How to Keep Your Space Vehicle Alive: Maintainability Design Principles for Deep-Space Missions

Maintainability Design Principles for Deep-Space Missions

Design for maintainability is an essential component of human-systems resilience beyond Low-Earth Orbit

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On past and present human space missions, the health and state of the vehicle have been primarily managed from Earth. The International Space Station (ISS) relies on frequent resupply of spare parts and other resources from visiting vehicles to maintain the vehicle, and large orbital replacement units (ORUs) can be sent back to Earth for repair. Flight Controllers in Mission Control provide crew with real-time direction and oversight for complex task execution including preventive and corrective maintenance and extravehicular activities (EVAs). Missions beyond Low Earth Orbit (LEO) will experience resupply limitations and increasingly long communication delays and blackouts that drastically alter the mission operations paradigm. A small crew will need to detect, diagnose, and respond to critical events with only intermittent and limited real-time ground support [1]. Achieving human-systems resilience on future long-duration exploration missions (LDEMs) requires increased onboard capabilities [2]. This paper expands on a critical challenge for missions beyond LEO: onboard preventive and corrective maintenance. Maintainability is an essential component of human-systems resilience because it enables crewmembers to sustain and/or return critical systems to an operational state. We present best practices for designing for maintainability in extreme environments and explore emerging supportive technologies including in-situ manufacturing and augmented reality training tools.

CCS CONCEPTS • Human-centered computing → Human computer interaction (HCI); Interactive systems and tools; HCI design and evaluation methods.

Additional Keywords and Phrases: Space Exploration, Interplanetary Research, Aerospace, Astronaut, Autonomy, Maintainability, Maintenance

1 A NEW PARADIGM FOR MAINTAINING HUMAN-RATED SPACEFLIGHT VEHICLES

Human spaceflight missions beyond Low Earth Orbit (LEO) will experience mass constraints, resupply limitations, and communication delays that necessitate new approaches to sustainability. Maintenance will be a key challenge.

1.1 Historical maintenance paradigms

Throughout the history of human spaceflight, critical operations have been largely managed from the ground. Flight Controllers in NASA's Mission Control Center (MCC) command the International Space Station (ISS) remotely and rely on real-time telemetry data from the vehicle and communication with the crew to manage the combined state of the vehicle, mission, and crew. MCC provides crewmembers with real-time direction and oversight for complex task execution including maintenance and extravehicular activities (EVAs). When vehicle malfunctions or anomalies occur, MCC responds quickly to detect, diagnose, and address the problem, often with minimal involvement from the onboard crew.

Similarly, throughout much of NASA's history of human spaceflight, maintenance was performed on the ground, by trained mechanics at depot facilities after vehicles returned from missions. Space Shuttle vehicles required intensive maintenance by a large team of experts in between relatively short missions. In contrast, the ISS has flown for over 20 years, relying on frequent resupply of spares, tools, and consumable resources from visiting vehicles. Large orbital replacement units (ORUs) reduce the need for intricate onboard maintenance; they can be removed and replaced, sent back to the ground for repair by experts and go through extensive testing before being recertified for flight [3].

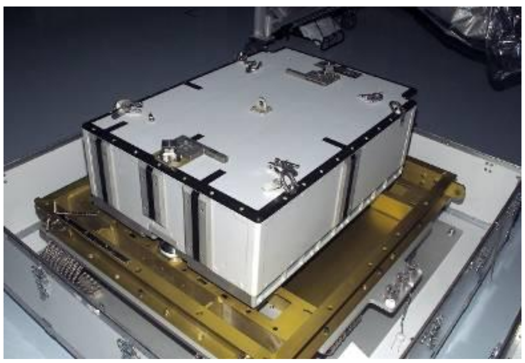

Figure 1: an example orbital replacement unit (ORU): a direct-current switching unit (DCSU).
Image courtesy of NASA. [4]

