Extreme Problem Solving: The New Challenges of Deep Space Exploration

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Enabling Earth-independent anomaly resolution

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On the International Space Station today, the crew has the near real-time support of a large group of system experts on the ground when dealing with problems on-board. For exploration beyond Low Earth Orbit, however, intermittent and delayed communication with ground will force small crews to take the lead in responding to vehicle anomalies. Enabling a flight crew of roughly four astronauts to perform the job that has traditionally been done by a ground crew of over 80 experts will require a fundamental rethinking of human-systems integration. Through observations of anomaly resolution processes, interviews with system experts and astronauts, and analyses of problem-solving models, we have identified the capabilities that are not currently available on-board but will be needed to enable safe exploration further away from Earth. These include increased data access, just-in-time training tools and technologies, and troubleshooting decision support. Important questions remain on *how* these technologies can be designed and implemented for increased crew autonomy. We present this critical challenge for deep space exploration to the human-computer interaction research community to reflect on the areas identified by our needs analysis and contemplate how they might be manifested as solutions.

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

1 ADDRESSING ANOMALIES IS ONE OF THE GREATEST CHALLENGES WE FACE IN DEEP SPACE

Evidence from a variety of domains, including commercial aviation and oil drilling, shows unanticipated, critical malfunctions cannot be entirely prevented in complex engineered machinery [1,2]. Despite the preparation and expertise NASA puts into every mission, spacecraft are not immune to this phenomenon. The crewed Apollo missions experienced a total of 362 anomalies across 11 missions [3-13], and our analyses show that the International Space Station (ISS) experienced 67 high priority anomalies from 2002 to 2019, 18 of which were vehicle subsystem-related incidents requiring urgent diagnosis [14]. Even with the best engineering processes in place, vehicle anomalies will continue to occur throughout the duration of a mission – we simply cannot anticipate or engineer-out every potential problem.

Why do NASA's missions continue to succeed despite these high anomaly rates? The crew has always had the near real-time support of a large group of system experts on the ground [15]. Data analysis on publicly disclosed information indicates that when an anomaly takes place on the International Space Station (ISS) today, there are over 80 system experts on 22 unique console disciplines ready to respond immediately. These experts have a combined over 600 years of system-specific, on-console experience [16]. They use telemetry and engineering data to detect and diagnose unanticipated anomalies. They also provide crew members with procedures and oversee procedure execution in real time. Often, the data used by the ground is not even available to crew members on-board the vehicle, and current training paradigms encourage crew members to follow procedures from the ground to the letter.

While NASA's processes and technologies for mission operations have evolved steadily throughout the years, they have not fundamentally changed. Apollo, Shuttle, and ISS-era missions all heavily relied on experts with access to data on the ground to facilitate real-time problem solving via communication tools.


Apollo, 1961 - 1973

ISS, 2000 - present

Figure 1: The evolution of mission control. Photographs courtesy of NASA. [Public domain], via NASA Image Gallery. (https://www.nasa.gov/multimedia/imagegallery/index.html)

All of these factors are expected to change on long-duration deep space missions, creating an unprecedented human-systems integration challenge. On a mission to Mars, the crew may experience communication delays of up to 20 minutes each way [17]. A small crew of roughly four astronauts will need to address urgent, unanticipated anomalies that have historically been handled by a team 20 times their size. While the ground will still have an important role, their input will lag behind activity, presenting a further challenge of managing asynchronous communication [18]. In the event of anomalies that require immediate response, crew will need to diagnose an exceptionally complex system in an isolated and confined environment, all while coping with the physiological and psychological effects of space [19]. The farther a mission travels from Earth, the more limited sparing, resupply, and evacuation opportunities will become [20]. Combined, these factors mean a crew of roughly four astronauts on their way to Mars will have to act with greater autonomy than any crew that precedes them.

During the Apollo 13 crisis, Flight Director Gene Kranz instructed Mission Control: “don't focus on your failures - figure out what's working, and work with that for a safe return” [21]. They famously did just that with remarkable success. Within minutes of the malfunction, ground operators were working the problem and providing crew with instructions that ultimately saved their lives. Imagine for a moment the challenge the Apollo 13 crew would have faced if it had taken 20 minutes for Mission Control to be alerted of the urgent malfunction, and another 20 minutes to get any message to the crew. Imagine if they had been on a seven-month journey away from Earth, with no resupply possible. Simply “safing” the vehicle into a stable enough state to abort would not have been an option. What tools and capabilities would the crew have needed to save the mission?

