Development and Testing of the Smart SPHERES Telerobotic Free-Flyer

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Smart SPHERES is a free-flying robot that can be remotely operated by astronauts in space, or by mission controllers on the ground. We are developing Smart SPHERES to perform a variety of intravehicular activities (IVA) inside the International Space Station (ISS). These IVA tasks include interior environmental surveys, inventory, and mobile camera work. During 2013, we tested crew-controlled remote operations and wireless network-based localization with Smart SPHERES on ISS. In 2014, we plan to test 3D vision-based navigation.

Telerobotic IVA Free-Flyer

Telerobots can increase the performance and productivity of human space exploration by performing tasks that are tedious, repetitive, dangerous or long-duration[4]. Free-flying space robots can be used to off-load routine work, to increase crew productivity, and to handle contingencies. The ISS, for example, is a manned orbital laboratory that requires significant manual upkeep by a small crew of 3 to 6 astronauts. A telerobotic IVA free-flyer can help crew perform in-flight maintenance, inventory, and monitoring of experiments [1].

For example, ISS astronauts are required to perform interior environmental surveys. A free-flying robot could be equipped with a variety of sensors to perform such surveys during crew sleep periods. In addition, logistics management is one of the most difficult problems faced by the ISS program due to the thousands of items (equipment, spares, consumables, etc) that have to manually tracked. A free-flying robot equipped with a radio frequency identification sensor, could be used to continuously inventory these items. Finally, a free-flying robot equipped with a camera could be used to off-load some monitoring and video tasks from crew to ground control.

Smart SPHERES

Smart SPHERES is an IVA free-flying robot that can be remotely operated by astronauts in space, or by mission controllers on the ground [3]. The robot (Figure 1) combines the “Synchronized Position Hold Engage and Reorient Experimental Satellites” (SPHERES), which were originally developed as miniature satellite test platforms, with an Android-based smartphone that provides robotic avionics. Each SPHERES is fully self-contained with propulsion, power, embedded digital signal processing, and navigation equipment. The smartphone provides a high-performance general-purpose processor, color cameras, additional sensors (temperature, sound, gyroscopes, accelerometers), a touch screen display, and wireless (Wi-Fi) networking.

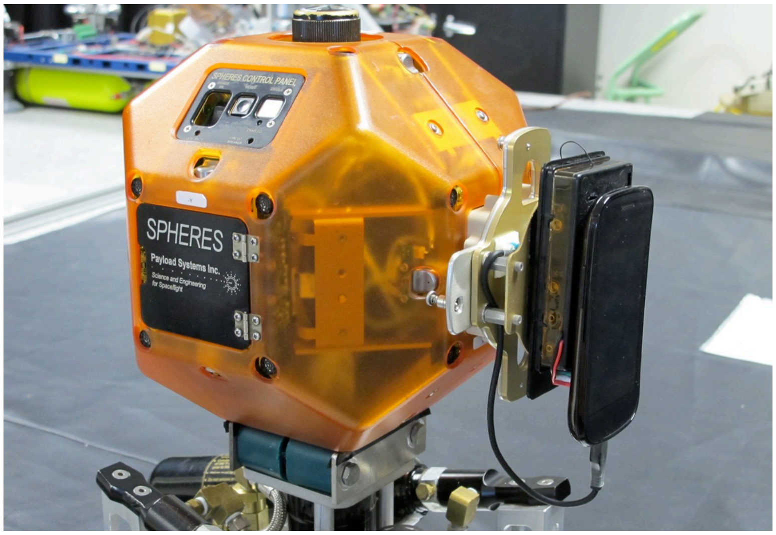
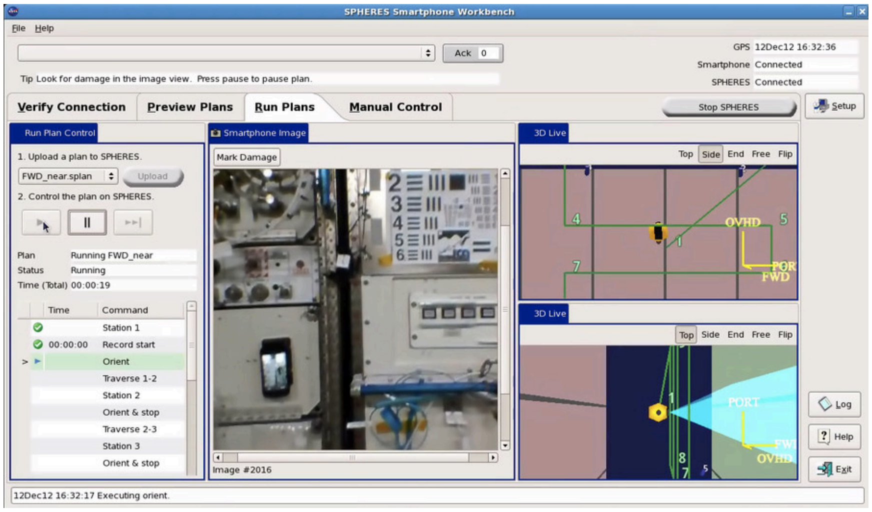


Figure 1. Smart SPHERES combines the SPHERES satellite platform with a modified Android smartphone.

Smart SPHERES is remotely operated using the Smart SPHERES Workbench (Figure 2). The Workbench supports supervisory and manual control. In supervisory mode, the operator selects a plan that contains a sequence of commands (fly to point, acquire data, etc), which is then transmitted to the robot for autonomous execution. In manual mode, the robot is operated with discrete commands (e.g., incremental motions). To facilitate situation awareness, the Workbench provides multiple displays including camera and 3D graphical views.



Tip Look for damage in the image view. Press pause to pause plan.

GPS 12Dec12 16:32:36
Smartphone Connected
SPHERES Connected

1. Upload a plan to SPHERES.
FWD_near.splan
2. Control the plan on SPHERES.

Plan Running FWD_near
Status Running
Time (Total) 00:00:19

	Time	Command
✓		Station 1
✓	00:00:00	Record start
> ▶		Orient
		Traverse 1-2
		Station 2
		Orient & stop
		Traverse 2-3
		Station 3
		Orient & stop

Image #2016

12Dec12 16:32:17 Executing orient.

Figure 2. The Smart SPHERES Workbench provides multiple modes, camera views, and 3D displays.

Crew-control testing on ISS

On September 5, 2013, we tested crew-control of Smart SPHERES. During this test, Astronaut Luca Parmitano setup the robot in the Japanese Experiment Module (JEM) and used it to perform visual inspection of a stationary target. This test had four primary objectives:

1) *Demonstrate crew control of Smart SPHERES*. Smart SPHERES successfully executed all commands sent from the Workbench, and all expected video and telemetry was received on the Workbench. Parmitano was able to remotely operate Smart SPHERES using both supervisory and manual control.

2) *Demonstrate waypoint-based navigation of Smart SPHERES*. Parmitano attempted to run seven plans. Three attempts were nominal from start to finish. Parmitano called off one plan and three others failed due to SPHERES low-level hardware problems.

3) *Provide real-time imagery, telemetry, health and status data to crew*. All expected video and telemetry was received on the ground and displayed in the Workbench.

4) *Demonstrate use of a free-flying camera for inspection tasks*. The test successfully demonstrated the ability to telerobotically inspect a stationary target. The free flyer translations and rotations were planned to keep the camera pointed at the target throughout robot motions.

Wi-Fi localization on ISS

The existing SPHERES localization system uses a set of external beacons. This system calculates position and orientation by determining time-of-flight differences between ultrasonic signals sent from multiple beacons. An infrared flash is used for synchronization. The system has several known deficiencies including crew time required for installation and calibration, crew time needed for maintenance, and failure under certain lighting conditions.

