69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018.

IAC-18,A5,3-B3.6,x47235

Telerobotic Operations with Time Delay, Results from the ISECG GAP Assesment Team

Armin Wedler[g]*, Laurie Metcalfe[a], David Alfano[b], Kimberly Hambuchen[b], Scott Vangen[b], Brian Wilcox[c], Kim Nergaard[d], Alessandro Bergamasco[d], Simone Fratini[d], Alessandro Donati[d], Michael Schmidt[d], Michel Delpech[e], Valerie Mousset[e], Hiroshi Ueno[f], Wen-Hong Zhu[a], David Gingras[a], Thilo Kaupisch[g], Bernd Sommer[g], Gerhard Grunwald[g]

armin.wedler@dlr.de [g]*, laurie.metcalfe@canada.ca [a], David.D.Alfano@nasa.gov [b]

[a] Canadian Space Agency (CSA), Canada
[b] National Aeronautics and Space Administration (NASA), United States
[c] Jet Propulsion Laboratory (JPL), California Institute of Technology (CALTech), United States
[d] European Space Agency (ESA), ESTEC, The Netherlands, and ESOC, Germany
[e] Centre National d'Etudes Spatiales (CNES), France
[f] Japan Aerospace Exploration Agency (JAXA), Japan
[g] German Aerospace Center (DLR), Germany

Abstract

Since the Global Exploration Roadmap has been released in the third generation early this year, the International Space Exploration Coordination Group (ISECG) has formed two technology working groups (TWG) to identify gaps in "Telerobotic Operations with Time Delay" and "Autonomy Operations", required by the mission profiles discussed in the Global Exploration Roadmap. This paper describes the compressed results from the Working Group "Telerobotic Operations with Time Delay", including the goal and objectives of the working team. It gives an overview of the different mode of operation, required to control robots remotely. Analysing the mission scenarios described in the roadmap, the required robotic tasks has been extracted and gaps within those have been identified. These gaps are discussed respect to the common capabilities, divided and classified in operational, performance technology and non-technical gaps.

Keywords: Robotic, Telerobotic, Time Delay, Shared Autonomy, Haptic tele presence, autonomy, exploration

1. Introduction

As documented in the new Global Exploration Roadmap (GER3) [1] there is a strong push for robotic missions to the Moon and Mars involving increased levels of complexity. Robotic exploration missions can be done using different approaches with respect to autonomy, ranging from pure remote control with direct sensory feedback to fully autonomous systems.

The International Space Exploration Coordination Group (ISECG) [4] formed two Gap Assessment teams to evaluate topic discipline areas that traditionally had not been assessed at an international level to-date. Accordingly, the ISECG Technology Working Group (TWG) recommended two discipline areas based on Global Exploration Roadmap (GER) Critical Technologies needs reflected within the GER Technology Development Map (GTDM); the first topic discipline being Telerobotic Operations with Time Delay, and the second topic discipline area being Autonomy [3]. The ISECG approved the recommended Gap Assessment teams, and tasked the TWG to formulate the new teams with membership comprised of Subject Matter Experts (SME's) from the participating agencies.

This paper describes the essential findings out of the first GAP assessment Group handling the issue: *"Telerobotic Operations with Time Delay"*

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, mission architecture trades, operator interface design, etc., are also important. However, this the TWG and therefore also this paper 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 is sent in a batch, 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 local autonomy to make time-critical decisions, such as how much force to apply in contact operations, or hazard identification and avoidance for rover navigation.

2. Goal, Objectives and Approach of the GAP Team

In order to advise the Agencies, Stakeholders and Industry Partners toward the future needs of robots operated with time delay from remote places, the Gap Assessment Team's assessment is provided in a summary report [2] as well as an accompanying presentation identifying the Critical Technology Needs and opportunities for international coordination and cooperation in closing identified technology gaps. When the ISECG TWG performs a more detailed GER3 portfolio analysis, the gaps identified herein should be readdressed and possibly expanded.

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

First findings:

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, inspection, 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 and planetary robotic capabilities lag behind.

3. Definition of modes of operation

In order to first establish a common understanding, the GAP Team has spent a while understanding each other's interpretation of common wordings and definitions of the different ways to command remote robots.

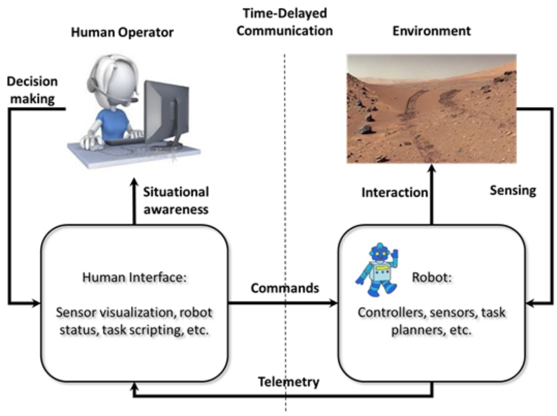

Fig. 1. Telerobotic Operation Paradigm

Fig. 1 shows the paradigm of the remote operation, where a human operator sends command via a human interface to a remote robot, and receives telemetry data of this robot and the environment of the robot. Considering time delay in communications in both directions, different modes of operation may be involved, depending on the required task, capabilities of the techniques and desired result.

