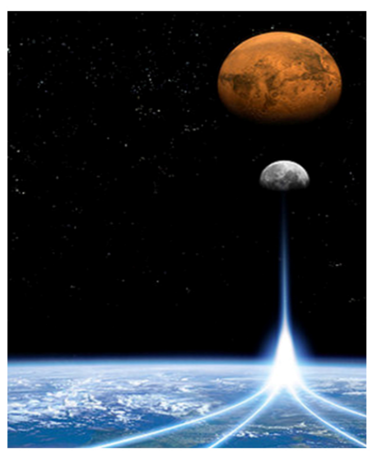
TELEROBOTICS CONTROL OF SYSTEMS WITH TIME DELAY – GAP ASSESSMENT REPORT



7/1/2018

ISECG Technology Working Group

TABLE OF CONTENTS

TABLE OF FIGURES

Acknowledgements

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1. EXECUTIVE SUMMARY

Robots play a crucial role in human space exploration. They are used for everything from scouting and conducting science on other planets to assembling, inspecting and maintaining the International Space Station (ISS) and supporting other crew vehicles. As humans move out into the Solar System as per the Global Exploration Roadmap (GER3) mission scenarios, and operations take place farther away from Earth, the time delay between the operator and the robot increases. While latency is only one factor in the effectiveness of a telerobotic system, other factors, including bandwidth, link availability, control modes, robot autonomy, operator training/proficiency/availability/etc., operator interface design, etc., are also important. However, this report specifically examines the challenges associated with teleoperating robotic elements in a time-delayed scenario.

Currently, most robotic operations used for space exploration are teleoperated, with the operator situated on Earth and either commanding a rover on Mars or the Moon or else operating a manipulator on the ISS. The state of practice for operations with a short time delay, as on the ISS, is to send a command and then wait for feedback before proceeding with the next command. For missions on Mars or other planets, a series of commands are sent, typically for a day of operations, and then operators evaluate the initial results before sending the batch of commands for the next day. Both types of missions use a limited degree of autonomy to make time-critical decisions, such as how much force to apply in contact operations, or hazard identification and avoidance for rover navigation.

In order to operate per the GER3 scenarios, telerobotic systems must be operated in an increasingly efficient manner. Simple tasks such as relocating from one point to another need to become less reliant on direct human control. Systems need to able to handle an increasing amount of complexity in order to perform tasks such as construction, maintenance, In-Situ Resource Utilization (ISRU) manufacturing, site preparation and scientific exploration in undefined, time-delayed environments. Many terrestrial systems are capable of handling these types of scenarios but there are several areas where on-orbit robotic capabilities lag behind.

- As robots handle increasingly complex tasks with an increased amount of autonomy for remote operations, the main limitation to implementation is in the lack of processing power, which lags terrestrial developments by approximately 20 years. Space-qualified high-speed processors and data busses are critical gaps to address.
- Inputs reliant on visual data are subject to poor lighting conditions. Low-power and low-mass versions of sensing technologies such as LIDAR would allow for better situational awareness for operators and would provide inputs to autonomous controllers.
- For systems with increased autonomy, advanced control software will need to be matured to ensure system stability. In parallel, a standard should be developed for verification and validation (V&V) of autonomous software to ensure mission safety and increase mission success.
- As more systems are operated beyond low Earth orbit, communications capabilities will need to be expanded in order to allow for greater amounts and different types of data to be passed between the robotic elements and remote operators.
- For robotic systems that interface with other vehicles, payloads or habitats, ISS experience has shown that standard interfaces greatly reduce the complexity and cost of mission planning and

increase the likelihood of mission success. International standards for robotic interfaces need to be developed and implemented to reduce the amount of pre-mission analysis.

- In-Situ Resource Utilization is expected to play a critical role in long-term human spaceflight missions, which will rely heavily on robotics. To date no missions have been conducted to demonstrate telerobotic capabilities to collect, transport and process resources in low-G environments. Technology demonstration missions such as the MOXIE experiment aboard Mars 2020, which will demonstrate ISRU for atmospheric processing, are recommended to close this experience gap.

Several agencies are working to advance technologies related to each of these gaps. Through continued international cooperation, the gaps can be reduced or closed and teleoperated robotic systems can continue to play an important role in the exploration of the final frontier.

2. GOALS, OBJECTIVES AND APPROACH

The International Space Exploration Coordination Group (ISECG) Technology Working Group (TWG) formed two Gap Assessment teams to evaluate topic discipline areas that had not been assessed at an international level to-date. Previous Gap Assessments have been done for Dust Mitigation and LOX/Methane Propulsion. The selected discipline areas are based on Global Exploration Roadmap (GER3) Critical Technologies needs reflected within the GER3 Technology Development Map (GTDM); the first topic discipline being Telerobotic Operations with Time Delay, and the second topic discipline being Autonomy. The goal of the teams was to do an assessment of the selected critical technologies and identify the major gaps that would advance each technology to the level required to support the GER3 mission scenario.

2.1. Working Group Membership

The ISECG Gap Assessment Team for Telerobotic Operations with Time Delay consists of Subject Matter Experts (SMEs) from the following participating agencies:

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2.2. TWG and SME's Gap Assessment Team Goals and Objectives

The Gap Assessment Team set out to provide a presentation on technology gaps related to the GER3 mission scenario. This activity was not limited to near-term activities (cis-lunar and lunar mission themes), but also looked at long-lead items for extended missions such as human Mars exploration. The assembled teams addressed current technology gaps as well as gaps in other areas, and identified opportunities for international coordination and cooperation in closing those identified gaps.

The Gap Assessment Team's assessment is provided in this summary report as well as an accompanying presentation identifying the Critical Technology Needs and opportunities for international coordination and cooperation in closing identified gaps. When the ISECG TWG performs a more detailed GER3 portfolio analysis, the gaps identified herein should be readdressed and possibly expanded.

2.3. TWG and SME's Gap Assessment Approach

A group of Subject Matter Experts (SMEs) and strategic planning personnel was formed, drawing from member agencies and organizations of the ISECG. This group was selected based on expertise, breadth of experience and heterogeneity, to ensure the broadest possible consideration of the topic. The group met via teleconference with video on a regular basis beginning February 2017 and continued through finalization of this document. Initial meetings featured high-level overviews of current technology as well as Research and Development (R&D) activities currently underway in each of the organizations. These overviews helped determine the breadth of the survey, and helped to establish where particular expertise and experience lie in each of the subdomains being discussed.

The group then identified high-level tasks that are representative of activities required within the mission architectures of the GER3 and extended human missions (e.g., Mars). The representative tasks were then broken down further into specific activities requiring particular technologies or technical capabilities. As was expected, there was a good deal of overlap from task to task, and these lower-level technologies and technical capabilities were addressed directly and evaluated for state of the art on Earth, state of practice in Low Earth Orbit (LEO), and environments required for GER3 scenarios as well as future Mars missions. In summary, the group set out to do the following:

- Identify what we can do now
- Identify what we want to do in the future
- Identify how we plan to do it (Operational Concept)
- Identify what needs to be improved in terms of capabilities
- Determine what gaps are associated with the needed capability improvements
  - Technology Gaps: Current technology does not meet need.
  - Experience Gaps: Technical capability exists (terrestrial) but not yet tested on-orbit
  - Resource Gaps: Inadequate funding or effort being spent in the necessary areas

3. DEFINITIONS

For the purposes of this report the following definitions are used:

Telerobotic Operations - Robotic operations at a distance. For space robotics applications this is nominally done by commanding the robot over a wireless communications link, independent of the control input method. The human operator is a located at remote system which is isolated from the robot.

Haptic Telepresence - A telerobotic control mode using continuous commands/telemetry for contact tasks which provides an immersive experience. A human operator makes all operational decisions and directly commands a robot using a hand controller with tactile feedback as well as high-resolution visual feedback and/or other telemetry, which contributes to the immersive experience for the operator.

Telemanipulation/Teledriving - A telerobotic control mode that uses continuous commands to operate the robot. A human operator makes all operational decisions and directly commands a robot motion using a hand controller, with access to telemetry feedback at the monitoring station.

Scripted Control - A telerobotic control mode at scripted level for motion and force control. A human operator makes high-level operational decisions and commands a robot using scripted motion and force commands, with access to telemetry feedback in the monitoring station. The remote robot is expected to execute the scripted commands using its own automated control system at the motion and force level.

Supervisory Control - A telerobotic control mode at task level. A human operator commands a robot by specifying required tasks and the operator observes execution results via telemetry from the robot. The remote robot is expected to have a task decomposition function and can execute the required tasks using its own automated control system.

Autonomous Decision-Making: This is an ultimate telerobotic control mode where the command input to the robot is a high-level goal or set of goals. The remote robot is expected to have local goal functions and further task decomposition functions and is expected to be able to make its own decisions to overcome anomalies in planning and executing tasks.

Shared Control: A combination of teleoperated and autonomous control.

4. BACKGROUND INFORMATION

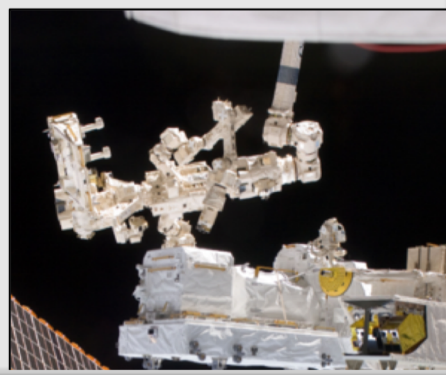
4.1. General

Telerobotic operations with time delay have not progressed at the pace of non-delayed telerobotic operations. Current telerobotic operations in space rely heavily on human-in-the-loop control and monitoring, producing the “bump-and-wait” strategy seen in many space robotic operations. However, robotic systems on Earth that incur no time-delay in communications and have few bandwidth limitations are teleoperated using methods that are smarter, more reliable, and more efficient. To make the leap from Earth-based operations to space-based operations, telerobotic methods for space need to progress at a much more rapid pace.

The most widely used paradigm for telerobotic operation over time delay is depicted in Figure 1 below. The left side of the figure shows the “local” side of the system, which includes the human operator(s), the operator station(s) and any interfaces needed to control the remote robot. The right side of the figure depicts the “remote” side of the system, including the robot and its environment. The communication network in the center may experience delays from time-of-flight travel and/or the method of network delivery. Most space robotic systems follow this paradigm, each with their own set of tools for the human, and their own “autonomy controller” on the robot. These are where differences emerge for existing systems.

State of the Art: ISS Robotics

Due to the lack of available crew time, robotic operations are conducted primarily via ground control from Houston, Montreal or Tsukuba with time delays varying between 2 -10 seconds depending on the telemetry and the location of the remote control centre. Operations include payload handling, ORU replacements, inspection, vehicle berthing and release of cubesats or cargo vehicles.



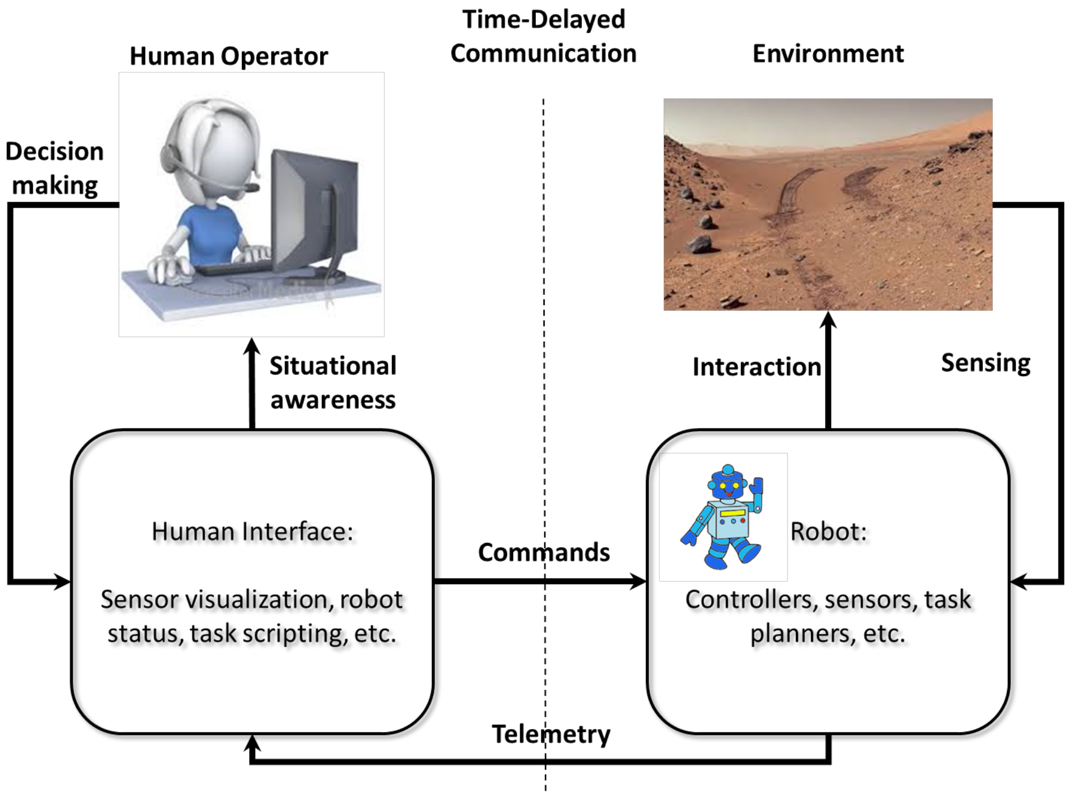


Figure 1: Telerobotic Operation Paradigm

Telerobotic operators may also be distributed across time and space. Earth-based controllers may operate part of a mission from Houston, USA and another part from Tsukuba, Japan, while on-board or local crew manage a separate set of telerobotic tasks. Therefore, the operations paradigms for future GER3 missions will be both distributed and delayed.