To address the limitations of the localization system, we have begun investigating the use of Wi-Fi localization. Numerous methods have been proposed for obtaining real-time position fixes by measuring signal strength to fixed

Wi-Fi access points. During 2013, we used the Smart SPHERES smartphone to record Wi-Fi signal strength on ISS and generated position maps using a Gaussian estimation process [1][5].

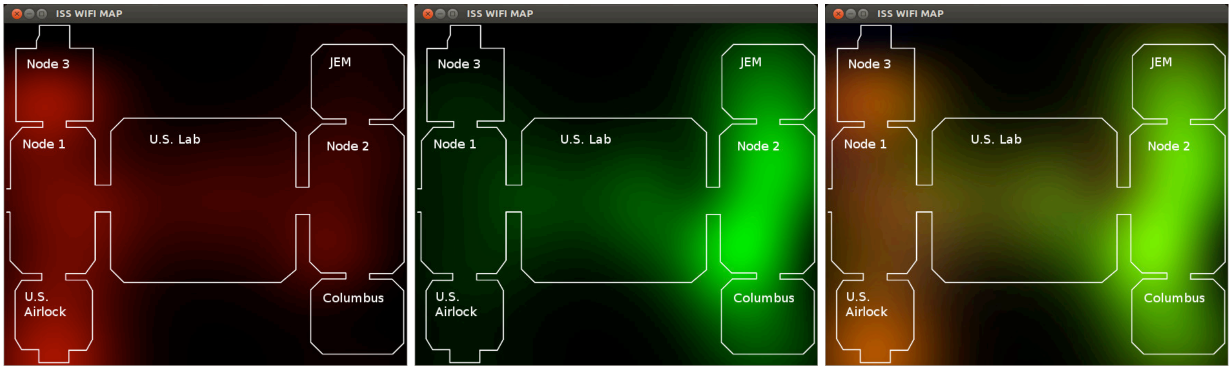


Figure 3. ISS Wi-Fi signal strength maps. Left-to-right: AP1, AP2, combined.

Figure 3 shows Wi-Fi signal strength maps of the ISS. We measured received signal strength in Nodes 1-3, the US airlock, the US lab, the Columbus module, and the JEM. The combined map indicates that it should be possible to obtain position fixes in all of these locations using Wi-Fi.

Vision-based navigation on ISS

In 2014, we will upgrade the Smart SPHERES smartphone with a new Android device that includes sensors for vision-based navigation. In particular, the new smartphone includes a fisheye lens camera, a narrow angle infrared and RGB camera, a structured light (infrared) projector, a high-resolution color camera, and a MEMS-based inertial measurement unit (IMU). The infrared projector and IR and RGB camera are used in conjunction to capture dense 3D measurements of the surroundings.

During Summer 2014, we will integrate the new smartphone to SPHERES and conduct on-orbit tests of vision-based navigation. Specifically, we will test different algorithms for estimating position and orientation. The algorithms use a combination of IMU readings, 3D range measurements, and knowledge of when the SPHERES thrusters are fired. The primary objective for the tests will be to ascertain if vision-based navigation is suitable (in terms of precision and update rate) for replacing the SPHERES beacon system.

References

[1] Ferris, B., Fox, D., and Lawrence, N. 2007. WiFi-SLAM using gaussian process latent variable models. International Joint Conference on Artificial Intelligence.

[2] Fong, T., Berka, R., et al. 2012. “The Human Exploration Telerobotics Project”. GLEX-2012.01.2.4x12180. IAF/AIAA Global Space Exploration Conference.

[3] Fong, T., Micire, M., et al. 2013. “Smart SPHERES: a telerobotic free-flyer for intravehicular activities in space”. AIAA-2013-5338. AIAA Space 2013.

[4] Fong, T., Rochlis Zumbado, J., Currie, N., Mishkin, A., and Akin, D. 2013. Space telerobotics: unique challenges to human-robot collaboration in space. Reviews of Human Factors and Ergonomics Society 9(1).

[5] Schwaighofer, A., Grigoraş, M., Tresp, V. and Hoffmann, C. 2004. GPPS: A gaussian process positioning system for cellular networks, Advances in Neural Information Processing Systems 16, MIT Press.

Crew-controlled Surface Telerobotics from the International Space Station

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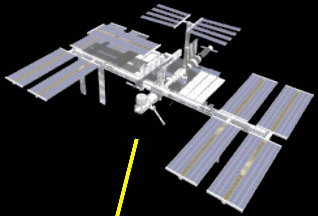


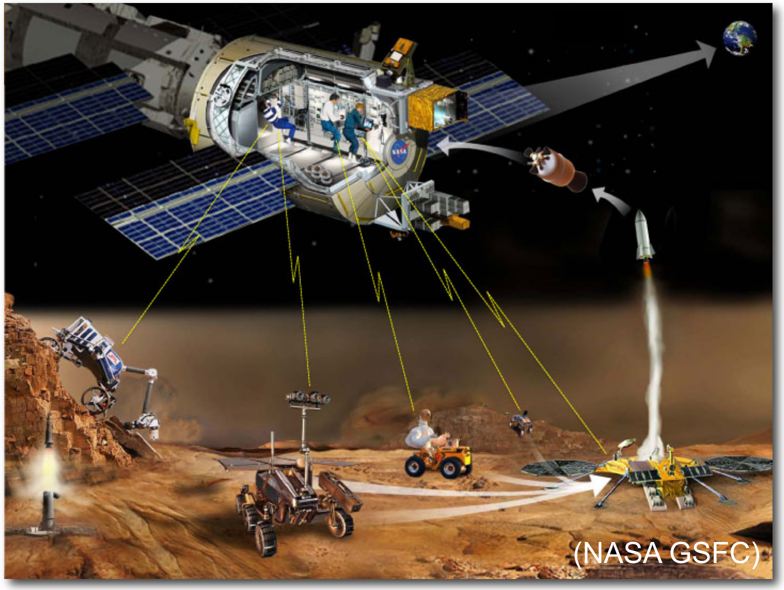
ISS R&D Conference
2014-06-19

Motivation

Recent exploration architecture study teams have made assumptions about how crew can remotely perform work on a planetary surface …

Candidate Exploration Missions

- **Lunar Farside**. Orion MPCV mission (libration point or distant retrograde)
- **Near-Earth Asteroid**. NEA dynamics and distance make it impossible to manually control robot from Earth
- **Mars Orbit**. Crew operates surface robot from orbit when circumstances (contingency, etc.) require


(NASA GSFC)

Assumptions

- Maturity of crew-controlled telerobotics
- Existing technology gaps (and how these can be bridged)
- Operational risks (proficiency, performance, failure modes)

➡ ***In 2013, we began testing these assumptions using the ISS …***

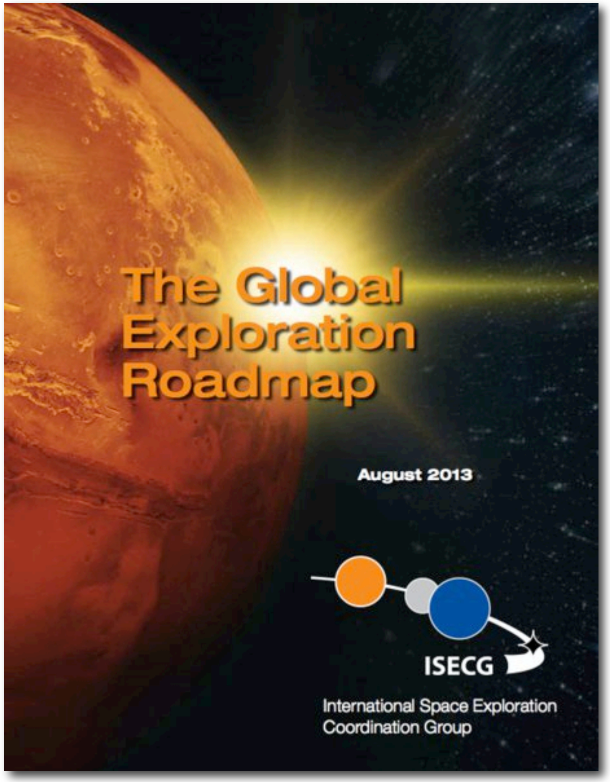
Global Exploration Roadmap 2013

Human-Robotic Partnership (p. 22)

