Results from Testing Crew-Controlled Surface Telerobotics on the International Space Station

Maria Bualat
Intelligent Systems Division
NASA Ames Research Center, USA
e-mail: maria.bualat@nasa.gov

Terrence Fong
Intelligent Systems Division
NASA Ames Research Center, USA
e-mail: terry.fong@nasa.gov

Debra Schreckenghost
TRACLabs, USA
e-mail: schreck@traclabs.com

Donald Kalar
San Jose State University Foundation, Inc.
e-mail: donald.j.kalar@nasa.gov

Estrellina Pacis
SSC Pacific, USA
e-mail: estrellina.b.pacis@nasa.gov

Brent Beutter
Human Systems Integration Division
NASA Ames Research Center, USA
e-mail: brent.r.beutter@nasa.gov

Abstract

During Summer 2013, the Intelligent Robotics Group at NASA Ames Research Center conducted a series of tests to examine how astronauts in the International Space Station (ISS) can remotely operate a planetary rover. The tests simulated portions of a proposed lunar mission, in which an astronaut in lunar orbit would remotely operate a planetary rover to deploy a radio telescope on the lunar far side. Over the course of Expedition 36, three ISS astronauts remotely operated the NASA "K10" planetary rover in an analogue lunar terrain located at the NASA Ames Research Center in California. The astronauts used a "Space Station Computer" (crew laptop), a combination of supervisory control (command sequencing) and manual control (discrete commanding), and Ku-band data communications to command and monitor K10 for 11 hours. In this paper, we present and analyze test results, summarize user feedback, and describe directions for future research.

1 Introduction

In planning for future human exploration missions, several architecture and study teams have made numerous assumptions about how astronauts can be telepresent on a planetary surface by remotely operating surface robots from space (i.e. from a flight vehicle or deep space habitat) [1,2]. These assumptions include estimates of technology maturity, existing technology gaps, and operational risks. These assumptions, however, have not been grounded by experimental data. To address this issue, we developed a series of tests called "Surface Telerobotics" to: (1) demonstrate interactive crew control of a mobile surface telerobot in the presence of a short communications delay, (2) characterize a concept of operations and (3) characterize system utilization and operator work for a single astronaut remotely operating a planetary rover with limited support from ground control [3].

2 Lunar Libration Point Mission

Surface Telerobotics focused on simulating a possible future lunar libration point mission. Missions to Earth-Moon libration points provide an avenue to develop expertise needed for future missions. One leading concept, the "NASA Orion L2-Farside" mission, proposes to send a crewed Orion spacecraft 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 lunar farside [4]. From L2, an astronaut would remotely operate a robot to perform high-priority surface science work, such as deploying a polyimide film-based radio telescope. Obtaining observations of the Universe's first stars/galaxies at low radio frequencies is a key science objective of the 2010 Astronomy and Astrophysics Decadal Survey. Such a mission would also help prepare for subsequent deep-space human exploration. For example, a similar strategy might be employed to enable humans to telerobotically explore the surface of Mars from orbit [5].

3 Surface Telerobotics System

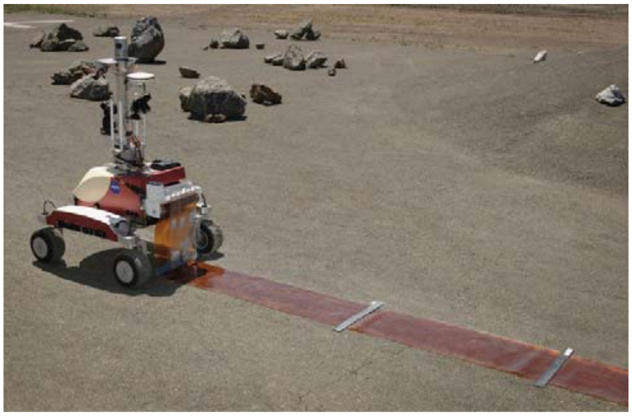

Figure 1 K10 deploys polyimide film to simulate deployment of a polyimide-based lunar radio telescope.

3.1 K10 Planetary Rover

The NASA Ames Research Center (ARC) K10 planetary rover is shown in Figure 1. K10 has four-wheel drive, all-wheel steering and a passive averaging suspension. K10 is capable of fully autonomous operation on moderately rough natural terrain at human walking speeds (up to 90 cm/s).

