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ISS CREW CONTROL OF SURFACE TELEROBOTICS

Maria Bualat
NASA Ames Research Center, USA, maria.g.bualat@nasa.gov

Matthew Deans, Terrence Fong, Chris Provencher,
Debra Schreckenghost, and Ernest Smith

As part of NASA's Human Exploration Telerobotics (HET) project, we are planning to conduct a test in which ISS crew remotely operates a planetary rover. This "Surface Telerobotics" test will obtain baseline engineering data and will improve our understanding of how to: (1) deploy a crew-controlled telerobotics system for performing surface activities and (2) conduct joint human-robot exploration operations. This test will also help reduce risks for future deep-space human missions, identify technical gaps, and refine key system requirements. In this paper, we first provide the context and motivation for Surface Telerobotics. We then describe the key systems that will be used in the test. Finally, we describe our test objectives and experimental design.

I. INTRODUCTION

I.I. Motivation

Surface Telerobotics is a planned 2013 test to examine how astronauts in the International Space Station (ISS) can remotely operate a surface robot across short time delays. This test will be performed during Increment 35/36, during the Summer of 2013, to obtain baseline engineering data and will improve our understanding of how to: (1) deploy a crew-controlled telerobotic system for performing surface activities and (2) conduct joint human-robot exploration operations. This test will also help reduce risks for future human missions, identify technical gaps, and refine key system requirements.

In planning for future space exploration, study teams have made numerous assumptions about how astronauts can remotely operate robots from a flight vehicle.[1,2,3,4,5,6,7,8] In particular, crew control of surface telerobots has been proposed as an effective operations concept for several possible future human missions:

L2 Lunar Farside

Crew orbits the Moon (or station keeps at L2) and a surface robot explores the lunar farside.[2,4,8] Crew must control the robot from the flight vehicle (e.g., Orion capsule) because there is no way (without a lunar orbital relay) to communicate with the robot from Earth ground control. (Fig. 1)

Near-Earth Asteroid

Crew is in a flight vehicle that is approaching, in proximity, or departing an asteroid and a robot is "landed" on the asteroid surface.[3,5] Crew must control the robot from the flight vehicle because NEA dynamics (rotation rate and microgravity) make it impossible to interactively operate robot from Earth.

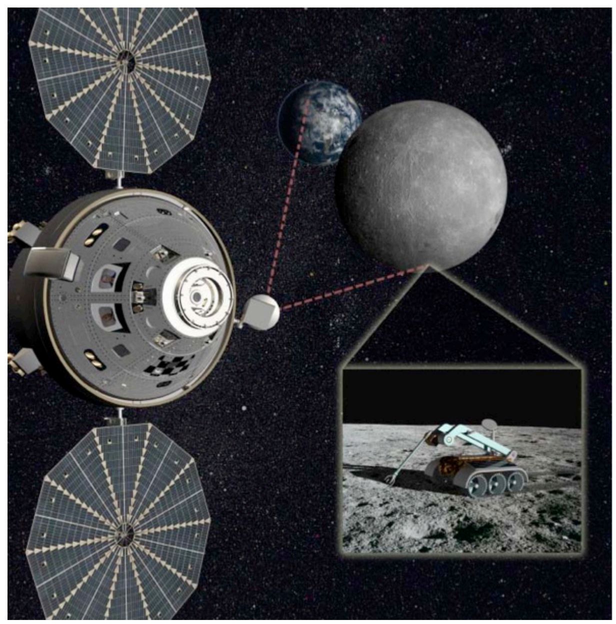

Fig. 1 Lunar L2-Farside mission concept with Orion MPCV. Image credit: Lockheed Martin.

Mars Orbit

Crew is in aerostationary orbit around Mars (or landed on Deimos or Phobos) and a robot operates on the surface of Mars.[1,3,6,7] Crew must control the robot from orbit when circumstances (time-critical activities, contingency handling, speed of operations) do not permit remote operation from Earth.

To do this, assumptions have been made regarding technology maturity, technology gaps, and risks (operational and functional) associated with crew-controlled telerobotic systems. These assumptions, however, are not supported by actual experimental data. Moreover, although significant ground-based analog tests of surface telerobotics systems have previously been performed, no crew-controlled surface telerobotics system has yet been flight-tested in a fully operational manner and characterized using detailed performance metrics.