Tele-Presence

Tele-presence can be defined as tele-operation of a robotic asset on a planetary surface by a person who is relatively close to the planetary surface, perhaps orbiting in a spacecraft or positioned at a suitable Lagrange point. Tele-presence is a capability which could significantly enhance the ability of humans and robots to explore together, where the specific exploration tasks would benefit from this capability. These tasks could be characterized by:

- High-speed mobility
- Short mission durations
- Focused or dexterous tasks with short-time decision-making
- Reduced autonomy or redundancy on the surface asset
- Contingency modes/failure analysis through crew interaction



Observation:

➔ New mission concepts, such as human-assisted sample return and tele-presence should be further explored, increasing understanding of the important role of humans in space for achieving common goals.

Surface Telerobotics Roadmap

Ground Analogs

Develop telerobotic systems (autonomy, data comm, interfaces)

Implement and test multiple conops

Simulate future human mission concepts

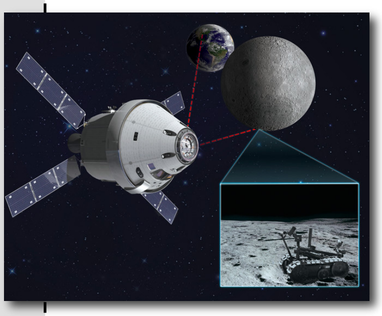
ISS Laboratory

Obtain baseline engineering and operations data

Validate prior ground simulations via high-fidelity ops sims

Reduce risk for future exploration systems (test assumptions)

Lunar Orbit



Enable “off-board” autonomy (use flight vehicle computing as part of robot system)

Use cis-lunar environment to prepare for human Mars missions.

Mars Orbit

Enable crew to explore surface using robot as an “avatar”

Enable “off-board” autonomy and data storage (use flight vehicle computing as part of robot system)

TRL 5 **Surface Telerobotics** *TRL 7*

Surface Telerobotics 2013

Key Points

- Demo **crew-control** surface telerobotics (planetary rover) from ISS
- Test **human-robot conops** for future exploration mission
- Obtain **baseline engineering data** (robot, crew, data comm, task, etc)

Implementation

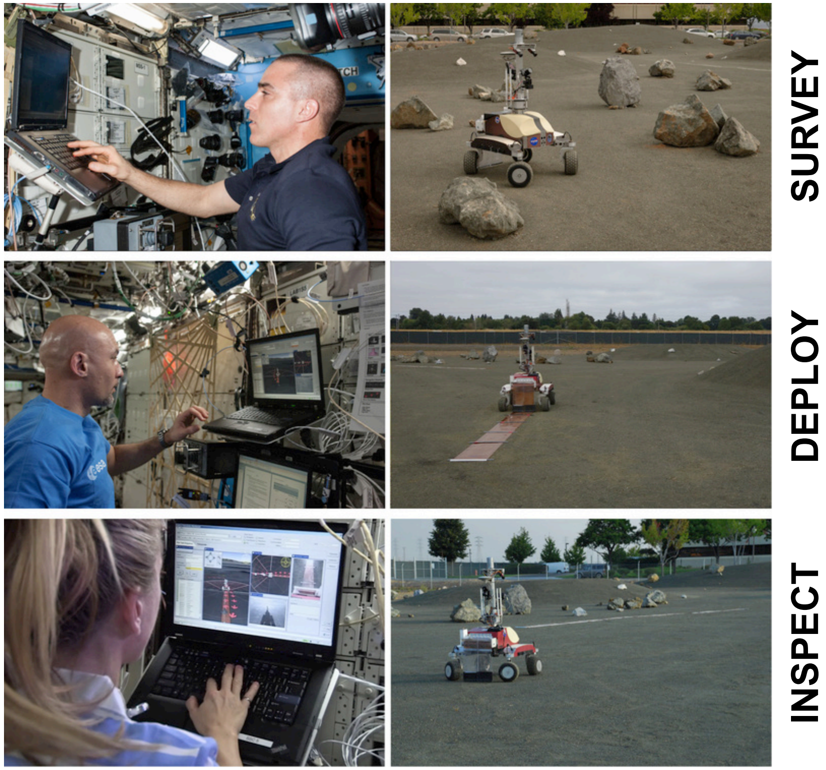
- Lunar libration mission simulation
- Astronaut on ISS (in USOS)
- K10 rover in NASA Ames Roverscape

ISS Testing (Expedition 36)

June 17, 2013 – **C. Cassidy**, survey

July 26, 2013 – **L. Parmitano**, deploy

Aug 20, 2013 – **K. Nyberg**, inspect



- **Human-robot mission sim**: site survey, telescope deployment, and inspection
- **Telescope proxy**: Kapton polyimide film roll (no antenna traces, electronics, or receiver)
- **3.5 hr per crew session** (“just in time” training, system checkout, ops, & debrief)
- **Robot ops**: manual control (discrete commands) and supervisory control (task sequence)

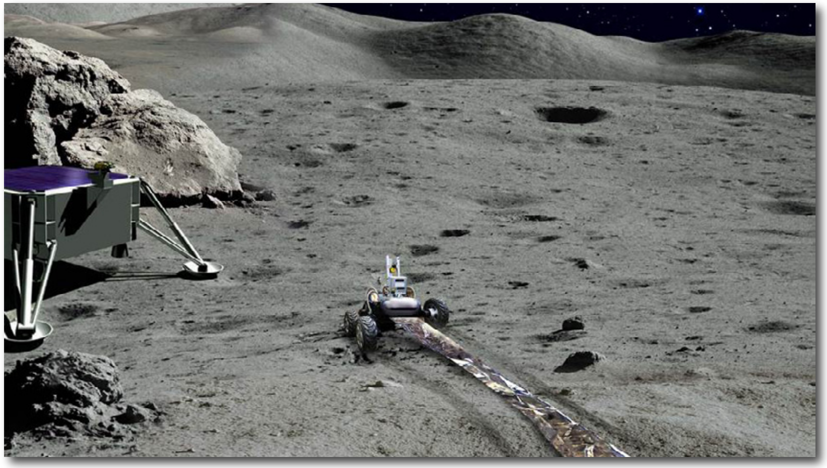
"Fastnet" Lunar Libration Point Mission

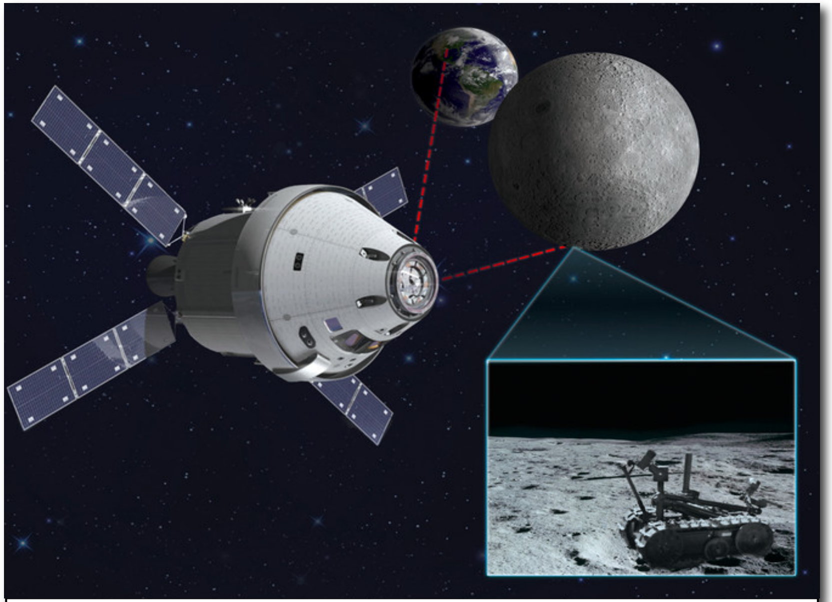
Orion MPCV at Earth-Moon L2 (EM-L2)

