SPHERES. As the robot executes the plan, the SS Ops Lead and support staff will monitor progress and stop/modify execution to handle contingencies. After this test, we will assess: (1) how close to plan was the survey carried out; and (2) how effectively the ground controllers were able to maintain situation awareness during robot operations.

Beyond mobile sensing, we anticipate that the Smart SPHERES can also provide ground controllers with mobile telepresence on the ISS. Specifically, because the Smart SPHERES is equipped with a camera and display, it is possible for the robot to provide real-time, mobile interaction between crew and mission control. Thus, in 2013, we will perform a crew interview where a ground-based interviewer interacts with astronauts using Smart SPHERES for mobile telepresence.

III.IV. Crew-centric ops tests

In addition to ground-control of Smart SPHERES, we also plan to perform several crew-centric ops tests. By installing the Smart SPHERES Workbench on a SSC, ISS crew will be able to remotely operate the Smart SPHERES in the same manner as ground control. This will enable simulation of a robotic free-flyer that might one day be used to remotely perform EVA work.

In one test planned for 2013, ISS crew will remotely operate the Smart SPHERES to perform visual inspection (Figure 11). This capability would be of use for routine inspection of the exterior of a spacecraft, along with rapid situational assessment during an emergency due to damage or failure of external components of the craft. Although the actual experiment will be internal to the ISS, emphasis will be placed on examining how well crew can: (1) maintain situation awareness when they are only intermittently interacting with the robot; and (2) intervene to cope with contingencies.

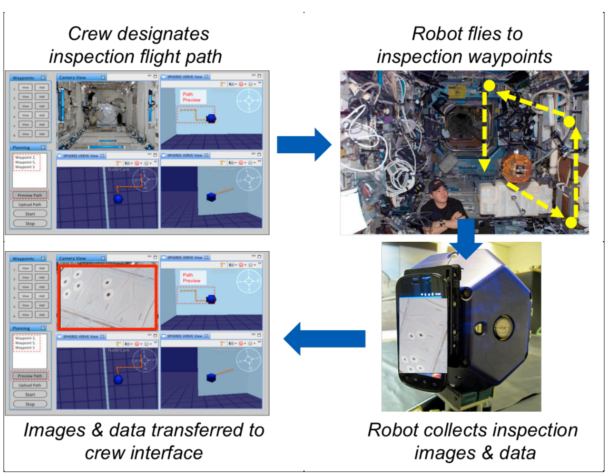

Figure 11. Smart SPHERES visual inspection.

IV. SURFACE TELEROBOTICS

IV.I. Motivation

Surface Telerobotics is a HET effort to examine how ISS astronauts can remotely operate a surface robot across short time delays. We are planning to conduct ISS tests starting in Summer 2013 (ISS Increment 35-36) in order to help reduce risks for future human missions, identify technical gaps, and refine key requirements for crew-controlled surface telerobotics.

In planning for future human space exploration, numerous NASA and international study teams have hypothesized that astronauts can efficiently remotely operate surface robots from a flight vehicle [2][16][17][18][19]. This concept of operations is seen as a cost-effective method for performing surface EVA activities for several possible missions:

- **L2 Lunar Farside**. Crew orbiting the Moon (or station-keeping at the L2 Earth-Moon Lagrange point) and a surface robot exploring the lunar farside [17][20]. Crew must control the robot from the flight vehicle to reduce communications requirements and to maximize robot utilization (i.e., for short-duration mission).
- **Near-Earth Object (NEO).** Crew in a flight vehicle that is approaching, near, or departing a NEO and a robot landed on surface [16][17]. Crew must control the robot from the flight vehicle because NEO dynamics (e.g., high rotation rate) rules out remote operations from Earth.
- **Mars Orbit.** Crew in aerostationary orbit around Mars (or landed on Phobos/Deimos) and a surface robot exploring Mars [2][16][17][18][19]. Crew must control the robot from the flight vehicle when circumstances (e.g., time-critical activities) do not permit remote operation from Earth.

Many assumptions have been made regarding crew-centric telerobotics, including technology maturity, technology gaps, and operational risks. Although many related terrestrial systems exist (e.g., remotely piloted vehicles), no crew-controlled surface telerobotics system has yet been tested in a fully operational manner, in a high-fidelity space environment, and characterized using detailed performance metrics.

IV.II. Objectives

The primary goal of HET Surface Telerobotics is *to obtain baseline engineering data for a crew-controlled surface telerobotic system through ISS testing*. In particular, our work focuses on: (1) collecting data from system operation under a variety of test conditions; (2) validating key functional issues; and (3) developing requirements for future mission systems.