K10's standard sensors include a Novatel differential GPS system and inertial measurement unit, a Honeywell digital compass, Manta Allied Vision GigE stereo cameras, a Velodyne 3D scanning lidar, and wheel encoders. K10's controller runs on a Neousys Technology Nuvo-1000 series Intel® Core™ i7/i5 embedded controller and communicates via a Tropos 802.11g mesh wireless system.

The K10 controller is based on our Service-Oriented Robotic Architecture (SORA) [6]. Major services include locomotion, localization, navigation, and instrument control. SORA uses high-performance middleware to connect services. Dependencies between services are resolved at service start. This approach allows us to group services into dynamic libraries that can be loaded and configured at run-time.

3.2 Science Instruments

To perform survey and inspection, we equipped the K10 rover with a panoramic camera and an inspection camera. Both instruments can provide contextual and targeted high-resolution color imaging of sunlit areas. These instruments are used for both science observations and situation awareness during operations.

The panoramic camera is a consumer-grade, 12 megapixel, digital camera on a pan-tilt unit. We operate the camera at 350 rad/pixel, comparable to the Mars Exploration Rover Pancam (280 rad/pixel).

The inspection camera uses the same camera model as the panoramic camera, but is attached to K10 with a fixed rear-pointing mount. The inspection camera is used to observe telescope film deployment.

3.3 Film Deployer

Together with the University of Idaho, we developed and integrated a rear-mounted polyimide film deployer for the K10 rover (Figure 1). The deployer spools out 60 cm-wide polyimide film, as a proxy for a lunar radio antenna. On-board software controls deployment: starting, stopping, and adjusting the tension on the film. For the purposes of these tests, the film does not contain antenna or transmission line traces.

Metal bars were manually placed on top of the deployed film to keep the wind from lifting and shifting the antenna. This of course would not be an issue on the windless lunar surface.

3.4 User Interface

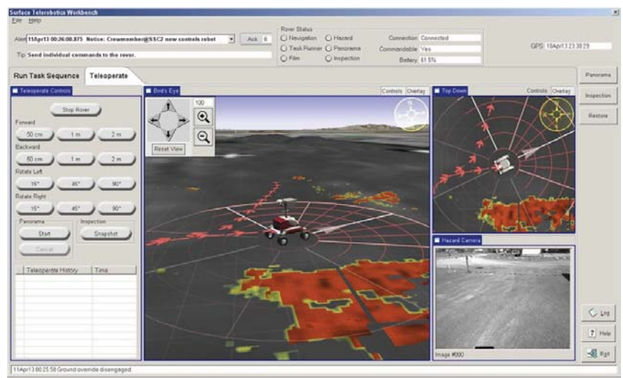

Figure 2 The Surface Telerobotics Workbench is an interactive 3D user interface for robot operations.

ISS crew remotely operated K10 using the "Surface Telerobotics Workbench" graphical user interface (GUI) (Figure 2). The Workbench runs on a Space Station Computer (SSC) and is based on the "Visual Environment for Robotic Virtual Exploration" (VERVE), an interactive, 3D user interface for visualizing high-fidelity 3D views of rover state, position, and task sequence status on a terrain map in real-time [7]. VERVE also provides status displays of rover systems, renders 3D sensor data, and can monitor robot cameras. VERVE runs within the NASA Ensemble framework (based on the Eclipse Rich Client Platform) and supports a variety of robot middleware, including the NASA Robot Application Programming Interface Delegate (RAPID), a set of software data structures and routines that simplify the process of communicating between multiple diverse robots and their command and control systems [8].

4 ISS Testing

To study this human-robot exploration approach, Surface Telerobotics simulated four phases of the Orion L2-Farside mission concept: pre-mission planning, site survey, simulated telescope deployment, and inspection of deployed telescope. After pre-mission planning, we performed the other three phases during three test sessions with the three US/European members of the ISS Expedition 36 crew. Each test session included 40 minutes of on-board "just in time" crew training for the robot user interface and two hours of mission operations.

A mission planning team at ARC and the University of Colorado (Boulder) performed the pre-mission planning phase in Spring 2013. The team used satellite imagery of the lunar analog test site – the ARC Roverscape – at a resolution comparable to what is currently available for the Moon (0.75 m/pixel), and a digital elevation map (1.5 m/post) to select a nominal site for the telescope deployment. In addition, the planning team created a set of rover task sequences to scout and survey the site, looking for potential hazards and obstacles to deployment.