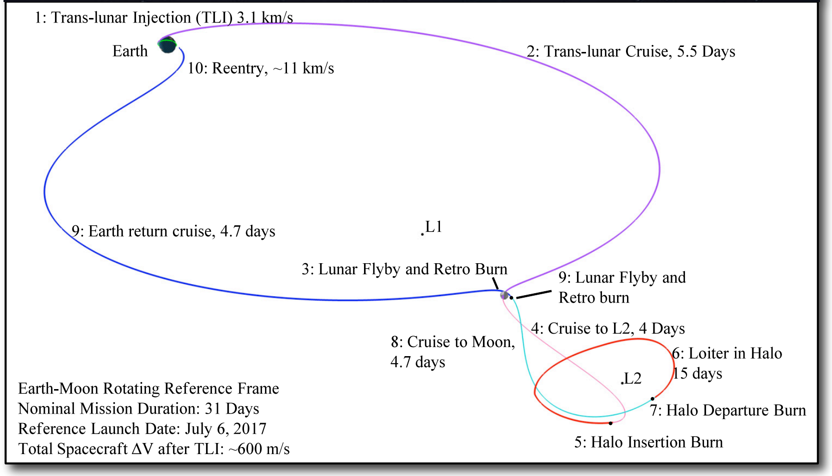
- 60,000 km beyond lunar farside
- Allows station keeping with minimal fuel
- Crew remotely operates robot
- Does not require human-rated lander

Human-robot conops

- Crew remotely operates surface robot from inside flight vehicle
- Crew works in shirt-sleeve environment
- Multiple robot control modes







Credit: (Lockheed Martin / LUNAR)

Surface Telerobotics

“Fastnet” Mission Simulation with ISS

Planning

Pre-Mission Planning

Ground teams plan out telescope deployment and initial rover traverses.

Spring 2013

Phase 1

Surveying

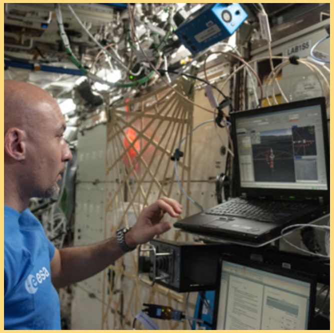
Crew gathers information needed to finalize the telescope deployment plan.

Crew Session 1

June 17, 2013

Phase 2

Telescope Deployment



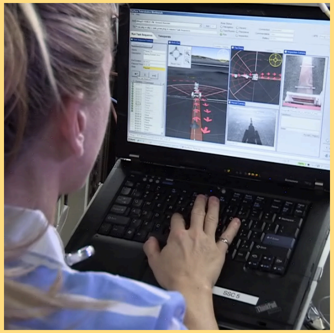
Crew monitors the rover as it deploys each arm of the telescope array.

Crew Session 2

July 26, 2013

Phase 3

Telescope Inspection

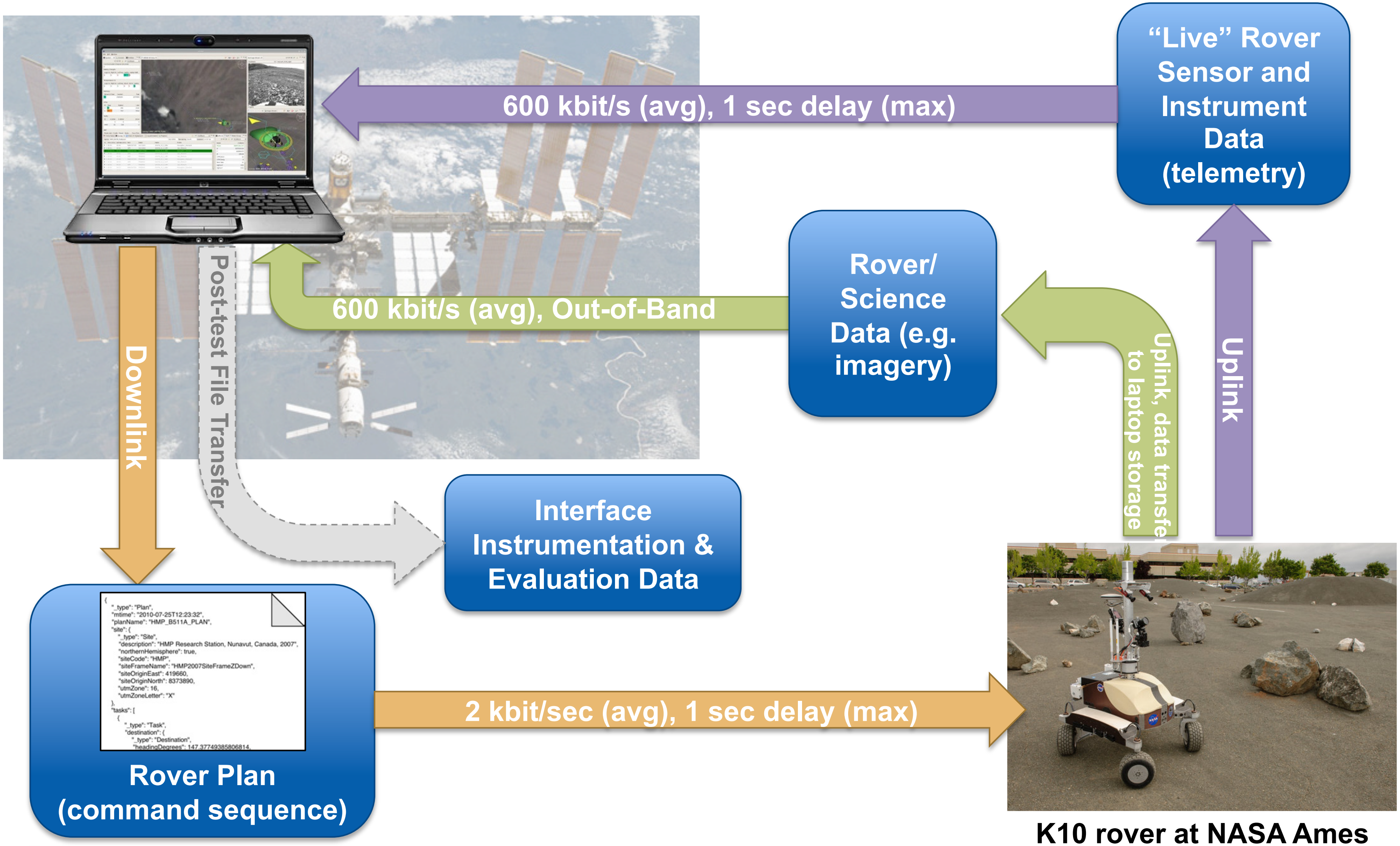


Crew inspects and documents the deployed telescope for possible damage.

