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Integrated Human-Robotic Missions to the Moon and Mars: Mission Operations Design Implications

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For most of the history of space exploration, human and robotic programs have been independent, and have responded to distinct requirements. The NASA Vision for Space Exploration calls for the return of humans to the Moon, and the eventual human exploration of Mars; the complexity of this range of missions will require an unprecedented use of automation and robotics in support of human crews. The challenges of human Mars missions, including roundtrip communications time delays of 6 to 40 minutes, interplanetary transit times of many months, and the need to manage lifecycle costs, will require the evolution of a new mission operations paradigm far less dependent on real-time monitoring and response by an Earthbound operations team. Robotic systems and automation will augment human capability, increase human safety by providing means to perform many tasks without requiring immediate human presence, and enable the transfer of traditional mission control tasks from the ground to crews. Developing and validating the new paradigm and its associated infrastructure may place requirements on operations design for nearer-term lunar missions. The authors, representing both the human and robotic mission operations communities, assess human lunar and Mars mission challenges, and consider how human-robot operations may be integrated to enable efficient joint operations, with the eventual emergence of a unified exploration operations culture.

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Nomenclature

AOS = Acquisition of Signal
LEO = Low Earth orbit
LOS = Loss of signal
MCC = Mission Control Center

Outline

I. Introduction

FOR the first half-century of the U.S. space program, human and robotic missions have been conducted almost entirely independently. Separate mission operations processes—and cultures—have evolved at Johnson Space Center and Jet Propulsion Laboratory, each geared to the unique challenges of the two classes of missions. Recently, under the Vision for Space Exploration, NASA has begun working toward returning humans to the Moon, with the eventual intention of moving on to Mars. This new program raises the possibility of integrating robotic elements into human missions, with robotic systems potentially operating in tandem with human presence to perform mundane tasks, minimize risk to human crews, and maximize human availability for critical tasks and exploration.

Robotic spacecraft on deep space missions must commonly function independently for hours, days, or even weeks without communications with ground operators, due to a variety of resource limitations. The interplanetary distances over which these spacecraft are controlled result in communications time delays of minutes to hours. Responding to these constraints, human operators of robotic missions have developed processes to produce carefully validated sequences of commands, which are uplinked and stored on the spacecraft during a communications opportunity, and subsequently govern spacecraft actions for an extended period of time. In addition, automated fault-recovery capabilities are built into the spacecraft system to ensure that, given an anomaly, the spacecraft will put itself into a state maximizing both survivability and probability of re-establishing contact with ground-based operators.

Current human missions to LEO are characterized by near-continuous communications, minimal time delay, and high bandwidth. Operators in mission control can observe the results of individual command executions prior to issuing the next command. Flight controllers and astronauts work together as an integrated team. Typically, space shuttle mission activities and critical operations activities onboard the space station are planned in detail months before the event, whereas steady-state quiescent operations planned for the space station are usually more relaxed and planned only weeks and days in advance. When anomalies occur, the crew and flight controllers are directed to caution and warning procedures for recovery and activities are re-planned to return to nominal operations.

Human Mars expeditions will present several challenges to the current approaches to mission operations. At Earth-Mars distances, communications time delays will prohibit normal voice conversations between astronauts and mission control; ground monitoring of systems will be unable to provide immediate response to onboard state changes; commands sent from the ground may no longer be appropriate by the time they are received onboard; onboard contingency response must be robust to possible long-term communications disruption. Robotic systems operating in the vicinity of human crews will raise safety concerns; control authority for robots may shift from local astronaut to remote astronaut to mission control and back.

II. Human Mission Operations Overview

[To be completed]

III. Robotic Mission Operations Overview

Due to the time-delays inherent in communicating with distant spacecraft, robotic deep space missions have adopted the approach of stored sequence execution. For some missions, a single command load may comprise tens of thousands of commands, governing the spacecraft's actions for weeks or even months. Since these spacecraft must perform without the benefit of immediate human feedback or intervention, the command sequences must be carefully validated to ensure that their results will be as intended, and that no risk to the spacecraft due to execution of the sequences. A command sequence that leaves the spacecraft in an unintended orientation, or inadvertently shuts off a key device could cause a premature end to the mission, with loss of the spacecraft.

