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

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Abstract—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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1. 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 low Earth orbit (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.

2. HUMAN MISSION OPERATIONS OVERVIEW

Human space operations endeavors are currently focused in Low Earth Orbit (LEO) and come in two flavors, long duration (ISS) and short duration (Space Shuttle missions, Soyuz missions, Shenzou missions). The general following overview addresses NASA human operations.

In common between both ISS and STS operations are the fundamental products and tools used and the rigorous crew and flight controller training programs. Among the key products are the crew and ground operations procedures, flight rules, and mission plans. Procedures spell out how to perform tasks ranging from commanding to physical maintenance and equipment assembly, and are verified and validated rigorously before use. Flight rules are developed pre-mission and document pre-determined mission controller decisions and responses to limit violations, off-nominal events, etc. Mission timelines are schedules specifying both crew and ground events (or activities) against time. Timelines are re-planned daily and supplementary information is provided to crews daily during the mission to supplement operations. Commands and command sequences are developed pre-mission and rigorously verified and validated before becoming available for use by mission controllers.

Shuttle operations can be characterized as highly optimized operations environments where crew and ground teams work in concert to achieve mission objectives while ensuring crew safety and maintaining vehicle integrity. Missions are short in duration, relative to the length of ISS expeditions, and timelines are highly choreographed. Detailed mission planning begins about one year in advance of the mission. Crews begin flight-specific training months in advance. Three to four months prior to missions a formal programmatic Flight Operations Review (FOR) is conducted of all mission products (e.g. timelines, procedures, flight rules, etc.). Following the FOR, ground controllers and flight crews begin performing flight-specific simulations in order to further refine mission procedures, flight rules, and timelines; off nominal scenarios are addressed as well. From a communications standpoint, shuttle missions are characterized by nearly continuous communications coverage, negligible communications delays, and high-bandwidth services for video and data exchange between crews and mission controllers. During mission operations, the flight control team monitors crew operations and vehicle performance, and provides necessary information to ensure crew safety, vehicle integrity, and mission success. Crews enter and execute commands to the vehicle through general purpose computers (GPCs). Command loads are rigorously developed, verified, and validated pre-mission. Plans and procedures are provided to crews in paper format. The optimized operating environment of STS operations provides a good starting point for developing systems and processes needed for future CEV operations.

There are several key differences between ISS and STS operations. Attributes of ISS operations include: a less optimized operations and planning environment, need for logistics and re-supply management strategies, multi-national participation at a partner level, reliance on ground controllers for daily vehicle systems management and long-term vehicle maintenance plans. ISS operations can be characterized as a continuously operating environment in LEO with nearly continuous communications coverage, high bandwidth uplink and downlink capability, and a less optimized daily operating focus, as compared to STS operations. To date, there has been a continuous human presence on the ISS for over 5.5 years. Further, ISS is a multi-national distributed operation with control centers located in four partner nations. Each partner is responsible for the management if its own element with the overall integrated operational responsibility residing with NASA at JSC. Each partner provides planning inputs to NASA for integration into a single plan for crew and ground execution. The long duration nature of ISS operations requires a less-optimized operations and planning approach as compared with STS operations. Additionally, the long duration continuously operating nature of ISS introduces the elements of on-orbit logistics, re-supply, and maintenance management not present in STS on-orbit operations. Both crew and mission controllers have the capability to command the vehicle.

ISS crews rely on mission controllers for day-to-day vehicle systems management, anomaly resolution and trend analysis, and to aide in contingency response. Conversely, crews are primarily responsible for physical systems maintenance and upkeep, vehicle assembly, and science operations. Finally, one additional key aspect of the long duration nature of ISS not encountered on STS missions is the crew psychological aspect. The long durations stays onboard ISS require a robust ground support system designed to provide both leisure and medical support for ISS crews. The crew interface with the vehicle for commanding and systems status is through laptop computers. Plans, procedures, and supplementary information are provided to crews and mission controllers electronically over a web-based network. The use of the web has proved a very effective means for disseminating operations information throughout the distributed environment of ISS. Since the beginning of ISS operations over 7 years ago, ISS systems and operations processes have undergone evolution. This evolution has occurred during manned operations, unlike any other NASA manned program to date.

The processes and mechanisms developed to handle the long duration continuously operating nature of ISS will be directly applicable to further long duration manned programs such as lunar base operations and future expeditions to Mars.

3. 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 thoroughly validated to ensure that their execution will be consistent with the original intent of the human operators, and that no risk to the spacecraft will be incurred. 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, two approaches are traditionally employed: rigorous sequence validation, often involveing high-fidelity testbed execution of sequences, and, onboard, fault recovery responses 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. (Onboard fault responses also mitigate the effects of environment-induced problems, such as cosmic-ray hits to electronic components.)

The huge consequences 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 of these 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 has been 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 effective and productive on a time scale useful to astronauts when they arrive on Mars.

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

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 the Mission Control Center (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 loss-of- signal (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-execute-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 acquisition of signal (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" to 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.

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.

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-orbiting 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 Earth-Mars range, automation can detect and potentially 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 MCC team will gain the capability to support multiple missions flying simultaneously without significant increases in overall team size, as a shrinking fraction of the personnel on the team must be dedicated 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?"

Two models have evolved for how Earth-based operators support the exploring astronauts. One is a reactive model where most decision making is occurring via local interaction with the crew, the results of their tasks and the conditions around them. The crew will be modifying their own plans, procedures and operational notes as they explore. The second is the more traditional proactive model where the many Earth-based operators consider all manner of data coming to them, analyze the information, and then produce new plans, procedures and operational notes for the crew to utilize in their next operation. Much has been learned about how to retrieve and downlink plan, procedure and crew notes from the ISS which should at least be used as lessons learned for designing this type of downlink capability for the exploration missions. However, even with an automated scheduling assistant for the crew, the Earth-based operators will likely still use the same tools and capabilities to "flight follow" the crew plan and pre-plan several optional plans for subsequent daily schedules.