The current telerobotic paradigms used for many existing and new robotic systems that are both located and controlled on Earth involve a much higher level of autonomy on the robot than existing space-based robotic systems. However, these systems do not anticipate communication latencies near those that space-based systems will experience.

Time Delay: Mars vs ISS

Robotic exploration missions on Mars rely on meticulously scripted and validated command sequences that are uplinked by mission control to the robot for independent execution. In contrast, human spaceflight missions conducted with the Space Shuttle and ISS use near-continuous communication (data and voice) with minimal time delays (i.e., less than a few seconds)

4.2. Time Delays

The round-trip time delay in a system refers to the time it takes for a signal to be sent from the operator, to the remote robot and for the corresponding feedback telemetry to be sent back to the operator. Time delays generally consist of two parts:

1) The time needed for signals traveling over a long distance
2) The communication latency intrinsic to the computer network and communications architecture

The delay due to distance travelled is easy to compute as it can be calculated using the distance divided by the speed of light, which is constant for a known distance. Delays due to communications architectures are more difficult to predict due to the complexity in computer data bus management, variability in the amount of times the signal is relayed, and the timing of the commands. For space operations that must pass through several Earth-based control points before being relayed via satellite networks, this delay can be significant. For instance, the time required to send a signal to the ISS with a direct line of sight is less than two milliseconds. However in practice, commands must be processed through numerous relays. The result is that for ground-controlled teleoperation, the delay is significant and highly variable. For example, the Mobile Servicing System (MSS) robotic system on the ISS experiences a nominal 2.5-second round-trip delay with up to five seconds of delay for some telemetry when commanded from Montreal, Canada. The Japanese Experiment Module Remote Manipulator System (JEMRMS) operates on the ISS with a worst-case delay of up to 10 seconds for operations when commanded from Tsukuba, Japan. For the purpose of this report, round-trip time delays of five seconds or more are considered for missions beyond Low-Earth Orbit.

4.3. Current Time-Delayed Telerobotic Operations

Teleoperation of robotic systems is currently used as the primary method of operating robots in space. There are two main areas of ongoing operation – ISS manipulators and Martian rovers.

ISS Manipulators: The original plan was for the crew to operate these manipulators for on-orbit maintenance and payload handling. However because crew time is extremely limited, the external robotics on the ISS have gradually transitioned away from crew operations to ground-controlled operations for all robotic operations that do not have a time-critical element, such as EVA support. Currently, all payload operations, vehicle berthing, inspection and ORU maintenance operations are carried out from one of three control centers on the ground – Houston, Montreal or Tsukuba – with varying time delays. Ground controllers typically send one command at a time and wait for the response from the system to verify that the command has been received properly. The human operators will then monitor the telemetry to ensure that the manipulator is responding as expected. This concept of operations is not particularly efficient but works adequately for smaller time delays of up to a few seconds and may be feasible for some lunar operations, but is not feasible for longer delays due to the reliance on humans to monitor telemetry and make decisions in near real time.

Since the telemetry is delayed, all commands are built to account for a 30-second operator response time, which includes 25 seconds to recognize the error, decide on the action and send the command, and five seconds for the command to be sent as a worst case. This requires that the rates be very slow for most operations in proximity to structures, as well as additional safety constraints such as ensuring that a command can complete safely without relying on human intervention. This is achieved in part by manually verifying procedures before the operations and checking clearances as the mission progresses. For some contact operations where loads can exceed the limits in a very short time (often less than two seconds), limited autonomy is used to sense forces so that the manipulator can stop on contact or when a certain load is reached, independent of communications with the ground control team.

Martian Rovers: The Mars Exploration Rovers (MER) mission is representative of the use of telerobots to explore space environments where humans cannot yet go. In contrast to the Space Station Remote Manipulator System (SSRMS) and the Special Purpose Dexterous Manipulator (SPDM) operations, the communications delay between ground control and the MER robots (only one of which is still operational) is measured not in seconds but in tens of minutes. The primary design drivers for MER operations were thus related to communication constraints. The rovers' capabilities and the mission operations strategy had to accommodate the inherent speed-of-light communications time delay between Earth and Mars (from six to 44 minutes round-trip, depending on relative distance). In addition, continuous communications were not feasible for a variety of reasons: A link was possible only when Earth was in the rover's sky, the Deep Space Network is an oversubscribed resource servicing spacecraft all over the Solar System, and the rovers had insufficient power to transmit for more than a few hours per sol. At best, each rover would be able to transmit a few thousand bps, with total telemetry restricted to about 20 Mb per sol. These communications constraints precluded the possibility of directly teleoperating the rovers with manual control. Instead, MER required use of stored command sequence execution, as is typically employed for deep-space probes (e.g., Voyager, Galileo, Cassini). However, those missions typically developed and validated command sequences in processes that took weeks—or even months—before uplinking them to the spacecraft. The combination of limited rover lifetime and the nondeterminism associated with exploring the natural unstructured Mars surface environment called for a much more rapid, reactive command generation process.

Rather than attempting to mitigate the impacts of communications time delay, this command generation process took advantage of the rovers' inherent inactivity during the Martian night to provide the ground control team with time necessary for command sequence planning. The tactical process consisted of the following steps: (a) receipt of downlink, (b) engineering downlink assessment, (c) science downlink assessment and science activity planning, (d) activity plan refinement and validation, (e) activity plan review and approval, (f) command sequence generation, (g) sequence integration and validation, (h) command sequence review, and (i) transmission of commands to the spacecraft. Upon receipt of critical telemetry (i.e., data required for planning the next sol's activities) by midafternoon (Mars local time), the rover engineering team assessed the health of the rover's subsystems and confirmed that the sol's activities were completed as planned.

Several key lessons were learned during the MER mission. First, high-fidelity resource modeling of command sequences prior to execution proved to be absolutely essential. Second, the use of stored command sequences to operate the rover autonomously for a day (or more) at a time was very effective. Third, because MER was discovery driven, the duration of the tactical cycle drove mission return: The shorter the command cycle, the more command opportunities over the life of the mission. Fourth, although long-distance rover traverse was originally envisioned to be solely reliant on stereo-vision-based autonomous navigation, the extensive time required for onboard processing led to a new, mixed strategy to maximize the distance covered per sol: For the first leg of a traverse, the vehicle would dead reckon a path designated by mission operators using stereo imagery captured from the rover's initial position, and for the second leg, the vehicle would make full use of its onboard autonomy to cross terrain beyond the limits of traversability data available to the operators.

4.4. Remote Autonomous Robot

For remote systems with large time delays, additional levels of autonomy may be implemented. Figure 2 shows a simplified block diagram of the control modes for a remote autonomous or semi-autonomous robot. The remote robot receives commands from and sends situational information back to the control station. The commands received from the control station can be at different levels, ranging from low-level continuous commands (e.g., hand controller inputs for desired trajectories), to discrete commands (e.g., move from X to Y), and finally to goal-level (e.g., "Go get a sample from that rock").

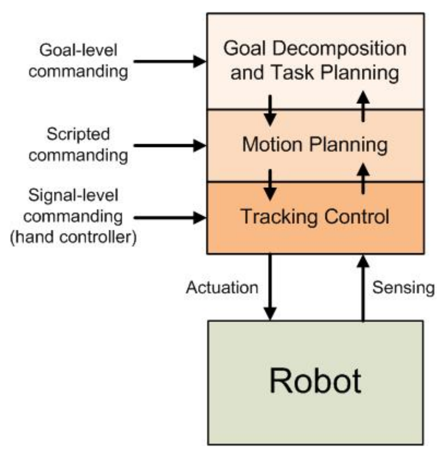


Figure 2: Command Modes for Remote Autonomous Robot

An autonomous control system such as the one described inevitably involves a top-down goal or task decomposition process as shown in Figure 2. This process, corresponding to the downward arrows, is needed to convert a large problem into several smaller problems. On the other hand, feedback closed-loops are built bottom-up, corresponding to the upward arrows in Figure 2, in order to verify task executions at each level. In this regard, an autonomous robot can be viewed as a "super control system."

State of the Art: Mars Rovers

The remote operation of the Mars Exploration Rovers (MERs; Spirit and Opportunity) and the Mars Science Lander (MSL) Curiosity by daily "uplink" of command sequences and "downlink" of recorded data are examples of supervisory control. Communication constraints brought about by long distances from Earth are a primary consideration for rover design and mission operations strategies.

Independent of the specific implementation, a telerobotic system can be depicted in the abstract as shown in Figure 3. This system is basically comprised of three parts: 1) a command center that includes the human operator, the monitoring station, and the command station; 2) a robot for task execution that includes the robot and its environment; and 3) the communication network that links the operator and the robot.

The telerobotic system diagram in Figure 3 shows that a human operator is always placed at the outmost loop to provide ultimate commands and perform intervention if necessary, regardless of the level of autonomy a remote robot may possess. This also suggests that robotic autonomy is a property associated with the remote robot itself and, therefore, can be incorporated into the general framework of a telerobotic control system. Human-machine interfaces may look very different depending on the level of autonomy or dependence on human oversight.

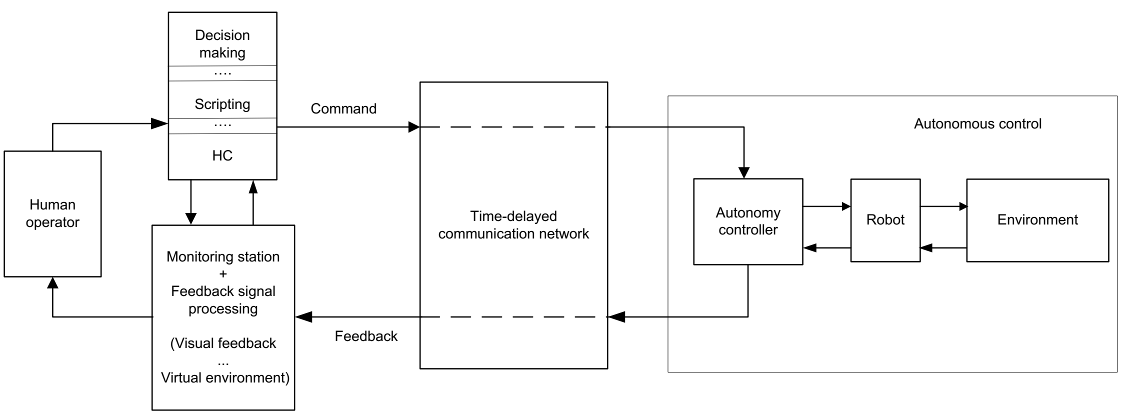


Figure 3: Diagram of an Example Telerobotic System

5. ROBOTIC TASKS

The current list of robotic operations is not well defined for Mars in GER3, and even for the Moon it is fairly loosely defined. Other destinations such as the outer planets are out of scope for these discussions. Missions that involve orbiters only are designated as “Robotic Missions” in the GER3 but are not considered as robotic systems and are also out of scope for these discussions.

In order to better define the needs of a future telerobotics system the team considered several high-level representative tasks that would be required for the long-term goal of supporting humans on Mars. The team considered eight representative tasks, many of which overlap to varying degrees with other tasks:

5.1. Relocation

In the context of this report, relocation refers to the teleoperation task of moving a surface vehicle (i.e., a rover) from one location to another. Depending on the operational scenario, the relocation might need to be achieved at various speeds ranging from low speed (e.g., a few centimeters per second) for precise parking manoeuvres to higher speed (e.g., a few kilometers per hour) for relocation between two sites of interest. Fast relocation would enable more science and more mission outputs. The level of human involvement in this task may vary from high involvement, in the case of a lunar operation for which the communication link might support many command cycles per day with high bandwidth, to low involvement in the case of Martian operations where bandwidth and the amount of command cycles per day are limited. For any mission scenario, autonomous long-range relocation (e.g., a few kilometers and more) for which a human operator is not required would reduce the operator’s workload and allow the vehicle to travel longer distances. Long-range and fast relocation would rely on advanced technologies such as complex planners, robust self-localization, better vision systems and onboard processing units.

