Extreme Problem Solving II: How Can 4 Astronauts Do the Jobs of 80 Experts?

How Can 4 Astronauts Do the Jobs of 80 Experts?

It will take high-stakes human-systems teaming to enable Earth-independent anomaly resolution in deep space

Megan E. Parisi

NASA Ames Research Center, megan.e.parisi@nasa.gov

Kaitlin R. McTigue

NASA Ames Research Center, kaitlin.r.mctigue@nasa.gov

Tina Panontin

San José State University, tina.l.panontin@nasa.gov

Shu-Chieh Wu

San José State University, shu-chieh.wu@nasa.gov

Alonso H. Vera

NASA Ames Research Center, alonso.h.vera@nasa.gov

On past and present space missions, resilience is largely dependent on the problem-solving expertise of flight controllers at Mission Control on the ground. Missions to Mars will instead experience long communication delays and blackouts that require a small crew to detect, diagnose, and respond to critical events with only intermittent and limited real-time ground support. Our 2021 SpaceCHI paper "Extreme Problem Solving: The New Challenges of Deep Space Exploration" introduced the paradigm shift of increasingly Earth-independent missions, and the increasing onboard capabilities needed for safe mission operations [1]. This paper investigates how the ground team achieves resilience today to inform what will be needed to achieve human-systems resilience on future long duration exploration missions – how can a crew of four generalists achieve the same outcomes as a team of 80+ experts? An actual ISS anomaly is analyzed and then reimagined under Mars transit conditions, to reveal critical decision-points and the onboard capabilities that will be needed for successful resolution. This paper also presents criteria for what makes urgent, unanticipated events so challenging to resolve.

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 A RADICAL SHIFT IN HUMAN SPACEFLIGHT OPERATIONS

Every human spaceflight mission so far has been largely controlled from the ground. Systems experts in Mission Control Center (MCC) manage the combined state of the crew and vehicle and handle mission-critical tasks including responding to urgent vehicle anomalies. Missions to the International Space Station (ISS) depend on 24/7 support from 80+ experts in MCC and frequent resupply of materials from visiting vehicles [1]; evacuation can be achieved in a matter of hours. In contrast, future long-duration exploration missions (LDEMs) to Mars will experience limited and delayed communication with Earth, limited sparing and resupply, and almost no opportunity to evacuate back to Earth in the event of a major system failure. A small crew of just four astronauts will need to act with greater autonomy than any past crew. They must be able to detect, diagnose, and adequately respond to urgent events to achieve the same outcomes as a team of 80+ experts—a radical shift in human spaceflight operations.

2 HUMAN-SYSTEMS RESILIENCE: WHAT WE KNOW

Unanticipated anomalies continue to occur in complex systems, from oil rigs to self-driving cars to spaceflight vehicles; ultimately these events cannot be completely "engineered out" [2]. When critical malfunctions (including unanticipated system interactions and automation failures) occur, human intervention and invention is often the last resort preventing total systems failure. On NASA missions, much of the resilience resides in the ground team's systems expertise, teamwork, access to data and analytical resources, intuitive pattern recognition, and creative problem-solving abilities. As NASA shifts from having 80+ experts available for immediate 24/7 response to just four crew members, it becomes more important than ever to use the respective strengths of humans and machines. 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. Supporting and amplifying the adaptive capacity and extensibility of the integrated human-system to manage complex operations and respond to surprises will be vital to the success of future, Earth-independent mission operations.

2.1 How the Ground Team Achieves Resilience Today

To analyze how a human-machine team onboard the vehicle can successfully address anomalies during LDEMs, we first must assess the tasks the ground team currently performs during unanticipated, safety-critical events. The features of these tasks are then characterized to examine what future technologies can help address. To do so, we created a timeline of resolution activities for the 2013 ISS Cooling Loop A Anomaly, using Mission Evaluation Room (MER) meeting documents, analyses, and publicly available articles [3]. Only publicly available anomaly details are presented here.

