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Lunar and Mars Exploration: The Autonomy Factor

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ABSTRACT

Long duration space flight crews have relied heavily on almost constant communication with ground control mission support. Ground control teams provide vehicle status and system monitoring, while offering near real time support for specific tasks, emergencies, and ensuring crew health and well being. With extended exploration goals to lunar and Mars outposts, real time communication with ground control teams and the ground's ability to conduct mission monitoring will be very limited compared to the resources provided to current International Space Station (ISS) crews. An operational shift toward more autonomy and a heavier reliance on the crew to monitor their vehicle and operations will be required for these future missions. NASA's future exploration endeavors and the subsequent increased autonomy will require a shift in crew skill composition, i.e. engineer, doctor, mission specialist etc. and lead to new training challenges and mission scenarios. Specifically, operational and design changes will be necessary in many areas including: Habitat Infrastructure and Support Systems, Crew Composition, Training, Procedures and Mission Planning. This paper will specifically address how to apply ISS lessons learned to further use ISS as a test bed to address decreased amounts of ground support to achieve full autonomous operations for lunar and Mars missions. Understanding these lessons learned and applying them to current operations will help to address the future impacts of increased crew autonomy for the lunar and Mars outposts and pave the way for success in increasingly longer mission durations.

INTRODUCTION

Long duration space flight crews have relied heavily on almost constant communication with ground control mission support. Ground control teams provide vehicle status and system monitoring, while offering near real time support for specific tasks, emergencies, and to ensure crew health and well being. With extended exploration goals to lunar and Mars outposts, real time communication with Earth and the ability to conduct mission monitoring will be very limited compared to the resources provided to the current International Space Station (ISS) crews. An operational shift toward more autonomy and a heavier reliance on the crew to monitor their vehicle and operations will be required for these future missions. Communication constraints, operator limitations, system complexity, and many other factors prevent complete human control of many functions and lead to the need for automated systems (Jónsson et al., 2007). Effective implementation of autonomy practices for the upcoming lunar and Mars spaceflight missions will depend on the crews' expertise and a strong level of trust in the mission support systems. This will require a shift in crew skill composition, e.g. engineer, doctor, mission specialist etc. and lead to new training challenges and mission scenarios. Each crew is planned to be composed of a physician and paramedic-skill level. Mission tasks for lunar and Mars sorties will include surface operations such as traverse; drilling, coring, or sampling objects; and assembly of structures and habitats, etc (Jónsson et al., 2007). When ground support is unavailable, trust in the automated systems that support the crew and their missions is critical to support true autonomy. In addition to a more profound reliance on Artificial Intelligence (AI), increased automation traditionally requires operators' roles to change substantially.

Increased automation and less reliance on the human, is one of the biggest issues NASA faces for the lunar and Mars missions. AI has been used successfully to support autonomous functions, but has been limited to those functions that are known and well-defined. As exploration endeavors are expanded to new habitats and unknown territories on the lunar and Mars surface, there will be more unidentified and ill-defined operational parameters (Jónsson et al., 2007). Application and integration of greater AI elements within a space vehicle and habitat will need to focus on technologies that empower the human to be autonomously successful while providing enhanced tele-operational capabilities (Jónsson et al., 2007). However, many operational parameters for the lunar and Mars missions are currently not well-defined. New technologies will need to be evaluated for their utility and suitability to this application, specifically with regard to what will be reasonably achievable in terms of crew tasks and activities, e.g. medical care, surface operations, science activities, mission reporting, etc. Communication latencies and the distances from key communication points, such as the Earth, will require the crew to be capable of activities such as, diagnosing and treating a range of medical issues autonomously, e.g. illnesses such as flu, lacerations, trauma, toxic exposures, bone fractures etc.

Addressing crew and system needs for lunar and Mars outpost missions have already begun within the space industry, but opportunities and analog environments to address new constraints, such as autonomy, are limited. Specific aspects of on orbit operations for lunar and Mars missions, can be partially addressed by assessing lessons learned from ISS long duration space flight data. Historically, ISS has not been maintained or controlled in an autonomous manner, especially regarding crew interaction and support from ground control. However, ISS provides an optimal opportunity to evaluate new technologies to address the new operational constraints introduced with lunar and Mars exploration.

