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TESTING ASTRONAUT-CONTROLLED TELEROBOTIC OPERATION OF ROVERS FROM THE INTERNATIONAL SPACE STATION AS A PRECURSOR TO LUNAR MISSIONS

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Missions to Earth-Moon libration points can advance capabilities for human exploration and provide unique opportunities to advance scientific knowledge. For example, NASA's Orion spacecraft, currently under development, could serve as a platform from which astronauts would explore the lunar farside using robots that they remotely operate from a libration point. During Summer 2013, we conducted initial testing of this "surface telerobotics" concept of operations using the International Space Station (ISS) as a proxy for Orion orbiting the Moon. Over the course of three test sessions, Expedition 36 astronauts Chris Cassidy, Luca Parmitano, and Karen Nyberg on the ISS remotely operated NASA's "K10" planetary rover in an outdoor terrain located at the NASA Ames Research Center (ARC). In this paper, we discuss the motivation for Earth-Moon libration point missions, describe the surface telerobotics tests performed to date, and outline directions for future ISS testing.

I. EARTH-MOON LIBRATION POINT MISSION

The Global Exploration Roadmap (GER) recommends that space agencies "develop the knowledge, capabilities, and infrastructure required to live and work at destinations beyond low-Earth orbit through development and testing of advanced technologies, reliable systems, and efficient operations concepts in an off-Earth environment"[10]. In the framework of a larger exploration strategy, Earth-Moon libration points provide both an avenue to develop expertise needed for longer-duration missions in deep space and a platform to help discover answers to critical scientific questions concerning the origin and evolution of our solar system. Potential mission objectives include performing real-time telerobotic exploration on the lunar surface, operating a libration point outpost to practice operations needed for deep-space exploration, and establishing an "interplanetary gateway", or assembly point for missions to more distant destinations.

Of the five Earth-Moon (EM) libration points, the two most relevant for human exploration are those closest to the Moon, i.e., EM-L1 and EM-L2. These two libration points are positioned above the nearside and farside of the Moon, respectively, as viewed from Earth. Though both are within reach of the Orion exploration vehicle currently being developed by NASA, and useful mission objectives could be performed at either location, EM-L2 is the better location for an early exploration mission. By taking advantage of a lunar flyby trajectory first identified by Farquhar[7], the delta-V (ΔV) to reach EM-L2 can be lower than EM-L1 despite the greater distance from Earth[8]. A crew-controlled telerobotics mission to the lunar farside from the EM-L2 region has been studied and shown to be within the capabilities of the Orion Multi-Purpose Crew Vehicle (MPCV)[4,20].

II. ORION MPCV L2 FARSIDE MISSION

II.I. Overview

There are two primary objectives for the "Orion MPCV L2-Farside Mission"[4,20]. The first would be to return multiple rock samples from the Moon's South Pole–Aitken (SPA) basin to Earth. A sample return from SPA was designated as a priority science objective in the National Research Council (NRC) Planetary Sciences Decadal Survey[18] as well as the NRC report on lunar exploration[16]. The second objective would be to deploy a low frequency radio telescope to explore the currently unobserved "Dark Ages" and "Cosmic Dawn" epochs of the early Universe. Such observations were identified as one of the top science objectives in the NRC Astrophysics Decadal Survey[17], as well as in the recently published NASA Astrophysics Roadmap[15].

Telerobotic oversight from an orbiting Orion MPCV would demonstrate capability for human and robotic cooperation on future, more complex, deep space, missions, such as exploring Mars. An Orion mission involving a halo orbit at EM-L2 would, for example, enable maturation of capabilities such as life support, communication, high-speed re-entry, and radiation protection prior to human exploration missions beyond cis-lunar space. Most importantly, this mission would provide crucial operational experience for proximity operations at Near Earth Asteroids and telerobotic control from Mars orbit[21]. In particular, this mission would demonstrate how astronauts can use a telerobot to be "virtually present" and to perform extra-vehicular activities, including field work requiring precision mobility, repetitive actions, and long-distance operations.

Crew-controlled surface telerobotics from EM-L2 would provide several key benefits. For example, the proximity between human spacecraft and robot (two-way speed of light latency is only 0.4 seconds) would allow for real-time, point-to-point data communications[14]. Such a link would enable computationally expensive processing (e.g., terrain hazard assessment) to be off-loaded from the robot to the spacecraft. Consequently, a simpler, cheaper robot (i.e., one that has minimal "rad-hard" computing) could be employed. Also, remote driving using manual control could potentially achieve speeds similar to Apollo (10 km/hr vs. 0.09 km/hr for the Curiosity rover on Mars), which would allow exploration operations to be performed across a significant area during the 14-day lunar day.