1.2 Future maintenance paradigm

Missions beyond Low Earth Orbit (LEO) will experience resupply limitations and increasingly long communication delays and blackouts as distance from Earth increases. On a mission to Mars, communication delays will range from 4 to 24 minutes one way during the mission [5], severely limiting the ground team's ability to manage safety-critical operations, respond to time-critical anomalies, and provide the oversight and verbal guidance that past missions have relied on. Like ISS, a mission to Mars will have a long mission duration of multiple years [5], increasing the probability of significant vehicle anomalies and normal wear and tear that occurs over time. But unlike the ISS, resupply of ORUs, spare parts, tools, and other resources as needed will not be possible. Consequently, a small Mars crew will likely need to respond to time-critical anomalies and perform complex preventative and corrective maintenance with an unprecedented level of onboard autonomy. This paradigm shift in mission operations necessitates new strategies for sustainability, including design for maintainability and new approaches to sparing and logistics [6]. Table 1 compares a Mars mission paradigm to past missions, revealing the mitigations of the past that will be unavailable in deep space.

Table 1: mission factors that impact maintenance.

Space Shuttle	International Space Station	Mission to Mars
- Short mission duration, LEO - Minimal onboard maintenance needed - Real-time comm - Vehicle maintained on the ground between missions by experts	- Long mission duration, LEO - Frequent resupply from visiting vehicles - Generous onboard supplies - Real-time comm - Large orbital replacement units can be shipped back to Earth for repair by experts	- Long mission duration, beyond LEO - No resupply possible - Mass constraints - Delayed comm and blackouts - Need for onboard repair to be performed

Certain Lunar mission architectures may experience 5-7 second one-way communication delays, and like Mars missions, will face limitations to onboard mass and resupply. Lunar missions will also be challenged by reduced opportunities to evacuate back to Earth in the event of an emergency. Planetary surface operations also introduce additional mission complexity and environmental factors that impact maintenance, including dust, partial gravity, and extreme fluctuations in lighting [5].

Figure 2: Artemis Lunar Surface Operations concept art (courtesy of NASA)

2 THE NEED FOR MAINTAINABLE SYSTEMS

Design for maintainability is essential to keeping the vehicle and crew alive on deep-space missions because these missions will almost certainly encounter safety-critical incidents. Maintainability is the probability and ease with which maintenance is conducted [8]; more specifically, the ability to preserve an operational system against failure or to restore a failed system to its operational state. System failures and unanticipated anomalies continue to occur in complex systems [5] and predicting the reliability of new complex one-off systems in extreme environments carries large uncertainties. When it is difficult to know what failures might occur, how do we decide which failures to prepare for? How can we make the best use of the extremely limited onboard mass available?

System designers must consider a broad range of supportability-related factors to answer these questions, including system reliability, maintainability (including repairability), redundancy, and sparing philosophy. Sparing philosophy refers to the set of decisions regarding the number and type of spare parts carried, including design decisions regarding commonality, level of repair, and other factors that determine the set of repairable items [6].

In general, deep-space vehicle systems will need to be designed for a lower level of repair (sub-ORU) than what is performed on ISS today to maximize mass-efficiency. Systems need to be designed to be diagnosable, maintainable, and repairable by a small crew with limited onboard tools in extreme environments, without the real-time expertise of MCC. The following section outlines system design strategies that contribute to design for maintainability.

3 PROCESS

To identify key themes and best practices of design for maintainability, our team conducted a literature review of government and industry standards and requirements relating to maintenance [7]. We also consulted a wide range of sources (e.g., NASA reports and guidebooks, maintainability/maintenance lessons learned from past space missions, crew comments, books and papers on maintainability and maintenance in general) and interviewed 50 Subject Matter Experts (SMEs) from NASA, DoD, and industries including automotive, oil & gas, and aviation [7]. Sections 4 and 5 present a selection of maintainability concepts that are reputable (appear in multiple trusted sources) and pertinent to the unique challenges of Missions beyond LEO.

4 PRINCIPLES OF DESIGNING FOR MAINTAINABILITY BEYOND LEO

We have characterized five key design areas which, if implemented, could vastly improve the crew's capability to successfully perform preventive maintenance and repairs with reduced ground support: standardization & interchangeability, modularity, accessibility & visibility, simplification, and diagnosability.