2.2 Cooling Loop A Anomaly: Actual Events

On December 11, 2013 on the ISS, the pump that circulates fluid through Cooling Loop A automatically shut down when the loop became too cold to operate safely (see Appendix A1). Suddenly, roughly half of the equipment on the ISS was at risk of overheating. As soon as alarms sounded, the flight controller responsible for the ISS Thermal Control System (TCS) began assessing the conditions surrounding the shutdown, as other controllers across MCC started analyzing possible, future impacts to their systems. Crew members were notified of the activities and told to proceed with nominal operations. Minutes into the failure, MCC started time-constrained procedures to recover the pump operation. Simultaneously, ground teams worked to determine which critical systems needed to be moved to contingency cooling and which could be safely powered down ("load shedding"). Half an hour into the incident, the ground realized the loop was still colder than expected, despite commands to the flow control valve (FCV) to fully bypass cooling. While MCC began manual troubleshooting for the FCV, the MER started reviewing FCV historical and manufacturing data, data available only on the ground. Over the next several days, the team continued characterizing the failure and many commanded-from-the-ground work-arounds were attempted, but ultimately an EVA was required to remove and replace the pump module.

3 ACHIEVING RESILIENCE ON FUTURE LONG DURATION EXPLORATION MISSIONS

3.1 Cooling Loop A Anomaly: Reimagined During Mars Transit

After creating a timeline of resolution activities as they occurred, we mapped the timeline onto Mars transit conditions, shifting immediate response, time-critical task execution, and vehicle commanding to the crew (see Appendix A2). The ground will remain a vital part of anomaly resolution processes even with a 20-minute delay, but here, we are presenting moments where the crew could not wait for ground intervention. At each critical point presented below, a wrong step by the crew could lead to unsuccessful resolution and Loss of Crew (LOC) or Loss of Mission (LOM) consequences.

3.1.1 Detection

Sustained data monitoring can be an onerous task for humans. In MCC, 80+ experts across 22 distinct console disciplines monitor individual systems 24/7 over three shifts. In the first 30 minutes of the anomaly, the Mars crew would need to parse 30+ alarms from multiple vehicle systems and rapidly interpret what has failed. They must gather and parse sensor data from all the equipment on the cooling loop to triage the systems by criticality. Failing to recognize above-normal equipment heat levels due to the cooling pump fault, could cause critical systems to overheat and fail before the ground has time to receive notice and warn the crew. Sensor fusion, data integration, and machine intelligence for detecting notable divergences in telemetry are some of the technologies needed to support the crew in detecting urgent problems.

3.1.2 Diagnosis

When an unanticipated anomaly occurs, the causal relationships of the problem are not immediately understood. MCC and MER engineers use their system expertise to analyze functional behavior, and their experience and intuition to contextualize the problem, uncover patterns, and form and test hypotheses. In Mars transit, the ground would not "command in the blind" to perform the manual troubleshooting activities to characterize the Flow Control Valve (FCV) problem; they would not alter the vehicle state based on stale data and without immediate feedback. The crew must investigate the problem and correctly isolate the problem to the FCV. If the crew does not recognize that the FVC is jammed open (despite being commanded to a full bypass) they may believe that the loop is in a safe state when it is actually circulating dangerously cold fluid that could freeze the heat exchanger, resulting in a disastrous ammonia leak. To make sense of why the loop is too cold, the crew needs engineering analyses and functional descriptions to understand loop behavior and diagnostic aids such as data visualization and AR/VR to isolate the fault.

3.1.3 Intervention

When complex systems fail in unexpected ways, there is no predetermined course of action with which to respond. The crew must evaluate the competing threats of equipment overheating (pump is off, loop too hot) and the pump freezing (pump is on, loop too cold) and quickly take action to prevent adverse outcomes. The crew must begin the pump recovery procedure almost immediately to return cooling to critical systems, and simultaneously begin triaging equipment and shedding heat loads, all without waiting on instruction from ground. Appendix A2 depicts an optimistic timeline of the first two critical hours of the anomaly: the crew successfully detects the anomaly, isolates the problem to the FCV, and completes the pump recovery procedure in time to prevent adverse outcomes.

In addition to making the right intervention decision (choosing what actions to take) the crew also faces the challenge of executing complex tasks (doing those actions) without real-time support. This anomaly eventually required an EVA to replace the pump module. Historically, execution of complex procedures and EVAs has been guided by ground operators via constant verbal communication. Augmented reality and virtual reality (AR/VR) should be investigated as a support aid for complex mission operations.