II.II.Radio astronomy from the lunar farside

The "New Worlds, New Horizons in Astronomy and Astrophysics" Decadal Survey[17] identified "Cosmic Dawn" as one of the three science objectives guiding the science program for this decade. The Survey asked, "What were the first objects to light up the Universe and when did they do it?" In other words, how and when did the first stars, galaxies, and quasars form in the early Universe leading to the rich structure that we observe today with observatories, such as the Hubble Space Telescope?

To address these questions, we must understand the evolution of the intergalactic medium (IGM) from an initially neutral state to a nearly completely ionized state, identifying when and what the first luminous sources were, and developing the observational capabilities to track the evolution of the early Universe. During the "Dark Ages" ($<10^8$ yrs after the Big Bang), gravity slowly condensed the gas into denser and denser regions. Theoretical models predict that the first stars eventually appeared in the densest regions, where sufficient gas was present for cooling and star formation.

It is possible to study the first luminous sources through their effects on the IGM. In particular, the "spin-flip" transition of neutral hydrogen, with an observed frequency of <100 MHz, is an ideal probe of Cosmic Dawn, as it provides a sensitive probe of the radiation fields generated by the first sources of light. This signal, while generated by an extraordinarily weak hyperfine transition, is nevertheless observable because of the huge volume of neutral hydrogen in the Universe at the onset of Cosmic Dawn. Numerous groups propose using the Moon as a platform for probing Cosmic Dawn via radio astronomy observations. In particular, at low radio frequencies (<100 MHz), the lunar farside is the only location in the inner solar system that is free of human-generated radio frequency interference and is also uninhibited by ionospheric effects, which can severely interfere with measurements made from terrestrial (ground-based) and Earth orbit observatories.

One intriguing concept for establishing a low frequency radio array on the lunar surface involves the use of polyimide film as a backbone for metallic, dipole antenna elements imprinted on the substrate of the film[12]. This approach has the advantage of being lightweight and easily deployable by a rover, which could simply unroll the polyimide film (Figure 1) as it moves along the lunar surface. Small arrays using polyimide film antennas would help prepare for the creation of larger, more extensive interferometric arrays as advocated by the NASA Astrophysics Roadmap[15].

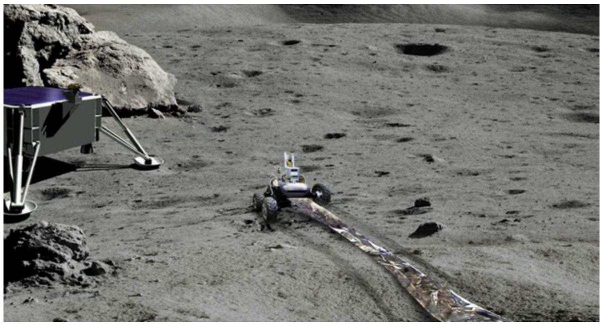

Figure 1. Artist's impression of teleoperated rover on lunar farside deploying a polyimide antenna.

II.III.Farside coverage

The EM-L2 libration point offers line-of-sight communications visibility to several scientifically interesting sites on the lunar farside (Figure 2). These include the geologically important South Pole-Aitken (SPA) Basin and Schrödinger Basin. A class of three-body orbits called halo orbits around EM-L2, roughly 65,000 km beyond the Moon, provides a good location for a communications relay to any of these sites. More specifically, our studies have shown that small amplitude, southern-class EM-L2 halo orbits would have continuous visibility to most of the lunar farside, and intermittent access to the limb and polar regions[11]. Even in some areas of intermittent visibility, such as Schrödinger Basin (Figure 2 inset), the duration of communication can be long enough to cover a full period of daylight (14 Earth days).

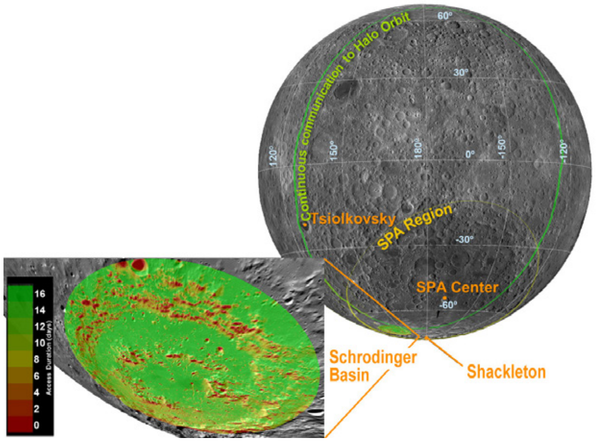

Figure 2. A halo orbit at EM-L2 can provide continuous coverage to a large portion of the lunar farside.

II.IV.Mission design

Figure 3 depicts a candidate 21-day trajectory for the Orion MPCV that would take astronauts over the lunar farside for approximately 13.5 days. Initially, Orion would leave Earth after the Trans-Lunar Injection (TLI) burn on a free-return trajectory around the Moon. The free-return trajectory is a safety feature that allows for a non-propulsive safe return to Earth in the event of an emergency. This is similar to the concept of operations used for the Apollo lunar missions.