5.2. Construction

Construction tasks on other planetary bodies, especially using regolith or other in-situ resources as the feedstock materials, can be accomplished telerobotically prior to human astronaut arrival or between visits. An especially important near-term task is to provide radiation protection for the crew by constructing shelters that can be covered with a few meters of regolith. Such shelters can be formed over either rigid or inflatable pressure vessels to provide habitable volume with order-of-magnitude lower radiation levels compared to being unprotected on the surface. One potential way to accomplish this is by sintering regolith into bricks that can be used to create arch structures. Another is to form the regolith into a concrete-like slurry that hardens so that structures can be 3D-printed. Other important construction tasks include creating landing pads that eliminate the generation of hypervelocity ejecta during landing events, or berms to prevent such particles from causing damage to nearby structures. Another important reason to have in-situ construction is to improve the thermal control situation for habitats, since the thermal inertia of regolith is high and the thermal conductivity is low, protecting habitats from the extreme thermal swings of the surface environment.

5.3. Manufacturing with In Situ Resource Utilization (ISRU)

In situ resource utilization is an important capability for future long-term robotic missions. Lunar and Martian regolith contain resources that could potentially be used to generate useful products, including oxygen for human consumption and LOX/LH2 (methane on Mars) as rocket propellant. It is estimated that 50 tons of water per person would have to be extracted from the lunar regolith to support human exploration of the Moon. ISRU is therefore a very important technology that must be refined and tested both in analog settings on Earth and in space applications.

5.4. In-space Maintenance and Support

Space assets including vehicles and orbiting habitats require maintenance, especially on long duration missions of several years. Based on ISS experience, crew time to perform necessary inspections and maintenance is limited, and may be more effectively carried out by teams of specialists on the ground via telerobotic operations. In addition, Extra-Vehicular Activities (EVA) are risky for crew and are limited in terms of time by the amount of consumables in an EVA suit.

Robots are used externally for most maintenance and repair tasks. This includes but is not limited to tasks such as replacing failed components, capturing and berthing visiting vehicles and inspecting structures for damage and relocating.

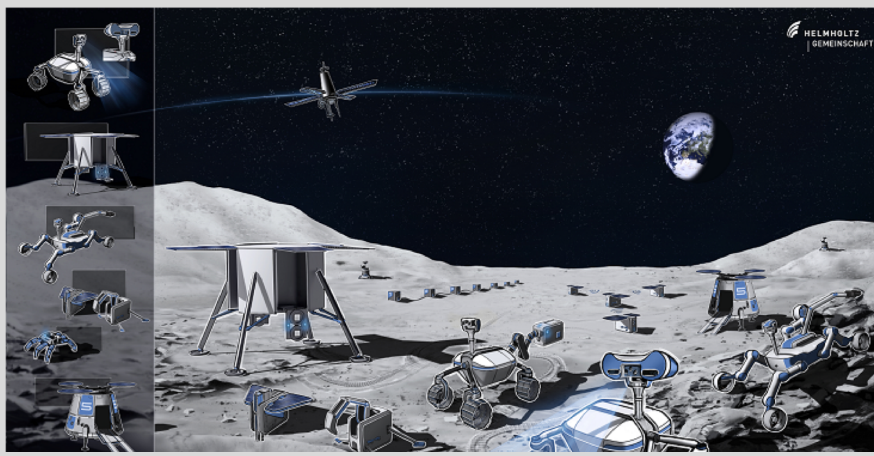
5.5. On-surface Site-preparation and Maintenance

Planetary exploration missions that involve human crew or multiple robotic systems are likely to incorporate infrastructure for mission support beyond the landed spacecraft itself. This infrastructure might require initial surveying and other site preparation in order to support its functionality. It is generally assumed that robots or other automated means, either controlled from Earth or by crew from orbit, would perform tasks for on-surface site preparation and maintenance prior to the presence of an onsite human crew. These tasks might involve surveying the local features of the site; measuring physical and chemical properties of regolith and features; moving rocks; flattening surfaces; drilling; setting up landed equipment, devices and habitat modules; setting up power generators and ISRU devices; establishing power, data, and communication grids and networks; placing beacons or other equipment for localization systems; and inspection, maintenance, and operation of all aforementioned before and after crew arrival.

5.6. Precursor Missions

To increase the likelihood of success, future crewed missions may rely on robotic precursor missions. These missions will send robotic agents to a destination where these robots will conduct research and prepare for the future human mission. Precursor missions can have many objectives, whether to scout landing sites for crewed missions on planetary surfaces or to demonstrate the feasibility of ISRU technologies. Capabilities needed for precursor tasks will be very similar, if not identical, to capabilities needed across the spectrum of tasks described in this section of the report. Precursor robots may need to map environments, detect important science targets, test novel technologies in flight environments, build or maintain resources needed for humans, and prove the validity of ISRU systems, among other tasks. All of these tasks will need to be done with limited human interaction.

The Robotics and Mechatronics Center (DLR-RMC) is DLR's competence center for research and development in the areas of robotics, mechatronics, and optical systems. Research in cooperative robotic assets that have heterogeneous capabilities is a key aspect of the Robotics and Mechatronics Institute within the RMC. This research envisions autonomous robots and robots operating under shared autonomy cooperatively solving tasks in future space missions. This research also produces spinoff technologies.



5.7. Scientific Missions

In order to find answers to major scientific questions such as the history of the Solar System and the existence of life beyond Earth, complex robotic systems are required that can collect scientific data remotely. These systems must be designed to last for long periods of flight time in non-operational status, and then to operate for a limited time on a planetary surface. To maximize science data return, human operational interactions should be limited as much as possible to those functions required for science data collection. Scripted operations, supervised control, and autonomy will allow robotic systems to handle tasks that will be required to manoeuvre scientific instruments to their targets. But teleoperation/telepresence will be required for the analysis of scientifically relevant environments. The scientific interpretation of data and measurements from robotic probes will undoubtedly produce unexpected results, which will require human interaction. Because of this, we expect a fundamental change in planetary research, from remote sensing to in-situ measurement, particularly in challenging environments with high scientific value such as craters, caves and subsurface operations.

5.8. Long-term Complex Tasks

To facilitate extended-stay human exploration missions, it is likely that infrastructure will have to be created at the local site. Activities include survey, site layout, creation of motion lanes, power and ISRU siting and deployment, as well as construction tasks that are associated with habitat and laboratory facilities. It is highly desirable to minimize the need for crew EVA activity associated with these tasks, for both safety and resource reasons. Additionally, these activities may take place over a long span of time. A robot or a group of robots working both independently and together would perform many of these tasks and it may be most feasible to perform these activities telerobotically. Depending on mission architecture and the long-term infrastructure tasks to be performed, this work may be controlled either entirely remotely, or through an exchange of control between remote and local operators. In addition to telerobotic control modes, attention must be given to issues around passing the Locus Of Control (LOC) among distance-separated operators, using the communications architecture of the mission design. These activities add complexity as more activities are performed concurrently or in a choreographed sequence, and may begin long before the arrival of the first local crew.

6. CONTROL MODES

Telerobotic operations with significant time delay are characterized by severely constrained opportunities for interaction and communication between the human operator and the robotic asset. Communication time delays and lack of models of remote planetary environments exacerbate the control problem for reliably conducting scientific and engineering operations. This is not only because fast reaction is sometimes needed, but also because without access to live data, decisions made remotely by human operators may be based on obsolete information, which could be inappropriate and even hazardous to the system.

Robots can be operated in various modes requiring various levels of autonomy depending on the complexity of the task and the time delays involved. In general the greater the amount of time delay present, the greater the need for more autonomy, as shown in Figure 4.

These capabilities are not mutually exclusive, rather they can be designed and provided on top of (or as a complement to) other approaches. Different control modes offer advantages and disadvantages for different scenarios. For example a rover could use an autonomous mode to navigate to a destination and then follow a scripted sequence to deploy a tool. Autonomy can be exploited for increased efficiencies in situations where it is considered safe and appropriate to rely on on-board deliberation and control. Safety can be increased by requiring the robotic asset to stop and wait for human intervention when on-board deliberation cannot determine how to achieve the desired result within the pre-determined validated constraints.

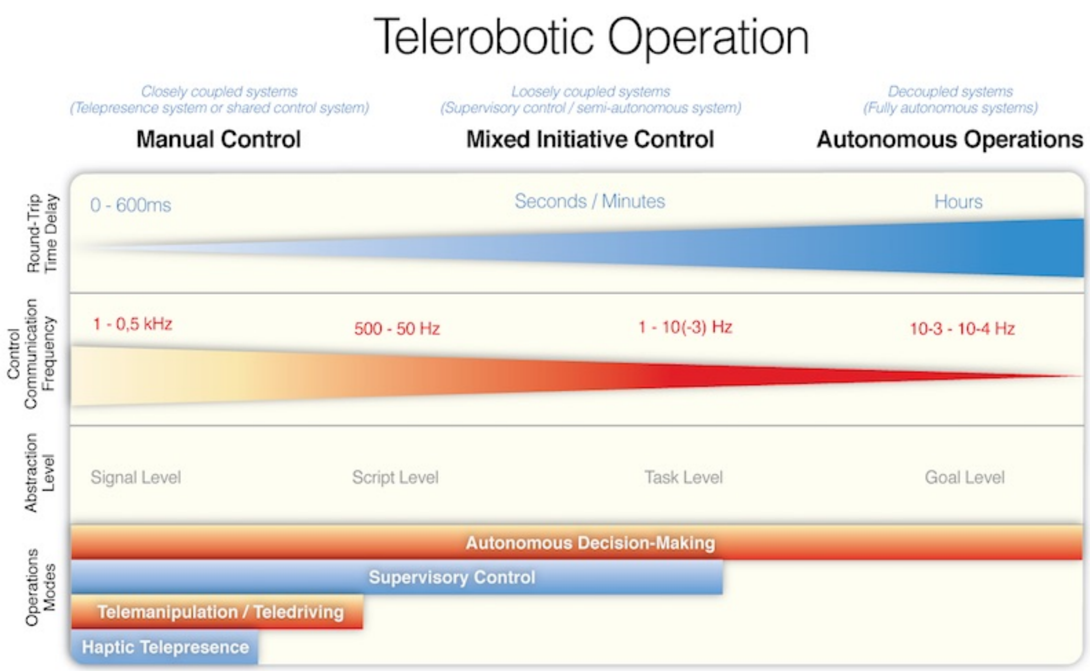


Figure 4: Telerobotic Operation

Four telerobotic control modes are described below, in terms of the degree of autonomy expected from the remote robot.

6.1. Haptic Telepresence

Haptic telepresence is a telerobotic control mode that uses continuous commands for contact tasks. A human operator makes all operational decisions and directly commands a robot using a hand controller with tactile feedback, in addition to telemetry feedback in the monitoring station.

Haptic telepresence is usually baselined with bilateral teleoperation with force feedback. The goal of haptic telepresence is to provide a contact transparency to the human operator, which can have great value in robotic operations where the time delay is very small and/or sensitive payloads are being manipulated or operated upon. Robotic tasks such as local assembly by crew may be enhanced or even enabled by force-feedback teleoperations.

However, this near perfect transparency is only achievable when one-way time delay is less than 0.1 second, a short time delay that has been confirmed by experiment. Realistic time delays in most space systems are typically on the order of two seconds and more, much larger than the specified 0.1 second threshold that guarantees instant transparency in force-feedback teleoperation.

Since transparency is fundamental for the use of force feedback control, the inability to ensure instant transparency makes the use of force-feedback teleoperation control impractical for use in time-delayed space operations, despite strong academic interest shown in the research community.

A possible solution lies in a version of haptic telepresence in which a virtual environment is added at the operator site to create an instant force feedback perception for the human operator. To make this safe and practical for time-delayed telerobotic control, the contact dynamics with the virtual environment must ultimately converge with the real contact dynamics at the remote site, despite the fact that they are occurring in different time frames and are subject to uncertainty (caused by model-mismatch between the virtual and actual environments) and external disturbances.

Advantages

Haptic telepresence provides the human operator with a "feel" for contact tasks, which is very useful for delicate operations such as surgery. It can also be useful as an input for machine learning for artificial intelligence systems, to teach the system how to react to different contact scenarios.

Disadvantages

Current state-of-the-art bilateral teleoperation control technologies can only ensure a transparent contact "feel" when one-way time delay is less than 0.1 second. For deep space interplanetary missions, where long time delays (>5 seconds) are often encountered, the use of sophisticated virtual environments to provide instant force feedback becomes necessary. However, the existence of inaccuracies in virtual contact models renders existing haptic telepresence technologies impractical and unsafe until new breakthroughs are made.

6.2. Teledriving/Telemanipulation

Teledriving is a telerobotic control mode using continuous input commands for motion control. A human operator makes all operational decisions and directly commands robot motion using hand controllers, with access to telemetry feedback in the monitoring station as required. This control mode is widely used in terrestrial telerobotics where the time delays are negligible. It's also an easy-to-use control mode for non-experts; for example, children can drive remote-controlled cars.

Teledriving is currently used by the ISS crew to operate the JEMRMS and MSS, with time delays that are transparent to a human operator for video feedback and hand controller commands, although feedback for some non-critical telemetry may be delayed by up to three seconds. Space manipulators tend to require steady hand controller inputs for motion commands to ensure stability and to avoid causing load issues or transient off-axis motion. This leads to variances in outcomes based on operator skill and proficiency on a specific system.