4.1 Standardization & Interchangeability

Standardized parts, tools, and test equipment should be used to the maximum extent possible. Lessons learned from past spaceflight missions indicate that crews often have difficulty locating the tools, parts, and test equipment needed for a given activity [7]. Utilizing common, interchangeable parts, as opposed to custom parts, increases the availability of mission-critical items and minimizes crew time spent on locating what they need. Eliminating custom or unique parts also reduces crew training demands. On missions beyond LEO when crews are constrained by mass requirements and limited resupply opportunities, standardization improves mass efficiency while still ensuring that the right parts and tools are available to the crew at the right time.

4.2 Modularity

Modularization can be used to facilitate easier repair and replacement in certain circumstances [9]. Modular design divides the system into physical and functional modules, which can be arranged to facilitate design and maintenance. A module is a part, subassembly, assembly, or component designed to be handled as a single unit. Easily replaceable modules with logical organization reduce repair time, troubleshooting, training, and engineering. Utilizing well-designed modules that are repairable at the maintenance site or a nearby workbench, instead of ORUs that need to be sent back to the ground for repair, may help the crew to perform in-mission maintenance with reduced ground support [8].

4.3 Accessibility & Visibility

Providing reasonable access to subsystems or components onboard the vehicle will allow for easier in-mission diagnosis, repair, and replacement while reducing maintenance time. The accessibility and visibility of components within a system should be prioritized by factors like mission-criticality, frequency of servicing, and part reliability. On deep space missions, *every* piece of flight hardware must be accessible and inspectable, even hardware with high reliability rates. Even if the equipment does not require *preventive* maintenance, or is not anticipated, due to reliability estimates, to require *corrective* maintenance, it may need to be accessed and opened due to unforeseen events. As sparing will be limited during extended missions without access to frequent resupply, it may also be necessary to scavenge parts from operating equipment to replace failed parts in higher priority systems.

4.4 Simplification

Designs should seek to minimize system complexity, as well as complexity of operations and maintenance. Techniques for achieving simplification include reducing the number of parts, consolidating functions, improving part access, and streamlining maintenance procedures [10]. A small crew on a deep space mission will have to perform maintenance on a variety of systems often years after they have been trained; making preventive maintenance and repairs as simple as possible is critical to successful Earth-independent missions.

4.5 Diagnosability

Deep space systems must be designed to facilitate on-orbit, crew-led diagnosis. As reliance on ground support necessarily decreases for missions beyond LEO, crew members will need to take on time-critical diagnostic activities [5]. Built-in test equipment, sufficient test point access, and access to specified sequences of troubleshooting checks can improve onboard capabilities. System simplification will also improve ease of diagnosis; system diagnosis can be simplified by minimizing the possible number of failures tied to a failure signature and by designing equipment based on the basic abilities and limitations of the crew. Critically, systems will need to provide data to the crew members at the maintenance site. Crews will need access to diagnostic sensor data, decision trees, test point readings and ranges, and test result interpretations, among other data sources, to successfully diagnose system failures. Presenting data to the crew in a way that is understandable and actionable is important.

5 EMERGING TECHNICAL SOLUTIONS

In addition to the design principles above, there are some emerging technologies that may enhance the capabilities of the onboard human-system team to maintain the vehicle if implemented effectively. These technical solutions require continued research and development, and maybe benefit from testing in analog environments.

As our 2022 SpaceCHI paper explained, when critical malfunctions (including unanticipated system interactions and automation failures) occur, human intervention and innovation is often the last resort preventing total systems failure. Human innovation will not be replaced by machines, but assistive technologies may augment human ability to monitor data, recognize patterns, and access the right information at the right time to aid a decision. [1]

5.1 In-situ Manufacturing

Reuse and recycling of onboard resources will be critical to make the most of available mass on long-duration exploration missions. In-space manufacturing technology capabilities are emerging, including three-dimensional printing of spares and recycling of materials [5]. If the technology can be developed to a point where the capability is robust, reliable, and efficient in terms of managing cost, onboard mass, quality control, and complexity, it has the potential to mitigate some of the risk introduced by mass limitations. However, 3D printing would need to be designed into the mission architecture from the outset to account for the constraints and opportunities associated with this emerging technology. NASA has initiatives in place to develop and test the materials, processes, and manufacturing technologies needed to provide an on-demand manufacturing capability for deep space exploration missions, including the In-Space Manufacturing (ISM) project and the Additive Manufacturing Facility (AMF). The ISS is being used as a testbed to assess the feasibility of using 3D printing on long-duration exploration missions [11].