I.II. Goal

The primary goal of Surface Telerobotics, therefore, is to obtain baseline engineering data for a crew-controlled surface telerobotic system through ISS testing. In particular, the test will collect data from on-board software modules, crew user interfaces, and operations protocols. The test is the culmination of hundreds of hours of ground-based simulations of surface telerobots.[9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26]

ISS testing will be used to validate the key functional issues, refine the draft system requirements, and confirm the conclusions drawn from these prior tests. ISS testing is also required to verify that prior ground tests included all significant factors and that these factors were simulated at sufficiently high levels of fidelity.

I.III. Objectives

The objectives of the 2013 Surface Telerobotics test are:

1. Characterize a concept of operations for a single crewmember supervising a remote planetary rover with limited backup from ground control
2. Characterize system utilization and performance for a single crewmember supervising a remote planetary rover with limited backup from ground control
3. Demonstrate interactive crew control of a surface telerobot

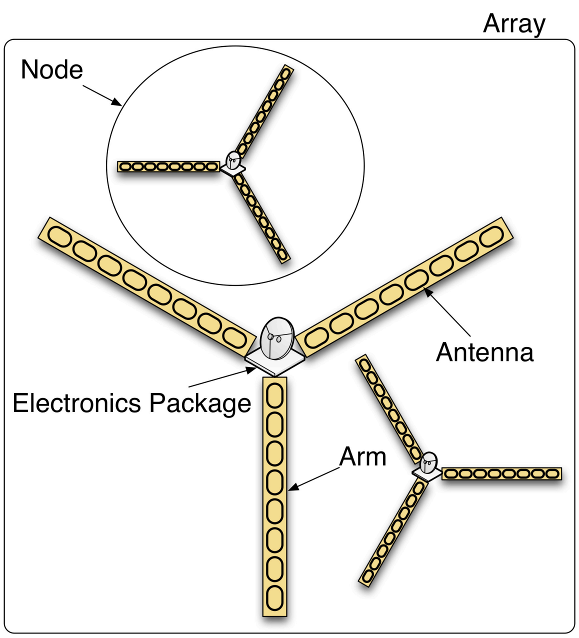

Fig. 2: Telescope terminology.

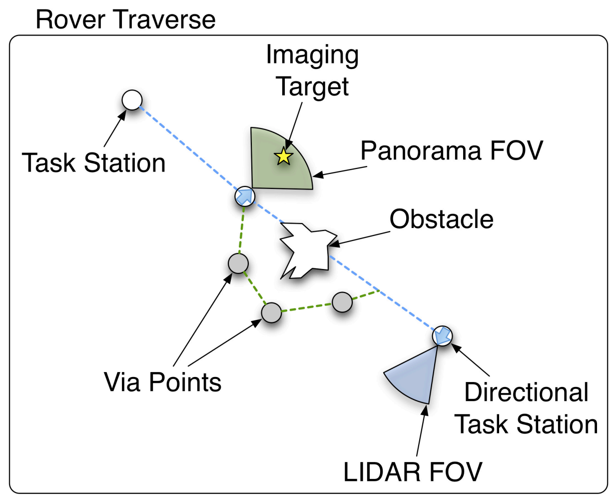

Fig. 3: Rover traverse terminology.

These objectives are further defined in the Approach section.

I.IV. Definitions

Fig. 2 and Fig. 3 depict telescope and rover traverse terminology, respectively.

Antenna	A single dipole antenna
Arm	A linear length of film embedded with multiple antennas
Electronics Package	A package made up of an electronics unit that collects and conditions signals from the antennas, and a communications dish
Node	A unit comprised of an electronics package and 3 antenna arms in a y-shaped configuration
Array	A set of telescope nodes
Rover Task	A non-driving rover action, for example, taking an image or LIDAR scan
Task Station	A location at which the rover will perform a task
Directional Task Station	A task station with a specific orientation for the rover. The rover will point in a specific direction when arriving at the task station.
Via Point	A location through which the rover will drive without performing a task. Via points are used to adjust the shape of the rover's path.
Imaging Target	A terrain feature of which an image is requested by the science or operations teams
Obstacle	A terrain feature over which the robot cannot drive
Rover Traverse	A set of rover motions (drives)
Rover Task Sequence	An ordered list of via points, task stations, and rover tasks