On June 17, 2013, in Crew Session 1, the K10 rover was remotely operated to survey the test site and to begin deployment of a simulated telescope array. The surface-level survey data collected with K10 enabled assessment of surface characteristics, such as terrain obstacles, slopes, and undulations that are either below the resolution, or ambiguous due to the nadir pointing orientation, of orbital images. During Crew Session 2, on July 26, 2013, K10 was used to deploy all three "arms" of the array. As operations were running ahead of schedule, we were also able to start the inspection phase of the mission. Crew Session 3 occurred on August 20, 2013. Seeing how quickly crew accomplished their tasks in Sessions 1 and 2, we started Session 3 midway through the deployment phase, and then performed remote visual inspection of the telescope. The primary objective was to obtain oblique, high-resolution camera views to document the deployed array. This overlap between sessions, though originally unplanned, enabled us to better assess rover performance across sessions and across astronauts.

5 Data Analysis

Each test session with an astronaut consisted of three parts – pre-operations, operations, and post-operations. Activities during pre-operations included crew training, crew conference, and robot setup for operations. Activities during post-operations were crew debrief and rover shutdown. Activities during operations accomplished the simulated mission. Figure 3 shows the percentage of the total phase time spent on operational activities for all phases of all sessions. Metrics for rover utilization and task performance are based on these activities.

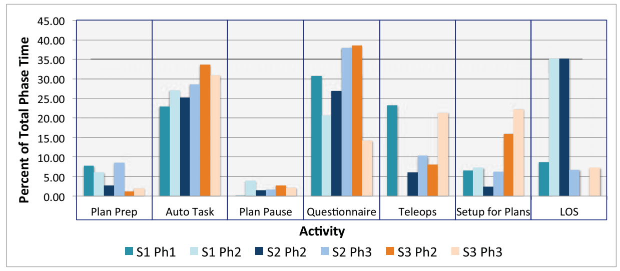

Figure 3 Activities performed by phase

We define the activities performed during operations below.

Plan preparation is the time between uploading a plan to the rover and starting the execution of that plan. In general, plan preparation time was low, ranging from 1%- 9% of the total phase time. In general, the astronaut in Session 1 waited longer to start rover plans than the astronauts in Sessions 2 and 3. This astronaut would always inspect the plan after uploading it to orient himself about what was going to happen before starting the plan. Note that the increased plan preparation time in Session 2 Phase 3 resulted from the astronaut being called away from the experiment after uploading the plan.

Autonomous task execution is the time the rover spent performing planned tasks. The crew supervised these autonomous rover activities. The percentage of the phase time spent in autonomous task execution ranged from 23% - 34%.

Plan pause time is the time the rover transitions between tasks in the plan. This time was below 5% of total phase time for all phases of all sessions.

Questionnaire time is the time each astronaut spent filling out the questionnaires on situation awareness and workload. The rover was idle during these time periods. A significant amount of phase time was spent answering questionnaires, ranging from 15% -38% of the total operation. One reason this activity took so much time was that 8-9 questionnaires were collected for each session. Also problems with the questionnaire format not working correctly on the Space Station Computers added time to this activity.

Teleoperations time is the time the astronaut manually operated the rover. For these experiments, teleoperations were performed using simple plans that translated or rotated the rover by a fixed amount, e.g., drive forward by 1 meter. The astronaut could sequence these simple plans to perform more complex teleoperations. Teleoperations were performed in response to problems that were inserted into the simulated operations. Problems included a panoramic image taken from the wrong heading and an obstacle that prevented the rover from moving to the next waypoint. These are further described in the Crew Intervention section below. Teleoperations time ranged from 6% - 24% of phase time.

Plan setup time was the time needed to setup the next phase of activity. When possible this activity was done between phases or during Loss of Signal (LOS), which kept plan setup time low for Sessions 1 and 2. This time was higher in Session 3 because it was necessary to interrupt the simulated activity to perform the setup.

LOS time was time when the ISS was out of communication with Earth. This time varied from 0% - 35% of the phase and was not part of the experimental design (i.e., was determined by the time assigned for the session).

Operations are further partitioned into in-sim and out-of-sim activities. In-sim activities include setting up for plans, preparing to execute a rover plan, executing autonomous tasks from plan, and pausing autonomy within plan. Out-of-sim activities include answering questionnaires and time in LOS. Time in LOS is considered out-of-sim because, during an actual L2 mission, the crew should be in continuous communication with the planetary rover. Note that plan setup includes such activities as reconfiguring the rover and restarting support software.

