Low-Latency Teleoperations: Operational Implications for Human Space Exploration

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Low-latency teleoperations (LLT) is envisioned to be an element of human exploration missions in a number of different applications. LLT can be broadly considered to encompass any remote operation of an asset with a communication delay that is less than the human response time to allow for what is effectively "real-time" or "near real-time" operations. This paper will explore motivations and operational implications for why and how LLT might be used for human exploration space missions. LLT analyses have been performed under the auspices of the NASA Human Spaceflight Architecture Team (HAT) and Evolvable Mars Campaign (EMC) [1]. The EMC created a flexible, evolvable, capability-driven architectural strategy to enable a sustainable long-term human presence at Mars [2]. LLT is envisioned to be part of that strategy for both in-space and on-surface applications, and this paper will expand on operational considerations within that broader strategic context, as well additional contexts.

Some operational implications explored in this paper, derived largley from previous work [1], are: (1) crew mission support, for which we will address roles for Mission Control on earth, balanced with the capability for crew and robotic assets to operate independently, (2) science operations, with a focus on "backroom" support, highly dynamic science, and enhanced science return and efficiency, and (3) operational efficiency at a deep-space destination such as Mars, including implications for communications infrastructures and how to leverage and balance system autonomy with crew operations, both of which can inform the overall operational "choreography" between crew members, multiple shifts, and exploration assets.

I. Introduction

A general motivation for low-latency teleoperations (LLT) is the ability to use human cognition and rapid response times in an environment without placing a human directly in that environment. Human exploration missions can be dangerous and costly, and planetary environments introduce the possibility of contaminating crew members, their environment, and earth when the crew returns. Operations performed via LLT can reduce the need for crew EVA, including exploration into hazardous areas on planetary surfaces.

The human response time can be thought of as a "cognitive timescale," and while it is often characterized as being less than .5 s [3], it is important to recognize that effective response times can vary significantly depending on the task and performance requirements – which are tightly related to a variety of operational considerations. Different cognitive timescales for different tasks can inform a distinction for "telepresence," which can be considered a special kind of LLT in which a remote human operator is more fully "present" in the environment, enabling highly complex and rapid decision-making for time-critical tasks that require significant human judgment, such as science

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reconnaissance. With the right data, robust tools, sufficient latency, and operational strategies, telepresence can facilitate a strong sense of presence at locations of interest. This can allow rapid, complex decision-making that could be as effective as "being there" – and in some cases, may have benefits over in-situ crew presence – giving rise to number of operational implications and considerations that are touched in this paper.

Certain environments may be problematic for in-situ crew presence for a variety of reasons such as: (1) safety, e.g. exploring distant or extreme terrains, (2) accessibility, including landing in the gravity well of a planetary surface, and (3) planetary protection, such as "special regions" exploration, defined as regions where life may be tenable. There is also significant potential for LLT medical assistance, including surgery [4], that may prove critical during long-term deep space missions to Mars and beyond.

II. Operational Value of Low-Latency Teleoperations

A primary advantage of having humans in an operations loop is the use of rapid reaction times and human judgment and in almost all activities – from system maintenance to science operations. Despite progress in autonomous systems, it is prudent to plan for scenarios that will not be safe, optimal, or feasible with only autonomous systems – including a wide range of unanticipated contingency events.

LLT can facilitate efficient and reliable task execution, particularly for tasks that may be preferable to perform prior to crew landing on Mars. Even if many tasks don't necessarily need to be completed prior to crew landing, any Mars program that incorporates orbital missions around Mars prior to a landed mission (for example, a crewed mission to Phobos [5]), could take advantage of being in Mars orbit to conduct LLT activities on the Martian surface [6-10]. LLT activities from Mars orbit can reduce the post-landing workload and also help inform outpost and science activities after crew has landed.

It is also possible that if a crewed landing is delayed for a long time, LLT could be used to slowly and "opportunistically" prepare for a crewed landing at a later time and to perform in-depth science for extended periods of time. In addition, there will likely be transient phenomena that would benefit from rapid science judgment and rapid response times (e.g., dust movement, certain kinds of geochemistry or biochemistry, boundary layer dynamics, and possibly subsurface liquid environments). Operation of highly dynamic vehicles (such as aerial vehicles or subsurface vehicles in potential liquid environments) would benefit from crew intervention and rapid human response times facilitated by LLT.

The degree of operational value of LLT depends partly on broader assumptions about campaign risk posture, resources, and requirements. Answers to the below questions will directly inform the operational value of LLT and depend largely on risk postures that need to be further evaluated in the context of a comprehensive risk analysis for human missions to Mars.

1. What activities or tasks are preferable to conduct prior to crew landing on Mars to help reduce operational risks associated with landing, surface ops, and crew workload?
2. What risk-reduction tasks should be done by traditional high-latency missions from earth or by highly autonomous missions?
3. What tasks should be conducted via LLT as a primary operations mode vs. as a backup mode?
4. What tasks are likely to have the greatest operational impacts, positive and negative?