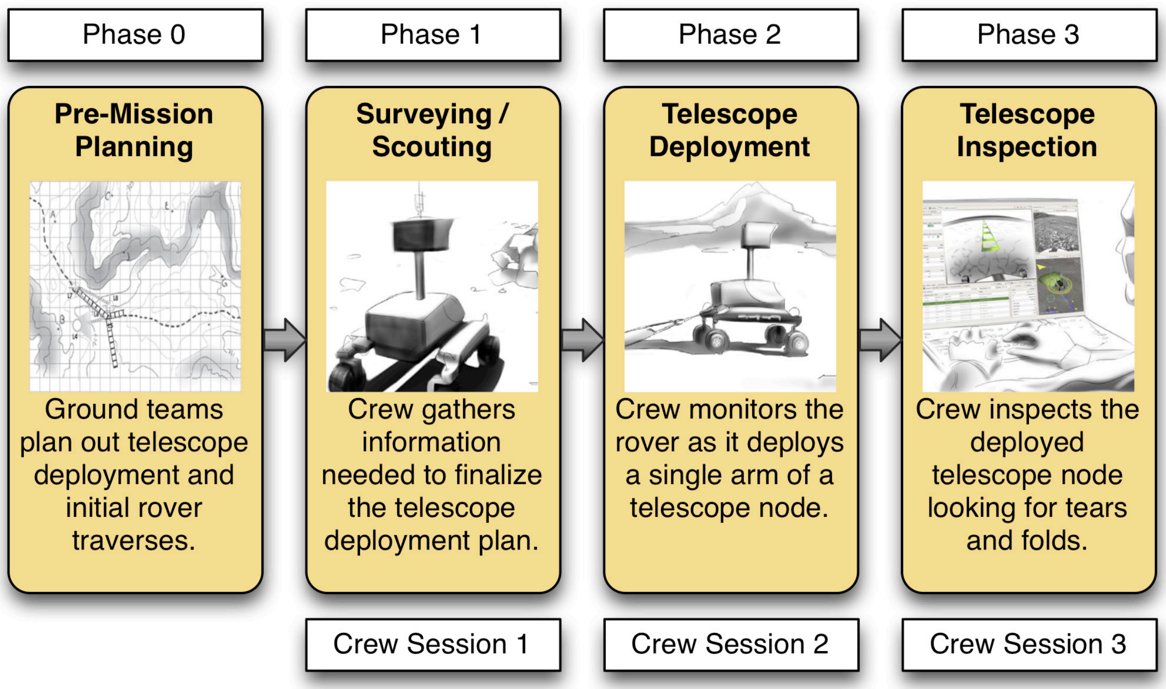

Fig. 4: 2013 The Surface Telerobotics mission is divided into 4 phases. Phases 1 - 3 correspond to ISS crew sessions.

II. EXPERIMENT

II.I. Mission Phases

Lunar L2-Farside Mission

The Moon's farside is a possible early goal for missions beyond Low Earth Orbit (LEO) using the Orion Multi-Purpose Crew Vehicle (MPCV) to explore incrementally more distant destinations. (Fig. 1) The lunar L2 Lagrange Point is a location where the combined gravity of the Earth and Moon allows a spacecraft to be synchronized with the Moon in its orbit around the Earth, so that the spacecraft is relatively stationary over the farside of the Moon. Such a mission would be a proving ground for future exploration missions to deep space while also overseeing scientifically important investigations.[27]

An astronaut would teleoperate a rover on the lunar farside that would obtain samples and deploy a low radio frequency telescope. Sampling the South Pole Aitkin basin (the oldest impact basin in the solar system) is a key science objective of the 2011 Planetary Science Decadal Survey[28] as is observations of the Universe's first stars/galaxies at low radio frequencies as described in the 2010 Astronomy & Astrophysics Decadal Survey.[29] Such telerobotic oversight would also demonstrate capability for future, more complex deep space missions.

A large numbers of radio antennas may be deployed on the lunar surface using polyimide film as a backbone. A conducting substance is deposited on the polyimide film to form the antenna. The film would be rolled for storage in a small volume during transport. Once on the Moon, the polyimide film would be unrolled to deploy the antennas. The film would also contain the transmission line system for conducting electrical signals back to the central electronics package at the intersection of the arms.[27] (Fig. 2)

While the Lunar L2-Farside Mission is not currently on NASA's mission manifest, the rover tasks that will be performed in this experiment are generally applicable to many mission scenarios for the Moon, NEA and Mars.