4 KEY ANOMALY CHARACTERISTICS

Analyzing this event points to the characteristics that make problem solving so difficult during unanticipated, safety-critical anomalies. First, there is *no perfect information* during initial stages. Sensors may not be optimally placed, and information needs to be gathered to even begin considering hypotheses. Even as information is gathered, *causal relationships are not immediately understood*. Time and expertise are needed to create hypotheses that explain the data, as the MER did during the cooling loop anomaly. These events are also *time pressured*. Teams may need to complete individual anomaly resolution elements within a tight timeframe (e.g., starting the pump recovery procedure within the first hour) to gain control and understanding; they must also work quickly to prevent disastrous cascading effects or common cause failures in other systems. Lastly, space environments are *resource limited*. Engineers build redundancy into critical systems, but even this redundancy is limited. During the entirety of the Cooling Loop anomaly, the spacecraft was one failure away (i.e., a failure in Cooling Loop B) from losing all cooling. Spare parts are onboard the vehicle for anomaly intervention, but environmental constraints limit the number and type of spares available.

These characteristics are exacerbated on a Mars mission when 80+ experts cannot intervene in real-time. A Mars crew will need to perform time-pressured anomaly detection, diagnosis, and intervention activities with imperfect information, hidden causal relationships, and limited resources all without immediate ground support.

5 CONCLUSION

Human-centered technologies will be crucial to future LDEM success, but technology development needs to be driven by the key characteristics identified here: imperfect information, lack of understanding of causal relationships, time pressure, and limited resources. We must develop simulation scenarios that incorporate these characteristics, so future technologies can be assessed in this vital context.

As we move from 80+ experts on the ground to four crew members onboard the vehicle for immediate anomaly response, we will need to prepare a resilient onboard team that uses the respective strengths of humans and machines to resolve unanticipated, safety-critical anomalies. Because human innovation and intervention will not be replaced by machines, well-designed human-machine teaming is critical to enabling mission success.

REFERENCES

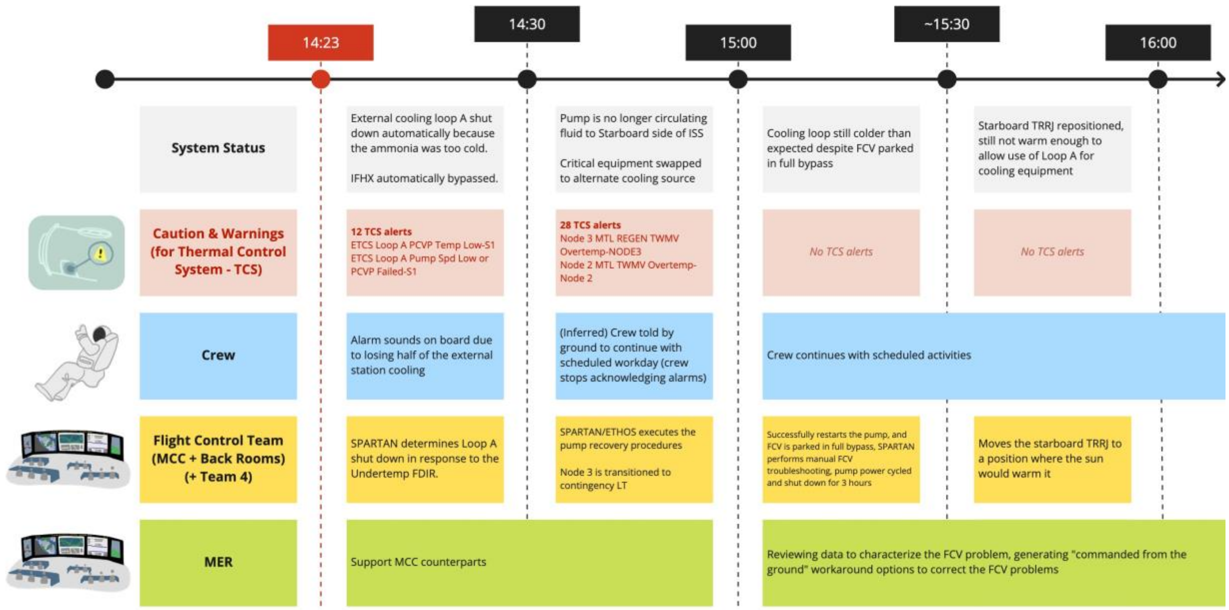
[1] Katie McTigue, Megan Parisi, Tina Panontin, Shu-Chieh Wu, and Alonso Vera. 2021. Extreme problem solving: the new challenges of deep space exploration. In Proceedings of the SpaceCHI: Human-Computer Interaction for Space Exploration (CHI '21) . May 2021.