Surface Telerobotics testing is informed by hundreds of hours of ground-based simulations of surface telerobots, which we have conducted in planetary analog environments [21][22][23][24][25][26][27][28]. This testing has included a wide range of robot control modes, operations team structure, operations protocol, and robot systems.

The three specific objectives for the first Surface Telerobotics test are:

1. Demonstrate interactive crew control of a mobile surface telerobot in the presence of short communications delay.
2. Characterize a concept of operations for a single astronaut remotely operating a planetary rover with limited support from ground control.
3. Characterize telerobot utilization, operator workload and operator situation awareness.

IV.III. 2013 Experiment: simulated L2-farside mission

The first Surface Telerobotics test is focused on simulating a possible lunar orbital mission. Exploration of the lunar farside is currently seen as a possible early goal for missions beyond LEO using the Orion Multi-Purpose Crew Vehicle (MPCV).

One leading mission concept focuses on sending a crewed MPCV to the L2 Earth-Moon Lagrange point, where the combined gravity of the Earth and Moon allows a spacecraft to easily maintain a stationary orbit over the farside. From L2, an astronaut remotely operates a robot to perform high-priority surface science work, such as deploying a radio telescope [20][29][30]. Such a mission would also help prepare for future deep-space human exploration missions.

To study this mission concept, we have developed an experiment that simulates four key mission phases: (1) pre-mission planning; (2) site scouting and survey; (3) payload deployment; and (4) inspection of deployed payload. It is important to note that the tasks that will be performed in each of these phases are generally applicable to many mission scenarios, not just the L2-Farside concept.

Phase 1: Pre-mission planning

The *pre-mission planning* phase takes place well in advance of operations. A mission planning team uses satellite imagery at a resolution comparable to that available for the lunar surface and a digital elevation map to select a nominal site for the telescope deployment. In addition, the planning team will create a set of rover task plans to scout and survey the site, looking for potential hazards and obstacles to deployment.

Phase 2: Scouting and surveying

During the *scouting and surveying* phase, the crew will remotely operate the robot to gather information about the site from surface level. The data collected will enable identification of surface characteristics such as obstacles, slopes and undulations that are either below the resolution, or ambiguous due to the nadir pointing orientation, of orbital instruments. The mission planning team will then analyze the data and develop final telescope deployment plans.

Phase 3: Payload deployment

In the *payload deployment* phase, the crew uses the rover to deploy the telescope array. First, the crew will execute the deployment task sequence (including rover motions), but with the deployment device disabled, to verify that the sequence is feasible. During actual deployment, the crew will monitor both the rover driving task and the telescope deployment. The mission planning team will use deployment imagery and astronaut-marked inspection points to develop inspection plans.

Phase 3: Payload inspection

During the final phase, pa*yload inspection*, the crew will remotely operate the robot to perform detailed inspection of the deployed telescope. Based on the inspection data, the crew will decide whether it is necessary to repair, or replace, array sections.

IV.IV. Robot Control Modes

In prior work, we experimented with having ground control teams of varying sizes (from 1 to 20 controllers, including backroom staff) remotely operate a single planetary rover[23][24]. Several robot control modes were employed, ranging from low-level actuator control to supervised autonomy. The primary control mode, however, was “command sequencing with interactive monitoring”, which we have found to be effective and efficient for operating in unstructured environments with short communication delays (up to 10s of sec).

This control mode requires that the robot have sufficient on-board autonomy for the tasks being performed. For example, mobile sensor applications, such as scouting, require the robot to be capable of autonomous driving between waypoints. Benefits of this control mode (vs. direct teleoperation) include: improved robustness to poor communication links (intermittent signal, low bandwidth, high-delay), increased task performance, increased robot utilization, and reduced operator workload.

IV.V. System description

K10 Planetary Rover

For the initial Surface Telerobotics test, we will use the NASA Ames “K10” planetary rover (Figure 12) [31]. K10 has four-wheel drive, all-wheel steering and a passive averaging suspension. K10 is capable of autonomous navigation, driving, and payload operations on moderately rough natural terrain at human walking speeds. The K10 controller is based on our Service-Oriented Robotic Architecture (SORA) [14].

Figure 12. The K10 planetary rover at Haughton Crater.