One day after TLI, Orion would execute a propulsive maneuver, putting it on a course to fly by the trailing side of the Moon. Near its closest approach to the Moon, Orion would perform a powered flyby, using both gravitational assist from the Moon and a propulsive maneuver, which would direct it toward EM-L2.

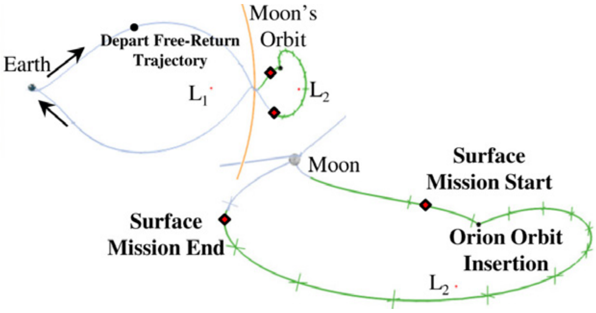

Figure 3. Illustration of a 21-day Orion MPCV mission. Trajectory (shown in green) tick marks indicate daily increments where direct, line-of-sight communications to the lunar farside is possible.

A few hours after lunar flyby, Orion would acquire line-of-sight visibility to the lunar farside. Within a day of the start of the surface mission, Orion would then perform a maneuver that puts it on the target EM-L2 manifold trajectory. Once completed, Orion would be on a coasting trajectory that flies by the Moon again about 12 days later to target an Earth return trajectory.

During the surface mission, the range from Orion to the lunar surface would vary between 40,000 km and 80,000 km, with an average distance of approximately 69,000 km. At these distances, a reasonably sized Ka-band communication system on the rover would permit data rates over 1 Mbps. Figure 4 illustrates the variation in data rate as a function of distance for three different combinations of rover transmitter size, power, and frequency. The plot shows that a trajectory that keeps Orion as close to the Moon as possible during the surface mission is desirable. For example, the achievable communications data rate at 50,000 km distance is four times higher than it would be at 100,000 km.

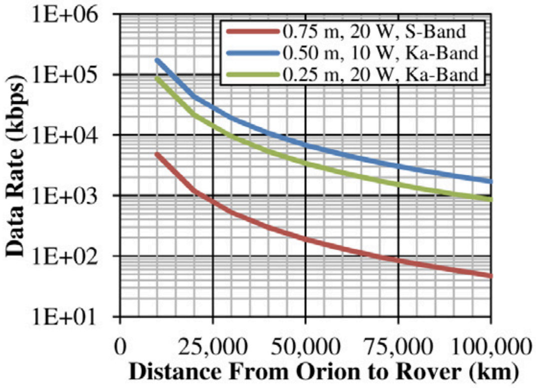

Figure 4. Communications rate for various combinations of rover antenna, transmitter power, and frequency. All curves assume a 0.75 m Orion antenna.

III. SURFACE TELEROBOTICS TESTS

III.I. Overview

To examine the concept of operations central to the Orion MPCV L2-Farside mission, we developed a series of ISS tests called "Surface Telerobotics". These tests were designed to study one possible system design for crew-controlled telerobotics[1,2,9].

Surface Telerobotics had three primary objectives: (1) Demonstrate interactive 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; and (3) Characterize system utilization and operator workload for a single astronaut remotely operating a planetary rover with limited support from ground control.

III.II.Implementation

During Summer 2013, we utilized the ISS as a proxy for the Orion MPCV at EM-L2. Over the course of three test sessions, Astronauts Chris Cassidy, Luca Parmitano, and Karen Nyberg on the ISS remotely operated NASA's “K10” planetary rover in the NASA Ames “Roverscape” (Figure 5), which is an analogue lunar terrain. The astronauts used a Space Station Computer (Lenovo Thinkpad laptop), supervisory control (command sequencing with interactive monitoring), teleoperation (discrete commanding), and Ku-band satellite communications to operate K10 for a combined total of 11 hours.

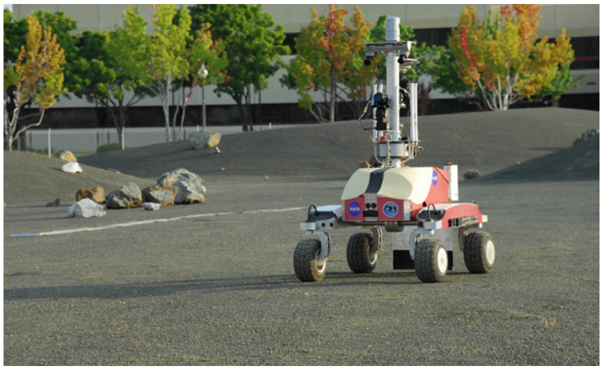

Figure 5. The K10 planetary rover driving in the NASA Ames Roverscape (Moffett Field, California).