Two mission phases were performed in-sim for each session. For Session 1, the astronaut and rover performed site survey (Phase 1) and antenna deployment (Phase 2). For both Sessions 2 and 3, the astronaut and rover performed antenna deployment (Phase 2) and antenna inspection (Phase 3).

5.1 Rover Task Performance

Robot task performance metrics characterize how well the robot performs assigned tasks. For Surface Telerobotics, rover tasks were represented as plans. A set of plans was prebuilt for each phase of activity. Two phases were scheduled for each session. Operational time with the Station astronauts was limited to 2 hours. As a result, it was not possible to complete two entire phases in one session. To allow time to complete Phase 3, we started Session 3 part way through Phase 2 (at plan 2.04).

For Session 1, all 6 plans in Phase 1 (site survey) were completed and 6 of 7 plans in Phase 2 (antenna deployment) were completed. The last plan of this session (Plan 2.06) was aborted before completion due to a failure on the rover's USB bus. The 10 minutes remaining in the session were deemed insufficient to switch to the backup rover and continue the mission. For Session 2, all 7 plans in Phase 2 (antenna deployment) were completed and 6 of 9 plans in Phase 3 (antenna inspection) were completed. Plan 2.06 was reloaded part way through execution, because it was necessary to restart the Workbench software on the ISS after LOS. For Session 3 the last 4 of 7 plans in Phase 2 (antenna deployment) were performed and all 9 plans in Phase 3 (antenna inspection) were performed.

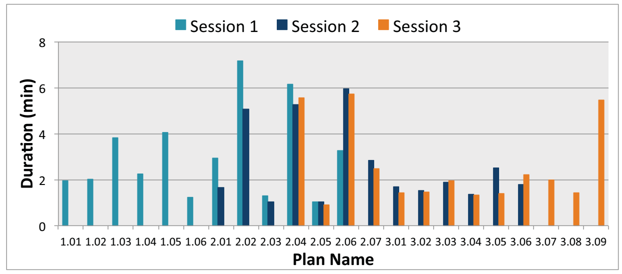

Figure 4 Total time performing plans for all sessions

The timeliness of robot task performance is a function of the time spent performing plans. The total time in plan is the sum of plan prep time, auto task time, and plan pause time, using the activity definitions in Figure 3. Figure 4 shows the actual time executing plans for all sessions. The Phase 2 plans (antenna deployment) in Session 1 took longer than in other sessions. This resulted from the Session 1 astronaut taking longer to start plans and inspect the images of the film collected during deployment than the other astronauts. Session 1 Plan 2.06 took less time because this plan was aborted part way through the deployment. Session 2 Plan 3.05 took longer because the astronaut was called away from the experiment during the plan. Otherwise the time in plan agrees well across sessions.

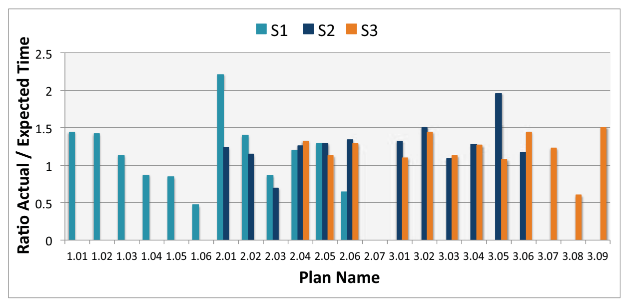

Figure 5 Ratio of actual to expected time in plan for all sessions

Figure 5 shows the ratio of the actual time executing plans to the expected time to execute these plans. A ratio of 1 indicates that the plan was executed in the expected time period. When this ratio is less than 1, the plan took less time than expected. When this ratio is greater than 1, the plan took more time than expected. With a few exceptions, the ratio of actual time in plan to expected time in plan varied between 0.5 and 1.5. Most of the variability not explained above is attributed to the difficulty of estimating of the time required for traverse tasks.

Operator Assessment

We assessed the crew's situation awareness (SA) using Endsley's three level model [9]:

- Level 1 (Perception): What are the status, attributes, and dynamics of the elements relating to the environment, system, people, etc.?
- Level 2 (Comprehension): What is the impact of the perceptions?
- Level 3 (Projection): How are future states affected?