In order to mitigate this problem, fault recovery responses are traditionally built into the spacecraft software. If the spacecraft has not received any commands within a specified time, the spacecraft may autonomously change its attitude to point its antenna at the Earth, to improve the chances of receiving new instructions. If the spacecraft is solar-powered, it will point its arrays toward the sun to ensure that it remains power positive, and therefore will not die while waiting for new instructions.

The risk of losing a mission has led to the evolution of an extremely conservative approach to command sequence development and validation. Traditional commands are time-tagged to specify exactly when they are to be triggered. The development of a command load may require weeks or more to progress through design of an activity plan and then to building actual command sequences. For orbiters and free-flyers, the space environment is unlikely to impact the spacecraft in unexpected ways, so building commands far in advance of use presents no problems.

For the less common planetary surface missions, such as Mars Pathfinder and Mars Exploration Rover (MER), the mission operations planning cycle is generally much more compressed. Since the results of interactions with the terrain are much less predictable, operations must be conducted using a far more reactive approach than for orbiter missions. Both surface rover missions were able respond to telemetry and generate new command loads daily.

One recent innovation of the Mars Pathfinder rover "Sojourner" and the MER mission was the use of "event-driven" sequencing. The time required for a rover to complete a traverse through a hazard-filled terrain while autonomously avoiding those hazards cannot be fully predicted. If the drive takes longer than expected, the next command in a time-tagged sequence may begin before the rover is ready. So, instead of clocking out commands, MER sequences are designed so that the next command starts when the prior command reports completion. This approach avoids command conflicts, at the expense of increasing the uncertainty as to when commands will execute.

While the approaches employed to date for robotic deep space missions have been highly effective, and have enabled exploration throughout the solar system, they too will need to evolve to make robotic systems useful to astronauts when they arrive on Mars.

IV. The Long View: Challenges of Human Missions to Mars

A. Time Delay

Communications time-delays of minutes have yet to be encountered on human space missions. Round trip communications delays of 6 to 40 minutes will transform conversations between MCC and astronauts to a series of emails and/or voicemails. What would be a two minute conversation between ground operators and crew in LEO, with four questions and responses, would easily require over 2.5 hours when the crew is on Mars.

Continuous communications time-delays are not necessarily analogous to frequent LOS that may occur during Earth-orbiting missions. For ISS, an upcoming LOS may force certain activities to be carefully planned to fall within a given time period, but the cycle of command-execution-monitor-command remains very short, allowing many cycles while the communications link is available. A more relevant analogy for time-delays would be a situation in which a single command is sent just before LOS, and the result of command execution cannot be discerned until AOS, after which only a single command can be sent before the next LOS.

A premium will be placed on unambiguous and complete message content, given the time impact and frustration inherent in requesting clarification. This may lead to the development of a "standard interplanetary English" ton ensure reliable communication of meaning when acknowledgment of transmission and correction of errors is costly.

Time-delays of significantly greater than 40 minutes may exist at Mars, unless infrastructure is emplaced to mitigate the problem. Any likely landing site on the surface of Mars will be in line-of-sight to Earth only about half of each Martian day, due to the planet's rotation. A communications satellite network in orbit over Mars could reduce the duration of LOS, but without such a network, crews would be out of contact for many hours at a time.

B. No "Escape to Earth"

Human LEO missions currently maintain an "Escape to Earth" option: In many anomaly cases, such as loss of redundancy in a critical system, the crew can de-orbit and return to Earth within hours. But with Earth-Mars transit times of several months, no such "Escape to Earth" safety net will be available.

C. Evolution from Mission Control to Mission Support

The two factors just described will drive the evolution of MCC teams from the traditional control role to an advisory function. First, the communications time delays inherent at Earth-Mars distances will preclude ground-based operators from commanding and monitoring time-critical functions, or addressing anomalies requiring rapid response. Second, with no rapid return to Earth possible, the crew will be required to handle contingencies (including potential loss of communications with the ground) over extended time periods.