The K10 planetary rover has four-wheel drive with all-wheel steering on a passive averaging suspension. The rover measures 1.1m (length) x 0.9m (width) x 1.3m (height). K10 is capable of autonomous driving on moderately rough, natural terrain at up to 90 cm/s. K10’s standard sensors include a differential GPS system and inertial measurement unit, a digital compass, stereo cameras, a scanning lidar, and wheel encoders. K10’s controller runs on a Linux-based computer and communicates via an 802.11g mesh wireless system.

For Surface Telerobotics, we equipped K10 with two cameras: a panoramic imager and an inspection imager. These cameras provide high-resolution, color imaging of illuminated areas. The panoramic camera is based on a consumer-grade, 12 megapixel, digital camera on a computer controlled pan-tilt unit. We operate the camera at 350 rad/pixel, which is comparable to the Mars Exploration Rover Pancam (280 rad/pixel). In addition, we developed and integrated a custom device to deploy a simulated plastic film-based radio telescope.

ISS crew remotely operated K10 using the “Surface Telerobotics Workbench” (Figure 6), which is a robot user interface that we developed to run on a Space Station Computer (crew laptop). The Workbench enables an astronaut to direct K10 to execute plans (command sequences) autonomously, to interactively monitor the rover while executing these plans, and to teleoperate the rover (using discrete commands) when manual intervention is required. Each plan consists of a sequence of rover activities. Activities include drive to a location, acquire a panoramic image, and deploy film. The user directs the rover by selecting a plan in the Workbench and sending it to the rover for execution. Data about plan execution are passed from the rover to the Workbench and used to annotate plan progress in the Workbench.

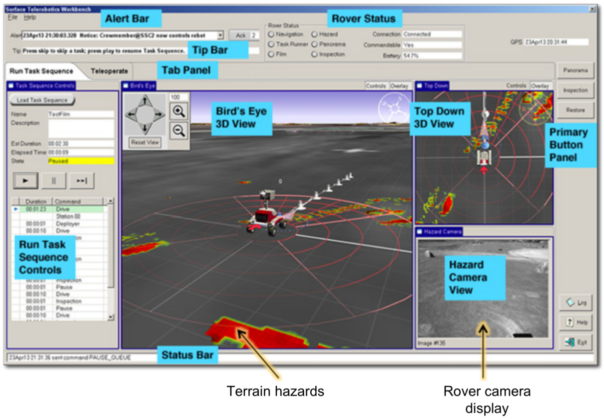

Figure 6. The Surface Telerobotics Workbench was used by ISS astronauts to remotely operate K10.

The Workbench 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[13]. 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)[23].

Figure 7 shows the communications configuration that was used for the Surface Telerobotics tests. Voice communications were carried over standard ISS payload voice loops. The Rover Operations Lead at NASA ARC communicated with the Payload Operations Director (POD) and Payload Communications Manager (PAYCOM) at the NASA Marshall Space Flight Center (MSFC) over the POD loop. Information for crew was relayed through PAYCOM to ISS via the “Space To Ground” loop. Communication among the ground support team and the ISS Mission Control Center (MCC) occurred over the “SS Coord” loop. K10 commands and telemetry were carried through a network data connection between the rover and the MCC, which used a proxy server on the MCC network. From there, traffic between the crew laptop and the proxy server uses standard ISS Ku-band data communications through the Tracking and Data Relay Satellite System (TDRSS).

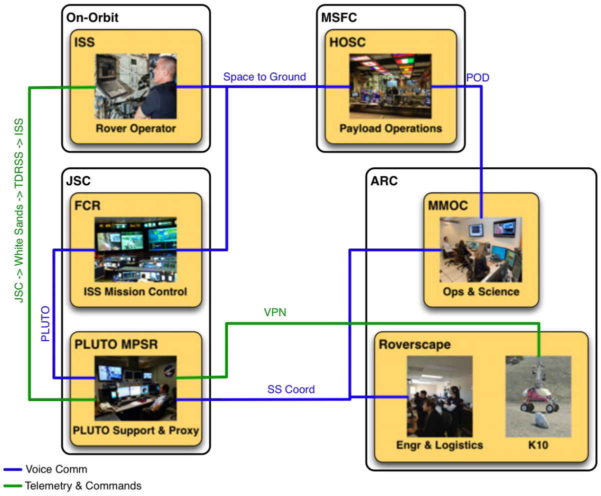

Figure 7. Communications for Surface Telerobotics included voice loops (blue) and data (green).

Except during scheduled loss-of-signal periods, all three test sessions were performed with a round-trip data communications latency of 500-750 msec, an average downlink (ISS-to-K10 commands) data rate of less than 3 Kbit/s, and an average uplink (K10-to-ISS telemetry) data rate of approx. 1 Mbit/s.