In addition, we used the five awareness categories defined by the LASSO technique [10] to characterize the crew's SA in terms of the robot's: *Location, Activities, Surroundings, Status,* and *Mission*.

To develop SAGAT [11] questions, we first performed task analysis, which we cross-referenced to the awareness categories. We then created questions spanning all SA levels. These questions included:

- Is the rover's navigation subsystem active? (SA Level – I; Status)
- Do you have enough battery life to complete the current task? (SA Level – II; Mission)
- If you teleoperated the robot at this moment, would it be safe to manually turn 1m to the right? (SA Level – III; Surroundings).

To assess crew workload, we employed the Bedford Workload Scale (BWS) [12]. The BWS is a ten-point interval rating scale, which is based on the concept of "spare capacity" and which is encoded as a decision tree chart. The BWS provides subjective ratings of workload during (or immediately following) task performance.

Table 1. SA levels (% of test session operations)

	Session 1	Session 2	Session 3
Perception	100%	71%	67%
Comprehension	89%	67%	89%
Projection	89%	100%	89%

Table 2. SAGAT responses by awareness category (correct / total)

	Session 1	Session 2	Session 3
Location	2 / 2	1 / 1	0 / 0
Activity	2 / 2	1 / 2	5 / 5
Surroundings	11 / 11	7 / 7	6 / 7
Status	2 / 2	3 / 3	1 / 1
Mission	8 / 10	4 / 7	10 / 14
Total (% Correct)	25 / 27 (93%)	16 / 20 (80%)	22 / 27 (81%)

We presented SAGAT questions and the BWS chart to crew at random times throughout each session on a secondary laptop. Crew was required to look away from the primary laptop that hosted the rover user interface while answering the questions and assessing workload. In total, we acquired responses to 74 SAGAT questions and made 26 measurements of workload.

Overall, we observed that all three crewmembers were able to maintain good SA with low workload during operations. Table 1 shows that each operator was able to maintain all three SA levels more than 67% of the time. Table 2 summarizes SAGAT responses by awareness category. During Session 1, for example, the operator correctly answered 100% of the "Surroundings" questions and 93% correct overall. Because we designed the test sessions to be increasingly difficult (in terms of task sequence complexity, number of contingencies, etc.), we expected SA to decrease between Session 1 and 3. The data confirms that this was, in fact, the case.

All three crew consistently reported low workload throughout their respective test sessions. During Session 1, workload varied on the BWS scale between 2 (low) and 3 (spare capacity for all desired additional tasks). In Session 2, workload was consistently and continuously 2 (low). Finally, during Session 3, workload ranged from 1 (insignificant) to 2 (low).

5.2 Rover Utilization

Rover utilization metrics are computed by (1) partitioning each phase into meaningful categories of work and rest (called *wait periods*), (2) detecting events that indicate transitions between these categories, and (3) aggregating the time spent in each category. The work and wait periods are defined such that only one category applies at any time. In Figure 6 activities are designated as time when the rover was working, when the rover was waiting, or out-of-sim. The sum of time when the rover was working and waiting is the time in-sim.

Rover utilization is measured by comparing the percentage of the in-sim time the rover spent performing tasks (i.e., working) to the time the rover waited for tasks (i.e., waiting). We excluded time spent filling out questionnaires and time in LOS because we consider these activities to be out-of-sim. Based on these definitions, the rover spent from 65% to 80% of the in-sim time working on tasks. Figure 7 shows rover utilization metrics comparing the percentage of the in-sim time the rover was working on tasks to the percentage the rover spent waiting for a task.

Rover utilization also is measured in terms of the distance traveled while executing plans. We compute the distance traveled in each plan for each session, and compare values across sessions in Figure 8. When a plan was performed in more than one session, the distance traveled in the plan agrees well across sessions, except when the plan includes periods of teleoperations. The total distance traveled for each session was as follows: 1) Session 1 - 221.43 meters, 2) Session 2 -170.14 meters, and 3) Session 3 - 200.15 meters.