[2] 2021. *Human-system integration architecture needs analysis: on-board anomaly resolution during autonomous operations.* Human Research Program Technical Report. NASA Ames Research Center, Moffett Field, CA.

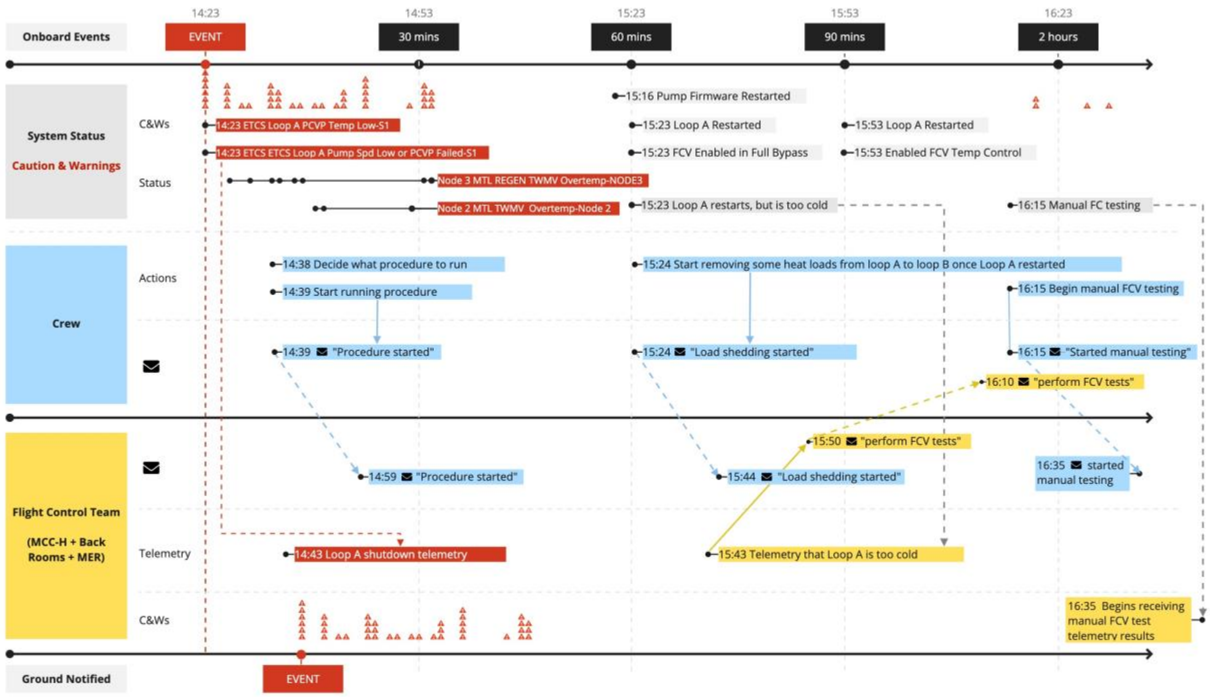
[3] Robert Dempsey (Ed.). 2018. *The International Space Station: Operating an Outpost in the New Frontier.* Retrieved from https://www.nasa.gov/feature/new-nasa-ebook-offers-inside-look-at-space-station-flightcontrollers

A APPENDICES

A.1 Cooling Loop A Anomaly Timeline: Actual Events (AppendixA1)



A.2 Cooling Loop A Anomaly Timeline Reimagined During Mars Transit (AppendixA2)



A.3 Level of Mission Control Expertise Supporting ISS Missions (AppendixA3)