In order to create tractable demonstrations for each of the ISS crew sessions, we have broken the Lunar L2-Farside mission scenario into 4 phases (Fig. 4):

0. Pre-Mission Planning
1. Surveying/Scouting
2. Deployment
3. Inspection

Phases 1 to 3 correspond to ISS crew sessions. While these sessions have yet to be scheduled, we assume there will be a minimum of one week between crew sessions.

Phase 0: Pre-Mission Planning

The Pre-Mission Planning phase takes place well in advance of the ISS crew sessions. A ground team comprised of radio telescope scientists, rover engineers and members of the experiment team will be given orbital imagery at a resolution comparable to that available for the lunar surface (approximately 0.5

m/pixel) and a digital elevation map of the lunar analog site, the Ames Research Center (ARC) Marscape. The ground team will label traversable and non-traversable areas and select a nominal site for the telescope deployment.

Also based on orbital data, the ground team will create a set of rover task plans to survey the site, looking for suspected hazards and obstacles to deployment.

Phase 1: Surveying/Scouting

During the Surveying/Scouting phase, the crew will gather information needed to finalize the telescope deployment location. Data collected by the rover will enable identification of surface characteristics such as obstacles, slopes and undulations that are either below the resolution of, or ambiguous due to nadir pointing nature of orbital instruments.

Given the set of rover task sequences developed during Phase 0, the crew will begin execution. While monitoring the progress of the rover, the crew will also observe the rover imagery for obstacles and hazards that were missed by the ground team, that is, objects that could pose problems that will not be imaged in the ground-developed task sequences. For instance, in Fig. 3, the object labelled "Obstacle," while large enough to require a deviation in the rover path, is not imaged by any of the planned panoramas or lidar scans in the rover task sequence shown. The crew will edit rover task sequences to adapt to contingencies.

Once the surface data has been downlinked, the ground team will analyze the data and reselect the telescope deployment site and develop the rover task sequences needed to deploy the radio telescope.

Phase 2: Deployment

In Phase 2, the Deployment phase, the crew will monitor the rover as it deploys a single arm of a telescope node. First the crew will execute the deployment task sequence with the deployment device off to verify that the selected path is indeed free of obstacles. During actual deployment, the crew will monitor both the rover driving task and the telescope deployment. A high resolution, downward pointing camera focused on the film will document the deployment. The crew will mark suspected flaws (tears and folds) in the telescope arm for future inspection.

The ground team will use the deployment documentation imagery and astronaut-marked inspection points to create a map of the telescope and a set of rover task sequences to obtain additional inspection data.

Note that if the first crew session is cancelled or unsuccessful, Phase 1 will replace Phase 2 in the next crew session. If the second crew session is cancelled or unsuccessful, the ground team will deploy the antenna at the analog site and we will continue on to Phase 3 in the next crew session.

Phase 3: Inspection

During the Inspection phase, the crew will further inspect the telescope node, using the rover to obtain new oblique views of suspected flaws (folds and tears). Based on this additional data, the crew will decided whether it is necessary to deploy a spare telescope arm.

II.II. Phase Components

A phase can be broken down into several components as follows:

Planning

Two types of planning are considered, strategic and tactical, as follows:

- Strategic planning is performed by the ground team (science, rover, & experiment teams) before the crew sessions.
- Tactical planning (re-planning) is performed during a crew session by either the crew or ground to handle contingencies.

Execution

Execution roles are divided among the robot, crew, and ground as follows:

- Robot
  - During nominal execution, the rover will perform driving and instrument data acquisition tasks.
- Crew
  - During nominal execution, the crew will monitor rover task execution and may have a secondary task, such as scouting for obstacles.
  - The crew will act as the "first responder" in cases of contingencies. Contingencies the crew will be expected to handle include compensating for poor autonomy performance, such as getting around an obstacle, or handling a surprise discovery, such as spotting a scientifically significant object or an obstacle missed from orbit.
  - The crew will also be responsible for data validation. This includes verifying that images are valid (e.g. not blank), and ensuring that the imaging target has been acquired.
- Ground
  - The ground team will handle any contingencies beyond those listed above, such as low-level problems like an instrument failure.

Analysis

Once surface data has been downlinked, the ground team is responsible for analyzing the data in preparation for the next phase of the mission.