5.2 Machine Learning

Deep space missions may benefit from machine learning, especially in areas with big data (e.g., telemetry) [5]. Pattern analysis over telemetry may help with early detection of anomalies, tracking subtle, unanticipated shifts over time and the interactions between sensors. Machine learning may help crewmembers conduct proactive maintenance, mitigating issues before they lead to breakdowns in operations (see, for example [12]). These tasks are possible based on today's technology, although the engineering impacts to processing and data architectures and implementations must be addressed through trade analyses. The most significant challenge, however, will be determining how to have such systems team with the crew to increase their onboard problem-solving capabilities without causing confusion, increasing workload, etc.

5.3 Sensor Technologies

Advances in sensor technology over the last decade have increased the cost and mass efficiency of using built-in sensors to provide diagnostic information [5]. Increasingly, diagnostic systems are being built into consumer-facing technologies (e.g., thermostats, computers, refrigerators, etc.) for use by end users as opposed to expert maintainers. Using similar strategies for the design on onboard data systems may help mitigate the challenge of a small crew troubleshooting without the real-time support of system experts in MCC. Significant advances have also been made by combining sensor data with machine learning (ML) algorithms to aid in detection and diagnosis. Industries including oil and gas and automotive have seen applications of ML-aided condition-monitoring to inform predictive maintenance strategies. Condition-monitoring using sensors will be an important strategy for missions beyond LEO to detect and diagnose anomalies, and to optimize preventive maintenance to make the most efficient use of spares.

5.4 AR / VR

Augmented and virtual reality (AR/VR) technologies can assist the crew in maintenance procedure execution and just-in-time training. Procedure execution tools have already been showcased on the ISS (e.g., [13]), though increased research and development in simulations is needed for these technologies to become common practice in-mission. On long-duration missions where crew will likely need to conduct maintenance activities years after their training, high-fidelity AR/VR tools can assist in crew refamiliarization with onboard systems for more efficient and successful maintenance.

6 CONCLUSIONS

Human-systems resilience refers to the adaptive capacity and extensibility of the integrated human-system to respond to surprises. Past work introduced the paradigm shift of missions beyond LEO and explored the onboard capabilities needed for a small crew to manage safety-critical operations with decreased support [1, 2].

Design for maintainability is an essential component of human-systems resilience because it enables crewmembers to keep or return critical systems to an operational state. If maintenance on a critical system is needed, but the crew cannot access the components, or does not have the right parts or tools available, they may not be able to keep the vehicle alive or themselves. Because human innovation and intervention will not be replaced by machines, well-designed human-machine teaming will be critical to enabling mission success [1].

HCI practitioners can contribute to mitigating this risk by continuing to develop supportive technologies that enhance the capabilities of the onboard human-system team to perform maintenance. Research areas including interaction with complex engineering data sets and immersive training tools are of special interest to the HCI community.

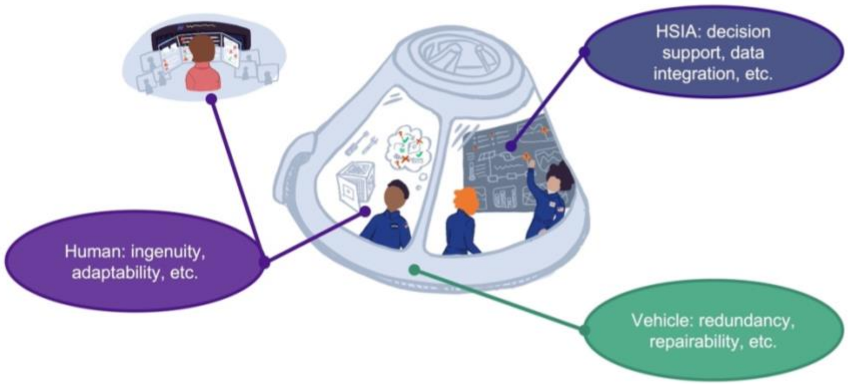

Figure 3: Concepts for human-systems resilience beyond low-earth orbit

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