III.III.Testing during ISS Expedition 36

We carried out Surface Telerobotics tests as a simulated lunar libration point mission with four sequential phases: pre-mission planning (Phase 0), site survey (Phase 1), telescope deployment (Phase 2), and documentation of the telescope (Phase 3). After Phase 0, which involved only remote sensing data, we performed the other three phases during test sessions with the ISS Expedition 36 crew. Since none of the astronauts had prior experience with K10 or the Workbench, each session included an hour of "just in time" training with both. After training, each astronaut remotely operated K10 for approximately two hours.

We performed pre-mission planning in Spring 2013. A mission planning team at NASA Ames Research Center and the University of Colorado (Boulder) used satellite imagery of a lunar analog test site 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, NASA Astronaut Chris Cassidy remotely operated the K10 rover during Session 1 to perform site survey (Phase 1) of the NASA Ames Roverscape (Figure 8). The survey data collected with K10 enabled assessment of site characteristics, including boulders, slopes, and other terrain features. Surface-level survey complements remote sensing data by providing measurements at resolutions and from viewpoints not achievable from orbit. In particular, K10 provided close-up, oblique views of the telescope deployment site. Cassidy also began, but did not complete deployment of the simulated telescope array (Phase 2).

Figure 8. Top: Astronaut Chris Cassidy remotely operating K10 from the ISS (ISS036-E-008908), bottom: K10 performing site survey using on-board cameras and instruments (Phase 1).

During Session 2 on July 26, 2013, ESA Astronaut Luca Parmitano used K10 to perform Phase 2 and fully deployed a simulated telescope array (Figure 9). Parmitano first executed each task sequence with the deployment device disabled, to verify that the sequence is feasible. He then commanded K10 to perform the actual deployment using rolls of polyimide film as a proxy for a polyimide film-based antenna. The three antenna "arms" were deployed in a "Y" pattern, which is a possible configuration for a future lunar radio telescope. Parmitano also began, but did not complete documenting the deployed telescope array (Phase 3).

Seeing how quickly crew accomplished their tasks in the first two test sessions, we started Session 3 on August 20, 2013 midway through telescope deployment (Phase 2). Astronaut Karen Nyberg remotely operated K10 to complete the deployment and then proceeded into Phase 3 (Figure 10). The primary objective of Phase 3 was to acquire high-resolution images of each antenna arm. These images serve two purposes: (1) in-situ, "as built" document of the deployed array; and (2) source data for locating and analyzing potential flaws (tears, kinks, etc. in the material) that may have occurred during deployment.

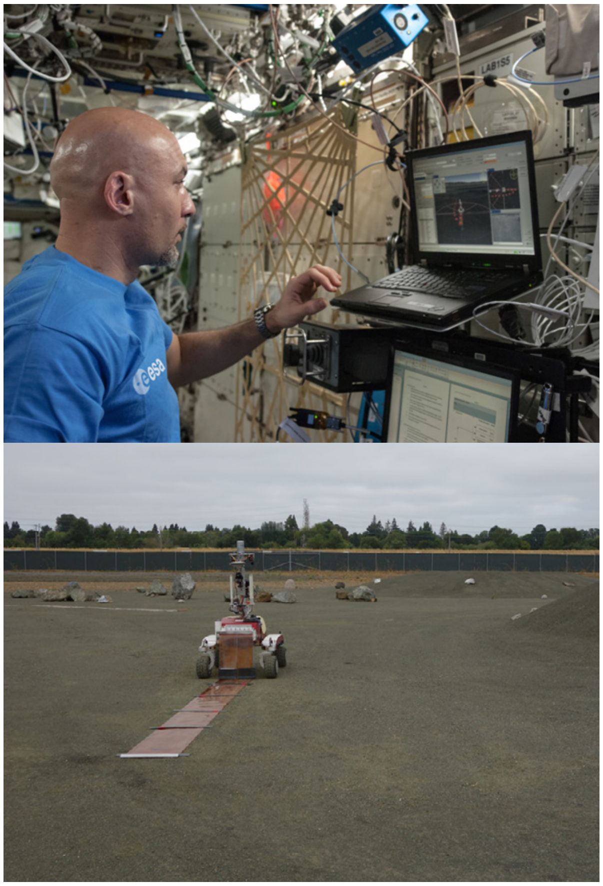

Figure 9. Top: Astronaut Luca Parmitano remotely operating K10 from the ISS (ISS036-E-025012), bottom: K10 deploying polyimide film to simulate lunar telescope deployment (Phase 2).

Figure 10. Top: Astronaut Karen Nyberg remotely operating K10 from the ISS, bottom: K10 documenting a deployed polyimide antenna arm (Phase 3).