II.III. Robot Control Modes

In prior tests, ground control teams of varying sizes (from 1 to 20 controllers, including backroom staff) remotely operated a single planetary rover. 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, natural environments with short communication delays (up to 10's of sec). This will be the primary mode of robot control for this experiment. The ground team will develop rover task sequences and the crew will adjust them as needed to handle contingencies. As the rover executes a task sequence, the crew will monitor live telemetry and interrupt execution as needed.

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 performance, and reduced operator workload.

A "manual" mode will be available to the crew in the form of pre-developed "mini-plans" of single rover drives or tasks that may be used to "nudge" the rover's location, or acquire instrument data.

Finally a low-level subsystem command mode will be available to the ground team only to handle contingencies beyond the crew's capabilities, e.g. low-level problems such as an instrument malfunction.

III. SURFACE TELEROBOTICS SYSTEM

III.I. K10 Planetary Rover

In our work, we use the third-generation "K10" planetary rover (Fig. 5). K10 has four-wheel drive, all-wheel steering and a passive averaging suspension. The suspension design helps balance wheel/soil forces and reduces the transmission of motion induced by travel over uneven ground. K10 is capable of fully autonomous operation on moderately rough natural terrain at human walking speeds (up to 90 cm/s).

K10 has mounting points on the front, back, and bottom as well as a 100 cm high mast. This allows attachment of antennas, sensors, and science instruments. K10's standard sensors include a Novatel differential GPS system, a Honeywell digital compass, Point Grey Research IEEE 1394 stereo cameras, an Xsens inertial measurement unit, a suntracker, and wheel encoders.

Fig. 5: The K10 planetary rover is a MER-class robotic rover testbed. K10 "Red", is seen with an ILRIS-3D Lidar system at the top of its mast.

K10's avionics design is based on commercial components. The robot is powered by twenty-four (24) hot-swappable Inspired Energy 14.4V, 6.6 AH Li-Ion smart battery packs. K10's controller runs on a Linux-based laptop and communicates via 802.11g wireless, or a Tropos mesh wireless.[30]

The K10 controller is based on our Service-Oriented Robotic Architecture (SORA).[31] 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.

III.II. Science Instruments

To perform fieldwork, we have equipped the K10 rover with a suite of science instruments: panoramic and microscopic imagers, and a 3D scanning lidar. Additionally we will be equipping the rover with a film deployment device for playing out a telescope antenna arm.

Imagers

The K10 rover is equipped with two science imagers: a custom panoramic imager "PanCam") and a microscopic imager ("MI"). Both the PanCam and MI can provide contextual and targeted high-resolution color imaging of sunlit areas. These instruments are

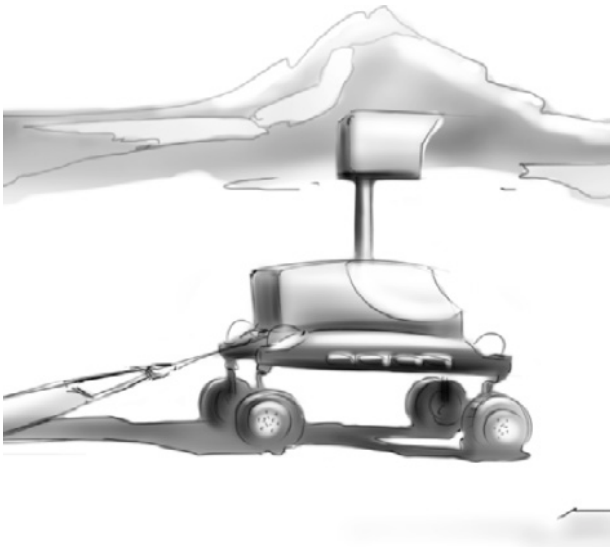

Fig. 6: Artist concept of the K10 rover deploying a telescope arm. Image credit: Academy of Art University.

used both for science observations and situational awareness during operations.

The PanCam is a consumer-grade, 12 megapixel, digital camera (Canon PowerShot G9 camera) on a pan-tilt unit. We operate the PanCam at 350 rad/pixel, which is comparable to the Mars Exploration Rover Pancam (280 rad/pixel). K10's PanCam, however, can be reconfigured for different resolutions by changing zoom. Images are mosaiced in software to create wide-field panoramic views.

The MI uses the same camera model as the PanCam. However, the MI camera is attached to K10 with a fixed ground (nadir) pointing mount. At highest resolution, the MI provides 33 microns/pixel at the ground, which is comparable to the spatial resolution of the MER Microscopic Imager. The MI will be used for telescope film inspection.