Teledriving in time-delayed scenarios becomes much more difficult as it requires the operator to time commands based on the anticipated response as opposed to the actual perceived feedback. One common solution for this is to use predictive displays and overlays to indicate the expected response based on a known time delay. This can include a range of possibilities, from commanding the robot based on static overlays to a full virtual environment, similar to haptic telepresence but without the force feedback.

Advantages

Teledriving can be easy to use for infrequent operators because of the intuitive nature of the controls. It also allows the operator to react quickly to real time inputs when the time delay is very small and is easy to adapt in real time to unexpected occurrences.

Disadvantages

Longer time delays make teledriving systems increasingly difficult to operate. Predictive overlays and displays used to provide feedback to the operator depend on the development and verification of accurate models of the robotic system that accurately predict the behaviour of the system and the reaction to the environment. Since the commands are based on continuous command signals, any interruption in communications can cause problems as they may appear as large, instantaneous changes in commands, which can cause high computing loads.

6.3. Supervisory Control

Supervisory control is a robotic control mode that involves a human both receiving information from a remote robot and sending commands to that robot. This control mode encompasses a continuum of human-in-the-loop discrete control. (See Figure 4.) On the left of this continuum is the most human-dependent mode, which requires humans to script control of a robot at a single-command level, whether this single command is joint-control or Cartesian control. The least human-dependent version nears full autonomy, with a human providing an overall plan and supervision of the robot, while the robot makes semi-autonomous decisions.

Many previous or current modes of operation for space telerobotics fall under the least autonomous boundary of supervisory control, often referred to as “scripted control.” This type of supervisory control relies heavily on a human operator to make the majority of operational decisions, while the robot manages its own control at the motion-planning and force-feedback levels. In this mode, the robot will follow the commands regardless of local conditions and is reliant on a human operator to identify and avoid any hazards prior to sending the commands.

Currently, scripted operations are typically used for ground control of rovers and for most ISS operations. The scripts can be executed in simulators prior to the operations to ensure that the command sequence is correct and that the commands will all complete safely while respecting any operational constraints, such as keep-out zones. This ensures that even if a loss of communication occurs the command will complete without any risk to the robot or the crew.

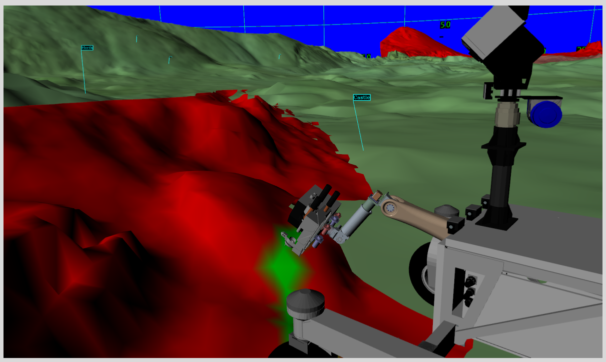
For increased safety on human spaceflight programs such as the ISS, the response from each command for motion must be verified prior to sending the next command. While this is feasible for the relatively small delays to ISS it becomes impractical as time delays increase. Martian rovers typically execute a long series of pre-scripted commands in order to accomplish a day-long task. This increases efficiency but may increase risk if any of the commands are incorrect or result in unexpected behaviour.

Conversely, the opposite end of the supervisory control continuum still relies on a human-in-the-loop operation, but involves the human operator sending task plans that the robot executes with a degree of autonomy. The operator plans the task and supervises the activity while being ready to make corrections to operational anomalies based on telemetry feedback at the monitoring station. The remote robot is expected to have a task decomposition function and to execute the required tasks using its own semi-automated control system.

Supervisory control is commonly used in time-delayed operations for all types of tasks, including everything from basic translation commands to complex contact operations, due to the ability of the command to complete safely without relying on communication with a remote human. Additionally, time-delayed operations can be bandwidth-restricted, providing minimal telemetry feedback to the human supervisor, which in turn necessitates more autonomous capabilities (including local sensory feedback and control) on the remote robot when performing complex contact tasks.

Example of a timed-delay robotic task performed under a supervisory control mode.

CSA MESR rover performing a rock abrasion task during the 2016 Mars Sample Return Analogue Deployment (MSRAD). The placement of an abrasion tool on a rock was conducted in a two-click sequence. The operator would pick the tool placement location in the 3D rover environment model of the CSA Apogy ground station. The first command would position the tool in hover mode at a location automatically calculated above the target, while the second command would bring the instrument in contact with the target.



Advantages

In supervisory control that is highly dependent on human intervention, robot responses can be easily pre-programmed in a series of scripted commands. This allows for a script to be developed and verified independently prior to operations, and greatly reduces the risk of operator command errors, practically eliminating the variance in performance between operators. Generic scripts can be re-used for common tasks, which reduces the overhead for human operators when developing procedures and reduces the risk of errors.

Supervisory control that requires minimal human intervention can be advantageous in that commands are usually task-level and the time delay does not adversely affect the success/completion of these commands. It also requires less human involvement, which reduces operator workload. In addition, the task process can be simulated beforehand and a nominal plan developed, but the robot can still adapt in real time if a response is unexpected.

Disadvantages

Robotic systems operating under supervisory control with high human involvement, with little to no autonomy enabled, have difficulty adjusting to unexpected responses in real time. Command sequences are pre-scripted and verified in advance of the operations and cannot always be altered quickly in real time to account for unexpected situations. In the absence of an overriding command from an operator, a scripted sequence will complete as commanded regardless of local events, which can result in undesired consequences if the response is not as expected.

Supervisory control with decreased human involvement needs assumptions to work, and automation works well in well-structured environments where all operational assumptions remain valid. In unstructured environments, the validation of some assumptions that the task-level automated control system is based on can be compromised, leading to operational anomalies. While some operational anomalies are recoverable with human intervention, others are not. Non-recoverable anomalies, such as collisions, becoming trapped in soft terrain, or dropping into a ditch, can be catastrophic for space missions. The system must be properly designed and verified to ensure that the autonomous controller prevents the robot from encountering any such hazardous conditions.

6.4. Autonomous Decisions

Autonomy is a telerobotic control mode in which deliberation capabilities are available on-board and the control action is carried out by the human operator at goal level. The rationale for autonomy in telerobotic operations with significant time delay is because of the severely constrained opportunities for interaction and communication between the human operator and the remote asset. Communication time delays and lack of models of remote planetary environments exacerbate the control problem for reliably conducting scientific and engineering operations. This is not only because fast reaction is sometimes needed, but also because without access to live data, decisions made remotely by human operators may be based on obsolete information, which could be inappropriate and even hazardous to the system.

A key aspect that distinguishes this control mode is deliberation. Autonomous robotic assets facing a diversity of environments, tasks and interactions cannot be rigidly programmed at the design stage by stating all possible courses of actions. These robotic assets need explicit deliberation capabilities, as well as flexibility in the course of their autonomously generated operations in order to adapt themselves as much as possible to unknown operational scenarios. This combination of autonomous capability, diverse environments and unknown scenarios requires explicit deliberation on the part of the robotic asset. The scope of the deliberation leads to possibly increasing levels of autonomy. The remote asset for instance can have task decomposition capabilities to perform complex activities specified as high-level commands without operator control. Or it can have proper deliberation capabilities enabling local decisions to overcome anomalies, avoid hazardous configurations, achieve scientific goals and properly manage resources. Full autonomy would entail the capability of pursuing a mission decided by the control center instead of simply achieving a series of goals provided by an operator.

Autonomous capabilities are not mutually exclusive of supervisory or scripted controls, but they can be designed and provided on top of (or as complementary to) other approaches. Autonomy can be exploited when no other control approach can achieve the result or in situations where it is considered safe and appropriate to rely on on-board deliberation and control. Safety can be increased by requiring the robotic asset to stop and wait for human intervention when on-board deliberation cannot achieve desired and validated behaviours.

Advantages

Autonomy can provide higher science return in situations where long time delays put serious limits on the decisional capabilities of remote human operators. Greater autonomy can also lead to increased safety, as it requires the least degree of human involvement, making it less susceptible to operator error due to communication delays and information obsolescence.

Disadvantages

Increased autonomy poses increased challenges. Autonomous decision-making adds another out-loop on top of supervisor control, beneath the human loop. This creates the need for transparency of the deliberation technology and explanation of the system's autonomous behaviour, since flaws in deliberation processes and models may not be detected until too late. Compared to supervisory or scripted control, full autonomy requires verification and validation of the whole deliberation technology, not only of the provided plans to be executed. This introduces increased risk in the form of a higher probability of deliberation issues due to inaccurate situational awareness because of sensor readings and interpretation.

6.5. Gaps Related to Control Modes

Different technology gaps currently exist, depending on which control option is used. As the options for control reside on a spectrum from haptic telepresence to full autonomy, the biggest gaps exist at either end of the spectrum and are discussed here. Technical gaps that apply to all modes of operation are discussed in Section 7.

6.5.1. Gaps Related to Haptic Telepresence

In haptic telepresence, the virtual contact dynamics between the human operator and the virtual environment must match the time-delayed actual contact dynamics between the remote robot and its environment, in order to provide a time-shifted contact "feel" with fidelity. Current state-of-the-art bilateral teleoperation control technologies can only ensure a transparent contact "feel" when one-way time delay is less than 0.1 second.

As the time delay increases, the feedback to the operator must be artificially generated based on the expected response – typically through the use of a simulator or artificial intelligence and a defined model. Modeled systems will always have some error in them, as some factors are difficult or impossible to predict accurately, such as friction in a dusty environment, or an unexpectedly failed soft-dock mechanism in a space power module. For contact operations, even miniscule differences in the model versus reality can quickly result in excessive loading or unsafe incorrect behaviour, possibly resulting in damage to the robot or payload. For haptic telepresence to effectively handle system dynamic uncertainties such as these, the virtual contact dynamics between the human operator and the virtual environment must approach the time-delayed actual contact dynamics between the remote robot and its environment in a closed loop manner, in order to provide a time-shifted contact "feel" with fidelity. The gap lies between the requirements for the convergence of the virtual environment to reality in presence of uncertainties. State-of-the-art research has yet to provide a solution.

6.5.2. Gaps Related to Autonomous Systems

The movement from telerobotic controlled systems to higher degrees of autonomy and shared autonomy is an important technological development for future space missions. In order to achieve this goal of increased autonomy, improvements are needed in robotic perception capabilities including identification, classification, and interpretation capabilities in terms of semantic reasoning.

Improvements are also needed in developing capable and verifiable mission planning and scheduling software, along with executive capabilities that can orchestrate the execution of complex tasks with reasonable reliability. In order to ensure reliability, software verification and validation must be done to minimize the risk of incorrect decisions or behaviour on the part of the autonomous controller.

An accurate model of the operational environment is essential to enable robots to navigate and manipulate objects in their surroundings. Continuous modeling and updating will be required to keep this model current during motion and change of environment. In order to handle these data streams in a bandwidth-limited environment, technology advancement will be required in image stream processing units, image stream pre-processing sensors (e.g., light field cameras, action and change based cameras, flash LIDARS) and redundant sensor systems to increase the reliability of perception while remaining energy and thermally efficient.

Currently, one of the main limitations for space robotics is the lack of advanced space-qualified processors capable of handling the large amounts of data required for autonomous systems. Many systems currently send telemetry to the ground for processing which results in delayed reactions that are undesirable and potentially unsafe in autonomous systems. In order to advance autonomous robotics in space, advanced high-speed flight-qualified processors are required. While advanced processors are highly desirable for all modes of operation, they are a critical gap for fully autonomous robotics.

6.5.3. Other Gaps Related to Control Modes

Figure 5 shows the different control modes and their potential for use in future tasks. In many cases there exists an experience gap for telerobotics time-delayed tasks using anything beyond simple scripted sequences of commands. Many of the tasks that are foreseen for space exploration are already carried out robotically on Earth or in low Earth orbit aboard the ISS. However, some adaptations are required for use beyond low Earth orbit.

Level of Autonomy/Method of commanding, non-terrestrial time delay > 5 sec

Human made decisions --> <-- Robot made decisions

Task Name	Timeframe	Haptic Telepresence			Teledriving/ Telemanipulation			Supervisory Control			Autonomous Decisions		
1: Relocation between sites	Present	++	o	--	++	++	++	++	+	o	++	o	--
	Future	Low			Low			Med			High		
2: Construction tasks	Present	++	+	--	++	++	+	++	o	--	++	o	--
	Future	Low			Low			Med			High		
3: Manufacturing with ISRU	Present	++	o	--	++	++	--	+	-	--	-	+	--
	Future	Low			Med			Med			High		
4: On-Orbit Servicing/ Maintenance	Present	o	o	--	++	++	++	++	+	--	+	+	--
	Future	Low			Med			High			High		
5: On-Surface site Prep/ Maintenance	Present	+	+	--	++	+	--	++	+	--	++	+	-
	Future	Low			Low			High			High		
6: Pre-cursor missions	Present	++	o	--	++	+	-	++	+	--	++	+	+
	Future	Low			Low			Med			High		
7: Scientific missions	Present	++	o	--	++	++	++	++	+	--	++	+	--
	Future	Low			Med			High			High		
8: Long Term Complex Tasks	Present	o	o	--	+	+	-	+	+	--	-	-	--
	Future	Low			Low			High			High		

Present:

Capabilities
Knowledge - HowTo
Capability on Earth
Capability in Space

Level of Capabilities

--	Low
-	
o	
+	
++	High

Future

Need Priority

High	Required for mission success or safety
Med	Useful for inceased mission success
Low	Not required based on current assessment/needs.