As NASA embarks on exploration of new space destinations, lunar and mars habitats, ensuring the safety of space flight crewmembers will be of paramount importance. This includes addressing all activities and their associated hazards, these hazards can lead to decreased human performance and overall well-being including: unintentional errors, injuries, or illness. Safety hazards are best addressed by designing to incorporate human limits while capitalizing on their strengths with human centered design. For the future, it will be important to focus on the activities, skills, hardware and systems that will lead to the success of the mission and facilitate autonomous operations. Specifically, operational and design changes will be necessary in many areas including: Habitat Infrastructure and Support Systems, Crew Composition, Training, Procedures and Mission Planning to preserve the safety and well-being of the crew and mission success.

METHOD

ISS human spaceflight data collection processes are continuous and the data is primarily qualitative in nature. This experiential data, unique to NASA operations for long-duration spaceflight, is collected at three different points in time during each mission: pre-flight, in-flight, and post-flight.

Pre-flight is the time before a scheduled flight/mission. During pre-flight periods, crewmembers and human factors experts often evaluate the hardware/system for its usability, maintainability, and effects on habitability. These evaluations are documented via verbal commentary, quantitative and qualitative questionnaires, photographs, or audio/video recordings.

In-flight refers to the period of time from launch until landing. During in-flight periods, personnel in the Mission Control Center (MCC) and the Mission Evaluation Room provide on-console support for all onboard functions and tasks.

Post-flight is the period of time that begins with the crew's landing back on Earth, and most crew debriefs are conducted post-flight. These debriefs provide an opportunity for NASA teams (e.g., human factors, engineering, payloads, medical operations, etc.) to obtain crew feedback to help address and collect detailed data regarding mission/Expedition issues and determine lessons learned for future missions.

The long duration spaceflight data is used to track and trend issues, and successes, over time to better address and identify areas that may need improvement and expertise that should be carried forward to the new exploration efforts.

DISCUSSION

HABITAT INFRASTRUCTURE AND SUPPORT SYSTEMS

Habitat Infrastructure

A habitats' infrastructure includes the design and configuration of the interior volume or space that encompasses the vehicle or habitat and supports all human activities. Specifically, nominal activities, translation, accessibility and anthropometric considerations (size, shape, or strength) contribute to habitability infrastructure. In regards to ISS habitability infrastructure, overall ISS topology and stowage allocations of the living and working environment have presented many issues for the crew in terms of optimized functionality. High traffic and incompatible activity centers were co-located together, which negatively impacted the crew's daily activities and perceived level of habitability while on orbit (Rando et al., 2005). The amount of stowage on ISS has surpassed the available storage allocations, causing many items to be stored in translation paths and causing obstructions. This has caused the crew extra time to access stowed items including emergency equipment and fire port locations (Baggerman et al., 2004).

Lunar and Mars

For the lunar and Mars outposts the infrastructure considerations will need to be different in terms of effects of 1/6th gravity and navigation. The crewmember will no longer be able to adapt and navigate as easily around a poorly designed habitat or obstructions in the translation path, as on ISS with 0 gravity conditions. To fully understand the effects of an inefficient internal architecture, the ISS crew activities will need to be closely analyzed at assembly complete stage and a crew of six. It will be important to utilize real time crew feedback opportunities on ISS with the larger crew sizes. Specifically, new evaluation processes should be created and instituted to take advantage of the real time monitoring ability available. These evaluation processes may include, viewing day-to-day crew interactions with the internal infrastructure via live or recorded video downlinks. Questionnaires may also be provided to capture real time comments associated with day-to-day operations within the given habitability infrastructure. Crew experience data from ISS has been primarily collected once the crew returns home and memories are not as fresh about specific aspects of daily living, such as frustrations with navigating around their habitat. In addition it will be important that lunar exploration tasks be clearly defined prior to construction of the lunar habitat, i.e. use of task analyses to identify critical operational tasks that will drive interior design and layout of the habitat's infrastructure. It will also be beneficial, once tasks are clearly defined, that crew's support "day" in the life or "week" in the life simulation evaluations in a fully functional lunar habitat mock-up. This will help identify unforeseen operation constraints at the concept design phase where it is easiest to fix.