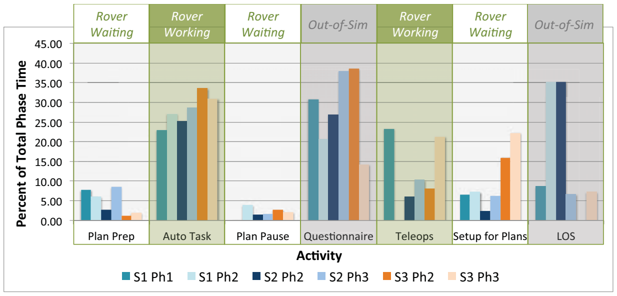

Figure 6 Designation of activities as In-Sim or Out-of-Sim

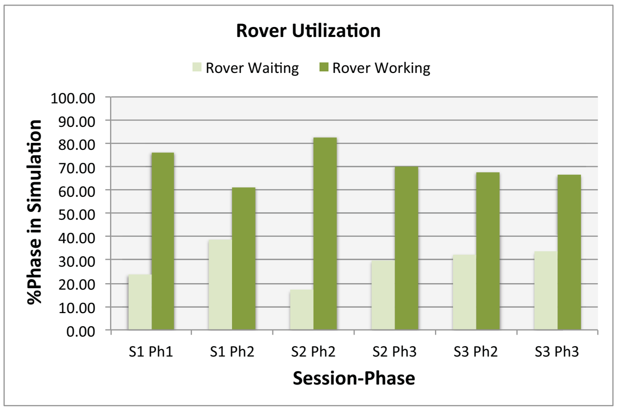

Figure 7 Rover utilization by phase

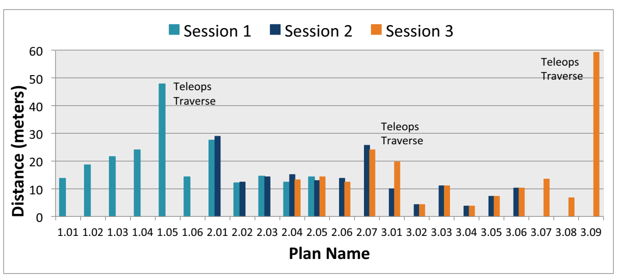

Figure 8 Distance travelled by plan for each session

5.3 Crew Intervention

In developing the Surface Telerobotics experiment, given our extremely limited crew training time, we decided to deal with crew intervention in a very strictly planned and controlled way. The ground team would handle any unexpected occurrences, such as a rover hardware failure or a software crash. Crew was only asked to intervene in the robot's autonomous task execution for three very specific events or contingencies: low battery level, inaccurate camera pointing, and impassible obstacle. Our goal was to observe whether the crew GUI provided enough situation awareness for the crew to understand the occurrence, and the proper tools to address it.

If the battery level dropped below 50%, crew was instructed to allow the rover to finish its currently executing task sequence and then call ground. If the battery level dropped below 25%, crew was to immediately stop the rover and call ground. The ground team injected battery level contingencies by manually adjusting the reported battery level on the robot. In the GUI, the battery indicator lit up at 50%, but there was no additional alert at 25%, and as might be expected, it often took crew longer to notice the drop below 25%. We describe the crew's feedback on battery contingencies in the User Feedback section below.

During the inspection phase, astronauts were asked to make sure that the panoramic images of a deployed antenna contained a view of the metal weight bar that had three yellow stripes (simulating a suspected flaw in the antenna). If he or she could not see that bar, the astronaut was to rotate the rover and command a new image acquisition. We injected inaccurate camera pointing contingencies by actually instructing the rover to point in an incorrect direction within the task sequence. In every instance, astronauts noticed the incorrect pointing and reoriented the robot to retake those images.

Finally, in case the rover encountered a large obstacle that it could not work itself around, crew was instructed to pause the task sequence and take over manual control of the robot to move it around the obstacle before resuming sequence execution. When pre-planning the rover traverses, we set up deliberate rover traps (box canyons) from which, with global path planning turned off, the rover could not find a safe route. These were very obvious contingencies that the astronaut could not fail to notice, however we did see differing strategies on overcoming the obstacle, ranging from just getting clear of the obstacle before resuming the plan, to teleoperating all the way to the next waypoint. Despite differences in style, all crewmembers were successful in handling the obstacle contingency.

5.4 Crew Training

Our training approach was just-in-time, on-board training. Training materials consisted of the Surface Telerobotics Workbench GUI software, the GUI User's Manual, a 2-page printed reference sheet with a legend of the color coding for elements of the GUI's 3D view, and 2 pre-loaded task sequences that exercised the various capabilities of the rover. Shortly before the Surface Telerobotics operations session, each subject was given 40 minutes for training. Ground controllers had started the GUI on a crew laptop and the rover was on-line and ready to operate. Astronauts were told to read the manual and "play with the rover." They were free to explore and move at their own pace.