Moving towards a common understanding of these modalities the following mode of operation has been considered as definition:

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. This modes involve the control methods and capabilities on the operator but as well the remote site.

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.

These capabilities are not mutually exclusive, rather they can be designed and provided on top of (or as a complement to) other approaches.

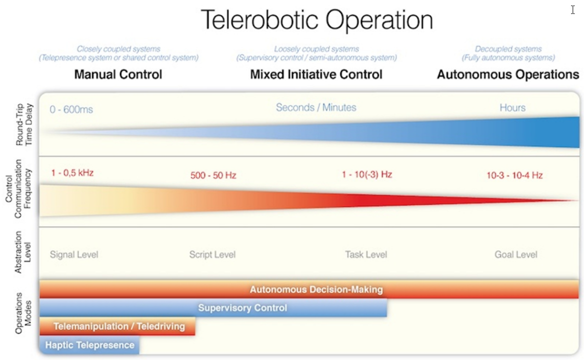

Fig. 2. Telerobotic Operation

Fig. 2 shows different possible modes of operation in respect to the communication and control capabilities of the remote slave and master system.

Communication time delays and lack of models of remote planetary environments complicate 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.

4. Possible Tasks for future robotic Missions

The current list of robotic operations is not well defined for Moon and Mars in GER3. 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:

4.1 Relocation

In the context of this paper, 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 or 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 and hazard detection systems and onboard processing units.

4.2 Construction

Construction tasks on other planetary bodies, especially using regolith or other in-situ resources as the feedstock materials, may be accomplished tele-robotically 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.

4.3 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.

4.4 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.

4.5 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 a 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.

4.6 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.

4.7 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 quiescent or 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.

4.8 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.

5. Extracted Results of the analysis

The first technology gaps identified are described related to the different modes of operation and control.

5.1 Performance Improvements

- 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 Interface
- Experience/Knowledge Gaps:
  - In-Situ Resource Utilization
  - Low-G Construction Tasks Using Local Resources

5.2 Critical Technical Gaps

- High-speed Space-qualified Processors
- Local Computational Resources Supporting Operations
- High-speed Data Buses
- Communications Bandwidth
- Communication Hardware
- Improved LIDAR
- Verification & Validation (V&V) of Autonomous Systems in Integrated Systems

5.3 Non-Technical Gaps

- Experience Gap: ISRU Robotic Missions
- Collaboration Gap: Implementation of Standard Interfaces

5.4 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.

5.5 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.

5.6 Other Gaps Related to Control Modes

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.

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 assesmment/needs.

Fig. 3. Operational modes for Telerobotics

Figure 3 shows the different control modes and their potential for use in future tasks. In many cases there exists an experience gap for tele-robotics 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.

The following capabilities were identified as needing improvement over the current on-orbit capabilities in order to achieve the tasks identified in chapter 4 of this paper. 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.

The suggested Improvements are sorted with respect to performance in capabilities, policy and experience gaps, while critical technical and non-technical gaps are summarized below. Please read the full report for furthers information [2].

6. Summary and Outlook

The review of the current state of practice shows that there are several options available as control modes, which operate on a sliding scale 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 paper and therefore also the report 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, standards 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, small in size, mass 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
- Localization Accuracy
- Advanced Motion Planning and Hazard Avoidance
- Visual Servoing for Auto Alignment

Some of the critical policy improvements needed include:

- Interoperability/Standardized Interfaces
- Software Verification and Validation standards for certification

Some of the critical experience/knowledge gaps include:

- In-Situ Resource Utilization
- Construction (low-G environments)

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

- Space-qualified Processing
- Visual Sensing Technology
- Advanced Controls and V&V
- Communication Bandwidth
- Standard Interfaces
- In-Situ Resource Utilization

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, new mission scenarios, 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.

Acronyms

ASI Agenzia Spaziale Italiana
CNES Centre national d'études spatiales
CSA Canadian Space Agency
DLR Deutsches Zentrum für Luft- und Raumfahrt
DSG Deep Space Gateway
ESA European Space Agency
EVA Extra-Vehicular Activities
GER3 Global Exploration Roadmap third generation
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)
LOC Locus of Control
MPCV Multi-Purpose Crew Vehicle
MSRAD Mars Sample Return Analogue Deployment
MSS Mobile Servicing System
NASA National Aeronautics and Space Agency
SMEs Subject Matter Experts
TWG Technology Working Group
V&V Verification and Validation

References

[1] GER3, Global Exploration Roadmap, January 2018, the third iteration of the GER, https://go.nasa.gov/2nCkbFV
[2] GAP Report, Telerobotic Control of Systems with Time Delay - Gap Assessment Report https://www.globalspaceexploration.org/wordpress/?page_id=811
[3] GAP Report, Autonomy GAP Assessment Report - Gap Assessment Report https://www.globalspaceexploration.org/wordpress/?page_id=811
[4] ISCEG Website, https://www.globalspaceexploration.org/