<u>3D Scanning Lidar</u>

K10 carries Optech's Intelligent Laser Ranging and Imaging System (ILRIS-3D) on top of a central mast (Fig. 5), which places the instrument approximately 1 m above ground. The ILRIS-3D is a scanning lidar designed for terrestrial survey. The instrument provides 3D scans over a 40x40 deg field-of-view and is capable of making measurements from 3 to 1,500 m range. Typical 3D accuracy is 10 mm at 100 m range. Point cloud data are captured at 2,000 points/second, which allows a single, full-resolution scan to be captured in approximately 20 min.

We use this instrument to make 3D measurements of terrain, to examine surface texture (e.g., of outcrops), and to assess terrain hazards (e.g., steep slopes) in sunlit and shadowed areas. During K10 operations, we acquire single scans when the robot is stopped. We also acquire

Fig. 7: The Visual Environment for Robotic Virtual Exploration (VERVE) is an interactive 3D user interface for monitoring robot operations.

360 deg panoramas by taking a series of scans with the rover turning in place between scans.

<u>Film Deployer</u>

During the Summer of 2012, together with the University of Idaho, we will develop and integrate a rear-mounting polyimide film deployer for the K10 rover. (Fig. 6) The deployer will spool out 60cm-wide polyimide film as the rover traverses the planned deployment route. For purposes of this test, the film will not contain antenna or transmission line traces.

<u>III.III. User Interfaces</u>

The "Visual Environment for Robotic Virtual Exploration" (VERVE), shown in Fig. 7, 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.[33] A modified version of VERVE will also allow crew to edit rover task sequences.

For ground planning, we will utilize the Exploration Ground Data System (xGDS) that provides software for dealing with mission data for science operations, including tools for planning, monitoring, visualization, documentation, analysis, and search.[34] xGDS is designed to support four mission phases:

1. Planning missions start with a-priori map information including remote sensing data, known operational hazards or constraints, and targets of interest. xGDS enables teams to create and share a-priori map content and collaboratively edit traverse plans.
2. Monitoring execution is done via map-based tools to visualize in real-time where things are. Telemetry panels show the current status of systems

and data. Real-time and post-hoc documentation and annotation are also supported.

3. Archiving tools ingest telemetry in real-time, reducing data to more meaningful or more efficient representations and organizing it into searchable databases.
4. Exploring data after it is collected requires the ability to quickly find out what data was collected, where and when it was collected, and search for particular kinds of data. Real-time semantic labeling greatly facilitates this, by users using xGDS tools to add notes to data products and timelines.

III.IV. Marscape

The K10 rover will operate in the Marscape Test Facility, an outdoor 3/4-acre high-fidelity planetary science test yard explicitly designed to incorporate those aspects of the Martian environment and geology of greatest scientific interest. Marscape's varied topography includes a dry streambed, dry lakebed, meteorite impact crater, and volcanic zone, with a generous balance of traversable and non-traversable areas.

IV. APPROACH

IV.I. Objectives

Objective 1: Characterize the Conops

Objective 1 of this experiment is to characterize a concept of operations for a single crewmember supervising a remote planetary rover with limited backup from ground control.

Our conops is characterized by the following:

- The type of robot control is task sequencing with interactive monitoring by crew.
- Ground control provides support for crew for major contingencies and for strategic planning.
- The crew is responsible for tactical execution and modifications (minor deviations from the strategic plan) to handle minor contingencies and to achieve secondary mission objectives.

Collection of this data will enable us to understand how this conops affects mission design and architectures, including mission time-lining, mission duration and tempo, and interleaving of the phases of a mission.

Objective 2: Characterize the System

Objective 2 of this experiment is to characterize system utilization and performance for a single crewmember supervising a remote planetary rover with limited backup from ground control. We will collect baseline engineering data to assess what is needed to make such a system work (e.g. the correctness or incorrectness of assumptions).