Figure 5: Operational modes for Telerobotics

For many missions it is likely that several different control modes will be used over the course of daily operations. Transfer of control between different operators and different modes (auto-pilot to pilot transition) needs to be addressed. Currently transfer between controllers is handled by voice communication as these transfers tend to be between human operators. As systems become more autonomous, transfer protocols should be developed to ensure safe transfer of control. Standard protocols should ensure that there is only one active controller so that an autonomous system does not unintentionally counteract manual inputs. The system should account for autonomous cooperative robotic systems that can also be controlled by local or remote human operators.

7. AREAS OF IMPROVEMENT/GAPS

7.1. Performance Improvements

The following capabilities were identified as needing improvement over the current on-orbit capabilities in order to achieve the tasks identified in Section 5. In some cases terrestrial improvements may exist that address the issue but have not been proven in a spaceflight environment, or may need further refinement in order to be suitable for use in space exploration missions.

- Capabilities to improve:
  - Robotic Vision in Poor Lighting
  - Localization Accuracy
  - Human Situational Awareness
  - Advanced Motion Planning and Hazard Avoidance
  - Visual Servoing for Auto Alignment
- Policy Improvements
  - Interoperability/Standardized Interfaces
- Experience/Knowledge Gaps
  - In-Situ Resource Utilization
  - Low-G Construction Tasks Using Local Resources

7.1.1. Capability Challenge: Robotic Vision in Poor Lighting

In future space exploration, numerous robotic operations will have to be performed in poor lighting conditions. Such conditions can be encountered in diverse situations and induce different levels of sensing difficulty. In operations on orbital or planetary infrastructures, a scene containing human-made objects can be characterized by a very high contrast due to the presence of dark shadows and sunlit surfaces with potentially high reflective properties. In surface exploration, the environment can be characterized by a combination of poorly lit areas due to a low sun incidence and shady areas (particularly in the exploration of totally obscure areas such as caves.) The challenge is to enable a large spectrum of robotic tasks in such conditions with high efficiency, reliability and safety. This can be realized by using one of two approaches: either rely on sensors featuring a low sensitivity to natural lighting conditions (such as LIDARs or thermal infrared cameras) or provide an adequate source of artificial lighting.

LIDAR is adequate to perform from coarse up to fine 3D reconstruction depending on the sensing range and is compatible with total darkness. However, due to a smaller pixel density, its spatial resolution is currently insufficient to compete with visible cameras when precise manipulation tasks or scene interpretation by humans are required (e.g., the space-qualified GoldenEye 3D Flash LIDAR from ASC features a 128x128 resolution, compared with classical 4Mpixels visible cameras). In addition, the power draw required by LIDAR is a major constraint on its deployment in space robotics. The technological challenge consists in the development of LIDAR-type sensors offering the same level of sensing/situational awareness that visible cameras provide in normal lighting conditions, at power levels that are compatible with current robotic platforms. This requires performance improvements in multiple areas such as detector pixel density, compactness, power efficiency and reliability.

Providing additional lighting enables the use of visible cameras and provides observations with the highest possible resolution even in the dark. This implies a wide-angle illumination system that emits light pulses from multiple synchronized sources such as LEDs. The limiting factor for space applications comes from the power budget needed to illuminate the scene over a large area and reduce the contrast in the shady zones to a sufficient level.

Considering that the required power is proportional to the square of both distance and field of view radius, the technological challenge is the development of a reliable and compact lighting device with a wide operational range (tens of meters range and tens of degrees field of view).

7.1.2. Capability Challenge: Localization Accuracy

Accurate position estimation is a capability challenge for space-based robotic operations. Earth-based robotic systems can localize to millimeter accuracy and it is difficult for Earth-based capabilities to cross over to systems for space. Earth-based systems have multiple means for accurate robot localization: Global Positioning Systems (GPS) provide robots with a world-frame positioning system, ensuring robotic localization systems can focus on local-frame pose estimation. Real-time human interaction can correct positioning errors. Well-understood dynamic systems provide highly accurate models of the systems for determining joint positions, and a priori maps provide a well-known world model to which sensory data can be compared for pose estimation. Some of these capabilities are available to space-based systems while others are not. The following GER3 task needs are impacted by this challenge:

High-speed surface mobility: Current space-based surface robots move slowly, thereby obviating the need for highly accurate and instant localization estimates. However, future missions may require relocation of assets across long distances, requiring high-speed surface mobility. Space-qualified LIDAR systems can enhance the localization capabilities produced by visual odometry; they can also provide a simultaneous localization and mapping capability for areas of planetary surfaces that are unmapped.

Visual servoing of manipulators: Current space-based manipulators do not perform autonomous visual servoing for alignment tasks. Multiple technologies can contribute to overcoming this capability challenge. One challenge is that processing the video data in real time to support alignment with local targets requires advancement in space-qualified high-speed processors. Additionally, cameras that can localize targets would be able to detect those targets without human intervention under most or all conditions, and space-qualified LIDAR systems would vastly improve target detection.

7.1.3. Capability Challenge: Human Situational Awareness

Better situational awareness for a human teleoperator requires improvements in sensing capability at the remote site and rendering capability at the operator station. This also requires improved communication between the two at a reasonable frequency with more bandwidth than is currently available. At present, situational awareness is achieved through a combination of cameras and telemetry but augmented telemetry is needed in order to enable capabilities like autonomous opportunistic science data collection.

Virtual environments provide good situational awareness that is easy to interpret by the operator, similar to the 360-degree camera views provided in some new cars. However virtual environments will always have the risk of errors, so this needs to be dealt with in order to improve reliability and accuracy.

Improved sensing and corresponding telemetry are needed to better represent actual conditions and items that cannot be seen through a camera, such as soil properties from a distance, which is very important for rovers. Ground-penetrating radar could be useful for this but needs to be optimized for rover applications.

Improved telemetry can also produce more useful hazard maps and allow human operations to form a more complete semantic interpretation of the remote environment.

7.1.4. Capability Challenge: Advanced Motion Planning and Hazard Avoidance

Safe motion planning requires the computation of a collision-free path to be followed by either a rover or a robot arm's end-effector. That path could be computed from exterioceptive data of the robot's surroundings (e.g., an environment sensor scan) which is called a local path. There are also global paths that are computed from global data (e.g., a digital elevation map built from orbital observations).

Autonomous robots must be able to automatically detect and avoid hazards/collisions. This is especially important if high-speed surface navigation is required. This detection/avoidance capability exists now but is limited by safety concerns and the need for robust verification and validation. Current embedded processing units do not have the capability to process the large amount of 3D data required to robustly detect hazards at high rates (e.g., 10 – 15 Hz). New methods, standards and procedures for qualification of such algorithms for space applications are required.

Currently on ISS pre-flight simulations are used to manually verify trajectories and allow for proper clearances to avoid unwanted contact during operations of the SSRMS, SPDM and JEMRMS. Automatic collision avoidance on articulating members would allow for safer, more efficient operations.

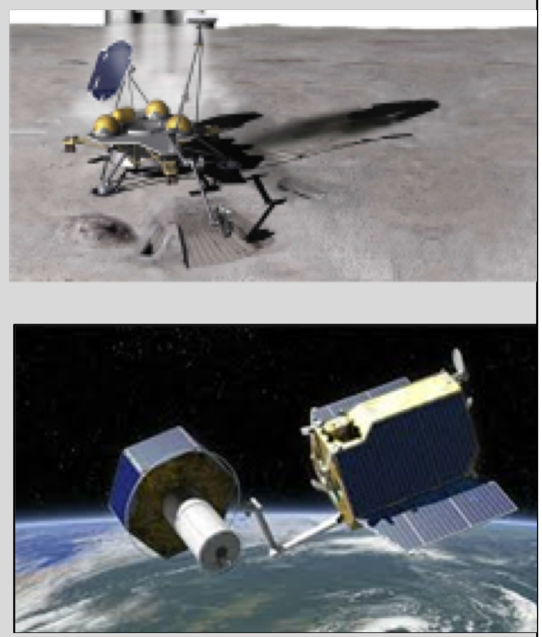
Capabilities are required to sense what is there, interpret the data to identify hazards (semantic interpretation) plan the motion in a safe manner, and execute the motion safely. Capabilities are required to account for the integration of resources, and planners are required that consider all operational constraints. (For example, plan a map that keeps you in sunlight.) These technological capabilities will improve the operational robustness of robotic platforms, but they require more local processing power than currently exists.

7.1.5. Capability Challenge: Visual Servoing for Auto Alignment

It is currently to be determined if this is still a gap for space operations; existing technology may be sufficient. However some challenges may remain such as sensor precision, end-to-end reliability, and the ability to deal with sensor uncertainty. There is also a need to verify dynamics and control stability inside visual servo control loops for space systems (long, light, flexible systems), along with other factors such as low lighting, undefined targets, etc.

Autonomous track and capture using visual cues can be done on the ground but is currently limited for space applications due to the lack of space-qualified processors capable of processing large amounts of visual data in real time, as well as high-speed data buses. There is a need for more investigation to determine the state of current capabilities, including failure correction methods, which depend significantly on the relative speeds and the area to be observed. Static captures are much easier than dynamic captures with flexible systems.

Controlled system bandwidth is important and is directly related to the time window allowed for the operation. In general, the requirements for dynamics/bandwidth derive directly from the applicable task. The robotic task of digging regolith on planetary surfaces requires less bandwidth than the grasping of uncooperative satellites. This includes the inner control frequency of the arm controller, and the overlaying artesian controllers and possibly cascade loops like the overlaying visual control loop. The conventional wisdom is to place the controlled bandwidth one tenth of the structural base frequency. Pursuing higher control bandwidths that approach or even go beyond structural base frequency would allow for improved performance in auto-capture of moving targets.



For operations with static targets and slow motion such as for Moonrise New Frontiers ops (top) a low control systems bandwidth may be used. But for complex tasks such as track and capture of non-cooperative satellites such as Deos (bottom) a higher bandwidth is required.

7.1.6. Collaboration Challenge: Interoperability/Standardized Interfaces

Standard interfaces are key technologies that will allow cooperation, interaction and connectivity between modules, elements and actuation systems for cooperative space projects and infrastructure plans such as ISS, Lunar Village, Mars Village, Lunar Orbital Platform – Gateway, etc. The use of standard interfaces on ISS has been shown to significantly reduce the planning, complexity, and analysis required to support telerobotic contact operations.

Standardization of common interfaces is necessary for elements that can be brought together. This includes grasping of a payload by a robotic manipulator, berthing one module to another, or installing a replacement module on a spacecraft or rover. The interface must allow transfer of mechanical loads, electrical signals and data, as well as thermal flux between the coupled elements.

The mechanical, electrical, data and thermal functions should be treated as sub-systems of the standard interface using modular approaches. In considering the design of the interface several factors should be considered in addition to the current Technology Readiness Level (TRL) of required components. These factors include:

- **Level of integration** (combined with carrier, separate module)
- **Commonality** (planetary and/or orbital)
- **Variants** (sizes, with or without dust covers, with different connectors)
- **Androgyny** (includes complexity in both parts, increases redundancy)