Support Systems

Habitat support systems include the design and maintainability of all hardware and systems that support human habitation and daily activities within a vehicle or habitat. Problems with hardware and system designs can have a significant impact on the crew's health, efficiency, training, etc. For instance, if the hardware has a unique, or non-intuitive, interface the crew's health could be in jeopardy in the event of a medical emergency. Specifically, if the crew can not operate the medical equipment quickly and reliably a crewmember may not have a chance fir full recovery. This can also cause additional maintenance, planning and crew training time costs when the hardware does not capitalize on human capabilities. On ISS, hardware and system designs have proven problematic in terms of maintainability and usability. Many hardware items have required many tools to be maintained and to access and the additional time cost to crew schedules has been excessive. Historically, many human factors requirements have been waived to support cost and scheduling impacts. The inconsistent application of human factors design requirements has come at a cost of increased maintenance and less available time for activities, such as science and research. In addition, the design of habitat hardware and systems were not standardized across ISS modules, which has also caused additional crew time and frustration with nominal living and working activities (Baggerman et al., 2004)

Lunar and Mars

Many operational parameters for the lunar and Mars missions are currently not well-defined and new technologies will need to be evaluated once tasks begin to be scoped more clearly. Specifically, what will be reasonably achievable in terms of nominal crew tasks and activities, e.g. medical care, surface operations, science activities, mission reporting etc. Hardware, system and tool designs will have to be much more reliable to reduce maintenance and repairs needed, and complex interfaces minimized with more commonality designed into each operating system across the habitat. Without intuitive hardware interface designs and computer display systems, the crew will be less able to operate optimally and safely while trying to maintain a fully autonomous state during lunar and Mars missions. Increasingly compact hardware and systems will place greater demands on the crew in terms of accessibility and maintenance. Tool design and maintenance for hardware and systems will be more difficult due to their size and limited accessibility, and complexity. The designs will need to maximize human capabilities and be designed to be easily used and maintained for the crew, such that operation of the item is implicit or conveyed by design. It will be important to minimize the total number of tools required and that all hardware and systems be maintainable with a set of common tools. Iterative user design evaluations will also help to ensure that human centered design practices are clearly adhered to during developments and hardware and systems are easily maintained.

CREW COMPOSITION

Optimal crew composition and positive crew interactions are a critical component of space missions. Factors including basic capabilities, personality characteristics, levels of training, level of rank within the crew, and culture can contribute to crew interaction and mission success. All of the aforementioned factors have contributed in some manner to issues with crews between the crew and with ground support while onboard ISS, e.g. communication, task delegation, performance etc. During early ISS missions, several communication frustrations were reported between the flight crew and ground personnel. Ground operators had difficulty understanding how much time it actually took to complete tasks on orbit, which caused stress and discord between the crew and ground. The ground should have relied on the crew to do many things, and by effectively overriding some of the crew's suggestions, the ground put the crew in unsafe situations. This was primarily due to miscommunications, unrealistic demands, ineffective interpersonal communication techniques and a lack of understanding of on-orbit life (Baggerman et al., 2004). In addition, the ISS and its crew is representative of a multi-national partnership with different cultures co-existing in the same habitat, consequently accurate language translation and information conveyance has been problematic (Baggerman et al., 2004).

Lunar and Mars

As ISS nears configuration complete stage, with multiple international modules and crews, an ideal opportunity is provided for evaluation of lunar and Mars analog activities. Lunar and Mars spaceflight crews and the subsequent autonomous aspects of these missions will require a shift in crew skill composition, e.g. engineer, doctor, mission specialist etc. and will lead to new training challenges and mission scenarios. The ISS environment can be used to experiment and test lunar and Mars analogous crew roles and responsibilities. It will be important to evaluate the effectiveness of cross training techniques in providing adequate flexibility for these missions. These skills will be necessary to allow for the crews to operate in a fully autonomous manner and easily adapt to changes during the missions. Focused task analyses with subject matter experts, onboard ISS or in simulated situations in ground based mockups or analogs (e.g. lunar habitat mock-ups), should be performed to provide more realistic identification of tasks and associated performance requirements. Cognitive workload analysis and human modeling of these evaluations and resulting tasks may prove useful in identifying additional necessary tools, software, training and testing needs to support future crews. Identification of crew composition constraints and additional needs for future missions may also be accomplished via video monitoring of daily crew interactions and activities and the provision of on orbit questionnaires and debriefs to acquire the crews' own perspective of aspects of crew composition.