More specific operations-related questions that inform the above questions are:

1. How important is it to do in-situ site assessment and validation prior to crew landing?
2. How important is it to prepare the surface in any way prior to crew landing?
3. How important is it to prepare/integrate assets on the surface prior to crew landing?
4. How important is it to do Mars surface science prior to crew landing? E.g. Should we search for and explore potential Special Regions prior to landing crew?
5. Should LLT be used for sample containment, inspection, and containment mitigation prior to crew capturing a sample and returning it to Earth?
6. Should LLT be used for Mars asset aggregation and maintenance in cislunar space prior to leaving for Mars?

III. Low-Latency Teleoperations Activities

This section will briefly touch on a number of potential human mission activities in cislunar space and Mars that have operational significance for LLT (many of which were covered in more detail in [1]), with an emphasis on science operations at Mars.

1. Crew-Assisted Sample Return. An example of a mission concept that helps highlight the operational value and operational challenges of LLT is the use of crew transportation vehicle such as Orion [11] or habitation module in cislunar space (e.g. a "Lunar Orbiting Platform-Gateway" or "Deep Space Gateway") to conduct LLT operations on the lunar surface to obtain samples and return them to the orbiting facility for analysis and/or return to earth [12-15].

2. Landing and Outpost Site Assessment and Validation. Assessing and validating areas on the Moon and Mars that are intended to be landing sites and outpost sites can be done via LLT rover activities such as optical surveys, shallow drilling, vibro-acoustic measurements, and cursory chemical analyses. "Ground-truthing" potential landing and outpost sites prior to crew arrival could be important to validate those locations for science value and safety (e.g. lava tubes) and can inform how the site will be used for permanent placement of surface assets. Tasks that are good candidates for LLT ISRU include prospecting, parts replacement, system servicing, instrument calibration, and cleaning.

3. Outpost Setup and Integration. Outpost setup and integration activities include tasks such as offloading assets from the landers, routing and connecting power cables, performing mechanical integration of hardware, and perhaps initiating ISRU production. Multiple lander missions are likely to have extensive manifests requiring much offloading and integration. Such activities are prime candidates for LLT because the tasks are more "sensitive" to communication delays or interruptions – including loss of signal (LOS) due to line of sight disruptions if continuous coverage isn't possible – because precisely manipulating those critical assets (e.g., mating electrical connectors) can present significant operational challenges and result in significant failure implications. LLT also affords a relatively fast abort capability if, for example, an asset being lifted is about to contact something. LLT can also help reduce the need for crew to handle hazardous assets such as fission power and cryogenic systems.

4. Science Operations. Science operations present unusual challenges for LLT in the sense that science judgement, particularly "real-time" science judgement, often benefits from being physically present in the environment (including lab environments) of interest [16], and yet also can benefit from humans not being in an environment – e.g. where the presence of humans could compromise the science with contamination [17-20]. One kind of operational stressing case could involve two LLT rovers, both operated by crew in Mars orbit. One LLT rover would be a fast-moving reconnaissance (recon or "scout") rover to locate sites with potentially high science return, and a second LLT rover would be a slower sampling rover to conduct detailed science measurements at selected sites and to collect and analyze samples. Such a scenario could focus on determining if life ever existed on Mars, including characterization of chemistry and morphology as context for more detailed life-detection measurements. Data collection could include, among other things, multispectral surveys, LIDAR scans, and surface and core samples, and perhaps even biomolecular sequencing [13, 21].

5. Outpost Operations. Outpost operations are considered to be tasks performed once the crew arrives at the landing site and can be performed via LLT by crew that is either on the surface or in Mars orbit while crew is also on the surface. LLT tasks for "nominal" outpost operations include routine tasks (e.g., logistics), periodic servicing and maintenance (e.g., cleaning, calibration), and repair tasks – particularly for hazardous operations. Science tasks would also be part of normal operations and can be considered distinct from outpost "housekeeping," maintenance, and repair – which would include a variety of maintenance tasks could be conducted via LLT such as replacing parts or cleaning critical surfaces (such as solar panels), to more complex activities such as servicing a solar-electric propulsion (SEP) system in space at or near an in-space "outpost/gateway" in preparation for a Mars transit. The primary benefit of utilizing LLT for these kinds of tasks would be to minimize EVAs for routine operations that could be more easily performed telerobotically. In the case of EVA, however, LLT could also be used to control "companion" rovers to assist the EVA crew members or to serve as contingency rescue in high-risk areas.

IV. Operational Implications

There are a number of different areas for which LLT has notable operational implications that can inform human space mission planning and operations – some of which is beginning to be tested with space assets such as the International Space Station [22, 23].

A. Crew Mission Support

1. Performing LLT at locations of interest does not replace the "backroom" in Mission Control on Earth. Earth-based scientists will continue to serve an important role in science data analysis and consultation with crew.
2. However, the ability of crew and robots to perform more tasks independently needs to be developed further, including dynamic scientific judgment and decision-making. This implies significant training and advanced systems to enhance science operations.
3. Much high-fidelity testing and operational preparation for LLT activities at Mars could be performed in cislunar space where shorter time delays reduce risk of operational failures.