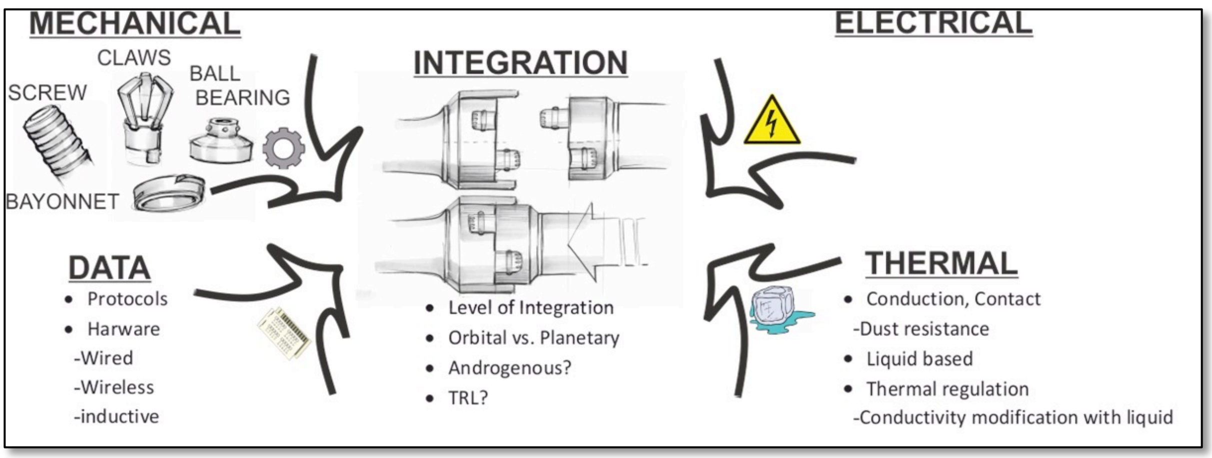
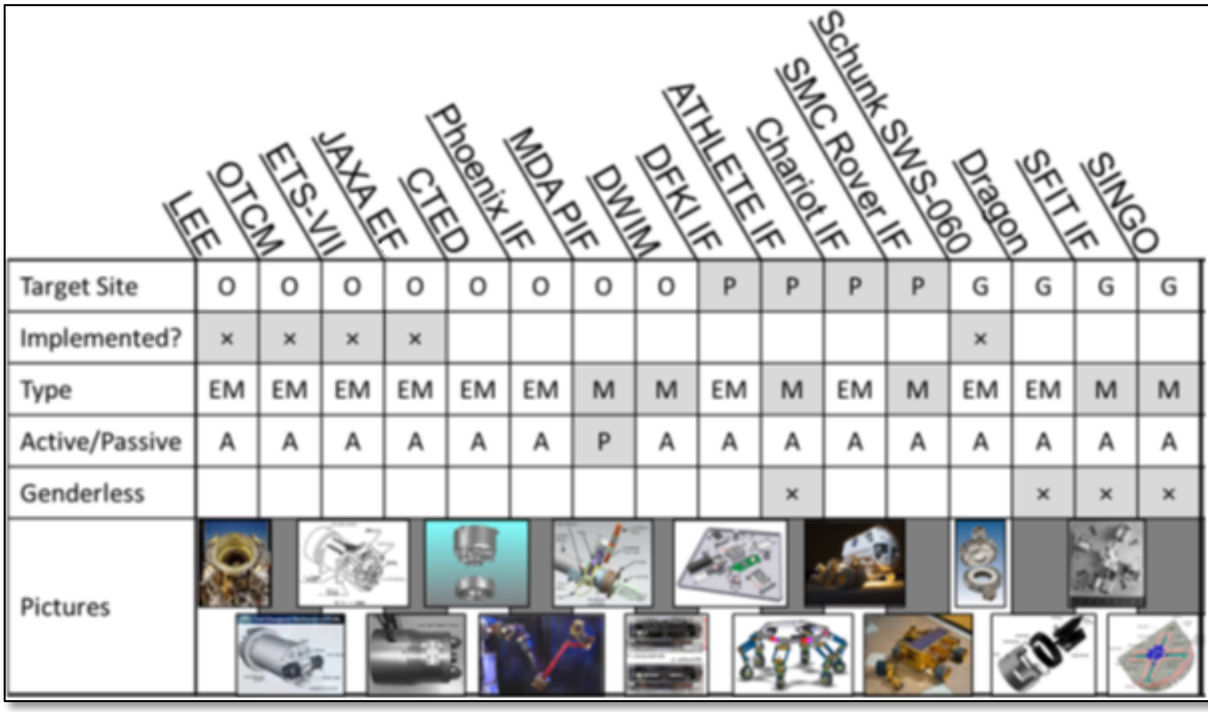


Figure 6: Standard Interfaces

The following figure shows a rough overview of some existing solutions classified by categories. Use scenarios are shown as Orbital (O), Planetary (P) and Ground-based (G). Active (A) and Passive (P) types are also indicated. The current technology level is indicated as Engineering Model (EM) or Functional Model (M) as well as the implementation case.



	LEE	OTCM	ETS-VII	JAXA EF	CTED	Phoenix IF	MDA PIF	DWIM	DFKI IF	ATHLETE IF	Chariot IF	SMC Rover IF	Schunk SWS-060	Dragon	SEIT IF	SINGO
Target Site	O	O	O	O	O	O	O	O	P	P	P	P	G	G	G	G
Implemented?	×	×	×	×									×			
Type	EM	EM	EM	EM	EM	EM	M	M	EM	M	EM	M	EM	EM	M	M
Active/Passive	A	A	A	A	A	A	P	A	A	A	A	A	A	A	A	A
Genderless										×				×	×	×
Pictures																

Figure 7: Sample of Interface Devices by Category

The Consultation Committee for Space Data Systems (CCSDS) (https://public.ccsds.org/) provides a good description of a common approach regarding software interfaces; however some work remains to be done. Still to be defined are the different communication lanes necessary for robotics applications, the definition of quality of services for different data sets, such as bulk data, telemetry, telepresence data, haptic data, video stream, and scientific download. (See also the discussion of Communication Gaps in Sections 7.2.4 and 7.2.5.

7.2. Critical Technical Gaps

7.2.1. High-speed Space-qualified Processors

Our consumer economy is driving the development of new technologies in IOT (Internet of Things), robotics and AI (Artificial Intelligence). In addition, high-performance processing in terrestrial applications is rapidly evolving following Moore's Law. Unfortunately these levels of high performance are not yet available in space-qualified processors, due to the difficulty in building computing hardware that can survive the hazardous radiation and thermal conditions in space.

High-performance space-qualified processors are required to manage and compute large amounts of data, manage high-speed communication, and execute computations with high efficiency and low power. Space telerobotics applications will require this computational power for visual recognition, autonomous navigation, and teleoperation over long distances from Earth.

The current state of the art in space-based computing is the BAE RAD750 processor, a circa 1995 design, implemented in a radiation-hardened semiconductor technology. The processor chip set has been in use for 20 years, delivering approximately 350 GP MIPS of theoretical maximum throughput. The RAD750 processor IP was licensed and available from Broad Reach Engineering (BRE) in their products as a single ASIC rather than a multi-chip set.

More recently, Geisler came out with the Leon-4 processor, a four-core processor implemented in a complex system-on-a-chip. Each of the four cores is capable of providing approximately the same throughput as a single RAD750, but at significantly lower power. The processor chip also provides a broad range of interfaces including SpaceWire, SPI, UARTS and has some power management capabilities as well. While a significant advance in computing throughput per watt as well as total throughput, the processor is only radiation hardened to approximately 300kRad (vs. 1MRad for the BAE RAD750). It also has a relatively low bandwidth memory interface, which will limit total throughput in many applications, and due to I/O pin limitations, it multiplexes the various I/Os so that all I/O interfaces are not concurrently available. Thus a decision must be made at board design time as to which I/O will be brought out. This processor is relatively new and few board-level products are commercially available at this time, though several companies are working on such. There has been discussion of a next-gen version of the Leon-4 with upgraded memory and I/O. If so, this would offer a significant performance improvement for relatively minimal additional complexity, power and cost.

As Cobham offers the Geisler Leon series of processors in various forms, from ASIC SOC to ASIC IP to FPGA- IP, there are several variants of the Leon-3 and 4 available from other vendors with different mixes of I/O and levels of radiation hardness (notably Ramon Chips but there may be others as well).

The Leon-3 is a forerunner to the Leon-4 processor. It is available in one and two-core configurations. The two-core variant offers RAD750 level performance with both cores active. Like the Leon-4, the Leon-3 is a system on a chip (SOC) ASIC, incorporating memory interface and I/O including SpaceWire. Its main advantage over the RAD750 is reduced power, some power management, and the fact that it is a single chip solution for many applications. Like the Leon-4, it is radiation hardened to 300KRAD. Board-level products are available from Cobham and others.

BAE's follow-on product to the RAD750, the four-core RAD5545 and a companion SIMD processor, the RADSPEED, as well as a range of RAD750-based systems on a chip, are currently in the qualification phase or in final development, and some have been announced for sale. These products are follow-on to the RAD750, offering a degree of software compatibility and a known architecture for future space computers. The RAD5545 will provide approximately. 4.5GOPS maximum theoretical throughput. The RADSPEED is more difficult to assess as its performance is highly algorithm dependent, but it is certainly capable of 10s of GOPS on specific algorithms such as fast Fourier transforms (FFTs) and many linear algebraic algorithms. The cost of this improvement in throughput coupled with legacy architecture is power utilization –both the 5545 and RADSPEED burn approximately 18 watts and have relatively primitive power management capabilities. When coupled with required memory and I/O, board-level products can easily exceed 40-60 watts. The RAD750-based system on chip ASICs, however, offer RAD750 compatibility with Leon-4-like reduced power, enhanced throughput, and on-chip I/O such as SpaceWire. Power for these devices varies significantly (and it is not yet clear how many variants will be offered) but it is expected to be relatively low (though higher than the Leon-4). Radiation hardness for all devices is expected to be in the 1MRAD range.

The HPSC Chiplet, in development by Boeing under contract to a NASA-USAF collaborative partnership, is a significant departure from the processors discussed above. It has an ARM-based design and will have multiple heterogeneous processor cores. The chip architecture has not yet been frozen, but PDR is tentatively scheduled sometime in mid 2018. Once the project passes PDR, it is expected that the architecture and top-level specifications will be published. The original specifications called for a design with 9-15 GOPS of GP parallel processing, two DDR3/4 memory ports, four-six SRIO ports at 40Gb/s each and a range of other I/O ports ranging from SpaceWire to Ethernet. Overall power was spec'ed for 5-10 watts with fine-grained power management, fault tolerance, and the ability to dynamically vary the performance-power-fault tolerance operating point. The Chiplet is also being designed to allow multiple Chiplets to be tiled for expansion of performance capabilities and fault tolerance in a variety of multi-Chiplet configurations. A library of heterogeneous Chiplets allowing a broad variety of multi-Chiplet configurations are envisioned as the HPSC ecosystem evolves. Companion projects, including advanced RAD-hard memories, heterogeneous co-processors/accelerators, and I/O expansion Chiplets are also envisioned. The HPSC Chiplet is expected to be available in the 2020-2021 timeframe, with a range of board-level products shortly thereafter.

7.2.2. Local Computational Resources Supporting Operations

The addition of space-qualified (e.g. RAD-tolerant) high-speed processors can enable greater capability, particularly in support of local autonomy. However, this alone will not solve time delay issues associated with data transmission over long distances, which is dependent on the operations architecture. One mitigation of this challenge may be to provide substantial computing capability local to the operations. As an example, a cloud server containing computing power necessary to perform planning and scheduling using constraint engines and other technologies physically located at or near operations could dramatically minimize light-time delays by providing a "mission control-like" capability in the locale of operations. On the lunar surface, this might be a cloud server protected from radiation through the use of regolith as shielding or existing on an in-orbit platform. In a Mars scenario, the cloud server might be situated deep inside a crater such as Stickney Crater on Phobos. The crater would provide substantial shielding for the server, and its Mars-facing orientation would facilitate communications with the Martian surface. In both cases, a local computing capability may be used to facilitate increased levels of local autonomy by offloading computation to a dedicated resource within a short light-time distance from operations. Synchronization with Earth-based assets would then be liberated to a lower frequency and thus lower bandwidth requirements.

7.2.3. High-speed Data Buses

Controlled system bandwidth is a very important performance indicator for any autonomous robot. It determines how precise, how efficient, and how fast a robot is able to execute its commands. Controlled systems are designed to achieve the highest possible bandwidth. In addition to sampling rates and data communication rates, the ability of feedback control software to handle robot dynamics plays a vital role in advancing controlled system bandwidth. This is particularly important for long and light robot manipulators.

In order to improve the controlled system bandwidth for advanced systems there is an inherent need for high-speed, low-latency data buses. This enables higher performance control loops and an overall increase in the self-reliance of robotic systems. Some operations require real-time performance, meaning that the travel times of signals need to be highly predictable.

Important factors for the selection of a data bus for space robotics applications are the transfer rate, real-time capability, compatibility with various physical layers, node number, resilience against node loss/topology changes/overall fault tolerance, and availability in space-qualified variants.

Typical candidate technologies in the space domain for high performance applications are sketched below. Every candidate has advantages and disadvantages regarding use in space and robotic applications.

- MIL-STD-1553 (used on ISS)
  - Advantage: Widespread use in space missions, reliable.
  - Limits: Maximum specification transfer rate of 1 Mbit/s.
- Time Triggered Controller Area Network (TTCAN)
  - Advantage: Widespread use (usually as CAN) in automotive industry, real-time capable.
  - Limits: Maximum specification transfer rate of 1 Mbit/s CAN which is significantly reduced by the TT-protocol.
- IEEE-1394B (“Firewire”)
  - Advantage: Used in some modern aircraft and some space missions, up to 800 Mbit/s data rate.
  - Limits: Increasingly obsolescent in terrestrial/industry applications.
- SpaceWire
  - Advantage: Backed and standardized by ESA, designed for use in space, up to 400 Mbit/s data rate.
  - Limits: Rigid network topology, does not meet Gbit/s requirements for high performance robotics or other data applications, low acceptance in terrestrial/industry applications.
- SpaceFibre
  - Advantage: Compatible with SpaceWire on the protocol level, multi-Gbit/s capability.
  - Limits: Rigid network topology, optical fibers susceptible to radiation effects.
- Time Triggered Ethernet (TTEthernet)
  - Advantage: Multi-Gbit/s capable based on electrical cables, expands plain Ethernet with real-time/fault-tolerant capabilities, some use in current/upcoming space missions.
  - Limits: Relatively new and not widely adopted.
- EtherCat
  - Advantage: Optimized for high update cycles with a low jitter (highly relevant for robotics applications), real-time capable.