TRAINING

Spaceflight crewmembers are provided with intensive preflight training, which includes both general day-to-day operations training, as well as complex and specialized training related to their roles and responsibilities within the crewed missions. Training for ISS crews is provided using Part Task Training (PTT) techniques and classroom lessons, using simulators and mock ups, computer based training (CBT) or onboard training (OBT) modules. The PTT is used to train flight crew and ground support personnel on the operation of the ISS onboard systems. The PTT provides a low cost part-task training environment by off loading training lessons from the high-fidelity trainers and simulators. Training is provided in structured training flows at the operator and specialist skill levels. Operator level crewmembers are qualified for performing all user tasks for a system/operation/payload. This includes maintenance, off nominal tasks and all tasks necessary to maintain the safety of the crew and vehicle. Specialist crewmembers are qualified to perform all Operator tasks, with minimal ground support consultation, all technical maintenance tasks, all tasks specific to the Expedition, and all repair tasks and off-nominal procedures, as directed by the ground. Efforts are consistently being made to institute a more skill based training protocol versus task based methodology for ISS training. However, ISS crews continue to comment that training is still too focused on a task based approach. In addition, simulators and mock-ups utilized for training have been an issue, due to the challenges associated with simulating 0-G conditions in a 1-G environment. On orbit, the crew can fly through the volume and move around obstructions or protrusions in the translation paths. On the ground, these facilities cannot completely represent the ISS onboard environment due to 1-G constraints, such as translations paths must be walked through not "flown" through. These differences in representation of the actual environment can contribute to poor task performance and initial operational learning curves upon on orbit arrival.

Lunar and Mars

New methodologies and training strategies can be addressed in terms of cross training for planetary missions. Specifically, to help understand how autonomy constraints will affect each crew's tasks and the crew's mission objectives. Once task analyses are completed and more detail is available on nominal required operational tasks, tools for ISS implementation and evaluation can be created. Specifically, ISS crews could be asked to perform lunar or Mars specific Internal Vehicular activities (IVA) and evaluations, with standardized tools, to evaluate training requirements and expectations for future missions. In addition, ISS crewmembers could be asked to conduct simulated operational scenarios with integrated constraints, such as communication latencies, off nominal emergencies, or redirection of necessary required tasks. Related OBTs could then be administered to allow the crewmembers to evaluate the utility of certain training scenarios and products. These simulated scenarios and the increased use of and reliance on onboard training protocols will provide an understanding of the crew's ultimate training needs. The OBT and CBT evaluations may prove useful in defining what ground based training is critical to support these missions, reduce training time required on the ground, and what the crew can be expected to learn remotely. Day in the life simulations, to mimic lunar and Mars habitat topology and operations, will also prove to be beneficial, but it is critical that any mockups used must be as hi-fidelity as possible to ensure accurate evaluation of each element.

PROCEDURES

Historically on ISS, procedures have been a problem for the crew primarily due to lack of usability and overly complex and detailed information content. As focus has shifted to a reduction in the amount of paper, supplies and configuration management needed, utilizing procedures electronically has become the preferred method of operations. However, the shift from paper to electronic based procedures has highlighted human computer interaction issues associated with the format and content of the procedures and their transference to computer display systems. Specifically, electronic procedures have been difficult to use because the crew has had to spend time navigating between various menus due to overly detailed and lengthy content. This is increasingly problematic when tasks are not located close to a display and the crew has to physically navigate back and forth from the task to the display. In many cases the content of the procedures has contributed to inadvertent procedure step-skipping and poor task execution (Baggerman et al., 2004). In addition to overly detailed procedure steps, there has been excessive use of cautions and warning notations within procedures. This has contributed to the desensitization of the crew to many cautions and warnings in procedures and an unsafe situation onboard ISS, i.e. accidental procedure step skipping and inattention to critical caution and warnings. Overall, the method in which the information has been conveyed and the way the tasks were designed around the procedures, has lead to the occurrence of errors while using the procedures and during task execution (Rando et al., 2007).

Lunar and Mars

As we look ahead to a mission paradigm where there is less and less ground control and support, it will be important to focus not only on human centered design of hardware and systems but the tools that support the tasks. Specifically, focus should be placed on the development of procedures and new methods of information conveyance to assist the crew in becoming fully autonomous operators. It will be important to start utilizing the ISS to test new formats of procedures for tasks that have historically been difficult to complete, because they have required very long and complicated procedures. Particularly, the ISS will need to be used to test new formats of procedures that can be displayed on portable electronic devices, such as heads up technologies and display formats. One important aspect procedure development will be the transition from relying on the written word to convey instructions to a method that relies primarily on schematics and drawings. It will be necessary to use the ISS to evaluate how to better utilize computer software programs, e.g. speech recognition devices, to assist the operator in procedure execution, i.e. potentially remove the need for displays for some tasks that are less complex.