B. Science operations

1. While much LLT science on Mars will likely be performed directly by crew in Mars orbit or on the surface, LLT science operations will also be enhanced through proper deliberation with "backroom" scientists and broader science communities on earth, and this interplay will present challenges given the communications delay to Mars.
2. Science return efficiency (e.g., science return per unit time) could go up significantly with real-time crew control of robotic and other science analysis assets – especially for highly dynamic science.
3. Certain dynamic science phenomena may benefit from quick crew reaction times and science judgment, suggesting the need for extensive science and operations training as well as sophisticated operations tools such as robust information systems.
4. Fast integration instruments for surface and subsurface will likely be needed to take advantage of faster overall science operations allowed by LLT science, including for life detection.

C. System-Operations Implications

1. Autonomous systems and "supervised autonomy" can help save crew operations time. Many common tasks may be candidates for autonomy or supervised autonomy, with LLT intervention as necessary:
   a. Functional tests of surface assets
   b. Standard soil analyses that can be performed during no-comm periods
   c. Rover/mobility operations traversing with autonomous positioning/guidance, hazard avoidance
   d. Cable deployment
   e. Sample handling
   f. Could include "goal-based commanding", including via voice commanding [24]
2. Time constraints from other important crew activities suggests the need for as much continuous operations capability as possible, implying robust communications infrastructure at Mars (such as orbital relays, surface assets, etc.) and effective "choreography" of crew and rover operations across multiple shifts.
3. Surface assets (e.g., rovers) with distributed functionality can provide redundancy, robustness, and reliability, and suggest the need for distributed asset operations strategies and techniques.
4. Additional mechanisms and autonomy for telerobotics systems require more mass, power, and command/data systems, and thus may introduce reliability risk. This should be weighed against the additional requirements associated with direct crew performance of tasks, such as ECLSS and EVA time, as well as the inherent risks

associated with EVA.

5. In order to take advantage of LLT and a robust communications architecture noted above, users need to have sophisticated systems that enable effective and rapid decision-making. Telepresence in particular would benefit from robust information systems including (a) well-designed and well-tested user interfaces to (b) detailed and highly responsive dynamic environmental models to (c) certain kinds of machine learning and artificial intelligence to help guide decision-making.

D. Specific Task Operations Implications

1. Asset off-loading from landers will likely require some level of “real-time” control/monitoring for critical operations such as grappling, lifting, center of gravity awareness, etc.

2. Drilling, including core drilling for science, is tedious and may have highest probability of anomalies, e.g. binding/choking, heating, bit failure, etc. [25]

3. Sampling density (sample per unit area/volume) and types will drive surface asset payloads and time needed to conduct recon. If needed, LLT can help perform sampling and analysis quickly.

4. Haptic, or force-feedback is likely to be useful for many tasks that would benefit from a sense of feel and touch [26].

5. Cross-Cutting Challenges:
   a. Manipulation of heavy or delicate equipment (e.g., drill heads) within close quarters
   b. Ensuring critical ops (e.g., lifts, drilling) are handled properly prior to loss-of-signal
   c. Unexpected delays in completing critical tasks prior to loss of signal may require unplanned safing of assets

6. Common Maintenance Tasks:
   a. Electrostatic discharge control/grounding
   b. Electrical connector mate/de-mate
   c. Fastener removal/installation
   d. MLI handling

7. Key Maintenance Challenges:
   a. Manipulating small components that have distinctly different geometries
   b. Ensuring fluid system integrity – for mate/de-mate during resource transfer
   c. Hardware alignment following replacement (bits, wheels, etc.)
   d. Ensuring purity of refill fluids or calibration samples
   e. Accessibility of item requiring maintenance

8. Contamination Control & Planetary Protection:
   a. LLT can be used for in-situ contamination analysis, Special Regions exploration, and science lab operations.
   b. Roving from one special region to another may raise cross-contamination concerns.
   c. LLT can be used for cleaning assets.
   d. Burying cables potentially introduces additional planetary protection considerations depending on the depth and prior recon results.
   e. Planetary protection is presently strict for Mars samples, suggesting the need for feed-forward testing for Mars samples, which could be assisted by LLT inspection, cleaning, and mitigation. Asteroid sample containment requirements are TBD, but the same functionality could apply.

V. Conclusion

Low-latency teleoperations has the potential to significantly enhance or enable many operational challenges associated with human space exploration. A number of risks for human missions to Mars can be reduced or eliminated, including by using LLT to prepare for a crewed landing – much of which can be tested in cislunar space. LLT should allow many tasks to be performed more quickly than from earth, and this has the potential to improve science return – especially for dynamic science that could be enabled by faster science judgment and a more robust telepresence experience. LLT can enable an additional exploration paradigm for human space exploration that could be used extensively during times when landing crew or conducting EVA's present high levels of risk. Additional analysis and operational testing would help address certain trades that are driven by overall risk posture and mission schedule constraints and should be conducted well in advance of sending humans to Mars.

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