- Limits: Currently limited to 100 Mbit/s data rate, only used on experiment level in space so far.

Future space robotics systems will benefit greatly from the introduction of bus technologies used in terrestrial industries and applications that meet the described requirements. Ethernet-based and SpaceWire-based technologies look the most promising so far. The information above (e.g. TTEthernet, EtherCat) shows a non-comprehensive representation of the state of the art; expansion of bandwidth capabilities to Gbit/s and beyond would greatly enhance system capability.

Although robotics drives data bus requirements in many aspects, it is still a niche subject in space system design. Increased effort will be required to incorporate the requirements robotics imposes on space systems in upcoming standardization activities regarding on-board data handling and interfaces for modularization. Cooperation with aeronautics, automation, terrestrial robotics, and automotive industries is vital in this regard and should be fostered.

7.2.4. Communications Bandwidth

Communication requirements vary with respect to different robotics operational scenarios. For Earth-based operators, round-trip transmission latency can range from a few hundred milliseconds (ground to LEO) to tens of minutes (Earth to Mars). Communication bandwidth for conventional space links ranges from a few hundred bits per second (bps) to a few megabits per second (Mbps).

The type of coupling between the operator and the remote system puts major constraints on each type of streaming data:

1. Decoupled systems (Fully autonomous system)
2. Loosely coupled systems (Supervisory control / semi autonomous system)
3. Closely coupled systems (Telepresence system or shared control system)

A major difference for data streams arises if data has to be streamed in real-time or if it is sufficient to use bulk data transfer. Data streams are also constrained by the types of data they carry:

1. **Bulk data**: Pools up data that is just classified by its size, e.g., 3D models of the environment, navigation cards, software updates, data logs and so forth. Bulk data tends to have high data volume, no time relevance, and can be highly compressed.
2. **Telemetry data**: This data is a live feed of a decisive state of the system. This also incorporates command data. Telemetry data tends to have low data rates with medium time relevance (seconds), and a medium compression scheme.
3. **Telepresence data**: Medium data rates with high time relevance (both varying with respect to the modality), and standard compression scheme (50% reduction). Telepresence data can in turn consist of:

a. **Video data**: Video data is often sent as compressed build data, for visual and maybe haptic telepresence; adequate real-time data stream and failure correction need to be considered.

b. **Audio data**: This data stream may be used occasionally for cases with humans on site using voice commands and/or telecommunications.

c. **Haptic data**: Combines data to directly control robotic movement and force display to human operators.

Optical (laser) communications can potentially provide higher link rates to deep space but will likely be subject to numerous performance-limiting factors, including atmospheric absorption, interference from background light sources, and pointing accuracy. Finally, intermittent loss of signal (LOS) and variable quality of service routinely occur due to orbital geometry, solar activity, and so on. Each of these communication constraints can have a significant impact on operational design, particularly in terms of modes of control, telemetry design, and operations tempo. For example, direct teleoperation (manual control) with force reflection and real-time, high-resolution stereo video is possible only with a very low-latency (0 to 25 ms) and high-bandwidth (3 Mbps or greater) communications link. For deep-space robots remotely operated from Earth such as the Mars rovers, supervisory control and command sequencing is likely to remain the only practical method for control.

7.2.5. Communication Hardware

Communication hardware is needed that is small in size, weight and energy consumption while providing transparent transmission (that is, providing operators with the information they need, when they need it.) With time-relevant data, e.g., with haptic feedback, communication needs to allow low latency. In this case failure correction at the bit level can and will be handled better on the endpoints—the master and slave local hardware. With bulk data, failure correction on the communication line will add latency and delay, but that ensures that corrupted data is detected and corrected, which in turn simplifies post processing. Therefore small and handy devices providing transparent transmission, and possibly implementing a different quality of service for data transmission, will be needed.

7.2.6. Improved LIDAR

Current space-qualified LIDAR with flight heritage (e.g., Neptec's TriDAR and LCS, ASC's DragonEye, NASA/Ball Aerospace's STORRM, JenaOptronik's RVS 3000) were designed to meet requirements for on-orbit operations like automated rendezvous and docking, or inspection. Their mass, power consumption, detection range and field-of-view could make these sensors unsuitable to support the planetary surface robotic tasks described in this report. Similar system specification gaps may be observed on the terrestrial side even for LIDARs built to be installed on vehicles (e.g., Velodyne, Quanergy, Neptec's OPAL-P500). While the latter are still relatively heavy and require high power sources, the former have lower accuracy in comparison. Most of these terrestrial LIDARs target the automotive industry, which context may not be directly applicable to space.

Currently, there are different leading LIDAR technologies. Flash LIDAR relies on arrays of detectors similarly to some extent to a Charge-Coupled Device (CCD) or a digital camera. Flash LIDARs have the capability to measure the range or the depth of a scene at each pixel even under harsh lighting conditions and require little computational resources. Usually the sensing field-of-view of a flash LIDAR remains narrow when compared with other LIDAR systems, making the flash LIDAR not directly suitable for rover situational awareness and mapping applications. However, flash LIDARs are good candidates for high-rate hazard detection.

Scanning LIDAR technology usually relies on a single laser beam propagated around the sensor using spinning mirrors. This technique could allow the sensor to scan in all directions (e.g., 180 degrees in a vertical plane and 360 degrees in a horizontal plane) and could provide much higher resolution than a stereo camera or a flash LIDAR at a cost of a limited scan rate. Its specifications make the scanning LIDAR a good option for the main robot perception sensor for which a single scan could offer high-resolution visibility all around the rover.

Current LIDARs (both scanning and flash) are too heavy, power hungry and large to be easily integrated to a flight rover. Improvements in space-qualified LIDAR may significantly change the way rovers are operated in space and would enable enhanced robot perception and safer higher-speed rover relocation. This improved sensing performance would benefit every robot control mode. This implies sensor improvement in several directions such as mass, power consumption and volume.

7.2.7. Verification & Validation (V&V) of Autonomous Systems in Integrated Systems

In order to ensure reliability, software verification and validation must be done to minimize the risk of incorrect decisions or behaviour on the part of the autonomous controller. Currently, verification and validation of autonomous systems has been carried out largely by extensive demonstrations and testing. Since testing in actual conditions is not always possible for extraterrestrial missions, a strong focus on new tools for V&V of autonomous systems is needed. These tools and methods should take into account and build on lessons learned from integrated software V&V methodologies used for ISS as well as terrestrial applications of autonomy technologies. New tools will increase the level of confidence in the reasoning of autonomous systems. Early focus will be on safety, with follow-on capabilities for systems that can handle increasing complexity. Current V&V technology is capable of providing safety assurance, but safety alone is not necessarily enough to ensure mission success, particularly in complex operational scenarios.

7.3. Non-Technical Gaps

7.3.1. Experience Gap: ISRU Robotic Missions

In-Situ Resource Utilization has been identified as critical to long-term human off-world presence. Water resources in the lunar regolith, for example, could be utilized for fuel for the reusable human ascent module, and potentially directly by astronauts. To date much effort has been put into detecting and quantifying the amount of water on the Moon and Mars, but no mission has demonstrated recovery of usable quantities of water or other resources.

Technology for In-Situ Resource Utilization has been demonstrated on Earth but the technology needs to be transformed into a spaceflight version and it should be thoroughly tested in analog missions. For example, in 2012, NASA and CSA carried out a nine-day lunar ISRU analog mission on the slopes of the Mauna Kea volcano in Hawaii. NASA's Regolith and Environment Science and Oxygen and Lunar Volatiles Extraction (RESOLVE) payload and other systems were integrated onto the CSA's Artemis Jr. rover to demonstrate how a robotic mission could prospect and extract water and volatiles from regolith. The operations were supported from three different remote centers (NASA JSC, KSC, and CSA HQ) and a science backroom was located at NASA ARC. Most of the mission objectives in terms of rover distance travel, volatile mapping, coring operations and water droplet demos were achieved.

A gap currently exists in terms of experience with actual off-world operations. While there is extensive experience to date in using robotics to scout, mine, and process terrestrial resources, the challenges of operating in the extreme conditions of the Moon and/or Mars mean that terrestrial techniques cannot necessarily be applied directly to extraterrestrial operations. Space agencies are limited to simulations in order to investigate operations in low-gravity environments. Many ISRU tasks, such as drilling, lasers etc., are very energy intensive, which may call for investigation into wireless energy transmission or orbital energy production or even lower-energy tools.

The main knowledge gap in ISRU is the knowledge required to optimize designs properly. There is a need for a better understanding of key parameters such as regolith properties (environment, water content, etc.) to allow for better designs. Better sensors are also needed to determine these regolith properties prior to operations. Technology demonstration missions would significantly aid in the design optimization of ISRU robotics and robotic tools for future long-term human missions as per the GER3 mission scenarios.

7.3.2. Collaboration Gap: Implementation of Standard Interfaces

Adopting standard interfaces for scientific payloads would allow for payloads to be more easily integrated into any future mission. Common command and communication protocols would allow for a single operator to oversee multiple assets.

One challenge has been the implementation of standards in large international projects. For example, early on, ISS waivers were often granted for payloads that did not meet robotic ICDs. This resulted in a multitude of interfaces being used, which required a significant amount of task-specific analysis required to support one-time operations. Using standardized interfaces and payload specifications would allow for generic analysis and procedures that only need to be done once per interface. In future projects it is recommended that standard interfaces be more strictly implemented.

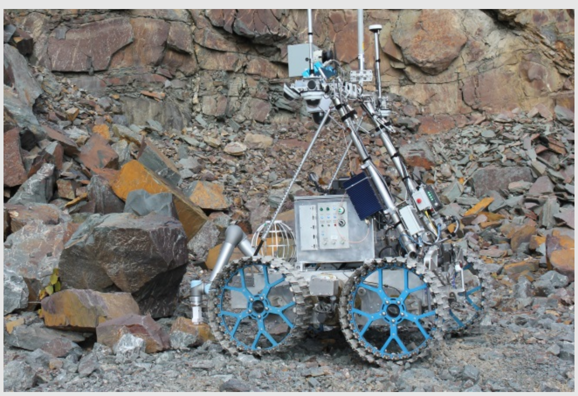
Another gap has been to ensure proper cooperation and coordination at an international level. The Consultation Committee for Space Data Systems (CCSDS) is currently working on developing standards for common software interfaces.

Additionally, the International External Robotic Interfaces Standards (IERIS) is working on developing standards for robotic interfaces for use on the Deep Space Gateway, but it is unclear if these standards could be expanded to apply to other space exploration operations. Other standards may emerge as international architectures are explored.

8. OPPORTUNITIES FOR PARTNERSHIP

One recent example of international partnership is the ESA/CSA Lunar Exploration Analogue Deployment (LEAD) Human Robotics Operations Preparation Experiments (HOPE) October 12-19-2017. In this experiment, a rover was operated with timed delays of up to five seconds in analogue terrain (a quarry in Canada) by remote operators from ESA and CSA.

The HOPE experiment was performed in the frame of the HERACLES mission, i.e. Human-Enabled Robotic Architecture and Capabilities for Lunar Exploration and Science. This is an ESA-led mission, the product of an international study in the frame of the ISECG activities. HERACLES aims to establish key elements and capabilities for sustainable human exploration of the Moon and human-robotic exploration of Mars by implementing lunar surface operations while maximizing opportunities for unprecedented scientific knowledge gain. A robotic lander, ascent stage and rover will land on the lunar far side, where the rover starts a traverse and gathers samples. A crewmember in the Deep Space Gateway (DSG) has the option to teleoperate the rover. When the rover ends its initial traverse, the sample container is stored in the ascent stage, which transfers it to the DSG. Together with the crew, the samples will be returned to Earth aboard the Multi-Purpose Crew Vehicle (MPCV). The mission is a cooperative effort between ESA and its partners CSA and JAXA, with NASA as observing partner.

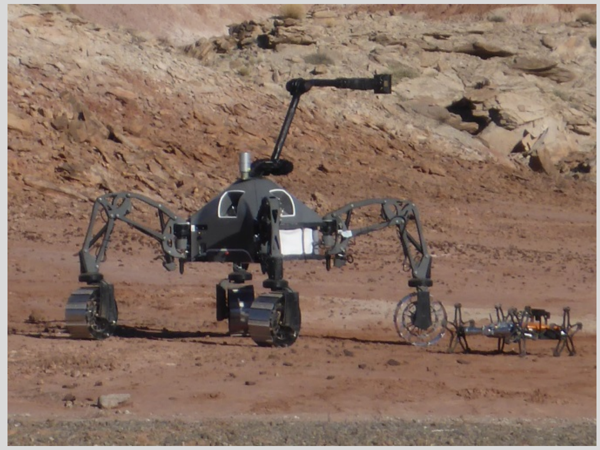


CSA rover performing an instrument placement during the 2017 LEAD/HOPE analogue mission

CSA Mars Exploration Science Rover *(*MESR) transferring a soil sample to a Mars ascent vehicle mock-up during the 2016 Mars Sample Return Analogue Deployment

In 2016, an international analogue mission took place in a desert of the United States. The Mars Sample Return Analogue Deployment (MSRAD) was a mission simulation that included many technical aspects such as science exploration, soil sample caching and transfer, as well as several parallel technology demonstrations and tests. An international team of collaborators, including NASA/Jet Propulsion Laboratory, the UK Space Agency (UKSA), the German Space Agency (DLR/DFKI), seven Canadian universities, and three American universities, participated in this deployment that involved simultaneous activities in Canada, United States, United Kingdom and Germany.