MISSION PLANNING

Typically, ISS mission planning is predominantly controlled by the ground; however the crew is permitted and encouraged to make inputs to their daily schedules. The ground support teams provide the crew with the tools to view mission plans, but the majority of mission planning and scheduling is done on the ground. With the exception of known communication latencies and occasional malfunctions, ISS crewmembers are rarely out of contact with the ground. However, when communication is unavailable it can greatly impact mission planning and mission objectives. In addition, contact capability with the ground has been critical for ISS crews as a habitability support, e.g. to allow for communication with family and friends. Any communication latencies caused by increased distances from key communication points, such as the Earth, will require that the crew be capable of supporting each other and be trained to carry-out activities such as, diagnosing and treating a range of medical issues autonomously (e.g. illnesses such as flu, lacerations, trauma, toxic exposures, bone fractures etc). In the event of an emergency, any impedance to quick and accurate communication and information could pose a threat to the crew returning the mission to a safe point and contribute to costly human errors.

Lunar and Mars

Independent mission planning has not been critical for ISS crews, but will be significantly important as the level of mission autonomy increases for lunar and Mars missions. Future missions will experience limited communication windows, long communication latencies, and limited bandwidth capabilities. ISS can be used to evaluate how mission planning and scheduling may be impacted. Specifically, extended communication delays can be implemented during evaluations with ISS crews to address how these constraints will impact mission objectives and planning. It will prove essential to purposefully put ISS out of communication or simulate communication latencies with the ground to study the affects of these delays on mission planning with limited ground support. NEEMO, and other analog environments, should be utilized to begin testing electronic scheduling and mission planning tools. It will also identify how communication latencies affect the ability of the crew to perform their tasks prior to ISS implementation. Interactive scheduling system prototypes should be developed and tested to create a base line for operational comparison. Specifically, the crew has the primary responsibility for maintaining the mission plan and ground just oversees as necessary and when possible. Once these tools are developed and tested in the analog environments, they can then progress to implementation to ISS. These evaluations regarding crew independent mission planning will also help to define what the crew's limitations for lunar and Mars will be in terms of remote emergencies, i.e. fire, medical care, depressurization, EVA issues etc.

CONCLUSIONS

The lessons learned from long duration space flight activities, specifically ISS, has shown that lunar and Mars exploration poses many new challenges, some of which are yet to be identified. With smaller vehicle spaces and new partial-gravity constraints, the Habitat Infrastructure and Support Systems will have to change and will not be as accommodating to poor task design as has been in a 0-g environment. With partial-gravity, adaptability of the human, in terms of complicated and inefficient layouts, will be reduced and uncomplimentary co-location of items will be exacerbated by new anthropometric concerns. Each activity center of the spacecraft or habitat will need to be configured to allow the crew to be efficient and productive. Longer duration missions, new mission objectives, and varied communication latencies, coupled with the effects of improper crew composition and poor interaction during missions may be detrimental. Crews will need to be able to adapt to mission constraints at a moments notice and interact appropriately. Crew composition via clearly defined roles and responsibilities must be determined prior to flight to allow for mission success. Training will also need to fully support new crew compositions and crew autonomy with independent scheduling practices. Procedures will be essential in supporting the new operation and training paradigms that the lunar and Mars mission introduce. Consideration will need to be given to new methods of information conveyance, while still achieving procedural-style instruction and positive task execution. Extended communication delays will require crews to plan and schedule mission tasks more independently based on communication and other mission constraints. It will be important to focus on human centered design for all aspects of the lunar and Mars missions including: Vehicle Infrastructure and Support Systems, Crew Composition, Training, Procedures, and Mission planning. Good human centered design practices will help to ensure the safety of the crew and future success in the exploration of new space territories.

REFERENCES

Baggerman, S. D., Rando, C., & Duvall, L. E. "Habitability and Human Factors: Lessons Learned in Long Duration Space Flight," *Proceedings of the American Institute of Aeronautics and Astronautics Space 2004 Conference Exhibit*, 2004

Endsley, M. Automation and Situation Awareness. R. Parasuraman, M. Mouloua (eds.), "Automation and Human Performance: Theory and Applications", Laurence Erlbaum Associates, Hillsdale, NJ: 1996.

Jónsson, A., Morris, R. A., Pedersen, L. "Autonomy in Space: Current Capabilities and Future Challenges," AI Magazine, 28(4), 27-43, Winter 2007.

Rando, C., Patel, D. G., & Duvall, L. E. "Use of Cautions and Warnings within International Space Station Procedures: When Too Much Information Becomes Risky," *Proceedings of the Human Factors and Ergonomics Society 51st Annual Meeting*, 1435-1438, 2007.