2 SPACEFLIGHT HUMAN-SYSTEMS INTEGRATION NEEDS A REVOLUTION, NOT AN EVOLUTION

This paradigm shift in mission operations entails fundamental changes in the communication, coordination, and cooperation between humans and cyber-physical systems that must occur for mission success. Our research is focused on identifying and prioritizing the on-board capabilities needed to independently detect, diagnose, and resolve anomalies. To do so, we have undertaken a variety of activities, including observing anomaly resolution teams in NASA’s Mission Evaluation Room (MER), interviewing past and present crew members and Mission Control Center (MCC) flight controllers, and analyzing domain-general problem-solving models.

Each activity revealed on-board needs for a long-duration mission, but further work is needed to realize the mechanisms by which these needs translate into tangible, human-centered technology. The primary purpose of this paper is to introduce this critical challenge of deep space exploration to the human-computer interaction research community, and to prompt reflection on how these needs might take form as interfaces and interactions on a future spacecraft.

2.1 On-board data systems

NASA’s MER anomaly response teams employ creative and critical thinking to collaboratively troubleshoot anomalies and invent adaptive and resourceful solutions. MER engineers have extensive access to historical data and resources, which they contextualize with their domain expertise and first-hand experiences. Future crews will need robust on-board data systems that support *accessing the right data at the right time*, something that MER engineers do systematically and intuitively.

- *How might the crew analyze vast quantities of engineering and telemetry data?*
- *How might we choose which data to bring to the crew’s attention?*
- *How might we visualize data in a way that make them actionable?*

2.2 Just-in-time training resources

Former crew members and flight controllers alike emphasize the importance of situational awareness for detecting and diagnosing anomalies. Our interviews with these key stakeholders have unveiled a need for future crew members to have a far deeper understanding of system performance and integration than is provided by current crew training. To successfully diagnose and address failures, crew members must be capable of diagnosis beyond specified protocols. They must understand the *downstream consequences* of their own actions across interconnected subsystems, the *time to effect* of those reactions, and the consequences of any given error. They will face the challenge of retaining a daunting amount of training information.

- *What technologies can we put in place to refresh training and keep crew members sharp?*

- *What support is needed for identifying, accessing, and accurately executing procedures?*
- *How might we make relevant tacit knowledge available and accessible?*

2.3 Troubleshooting decision support

Problem-solving models from analogous engineering domains can help characterize the skills that must be demonstrated by human-machine teams in order to increase on-board human-systems resilience [22, 23, 24]. These models tell us that in order to troubleshoot effectively, human-machine teams will need to generate hypotheses, follow domain-agnostic diagnostic best practices, and document steps taken and their corresponding outcomes.

- *How might we enable hypothesis generation for anomaly diagnosis?*
- *How might the crew follow domain-agnostic troubleshooting best practices without ground oversight?*
- *How might we enable seamless documentation without burdening the crew?*

2.3.1 The Cynefin Model

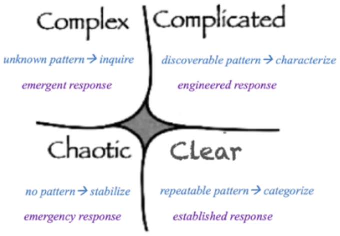

Figure 2: The Cynefin Model [22].

2.3.2 Keys to Diagnostic Success: The ABCD Model (developed based on a case study of analogous engineering domains)

Figure 3: The ABCD Model [23].

2.3.3 The Four Cornerstones of Resilience

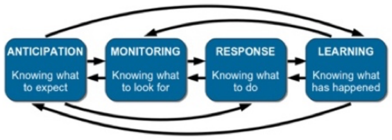

Figure 4: The Four Cornerstones of Resilience [24].

3 "MISSION CONTROL IN A BOX" IS NOT AN OPTION

With a premise of "from 80+ to 4" people immediately available for front-line anomaly response, it is appropriate to consider using intelligent technologies to compensate for human limitations. However, humans are superior adaptive problem-solvers when compared to existing technology. Intelligent systems may be very useful for tasks such as data monitoring, pattern recognition, and recommending resources, but the over 600 years of experience of 80+ Mission Control personnel cannot simply be replicated on-board by artificial intelligence.

Anomaly response may not be performed by humans or by machines alone; using the strengths of both will be essential for mission success. Just like crew members, the on-board system must be a good team member, demonstrating observability, predictability, and detectability [25]. The vehicle habitat must be designed for maintainability, repairability, understandability, and data accessibility.

Together, the human ingenuity of crew members and the computing power of thoughtfully designed systems can make for a resilient team that will take us to where no human has gone before.

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