Crew Session 3

August 20, 2013

ISS Test Configuration



“Live” Rover Sensor and Instrument Data (telemetry)

600 kbit/s (avg), 1 sec delay (max)

Uplink

Rover/ Science Data (e.g. imagery)

600 kbit/s (avg), Out-of-Band

Uplink, data transfer to laptop storage

Downlink

Post-test File Transfer

Interface Instrumentation & Evaluation Data

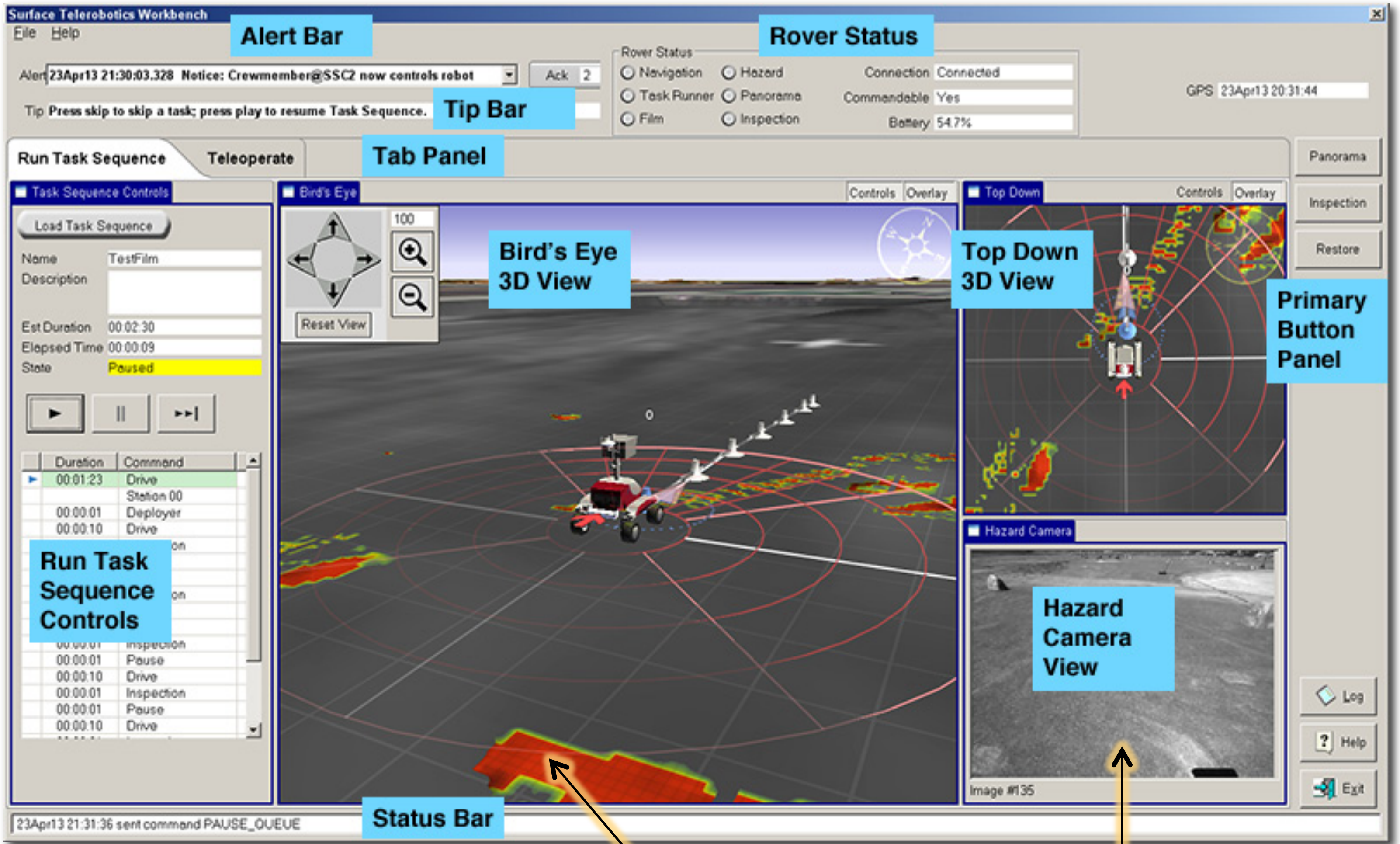
```
{
    "_type": "Plan",
    "mtime": "2010-07-25T12:23:32",
    "planName": "HMP_B511A_PLAN",
    "site": {
        "_type": "Site",
        "description": "HMP Research Station, Nunavut, Canada, 2007",
        "northernHemisphere": true,
        "siteCode": "HMP",
        "siteFrameName": "HMP2007SiteFrameZDown",
        "siteOriginEast": 419660,
        "siteOriginNorth": 8373890,
        "utmZone": 16,
        "utmZoneLetter": "X"
    },
    "tasks": [
        {
            "_type": "Task",
            "destination": {
                "_type": "Destination",
                "headingDegrees": 147.37749385806814,
```

Rover Plan (command sequence)

2 kbit/sec (avg), 1 sec delay (max)

K10 rover at NASA Ames

Robot Interface (Supervisory Control)



Alert 23Apr13 21:30:03.328 Notice: Crewmember@SSC2 now controls robot

Ack 2

Tip Press skip to skip a task; press play to resume Task Sequence.

Rover Status
○ Navigation ○ Hazard
○ Task Runner ○ Panorama
○ Film ○ Inspection

Connection Connected
Commandable Yes
Battery 54.7%
GPS 23Apr13 20:31:44

Name TestFilm
Description
Est Duration 00:02:30
Elapsed Time 00:00:09
State Paused

	Duration	Command
►	00:01:23	Drive
		Station 00
	00:00:01	Deployer
	00:00:10	Drive
	[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]
	[illegible]	[illegible]
	00:00:01	Inspection
	00:00:01	Pause
	00:00:10	Drive
	00:00:01	Inspection
	00:00:01	Pause
	00:00:10	Drive

Image #135

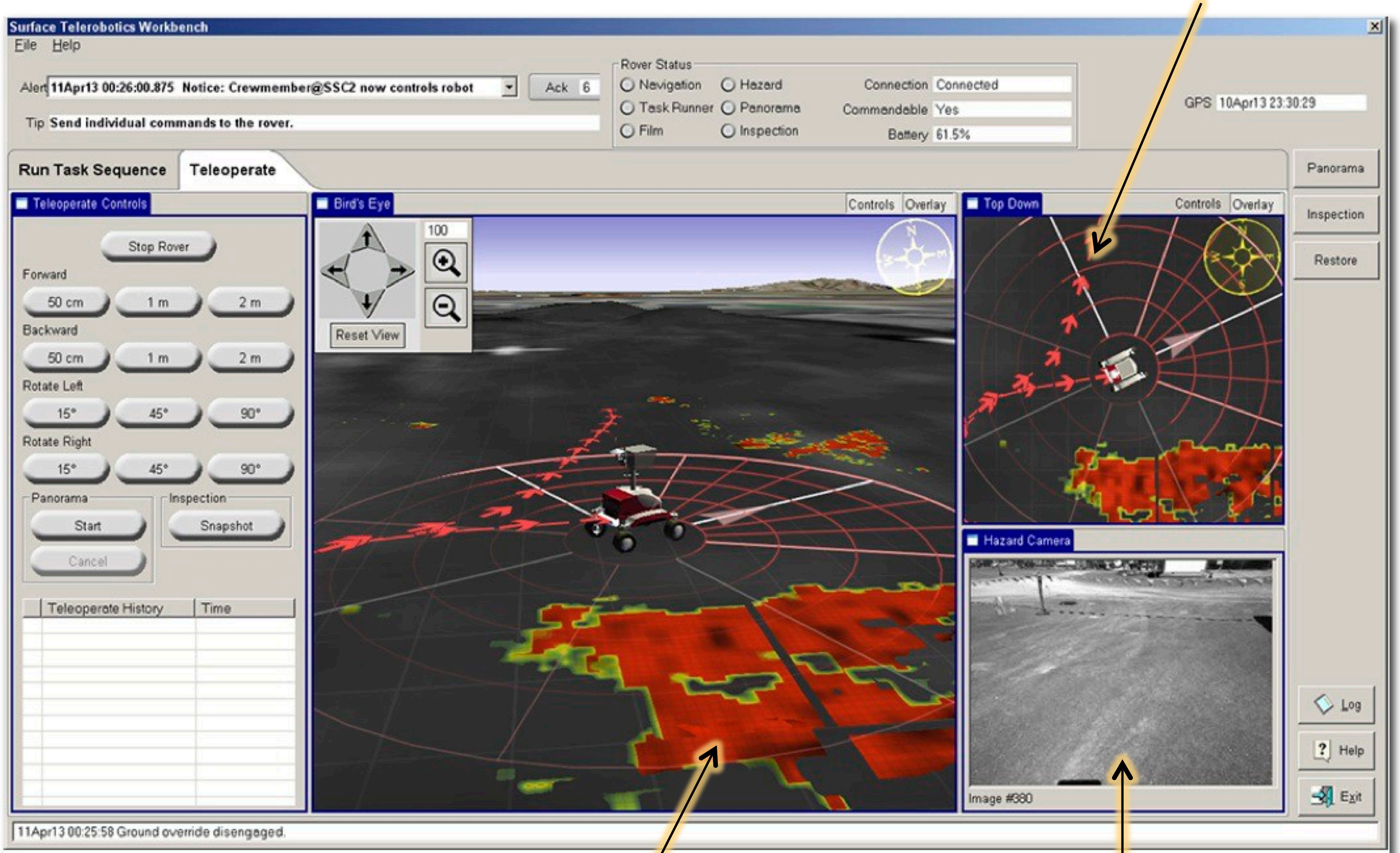
23Apr13 21:31:36 sent command PAUSE_QUEUE