Even in the current environment, it is unacceptable to put a crew at risk in the event of a communications failure between mission control and the spacecraft. While it has never been necessary, the Shuttle is capable of (and required to by policy)—independent of the MCC—de-orbit within 24 hours if a sustained communications outage occurs.

If we accept the contention that crews at Mars may need to respond to significant anomalies on their own, then we must ensure that they have the tools at hand to do so. Under these conditions, astronauts will necessarily take ownership of many traditional MCC functions. (In the parlance of the Vision for Space Exploration, "autonomy" is defined as this independence from ground controllers.) Given present-day implementations of operations, and the complexity of the spacecraft that will take humans to Mars and sustain them there, manual control of these assets would quickly overwhelm or exhaust an un-augmented crew, even without considering the workload impact of handling an anomaly. This implies a requirement for significant onboard automation capable of real-time monitoring and performing routine and repetitive activities without continuous supervision. Such onboard automation will free the crew for critical functions: responding to time-critical anomalies, implementing repairs, and exploring.

As onboard automation is implemented to control standard functions under extended duration off-nominal conditions, the use of this automation during normal operations must be considered. Onboard automation has one major advantage over an Earthbound operations team: at maximum range, automation can detect and respond to a state change twenty minutes before the ground is even aware of a problem and forty minutes before the earliest command from the ground could arrive at the spacecraft. As automation becomes trusted, the size of the MCC team will fall, with fewer personnel devoted to system monitoring and response. A larger fraction of the team will instead be focused on strategic planning in support of crew exploration and survival.

When astronauts are operating in an exploration mode, activity plans will depend on prior results. One possible model is for Earth-based operators to regularly receive (delayed) telemetry, running commentary, questions, and issues from the crew, ingest these inputs, and then generate plans for the next day while the crew on Mars sleeps. For plan changes during a surface EVA, a Mars crew will not be able to wait for a response from Earth, since the roundtrip communications delays would leave them idle—consuming resources—for a significant fraction of the Martian day. Instead, crews will need the capability to re-plan on the fly, without putting themselves at risk. For example, an automated scheduling assistant could answer the question: "Do we have enough oxygen and energy to deviate from the current EVA plan, and go up that hill and take samples of that shiny boulder, and still get back to base with sufficient margin?"

D. Types of robotic and automation support to human missions

One of the most valuable resources in the solar system will likely be a workhour of an astronaut's time on Mars. This will lead to application of technology to offload crews of as many mundane and support activities as possible. There are several distinct classes of robotics and automation that may offload different crew activities:

- Automation for habitat and other system operation, maintenance, and diagnostics
- Software tools for planning, scheduling, and other applications
- Robotic systems that interact with structured environments and assembled elements
- Robotic systems that interact with natural terrain for earth-moving, site preparation, and infrastructure emplacement

E. Efficiency of robotic mission operations

As described earlier, current mission operations for deep space tend to function at a deliberate pace to ensure the correctness of command loads. Even MER, the Mars mission with the shortest command-turnaround cycle to date, and perhaps the robotic mission most analogous to eventual human missions, can manage only one command cycle per Martian day. Many people have anecdotally estimated the relative effectiveness of the MER rovers compared to a hypothetical spacesuited human geologist on Mars, often presuming that the human would be 50 to 100 times faster than the robot at completing mission objectives.

In the absence of human presence, this level of performance has been acceptable; but in support of astronauts, the current approach to commanding robotic systems would likely be too cumbersome to even be attempted. However, there are several options for operation of robotic systems:

- Direct teleoperation: "Joysticking" of a robot may be extremely useful, if an astronaut is available. The primary benefit is derived
- Traditional sequenced control – which is cumbersome (local or from Earth)
- Goal-based control

Operations of robotics interacting with natural environment

Automation for nominal functions

F. Exploration-driven operations

To date, the human space program has conducted only limited duration exploration missions, the Apollo Moon landings of the late 1960's and early 1970's.