III.IV.Results

Two simulated mission phases were performed during each ISS test session. In Session 1, the astronaut used K10 to perform site survey (Phase 1) and partial antenna deployment (Phase 2). In session 2, the astronaut used K10 to perform full antenna deployment (Phase 2) and partial antenna documentation (Phase 3). In Session 3, the astronaut used K10 to perform partial antenna deployment (Phase 2) and full antenna documentation (Phase 3). This overlap of simulated mission phases, enabled us to better assess rover performance across sessions and across astronauts. Figure 11 shows the percentage of the total phase time spent on operational activities for all phases of all sessions.

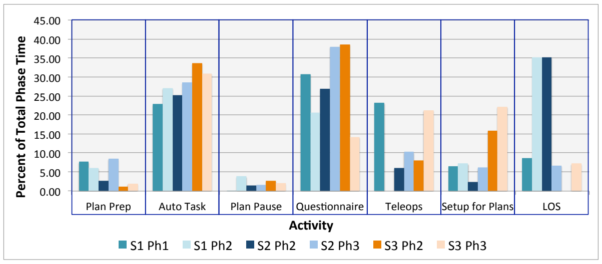

Figure 11. Activities performed during ISS test sessions. "S*X* Ph*Y*" indicates that during Session *X* (1-3) activities for Phase *Y* (1-3) were performed.

For Surface Telerobotics, rover tasks were represented as plans[3]. *Plan preparation* is the time between uploading a plan to the rover and starting the execution of that plan. In general, plan prep time was low, ranging from 1% to 9% of the total phase time. *Autonomous task* execution is the time the rover spent performing planned tasks. The crew supervised these autonomous rover activities. The percentage of the time spent in autonomous task execution ranged from 23% to 34%. *Plan pause* time is the time the rover transitions between tasks in the plan. This time was below 5% of total time for all phases of all sessions. *Questionnaire* time is the time each astronaut spent filling out questionnaires on situation awareness and workload. The rover was idle during these time periods. *Teleoperations* time is the time the astronaut manually operated the rover by issuing discrete commands. Teleoperations time ranged from 6% to 24%. *Plan setup* time was the time needed to setup the next phase of activity. *Loss of Signal (LOS)* time was time when the ISS was out of communication with Earth.

Rover utilization was consistently high throughout all test sessions and all crew interventions were successful. Across the three test sessions, we found that rover utilization was in excess of 50%, i.e., the robot was actively in use more than half the time. Given the limited training that crew received, this performance is surprisingly high. During Session 1, all 6 rover plans in Phase 1 (site survey) were completed and 6 of 7 plans in Phase 2 (antenna deployment) were completed. During Session 2, all 7 plans in Phase 2 (antenna deployment) were completed and 6 of 9 plans in Phase 3 (antenna documentation) were completed. During Session 3 the last 4 of 7 plans in Phase 2 (antenna deployment) were performed and all 9 plans in Phase 3 (antenna documentation) were performed.

Figure 12 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.

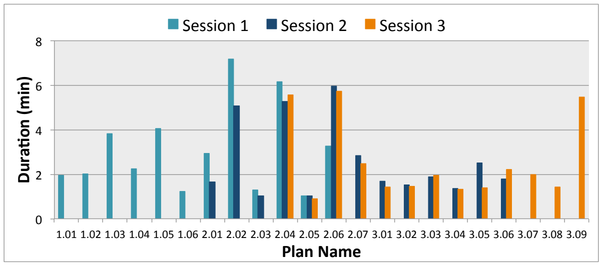

Figure 12. Total time performing rover plans.

Figure 13 shows the ratio of the actual time executing plans to the expected time to execute these plans. A ratio of 1.0 indicates that the plan was executed in exactly expected time. When this ratio is less than 1.0, the plan took less time than expected. When this ratio is greater than 1.0, 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 in plan time can be attributed to the difficulty of estimating the amount of time required for traversing from location to location.

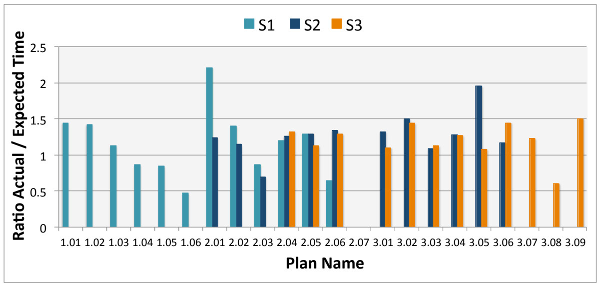

Figure 13. Ratio of actual to expected time in plan for all sessions.

Data analysis indicates that supervisory control is a highly effective strategy for crew-centric surface telerobotics[3]. We found that planetary rover autonomy (especially safeguarded driving) enabled the human-robot team to perform missions safely with low crew workload. Subjective measurements made with the Bedford Workload Scale (BWS)[22] indicate that task load was low. 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. 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).