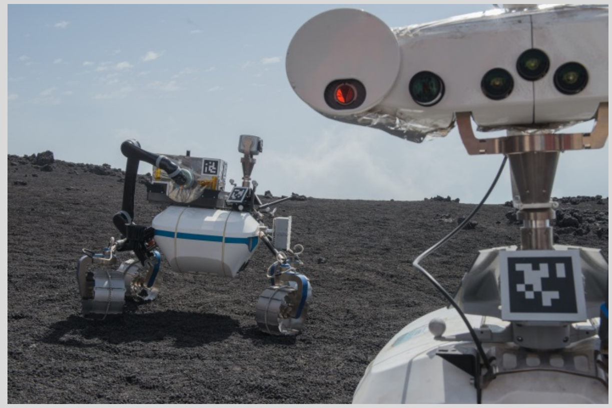
DFKI rovers (Sherpa and Coyote)



DFKI rovers (Sherpa and Coyote)

During the one-month ROBEX (Robotic Exploration in EXtreme Environment) analog mission campaign on Mt. Etna, Italy in 2017, a highly autonomous robotic operation was demonstrated. Within the ROBEX five-year research project, scientists from the deep sea and space domains exchanged and cooperatively developed key aspects for robotic challenges and operations towards future missions. The demonstration mission on Mt. Etna included long-term autonomous navigation and the autonomous deployment and installation of scientific instruments such as geophones and seismometers. This demonstration included object detection, grasp and path planning, energy exchange, and infrastructure docking. The ROBEX project team consisted of many German institutes, mainly the German aerospace agency (DLR) but also European participation such as the Italian Space Agency (ASI) and the European Space Agency (ESA).

Small rover approaching the landing infrastructure on Mt. Etna during the ROBEX demonstration mission in 2017



Cooperative robotic exploration

The mission also demonstrated a mobile rover manipulating the modular payload carrier containing seismic instrumentation. This modular payload carrier was designed and developed during the project and is an example of an integrated robotic payload/instrumentation system with different application scenarios. This modular approach supports open cooperation possibilities with other institutions.

In the near future, several opportunities may be envisioned within the framework of the H2020 Strategic Cluster in Space Robotics. This program, funded and managed by the European Union, with the support of several space agencies (ESA, ASI, CDTI, CNES, DLR and UKSA) within a Program Support Activity (PSA) called PERASPERA, aims to develop robotic technologies for planetary exploration and also in-orbit applications such as satellite servicing, large structures assembly and maintenance/upgrade of modular satellites.

Multiple demonstrations of planetary robots on analog sites will be performed in the course of the program. The nearest planetary demonstration will take place in Morocco in the fall of 2018 and will be essentially focused on the validation in representative conditions of major robotic building blocks such as sensors, data fusion algorithms, autonomous navigation and decision-making framework. The next round of rover testing on analog sites (Morocco or Tenerife) will take place at the end of 2020 with the exploitation of two independent demonstrators addressing the following topics: (1) autonomous decision-making to manage long traverses and opportunistic science, (2) multi robot interaction for locomotion in difficult areas and construction of infrastructure.

Such demonstrations that already involve multiple international partners have a great potential for the maturation of robotic technologies for planetary exploration. Opportunities for additional contributions can be envisioned in the following areas:

- Validation of new equipment (sensors, lights, etc.,) through their inclusion on the existing platforms and their comparison with nominal candidates
- Validation of new functionalities (or alternate algorithms) through the integration of complementary software
- Validation or consolidation of telerobotic concepts through the organization of remote operation sessions
- Creation of more complex robotic scenarios through the addition of robotic agents
- Validation of operations involving multiple organizations in a coordinated manner

Additional indirect benefits can be also considered:

- Collection of referenced sensory data for offline validation of perception algorithms and calibration of simulation tools by third parties
- Inputs to promote standardization activities in the telerobotic domain

9. SUMMARY

As humans move out into the Solar System and operations occur as per the GER3 mission scenarios, the time delay between the operator and the robot increases. This report has provided an examination of the challenges associated with teleoperating robotic elements with time delays of greater than five seconds for operations beyond Low Earth Orbit.

The review of the current state of practice shows that there are several options available as control modes, which operate on a sliding scale wavering between direct human teleoperation and full robotic autonomy.

The current state of practice for operations mainly falls under a form of supervisory control with limited automation. For operations with a short time delay, as on the ISS, the concept of operations is to send a command and then wait for feedback before proceeding with the next command. For missions on Mars or other planets, a series of commands are sent, typically for a day of operations and then the initial results are evaluated by operators before sending the next batch of commands for the following day. Both types of missions use a limited degree of autonomy to make time-critical decisions, such as how much force to apply in contact operations, or hazard identification and avoidance for rover navigation.

As the time delay increases it becomes more efficient for the remote robot to be as autonomous as possible, although some level of human control is required for any operation. Each control mode has its advantages and disadvantages and ultimately many tasks will require a combination of several of the various control modes during the course of a mission, depending on the particular task.

To better determine what capabilities need improvement for telerobotic control over time delay, an examination of the required tasks was carried out. Given the current proposed timelines, the technology to meet the near-term GER3 mission scenarios will likely be based largely on current technology. As a result this report also considered the long-term goals of the GER3, ultimately leading to humans on the Martian surface. In order to accomplish the GER3 long-term goals the following tasks were considered:

- As robots handle increasingly complex tasks with an increased amount of autonomy for remote operations, the main limitation to implementation is in the lack of processing power, which lags terrestrial developments by approximately 20 years. Space qualified high-speed processors and data busses are a critical gap to address.
- Inputs reliant on visual data are subject to poor lighting conditions. Low-power and low-mass sensing technologies such as LIDAR would allow for better situational awareness for the operator and to provide inputs to autonomous controllers.
- For systems with increased autonomy, advanced control software will need to be matured to ensure system stability. In parallel, a standard should be developed for verification and validation of autonomous software to ensure mission safety and increase mission success.
- As more systems are operated beyond low Earth orbit, the communications bandwidths will need to be expanded in order to allow for different types of data to be passed between the robotic

elements and remote operators. Communication hardware, in small size, weight and energy consumption is needed which is transparent in terms of data transmission.
- For robotic systems that interface with other vehicles, payloads or habitats, ISS experience has shown that standard interfaces greatly reduce the complexity and cost of mission planning and increase the likelihood of mission success. International standards for robotic interfaces need to be developed and implemented to reduce the amount of pre-mission analysis.
- In-Situ Resource Utilization is expected to play a critical role in long-term human spaceflight missions, which will rely heavily on robotics. To date there have been no missions that have demonstrated telerobotic capabilities to collect, transport and process resources in space-based environments. Technology demonstration missions are recommended to close this experience gap.

To align with the GER3 scenarios, telerobotic systems must be operated in an increasingly efficient manner. Simple tasks such as relocating from one point to another must become less reliant on humans in order to allow operators to focus on more complex tasks or off-nominal recovery situations. For more complex tasks such as construction, maintenance, ISRU manufacturing, site preparation and scientific exploration, robotic systems must be able to handle an increasing amount of complexity in an undefined, time-delayed environment.

Many terrestrial robotic systems are capable of these types of operations, but several areas exist where space-based robotics lag. Some of the critical capabilities to improve include:

Robotic vision in Poor Lighting: Lighting conditions for on-orbit or planetary operations are such that robotic operations often have to be performed in poor lighting conditions for which negative effects need to be mitigated or else the ops may be delayed until conditions improve. This can be mitigated through the use of sensors that have a low sensitivity to natural lighting or that provide an adequate source of lighting in the system.

Localization Accuracy: Earth-based robotic systems can localize to millimeter accuracy; however, it is difficult for Earth-based capabilities, such as GPS positioning and human correction, to cross over to systems for space. Future missions will require manipulators to accurately position a payload with respect to a worksite, and rovers to position themselves relative to a local target or a planetary coordinate frame.

Human Situational Awareness: With time delays and low-frequency communications, situational awareness for the operator can be poor. Current camera views coupled with telemetry should be improved through augmented virtual views, and improved feedback at higher frequencies.

Advanced Motion Planning and Hazard Avoidance: Autonomous robots must be able to automatically detect and avoid hazards/collisions. This is especially important if high-speed surface navigation is required. Autonomous planning capabilities that take into account all necessary mission constraints (safety, power, timeline) need to be improved beyond the current state of the art.

Visual Servoing for Auto Alignment: Autonomous track and capture using visual cues can be done on the ground but capabilities are currently limited for space applications. There is a need for more investigation to advance the state of current capabilities, including failure correction methods and recognition of known targets.

Some of the critical policy improvements needed include:

Interoperability/Standardized Interfaces: The use of standard interfaces on ISS has been shown to significantly reduce the planning, complexity, and analysis required to support telerobotic contact operations.

Some of the critical experience/knowledge gaps include

In-Situ Resource Utilization & Construction: Current efforts related to ISRU have focused mainly on finding the resources. Little has been done in the areas of robotically recovering, transporting and processing resources for use as fuel or as construction materials. In particular, in-space demonstrations of these critical capabilities are completely lacking.

In order to enable the identified capabilities, the following technologies need to be advanced, specifically for use in space.

Space-qualified Processing: As robots handle increasingly complex tasks with an increased amount of autonomy for remote operations, one of the main limitations to implementation in space is in the lack of space-qualified processing power, which lags terrestrial developments by approximately 20 years. Space-qualified high-speed processors and data busses are seen as a critical technology gap as they allow for improved capabilities in all areas, including increased autonomy, visual servoing, and improved sensing.

Visual Sensing Technology: Inputs reliant on visual data are subject to poor lighting conditions. While sensors exist for terrestrial applications, they are not always suitable for space applications, owing to their mass and/or power requirements. Low-power and mass sensing technologies such as LIDAR would allow for better situational awareness for the operator, as well as providing inputs to autonomous controllers.

Advanced Controls and V&V: For systems with increased autonomy, advanced control software will need to be matured to ensure system stability. In parallel, a standard should be developed for verification and validation of autonomous software to ensure mission safety and increase mission success.

Communication Bandwidth: As more systems are operated beyond low Earth orbit communications bandwidth will need to be expanded in order to allow for different types of data to be passed between the robotic elements and remote operators. Communication hardware, in small size, weight and energy consumption, is needed which is transparent in terms of data transmission.

Standard Interfaces: For robotic systems that interface with other vehicles, payloads or habitats, ISS experience has shown that standard interfaces greatly reduce the complexity and cost of mission planning and increase the likelihood of mission success. International standards for robotic interfaces need to be developed and implemented to reduce the amount of pre-mission analysis.

In-Situ Resource Utilization: ISRU is expected to play a critical role in long-term human spaceflight missions, which will rely heavily on robotics. To date there have been no missions that have been conducted to demonstrate telerobotic capabilities to collect, transport and process resources in low-G environments. Technology demonstration missions are recommended to close this experience gap.

Several agencies are working to advance technologies related to each of these gaps. As telerobotic operations are inherently distributed with the robot at one site and operators located at one or more remote sites, telerobotic operations tend to lend themselves well to international co-operation without requiring all members to be co-located. Demonstrations that include multiple international partners have a great potential for the maturation of robotic technologies for planetary exploration, most notably in the areas of verification of new equipment, and new concepts that make use of existing resources. It is also useful to promote operational standards in the telerobotic domain.

This analysis has shown that while there remains work to be done to catch up to terrestrial applications, the gaps are not insurmountable and rather represent a natural progression of space exploration through the increasingly efficient use of telerobotics.

10. APPENDIX – ACRONYMS

ASI *Agenzia Spaziale Italiana*

CNES *Centre national d'études spatiales*

CSA Canadian Space Agency

DFKI *Deutschen Forschungszentrums für Künstliche Intelligenz*

DLR *Deutsches Zentrum für Luft- und Raumfahrt*

DSG Deep Space Gateway

ESA European Space Agency

FFT fast Fourier transform

GER3 Global Exploration Roadmap

GTDM GER3 Technology Development Map

ISECG International Space Exploration Coordination Group

ISRU In-Situ Resource Utilization

ISS International Space Station

JAXA Japanese Aerospace Exploration Agency (JAXA)

JEMRMS Japanese Experiment Module Remote Manipulator System

LOC Locus Of Control

MESR Mars Exploration Science Rover

MPCV Multi-Purpose Crew Vehicle

MSRAD Mars Sample Return Analogue Deployment

MSS Mobile Servicing System

NASA National Aeronautics and Space Agency

ORU Orbital Replacement Unit

ROBEX Robotic Exploration in EXtreme Environment

SMEs Subject Matter Experts

SPDM Special Purpose Dexterous Manipulator

SSRMS Space Station Remote Manipulator System

TWG Technology Working Group

UKSA United Kingdom Space Agency

V&V Verification and Validation