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 encourage the 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
- Robotic systems for sample return/exploration/helping humans determine where to go next
- Robotic systems to aid humans with exploration tasks—handling supplies, samples, tools as humans explore in tandem

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

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.

Transfer of Control Authority

As NASA enters a new era of exploration of the Moon and Mars, it is evident that humans and robotics will continue to work together in space, both in ways that are well understood—astronauts manipulating robotic arms such as on the Space Shuttle and ISS—as well as in new ways that have not yet been envisioned. New practices to conduct mission operations have to be identified and developed in order to control many elements in space and on the ground simultaneously, elements which need to operate, interact and depend on each other—one of key factors for growing mission operations complexity.

For example, during the first Lunar Sortie mission (See Fig. 1), Lunar Sortie Crew Design Reference Mission), one of the operations scenarios involves several ground stations, at least two operations centers such as at KSC and JSC, a Crew Exploration Vehicle (CEV), a Crew Launch Vehicle (CLV), a Cargo Launch Vehicle (CaLV) with an Earth Departure Stage (EDS), a Lunar Surface and Access Module (LSAM), lunar surface extra-vehicular activity (EVA) systems, exploration rover(s), and one or more telecommunications relay orbiters around the Moon. Thus, humans and robotic elements will be simultaneously on the ground, in low Earth orbit (LEO), in transit to/from the Moon, in orbit around the Moon, and eventually on the surface of Moon. During the Lunar Outpost and Mars missions, the number of mission operations elements along with the locations of human and robotic elements will significantly grow. These mission operations scenarios illustrate new and increasing mission operations challenges of a multi-mission and multi-element nature that NASA must learn to cope with by: (1) designing mission operations that can handle an unprecedentedly complex network of operating elements with humans and robots in several locations around the solar system, and (2) integrating the multi-mission robotic and human space flight operations effectively and efficiently.

Simultaneously executing missions with multiple elements requires careful development of the Control Hierarchy among those multiple involved operating elements to minimize conflicts that can arise from the transfer of control authority and to provide over-ride among multiple sources. It becomes essential to develop a well planned and executable control structure that will facilitate: (1) mitigating and managing operations-related risks and safety, (2) developing effective and efficient operational requirements on the system design, (3) guiding system implementation to address overall operations costs, and (4) performing system verification and validation.

Some approaches can be taken to develop the hierarchy to facilitate effective transfer of control authority among multiple elements and to clearly delineate the boundaries of control:

- Examine Constellation Program operations scenarios. Identify how the elements of the space-mission architecture work together to complete the mission (element-oriented operations scenario), how the user interacts with the system's elements and received data (user-oriented operations scenario), how the crew interacts with the flight and ground crew (crew-oriented operations scenario) and how systems and subsystems within an element work together (system-oriented operations scenario).
- Overlay mission operations timelines (phases) for each scenario for each set of steps and determine which steps are carried out in parallel and in serial to identify candidate areas to be examined further.
- Determine which element will play what role for each scenario, especially during those periods where multiple elements are engaged in parallel operations
- Integrate the above information to identify the areas that need further clarification in terms of roles and responsibilities of each element

A few key factors that can have a great impact on the development of the Control Hierarchy need to be recognized and examined:

- The degree of automation and autonomy
- The characteristics of each mission, mission phase, and each control authority option
- Human factors in the decision making process
- Mission modes during both nominal and off-nominal conditions

The transfer of control authority among multiple elements has a great implication on mission operations design and lifecycle costs. Perhaps, the following questions can be answered through careful analysis and evaluation of control information flows during mission phases:

- What it is to have control authority
- What it is to transfer control authority
- Circumstances under which control authority is transferred
- How control authority transfer is mechanized or implemented
- Hierarchy of needs relative to control authority transfer, and
- Rules under which control authority transfer takes place

5. The Closer View: Challenges of Human Lunar Missions

Humans have been to the Moon before. However, some of the attributes of the missions that will 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 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 that likely represents the single greatest challenge to current human operations models. Only a mandated effort to impose Mars-like constraints on at least some lunar missions will lead to the development and validation of technologies and operations approaches during the upcoming lunar exploration phase. Without such a mandate, our preparedness for the challenges of human Mars missions will remain severely lacking.

6. 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 and when it will occur on the spacecraft 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.)

Operations in the Mars mission scenario will require a different division of responsibility between ground teams and crews. In the general context, mission operations should be viewed as comprising both the crew and the ground control team. In the Mars mission scenario, responsibility for strategic and tactical operations will reside primarily with the ground team with the execution operations residing primarily with the crew with involvement from the ground. Crews will require new tools to allow resource scheduling and conflict resolution to implement strategies and goals set by the ground teams. Further, crews will require more sophisticated situational awareness or "battlefield management" tools to keep track of resources (robots, other crew, etc.) in the field. During execution, ground teams will focus on systems performance trending, data archiving, long range planning, and data dissemination.

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.

7. 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. Current approaches to the conduct of mission operations—whether for human or robotic missions—are insufficient to the needs of human Mars missions. 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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Biography

Andrew Mishkin has held systems engineering positions on both autonomous vehicle technology efforts and flight projects at the NASA Jet Propulsion Laboratory. He was the principal architect of the operations process for the Spirit and Opportunity rovers, and has been both a MER Mission Manager and sequencing team chief. Mr. Mishkin is the author of the book **Sojourner: An Insider's View of the Mars Pathfinder Mission**. He received B.S. and M.S. degrees in systems engineering from the University of California at Los Angeles.

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