In addition, from SAGAT questionnaires[5], we determined that all three astronauts were able to maintain a high level of situation awareness (SA) during operations. In particular, we found that each astronaut was able to maintain all three SA levels (perception, comprehension, and projection) in Endsley's model[6] more than 67% of the time.

From post-test debriefs, we determined that interactive 3-D visualization of robot state and activity employed in the Workbench was a key contributing factor to achieving high levels of SA. Additionally, because we designed the test sessions to be increasingly difficult (in terms of task sequence complexity, number of contingencies/difficulties encountered, etc.), we expected SA to decrease between Session 1 and 3. The data confirms that this was the case.

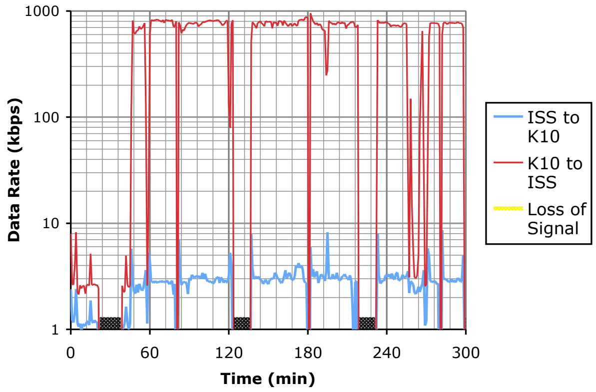

Figure 14. Data communications between ISS and K10 during Session 1. Due to gaps in TDRSS coverage, several "Loss of Signal" (no data communication) periods were encountered during the session.

Data communication between ISS and K10 was very consistent throughout all test sessions. Except for several planned, short duration, "Loss of Signal" periods during each session, bandwidth usage for both ISS-to-K10 commands (downlink) and K10-to-ISS telemetry (uplink) was very uniform.

For example, Figure 14 shows the network bandwidth utilized in Session 1. During the session, ISS-to-K10 commands consumed a nearly constant 3 Kbps of bandwidth during all remote operations, with a peak utilization of approximately 9 kbps. Similarly, K10-to-ISS telemetry consumed a nearly constant 800 Kbps of bandwidth (primarily image transmission), with a peak utilization of just under 1 Mbps.

IV. FUTURE TESTING

The 2013 Surface Telerobotics tests demonstrated how the ISS can be used as a testbed for research and development of crew-controlled telerobotics concepts. Future ISS testing could be designed to examine a variety of different aspects in greater depth, including crew training, data communications, spacecraft facilities, and surface activities.

IV.I.Crew training

Future deep-space exploration missions will require astronauts to be in space for months, or even years, at a time. Consequently, there can be long periods of time between the pre-mission training an astronaut receives on Earth and the use of this training in space. Thus, to ensure appropriate task proficiency, it is necessary to provide training closer to the time when skills are used. This training would have to be performed on a spacecraft during transit, or after arrival while in orbit.

In addition, as humans move deeper into space they must also become more autonomous from mission control on Earth. As a result, astronauts will take on additional responsibilities for jobs typically performed by flight controllers today. This will require efficient techniques for in-mission training, such as "Just In Time" (JIT) training. Increased crew autonomy from Earth also is expected to result in increased use of robot automation. Training techniques should be designed with these new requirements in mind.

Our 2013 tests employed a custom JIT approach, which involved an orientation video, reading material, and short duration practice. This approach appears to be well suited for crew-control of semi-autonomous surface robots. However, additional study is needed to better understand the benefits and risks associated with JIT. For example, additional ISS testing could assess the efficacy of different JIT strategies including: protocols to focus operators on mode awareness and transitions, protocols to focus on task switching, and protocols to focus on skill acquisition. Assessment might involve measuring cognitive workload and task performance using non-invasive monitoring and questionnaires combined with robot performance monitoring.

IV.II.Data communications

A significant benefit of crew-controlled telerobotics performed from orbit is reduced communication latency. For example, remotely operating a lunar rover would take an Earth-bound operator at least 2.5 seconds to observe the results of a sent command (round-trip time including minimal ground station delay)[19]. In practice, the round-trip latency between ground control and a lunar rover using "Direct to Earth" communications and the Deep Space Network would likely vary between 10 to 20 seconds. With an operator at EM-L2, however, latency is reduced to less than 0.5 seconds. In general terms, lower latencies improve telerobotics performance and supports faster operations tempo, particularly when manual control is employed.

The Surface Telerobotics test was performed with round-trip communications latency and data rates that are qualitatively similar to the anticipated values of an EM-L2 crew-controlled telerobotics mission. For a given mission, however, the latency and data rate will be a function of the communication system on both rover and spacecraft (antenna size, beam geometry/pointing, link frequency, radiated power, etc.) and the distance between them. To better understand the impact of communications on telerobotic system design, future tests could be performed to simulate both the latency and data rates of various mission scenarios. Other studies could also be performed to investigate methods for optimizing use of available bandwidth.