Although it was not originally part of our experiment design, we decided to analyze video of the crew training sessions to see if there were any discernable differences in the training styles of the crewmembers and whether those differences showed in the subsequent performance during operations. We had 3 subjects performing 3 different tasks, so no statistical results can be obtained, however we can make a few anecdotal observations.

Firstly, despite differences in training styles, all the subjects performed at a high level, based on the survey/metric data gathered to assess SA, but not perfectly. This leads us to believe that our measures have real sensitivity. The first subject was very conservative and methodical in his approach to training. He was slow to issue commands and appeared to read the manual while controlling the robot. In contrast, the second subject was very proactive in his training and appeared to frequently refer to the icon legend sheet. Finally, the third subject performed her training in a style somewhere in between the previous two. We also observed that while there was an issue with the panorama function during her training session, the third subject was aware of it but appeared completely unfazed and continued on with her work.

Possible reasons for the differences in training include personality differences or communication between crewmembers between sessions. For instance, during Sessions 1 and 2, it is clear from the video that the subject is talking to a second crewmember in the background. Also, when asked during the crew debrief, whether she had had prior discussions about the Surface Telerobotics experiment, Subject 3 replied in the affirmative. Although she could not recall the exact content of her discussion, she said it was at a pretty high level. However, while the later 2 subjects appeared to benefit from an institutional knowledge within the crew during training, there was no significant difference in performance during operations between the 3 subjects. This points to a learning curve for the UI that is steep, but asymptotes very quickly.

Given that the crew performed well despite having varying amounts of exposure to the system, having different styles of approaching the open-ended "sandbox" training protocol, and performing different tasks in the various phases of the mission, this provides strong anecdotal evidence to suggest that the interface was effectively designed to meet the measured task objectives, as observed behavior was robust to all of these uncontrolled differences.

6 User Feedback

Almost immediately after Surface Telerobotics mission operations, we spent approximately half an hour debriefing each crewmember. We asked question designed to elicit feedback on specific topics relating to the user interface, the robot, and training. Topics included: awareness of robot activities, awareness of robot problems, task allocation, robot functionality, directing the robot, decision-making, awareness of the environment, availability and timeliness of information, just-in-time training, and design and evaluation of automation interfaces.

We received an overall positive response from each of the astronauts, with each of them feeling that operations had generally gone well and that they had had a lot of fun controlling a robot on the ground. They each responded that they felt they had the information they needed to complete their tasks and their situation awareness was high.

Crew demonstrated a good understanding of the rover's environment. They stated that the visualization tools (3D visualization and live imagery) were very effective.

Crewmembers could generally tell when the rover encountered a problem, though they would often miss when the battery level first dropped below 25%. This was in part because, while the battery indicator lit up at 50%, there was no additional alert at 25%. Crewmembers expressed some frustration with not knowing how long the battery level had been low before noticing it and suggested the addition of sound alerts.

Understanding battery behavior was of particular interest to the crew, as they had been asked to respond to its levels. They found it difficult to develop a mental model of its behavior, since they were unaware that we were manually changing the indicator value, and they requested some sort of indication from the user interface of how much time was left on the battery.

Crew demonstrated a good understanding of the robot's capabilities and developed trust in the rover quickly. However, crew noted that they would have liked better insight into the robot's intentions, as the reasons for some of its maneuvers were unclear. Despite a communication latency to the robot that was at most 1-2 seconds, crewmembers felt the robot was responsive to their commanding.

The astronauts felt that the just-in-time training was sufficient, and when asked if they would want to practice controlling the robot if they were asked to perform operations again, universally responded that it would be unnecessary.

7 Conclusions

Interactive control of a mobile surface robot by an astronaut in low earth orbit was demonstrated successfully in all sessions of this experiment. Data analysis indicates that command sequencing with interactive monitoring is an effective strategy for crew-centric surface telerobotics for rover survey, deployment, and inspection tasks: (1) planetary rover autonomy (especially safeguarded driving) enabled the human-robot team to perform missions safely with low crew workload; (2) the crew maintained good situation awareness with low effort using interactive 3D visualization of robot state and activity; and (3) rover utilization was consistently in excess of 50% time. In addition, we observed that crew workload was sufficiently low to posit that they could multi-task during rover operations.