Our system is defined by the following:

- Robot: ARC K10 rover with the following instruments:
  - "PanCam" panoramic color camera system
  - Optech ILRIS-3D LIDAR
  - "HazCam" forward-facing monochromatic stereo cameras
  - "DeployCam" rear-facing deployment context camera
  - "MI" downward-facing high resolution camera for film documentation
- User interfaces
  - xGDS rover task sequence planning tool for use by the ground team
  - Surface Telerobotics Workbench (VERVE-based) rover monitoring and task sequence editing tool for use by both the ground team and crew
- Middleware
  - Rapid DDS

Objective 3: Demonstrate Surface Telerobotics

Demonstrate interactive crew control of a surface telerobot.

IV.II. Data Collection

Surface Telerobotics will obtain engineering data through a combination of automatic logging (time-stamped telemetry, software events, etc) and manual collection (crew questionnaires, interviews, and debrief session). Five categories of data will be collected:

Data communication

The amount and types of data transmitted between the graphical user interface (on ISS) and the surface robot will be automatically recorded. This includes data transfer direction (uplink/downlink), message type (robot state, sensor data, etc.), message volume (size and frequency), delay, and other parameters of interest.

Robot telemetry

Information associated with robot activity including position, orientation, power, health, instrument state (commands, failures), etc. will be automatically recorded.

User interface

The software will be instrumented to automatically record mode changes, data input, graphical button presses, etc. Access and use of reference data (maps, robot procedures, etc.) will also be automatically logged, including start/end times where possible.

Robot operations

The start, end and duration of the three phases of robot operations (planning, monitoring, and analysis) will be automatically recorded. This includes logging task sequences developed by the crew, execution success/failure, contingency handling, and key events.

Team	Location	Personnel	Role
Rover	ISS	- Rover Operator – Crew Member	- Controls the K10 rover
	Ames	- Rover Engineer	- Handles low-level rover problems - Answers technical questions on rover
	Marscape	- E-stop Operator	- Emergency stops the rover
Operations (Ops Team)	Mission Control Center - Houston	- Flight Director - PLUTO - Surface Telerobotics Ops Lead	- Handles all ISS operational issues - Oversight and approval of all operations - SSC and comm set up - Interaction with crew
Experiment (X-Team)	Ames	- Surface Telerobotics Project Director	- Provides overall engineering and programmatic direction to Ops Team - Decides on what is in-sim/out-of-sim - Ensures experimental data is collected
Science	Ames	- Mission PI - Telescope Engineer	- Leads Phase 0 Pre-Mission Planning - Answers science/telescope questions during crew ops

Table 1: Surface Telerobotics teams with their locations and roles

Crew questionnaires

The crew's cognitive workload and situation awareness will be manually recorded through questionnaires, which the crew will complete during and after robot operations. In addition, critical incidents will be examined through crew interviews and/or post-test debriefing.

IV.III. Metrics

Surface Telerobotics will use a variety of metrics to analyze the collected data and assess human-robot system operation. The assessment approach follows methodology employed during prior analog field testing with the K10 rover, notably [15, 22, 23, 24, 26, 33]. Three categories of metrics will be used:

Human

Work Efficiency Index, Situation Awareness Global Assessment Technique (SAGAT), and NASA Task Load IndeX (TLX) will be used to assess the workload imposed on crew and the effectiveness of the situation awareness support techniques.

Robot

Mean Time Between Intervention (MTBI) and Mean Time Completing Interventions (MTCI) will be used to assess the productivity and reliability of the telerobotic system.[33]

System

Productive Time, Team Workload, and task-specific measures will be used to assess the effectiveness and efficiency of the human-robot system for performing surface exploration work.[24]

IV.IV. Teams/Roles

Table 1 shows the notional make up, location and roles of each of the teams involved in the Surface Telerobotics experiment. Note that the ground operations of this experiment are still under design.

V. SUMMARY

The Surface Telerobots Experiment will test how astronauts in a flight vehicle can remotely operate a surface robot across a short time delay. This ISS Increment 35/36 test will obtain critical baseline engineering data and will improve our understanding of how to: (1) deploy a crew-controlled telerobotics system for performing surface activities and (2) conduct joint human-robot exploration operations. This test will identify remaining technical gaps, refine key system requirements, and validate operational risks for future missions. Surface Telerobotics is an element of the OCT Human Exploration Telerobotics Project.

Surface Telerobotics will collect and analyze data from on-board software modules, crew user interfaces, and operations protocols. The results and lessons learned from this test will be used to further mature technologies required for future deep-space human missions, including robot planning and commanding interfaces, automated summarization and notification systems for situation awareness, on-board robot autonomy software, data messaging, and short time-delay mitigation tools.

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