Science Instruments

To perform scouting and survey, we have equipped the K10 rover with a suite of science instruments: panoramic and microscopic imagers, and a 3D scanning lidar. Both images can provide contextual and targeted high-resolution color imaging of sunlit areas. These instruments are used both for science observations and situational awareness during operations. The 3D lidar system provides 3D scans over a 40x40 deg field-of-view and is capable of making measurements from 3 to 1,500 m range with 10 mm accuracy (at 100 m range).

User Interfaces

The "Visual Environment for Robotic Virtual Exploration" (VERVE), shown in Figure 13, is an interactive, 3D user interface for visualizing high-fidelity 3D views of rover state, position, and plan status on a terrain map in real-time. VERVE also provides detailed status displays of rover systems, renders 3D data (e.g., range data acquired with 3D scanning lidar), and can monitor robot cameras. VERVE runs within the NASA Ensemble framework [32] and supports a variety of robot telemetry, including the NASA Robot Application Programming Interface Delegate (RAPID) messaging system [34].

Figure 13. The Visual Environment for Robotic Virtual Exploration (VERVE) is an interactive 3D user interface for monitoring robot operations.

V. TELEROBOTIC MIDDLEWARE

Modern robots are highly complex systems. Consequently, the software for these robots must be implemented as multiple modules (perception, navigation, operator controls, etc.) by multiple developers, who often work in a distributed team. To facilitate the integration of independently developed modules into fielded systems, as well as to encourage adaptability, flexibility, interoperability, maintainability, and reusability, telerobotics middleware is required.

V.I. RAPID

The Robot Application Programming Interface Delegate (RAPID) is an open-source framework for remote robot operations [34]. RAPID is designed to: facilitate integration of experimental robot software modules created by a distributed development team; improve the compatibility and reusability of robotic functions; and speed prototype robot development in a wide range of configurations and environments.

For HET, we are using RAPID to support remote operations of the Smart SPHERES and K10 robots. In particular, we use RAPID for robot commanding (primitive actions and command sequences), for monitoring (telemetry including robot state, position, task progress, etc.), and transfer of large-volume datasets (e.g., panoramic image sets).

One significant benefit of RAPID is that it encourages the development of loosely coupled, but highly-cohesive systems across distributed and networked computing. This means that software modules are inherently portable and can be easily redeployed to fit different applications. Consequently, robot user interfaces, such as the SPHERES Workbench, can be developed for use at mission control, but then reconfigured for use on-board ISS with relatively little effort.

V.II. Delay Tolerant Networking

We are currently extending RAPID to deliver commands and telemetry more reliably over the multi-hop, delayed and disruption-prone communication links that are common to space operations. To do this, we are leveraging the emerging Delay Tolerant Network (DTN) technology [12][13]. DTN makes use of "store and forward" techniques within a data network to compensate for intermittent communication link availability or connectivity.

We have already tested RAPID over DTN using the BPTAP [34] system in the Communications Networks Laboratory at JPL and are now adding "quality of service" interfaces to the RAPID/BPTAP system. During the next year, we will test the fully integrated system for its ability to reliably transport RAPID data in the presence of variable delay and disruptions on the communications network.

VI. CONCLUSION

The Human Exploration Telerobotics project is studying how advanced remotely operated robots can improve human exploration missions. By developing, demonstrating, and testing advanced, remotely operated robots with astronauts on the International Space Station, we are working to evolve approaches to human controlled robotics, to inform the development of new design reference missions, and to enable new ways to explore space with humans and robots.

In our work, we are examining how robots can be used to perform a wide range of human exploration tasks. To do this, we are making use of robots capable of IVA work (including dexterous manipulation and mobile sensing), simulated EVA work outside of a crew vehicle, and surface work (scouting, survey, etc.) on unstructured, natural terrains. In addition, we are studying different concepts of operations, including ground control ops, crew centric ops, and combinations of the two.

Overall, we anticipate that the results of our research will help mitigate risk by validating methods and designs that can be used in future missions. Additionally, the results of our tests will help mission planners to define appropriate requirements and to develop appropriate operational protocols. In short, through our work, we hope to improve the capability and likelihood for success of human space exploration.

VII. ACKNOWLEDGEMENTS

The NASA Technology Demonstration Missions program (TDM) and the International Space Station (ISS) program sponsored this work. We thank Jason Crusan, Bonnie James, James Reuther at NASA Headquarters for their support. We also thank John Mcdougal, Susan Spencer, and Karen Stephens of the TDM program office for their management assistance. Finally, we gratefully acknowledge the help of the ISS Payloads Office (particularly George Nelson) and the JSC Mission Operations Directorate.

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