Task Sequence

Terrain hazards

Rover camera display

Robot Interface (Manual Control)



Alert 11Apr13 00:26:00.875 Notice: Crewmember@SSC2 now controls robot

Tip Send individual commands to the rover.

Connection Connected

Commandable Yes

Battery 61.5%

GPS 10Apr13 23:30:29

11Apr13 00:25:58 Ground override disengaged.

Rover path

Motion controls

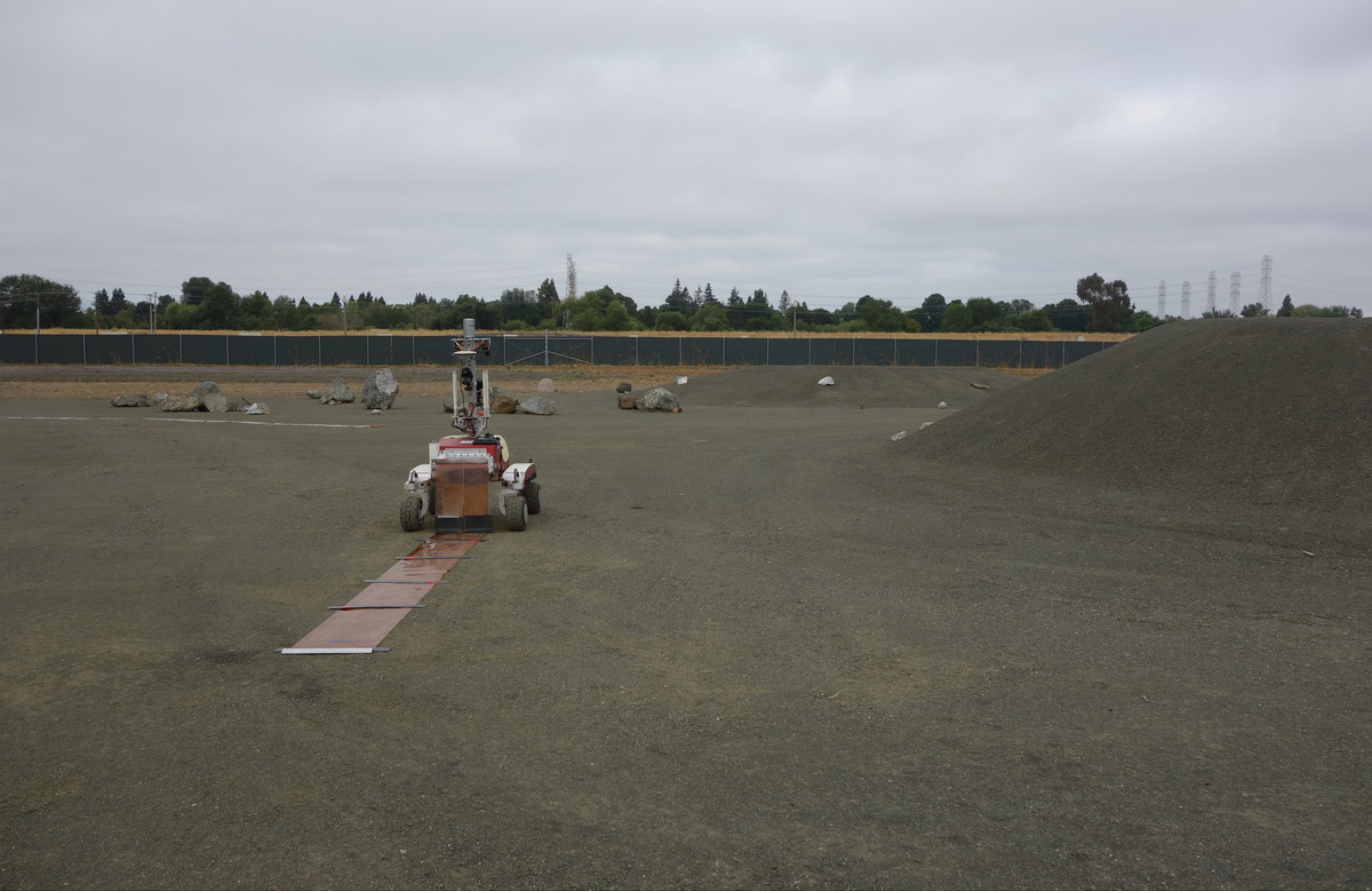
Camera controls

Terrain hazards

Rover camera display

Crew Session #1 – **K10 performing surface survey (2013-06-17)**

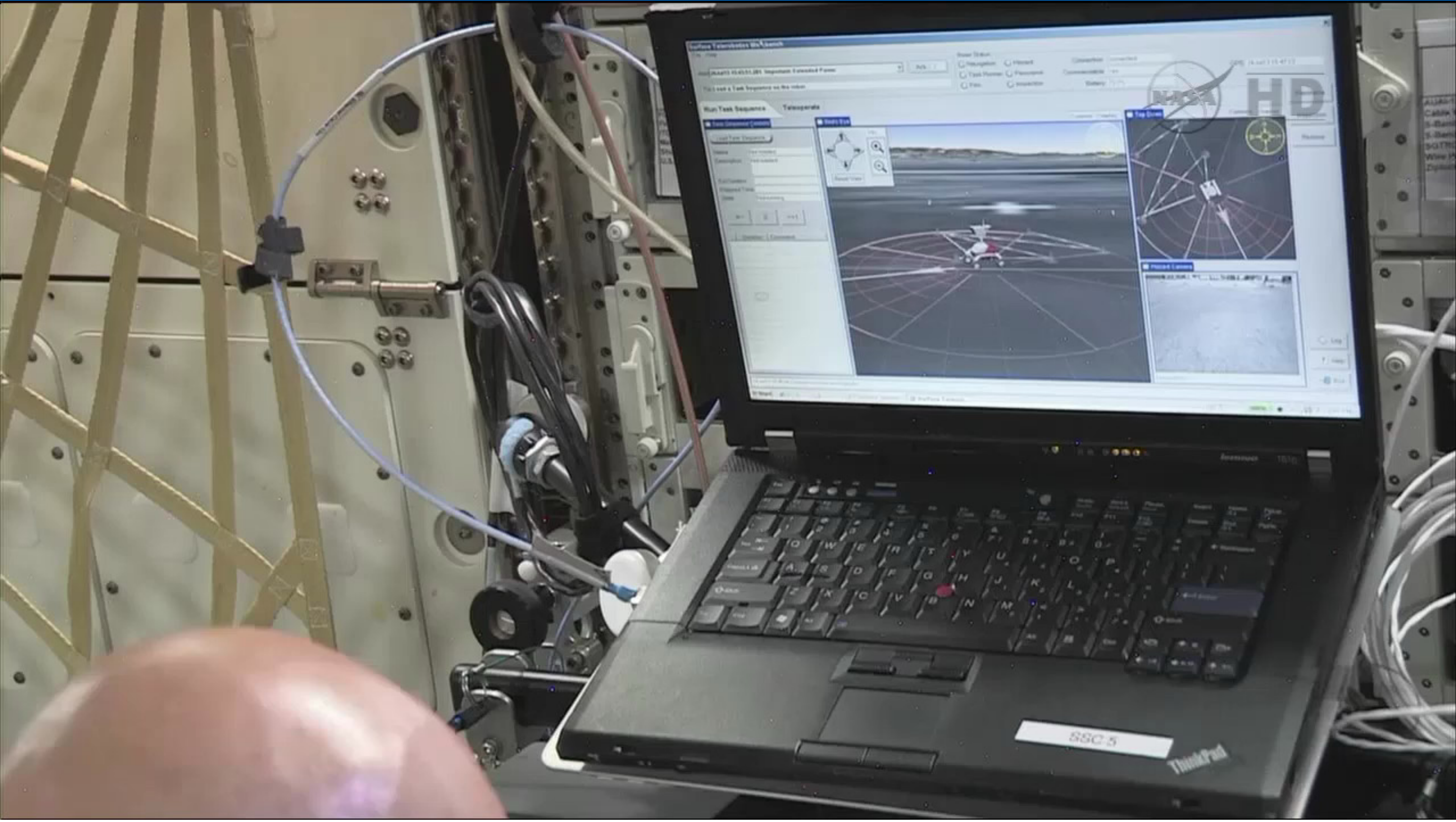
Chris Cassidy uses the “Surface Telerobotics Workbench” to remotely operate K10 from the ISS



Crew Session #2 – K10 deploying simulated polymide antenna (2013-07-26)

ISS Mission Control (MCC-H) during Surface Telerobotics test
View of robot interface and K10 at ARC

Surface Telerobotics



Deployed simulated polymide antenna (three “arms”)

Crew Session #3 – Karen Nyberg remotely operates K10 (2013-08-20)

K10 documenting simulated polymide antenna

Assessment Approach

Metrics

- **Mission Success:** % task sequences: completed normally, ended abnormally or not attempted; % task sequences scheduled vs. unscheduled