The concept of operations characterized for this experiment assumes high quality communications between astronauts and the rover, and the availability of Earth-based mission support. For future missions where astronauts would operate surface robots from a halo orbit, or distant retrograde orbit, it is important to design the system and operational protocols to work well with variable quality communications (in terms of data rates, latency, availability, etc.) In addition, for deep-space missions, it will also be important to understand how efficiently and effectively a small crew of astronauts can work when operating robots largely independent of mission control support.

Future "Surface Telerobotics" testing with the ISS could be designed to accurately simulate the data rates and latencies involved in an actual lunar far side mission. The planetary rover tasks could also be modified to test different mission objectives, such as field geology or sample collection. The ISS presents a highly configurable and unique opportunity to explore mission constraints with a high-fidelity environment for crew. Potential benefits to future missions include: creating optimized crew training techniques and procedures, reducing operational risk and technology gaps, defining preliminary mission requirements, and estimating development and mission cost.

8 Acknowledgments

First and foremost, we would like to thank Jack Burns, Laura Kruger, and the Lunar University Network for Astrophysics Research (LUNAR) for developing the Orion L2-Farside mission concept and for their support of Surface Telerobotics. We also thank Josh Hopkins, William Pratt, and Chris Norman of Lockheed Martin Corporation for insightful discussions on the Orion spacecraft. Sophie Milam and George Korbel of the University of Idaho developed the polyimide film deployer for K10. Industrial design students from the Academy of Art University in San Francisco collaborated to create the Surface Telerobotics Workbench.

We would like to acknowledge the dedication and tireless effort of the crew office (particularly Chris Cassidy, Luca Parmitano, and Karen Nyberg), the JSC Mission Operations Directorate (particularly Mike Halverson), the NASA Lunar Science Institute, the ISS Tech Demonstration office, and ISS Avionics and Software.

The NASA Technology Demonstration Missions Program (NASA Space Technology Mission Directorate) provided funding for this work.

References

[1] N. Augustine, et al., “Seeking a Human Spaceflight Program Worthy of a Great Nation”, Review of U.S. Human Spaceflight Plans Committee, Doc No. PREX 23.2:SP 1/2, 2009.

[2] D. Korsmeyer, et al. “A Flexible Path for Human and Robotic Space Exploration”, AIAA Space Ops, 2010.

[3] M. Bualat, T. Fong, et al. “Surface telerobotics: development and testing of a crew controlled planetary rover system”, AIAA Space, 2013.

[4] J. Burns, D. Kring, et al. “A Lunar L2-Farside Exploration and Science Mission Concept with the Orion Multi-Purpose Crew Vehicle and a Teleoperated Lander/Rover,” Advances in Space Research 52, 2013.

[5] M. Bualat, W. Carey, et al. “Preparing for Crew-Control of Surface Robots from Orbit”, IAA Space Exploration Conference, 2014.

[6] Flückiger, L., and Utz, H., "Field tested service oriented robotic architecture: Case study," International Symposium on Artificial Intelligence, Robotics, and Automation in Space (iSAIRAS), 2012.

[7] Lee, S. Y., et al, “Reusable science tools for analog exploration missions: xGDS Web Tools, VERVE, and Gigapan Voyage,” Acta Astronautica, Vol. 90, No. 2, October 2013, pp. 268-288.

[8] Torres, R. J., Allan, M., Hirsh, R., Wallick, M.N., “RAPID: Collaboration results from three NASA centers in commanding/monitoring lunar assets,” IEEE Aerospace Conference, IEEE, 2009.

[9] Endsley, M., “Toward a theory of situation awareness in dynamic systems,” Human Factors, Vol. 37, No. 1, 1995. pp. 32–64.

[10] Drury, J., Keyes, B., and Yanco, H., “LASSOing HRI: Analyzing situation awareness in map-centric and video-centric interfaces,” Second Annual Conference on Human-Robot Interaction, ACM/IEEE, 2007.

[11] Endsley, M., “Situation awareness global assessment technique (SAGAT),” National Aerospace and Electronics Conference, IEEE, 1988.

[12] Roscoe, A. and Ellis, G., “A subjective rating scale for assessing pilot workload in flight: a decade of practical use,” Technical Report TR 90019, Royal Aerospace Establishment, 1990.