Different mission scenarios will require different operating modes, especially in terms of the nature and complexity of surface activities. The ISS test showed that meaningful surface work can be performed with “limited” data rates for missions that contain a higher degree of automation, such as an antenna deployment. For tasks that require a higher degree of human intervention, such as geological sampling, operating modes will have to be designed that make efficient use of the available data rates. This is most applicable to video and imagery. In limited bandwidth scenarios, pixel resolution, compression, frame rate, and other factors can be optimized to fit the current task being performed.

IV.III.Spacecraft facilities

The Surface Telerobotics test demonstrated the ability of an astronaut to perform complex rover tasking with a graphical user interface running on a single Space Station crew laptop. While an actual lunar mission would require additional rover system data and control, it would not necessarily be required to integrate these capabilities directly into the spacecraft flight software or avionics. For example, the Orion vehicle has been designed with the ability to host independent payloads in a manner similar to the ISS. Thus, if a “telerobotics workstation” (e.g., a crew laptop) were plugged into the communication backbone of the Orion vehicle, the workstation would have access to both the data stream back to Earth and to the rover.

Future telerobotics testing will likely place more autonomy on the crew to simulate deep space operation. Therefore modifications will need to be made to the user interface software to include additional status information on the health of the rover for monitoring and troubleshooting. In addition, the crew will need to be able to manage rover subsystems (thermal control, power, avionics, etc), perform rover system diagnostics, and perhaps manage rover start-up and shutdown. Most importantly, the crew will need to be capable of addressing contingency situations with the rover, especially those that may be time, or safety, critical. To address these needs, it is likely that dedicated displays – perhaps multiple, large screens – will be needed on future spacecraft.

Additional ISS tests can be devised to examine the costs and benefits of providing different interface infrastructure (displays, controls, decision support software, etc) to the astronauts. Other tests could be performed to assess the impact of workspace design (size, layout, etc) in a spacecraft on operator performance. The results of these studies would help identify telerobotic facility requirements for future human spacecraft.

IV.IV.Surface activities

Our 2013 tests focused on the collection of camera images (for site survey and telescope documentation/inspection) and polyimide film deployment. These tasks required relatively little human intervention, i.e., robot autonomy was robustly able to perform the work. Additional ISS tests could examine a broader range of surface activities, especially those that are more unstructured in nature, that require more complex decision making, or that demand switching between robot control modes.

For example, future human missions to lunar, or Martian, orbit may include remotely operating surface robots for field geology studies. These robots would be used for mapping (at various scales and with a variety of instruments), sampling (coring, drilling, and/or material collection), and instrument placement (at different locations and on specific targets of interest). To perform these tasks, astronauts may need to perform traverse planning, carry out long distance navigation, and be able to direct robots through rough and steep terrain.

Other missions might require robots to be used for assembly tasks (mating of subassemblies, connection of power/data cables, etc.), or maintenance work (e.g., repair of damaged telescope components). These activities will require remote operation of a variety of mechanisms, including manipulator arms. Moreover, astronauts may have to execute lengthy, complex, and detailed procedures while achieving precision alignment and management of interaction forces. The European Space Agency is currently studying how haptic interfaces and force reflection methods might facilitate these types of telerobotic activities[2].

V. CONCLUSION

We have demonstrated how the ISS can be used as a platform for testing of concepts of operation for future missions. The results of our tests indicate that command sequencing with interactive monitoring is an effective strategy for crew-centric surface telerobotics. In particular, we found that: (1) planetary rover autonomy (especially safeguarded driving) enabled the human-robot team to perform missions safely; (2) the crew maintained good situation awareness with low effort using interactive 3-D visualization of robot state and activity; and (3) rover utilization was consistently in excess of 50% time; and (4) all crew interventions were successful. Finally, we observed that crew workload was consistently low, which suggests that multi-tasking may be possible during telerobotic operations.

For a future lunar telerobotics mission where astronauts would operate rovers on the moon from a remote location high above the lunar surface (such as a halo orbit or distant retrograde orbit), it is important to design the telerobotics system and operational protocols to work well with variable quality data communications (in terms of data rates, latency, availability, etc.) In addition, the extended distance from Earth means that it will also be important to understand how efficiently and effectively a small crew of astronauts can work when placed in a more independent role, i.e., autonomous from mission control.

Future Surface Telerobotics testing with the ISS could be designed to accurately simulate the data rates and latencies involved in an actual lunar farside mission. The planetary rover tasks could also be modified to test different mission objectives, such as field geology or sample collection. Potential benefits to future missions include: creating optimized training procedures, reducing operational risk and technology gaps, defining preliminary mission requirements, and estimating development and mission cost.

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