- **Robot Utilization:** % time robot spent on different types of tasks; comparison of actual to expected time on; did rover drive expected distance
- **Task Success:** % task sequences per session and per task sequence: completed normally, ended abnormally or not attempted; % that ended abnormally vs. unscheduled task sequences
- **Contingencies:** Mean Time To Intervene, Mean Time Between Interventions
- **Robot Performance:** expected vs. actual execution time on tasks

Data Collection

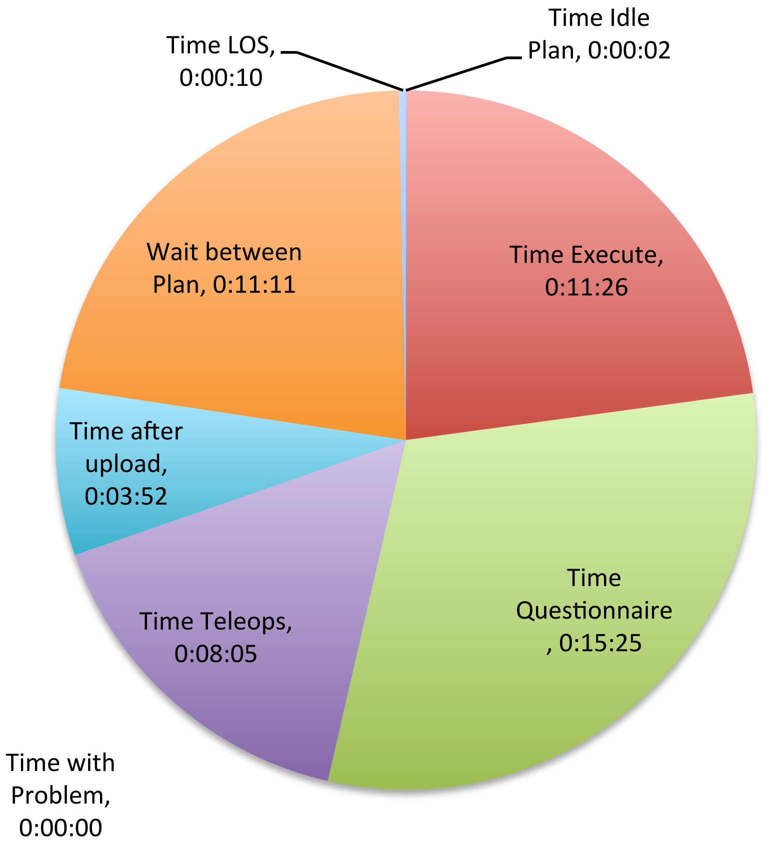
automatic

- **Data Communication:** direction (up/down), message type, total volume, etc.
- **Robot Telemetry:** position, orientation, power, health, instrument state, etc.
- **User Interfaces:** mode changes, data input, access to reference data, etc.
- **Robot Operations:** start, end, duration of planning, monitoring, and analysis
- **Crew Questionnaires:** workload (Bedford Scale), situation awareness (SAGAT)

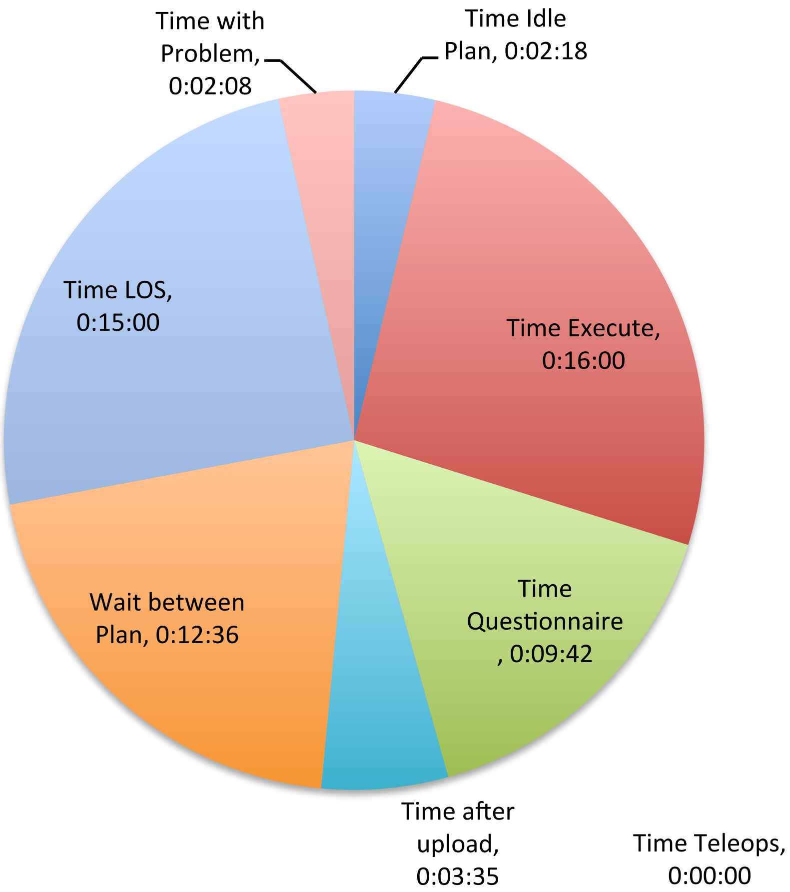
M. Bualat, D. Schreckenghost, et al. (2014) "Results from testing crew-controlled surface telerobotics on the International Space Station". Proc. of 12th I-SAIRAS (Montreal, Canada)