G. Transfer of control authority

V. The Closer View: Challenges of Human Lunar Missions

Humans have been to the Moon before. However, some of the attributes of the missions that return people to the lunar surface, in particular for extended habitation of a permanent lunar outpost, will be unprecedented:

- Far more conservative risk posture than during the Apollo era
- Buildup and maintenance of permanent infrastructure

- Multiple missions to the same site
- Eventual sustained human presence during lunar night
- Long-duration stays on the lunar surface
- Monitoring and maintenance of infrastructure in during gaps in human presence
- Use of lunar missions as analogues for later Mars missions

Many of the items in this list provide opportunities to make use of the Moon as a testing ground for later Mars missions. However, the Moon does not inherently mimic the level of isolation that will exist for astronauts on Mars, and lunar missions will not address the impact of significant communications time-delay which likely represents the single greatest challenge to current human operations models.

VI. A Mission Operations Paradigm

What strategy will support effective mission operations given the challenges that will be present when astronauts are exploring the surface of Mars? Most of the challenges identified derive from communications time-delays that simply do not permit the immediate knowledge of and capacity to influence spacecraft state that we are currently comfortable with and reliant upon in human spaceflight. (The same desire to be fully in control of exactly what will occur on the spacecraft and when holds in the robotic mission arena as well. The acceptance of autonomous rover navigation and event-driven command sequences represents just the beginnings of change in this culture.)

We suggest here a multi-layered distributed approach responsive to the multiple regimes of time-delay that will exist for a Mars mission. Mission planning and execution functions must be shared across ground operators and crew, and between the Earth and Mars, to enable effective conduct of the mission. Consider four timescales:

- Long-term: weeks or months
- Strategic: a day or more
- Local: minutes to hours
- Immediate: seconds to minutes

Long-term planning, looking ahead weeks or months, will be performed by operations team members on Earth. While the long-term planning cycle will respond to new information received from the distant crew and spacecraft systems, barring a major anomaly, this planning should not be significantly impacted by short-term changes to crew activities. Within the purview of long-term plans will be schedules for crew exploration excursions, ensuring overall management of consumables, etc.

Strategic planning may be shared between the ground and the crew. At this level, the Mission Control Center will provide plans for what the crew will do "tomorrow." Given messages, images, instrument data, and requests received from the crew on a given day, this function will provide overnight a daily plan of activities, consistent with the long-term plan and current resources. At times, this function may be delegated to the crew, as they should have the necessary information and tools in hand, consistent with the need to make strategic plans in the event of an anomaly. At this same level, ground operators will define activity plans for on-site robotic systems that are not being operated directly by the crew.

The local planning level must be executed at Mars, since the Earth-Mars time-delays would not permit timely responses on the timescale of minutes. (An astronaut would not wait for Earth-based operators to render a decision regarding the conduct of an EVA, since waiting for a response could make the question moot.) At this level, daily strategic activity plans for the crew or robotic systems may be modified in response to new observations or other information. Astronauts at different sites on Mars (e.g., an astronaut in the habitat and others on EVA or driving on a rover kilometers away) will coordinate their activities at this level. One or more crew in a habitat may serve in the MCC role for other crew members performing an EVA. Astronauts will specify new goals or high-level commands to robots that are operating in the vicinity. Relevant time delays will be seconds to a minute or so, if relay communications between sites is necessary.

At the immediate level, planning and execution are inextricably linked: astronauts are carrying out tasks, and making real-time decisions regarding their next steps. At this level, one astronaut may be working alone or in direct line-of-sight with additional astronauts. An astronaut would directly teleoperate a robot and control its progress. There are essentially no time delays at this level.

Each of these levels works to a timeline at a different resolution. Interactions between timelines must be coordinated to ensure smooth execution of the mission.

VII. Conclusion

As humans return to the Moon and then prepare to make the first journeys to Mars, the perception of human and robotic missions as independent programs will wane. Automation and robotics will become integral elements of human missions, ever more essential tools for both ensuring human survival and maximizing crew effectiveness during each exploration mission. As crews must function more and more distant from the Earth—in time as well as space—direction of semi-autonomous robotic systems will become a key role of Earth-based mission controllers, extending their reach to support astronauts while freeing crews for exploration, discovery, repair, and anomaly response.

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