Robot Utilization

SURVEY Work & Wait Periods



DEPLOY Work & Wait Periods



Human-Robot Teaming

Productivity

- Productive Time (PT) = astronaut and robot performing tasks contributing to mission objectives
- Overhead Time (OT) = astronaut and robot are waiting
- %PT = percentage productive time
- %OT = percentage overhead time
- Work Efficiency Index (WEI) = PT / OT

Productivity	Total Phase Time	PT	OT	%PT	%OT	WEI
Survey	0:50:01	0:34:58	0:15:03	69.90	30.10	2.32
Deploy	0:46:19	0:28:00	0:18:19	60.45	39.55	1.53

Future Work: Spacecraft Constraints

Objectives

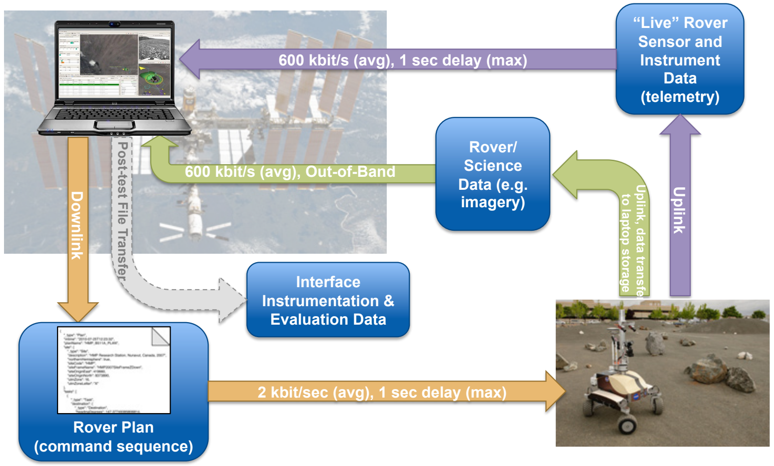
- Study **integration impacts** to spacecraft
- Assess viability of **off-loading rover processing** to spacecraft for certain tasks
- Test crew **real-time decision making**

Approach

- Repeat **prior mission sim** with mods
  - More crew training on robot operations
  - Crew operates with little ground support
  - Human-in-the-loop contingency handling
- Give crew low-level control of rover
- Off-board some rover functions (hazard detection, localization, etc) to spacecraft

Metrics

- Crew: Work Efficiency Index, Situation Awareness, Bedford Workload Scale
- Robot: Mean time between/to intervention
- CPU load, RAM/disk, bandwidth



"Live" Rover Sensor and Instrument Data (telemetry)

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Rover/ Science Data (e.g. imagery)

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Uplink

Uplink, data transfe to laptop storage

Downlink

Post-test File Transfer

Interface Instrumentation & Evaluation Data

Rover Plan (command sequence)

2 kbit/sec (avg), 1 sec delay (max)

Future Work: Different Surface Tasks

Objectives

- Examine **surface tasks** that are more unstructured, complex and unpredictable
- Assess **system capability** to support increased SA and control mode changes
- Enhance **operational knowledge** of crew-controlled surface telerobotics

Approach

- Run **new mission sim** with:
    - Assembly/cabling of a functional instrument
    - Planetary fieldwork
- Enhance user interface for science ops

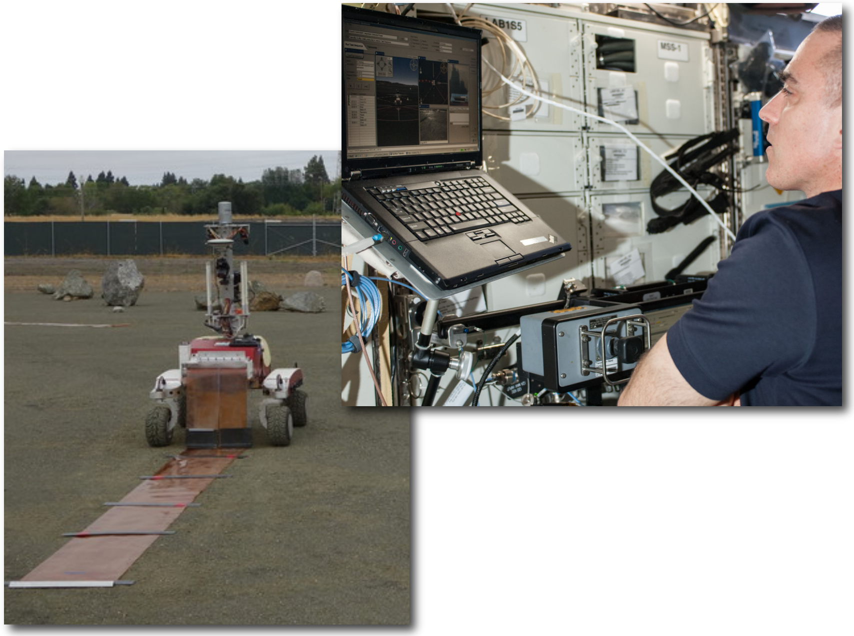
Metrics

- Crew: Work Efficiency Index, Situation Awareness, Bedford Workload Scale
- Robot: Mean time between/to intervention
- Task: Time on Task, Idle Time, Success rate, % Incomplete

Future Work: Multi-Robot Conops

Objectives

- Examine how **multiple humans and robots** can be employed
- Test **different control strategies**
  - Single crew operates both robots
  - Crew + mission control



Approach

- Repeat **prior mission sim** with mods
  - Two robots operating in parallel
  - Diifferent modes of control
- Enhance crew user interface
- Study operational efficiency & bottlenecks

Metrics

- Crew: Work Efficiency Index, Situation Awareness, Bedford Workload Scale
- Robot: Mean time between/to intervention
- Task: Time on Task, Idle Time, Success rate, % Incomplete

Conclusion

Successfully completed 3 test sessions in Summer 2013

- 3 ISS astronauts remotely operated K10 rover (approx. 10.5 hr)
- Astronauts used combination of **supervisory control** (task sequencing) and **manual control** (discrete commanding)
- **500-750 msec comm latency** and intermittent LOS periods
- Crew consistently had **low workload** and **high SA level**
- Robot utilization was consistently high (**> 50% time in operation**)

Telerobotics technologies

- **Rover autonomy** enhances operational efficiency and robot utilization (particularly hazard detection and safeguarding)
- **Interactive 3-D visualization** of robot state and activity supports low operator workload and good situation awareness
- **Supervisory control with interactive monitoring** is a highly effective strategy for crew-centric surface telerobotics

Acknowledgements

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- Mike Halverson

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- Josh Hopkins
- Bill Pratt
- Chris Norman

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NASA Lunar Science Institute

NASA Public Affairs

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- Dave Steitz
- Maria Quon

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- Randy Lillard
- Susan Spencer

University of Idaho

- Sophie Milam
- George Korbel

Dedicated to the memory of Janice Voss who served as the initial NASA Crew Office liaison for the Surface Telerobotics project