Information Systems for Crew-Led Operations Beyond Low-Earth Orbit

Can we design data systems that guide crewmembers to think like expert problem solvers?

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Problem Statement

Historically, the monitoring and management of spacecraft health and status has been primarily managed from Mission Control Center (MCC) on Earth (Valinia, 2022). Programs such as Apollo, the Space Shuttle, and the International Space Station (ISS) have relied on a safety infrastructure of ground-based experts with access to real-time telemetry data, broad and deep systems expertise, and powerful analytical and computing capabilities. The ground team monitors and manages the vehicle's health in real-time and quickly responds to emergencies and system failures. Ground operators also provide real-time oversight and guidance to flight crewmembers, especially during complex procedure execution and high-risk activities like extra-vehicular activities (EVAs).

This operational paradigm, in place for over 60 years, faces challenges with future long duration exploration missions beyond low Earth orbit (LEO). Crewed lunar and deep-space missions will encounter communication latencies that prohibit real-time operational and medical support. Additionally, these missions will have infrequent resupply opportunities and a diminished capacity to evacuate or rescue crewmembers. Consequently, astronauts will need to operate more autonomously, adeptly managing the vehicle's state, responding to time-critical events, and executing complex procedures, without the safety net of real-time support on Earth.

What types of problems do crew need to be prepared to solve on board beyond LEO?

Time-critical Events Requiring Diagnosis to Determine Appropriate Action

During a Mars mission, anticipated communication delays between the crew and ground support are expected to range between 3 to 22 minutes one-way (Valinia, 2022). This significant lapse in real-time support necessitates that crewmembers onboard must be capable of detecting and diagnosing vehicle problems, identifying the times-to-effect of the faults' impacts, and responding in time to prevent irreversible damage to the critical systems that keep both the crew and vehicle alive. While the ground team will still play a strategic role in fault analysis and devising workaround options, the crew cannot risk waiting over 40 minutes for their instructions.

Our research into historical anomalies encountered during Apollo and ISS missions has revealed key characteristics that make unanticipated, time-critical anomalies particularly difficult to resolve (Panontin, McTigue, Parisi, & Wu, 2023). Table 1 outlines signature traits of the types of anomalous events that pose the most significant challenges for future crews. This list demonstrates *why* problem-solving is such a key skill, provides insight into *how* crews will need to approach problems and identifies *what* information they need in their mental models to support decisions.

Signatures of the types of anomalous events that pose the greatest challenge to future crews	
Impact to a critical system with the following characteristics:	
Causal relationships are not immediately understood • Competing alarms across systems – challenge of isolating the initiation • Specific expertise required; challenge of "from 80+ people to 4" working the problem • Complexity of system and of anomaly • Challenge of safely perturbing the system to gain understanding of cause and effect • Procedures with unexpected outcomes	Novel intervention required • Creativity to generate workaround options • Systems thinking to perform risk assessments • Rapid synthesis and decision-making • Resource limited environment, limited redundancy, sparing, etc.
Imperfect information during initial stages • Sensors data that may be incorrect or incomplete • Sensors that do not cover all parts of the system • Historical data may be limited or unavailable • Challenge to parse out relevant data	Time pressure • Short time-to-effect (to prevent adverse outcomes) • Time pressure on execution/completion of procedure • Competing priorities (e.g., inattention to other critical operations) • Simultaneous efforts required (safing, investigating, downstream impact)

Table 1: Off-Nominal Events Criteria

The anomalous events described in Table 1 are *unanticipated*, meaning that there is no prepared response in place such as there are with emergency events like fires. In these scenarios, responders may need to consult various procedures and data sources to determine the best course of action. Initially, the source of the fault is *unknown,* requiring diagnosis to identify the causal relationships behind the fault. Responders must rely on their mental models of the system, supported by onboard systems that assist them to access the right data at the right time. These events are *urgent*, due to their potential to impact critical systems essential for the survival of both the crew and the vehicle.

Data Challenges Beyond Low-Earth Orbit

A key challenge for a small, Earth independent crew is managing the overwhelming volume of data necessary for executing procedures and responding to anomalies. As problem-solving responsibilities shift to onboard crewmembers for missions beyond LEO, mere access to this wealth of information is insufficient. It must be compiled, refined, and presented appropriately to support a small crew with far less attention, time, and expertise. This challenge is further exacerbated by the relatively underpowered computing capabilities available to crews in space, which, designed to endure radiation and other environmental hazards, often lags behind their terrestrial counterparts by years or even decades. For instance, the Space Shuttle, originally equipped with CRT displays from its design phase in the early 1970s and first launch in 1981, did not receive any major updates or new displays until 1998. This update followed the completion of the Cockpit Avionics Upgrade (CAU), aimed at easing the maintenance of outdated technology and modernizing the U.S. Space Shuttle orbiter fleet (McCandless, 2005). Crewmembers in space must also contend with a significant limitation in terms of display space. Unlike ground-based operators who can utilize multiple large displays, crewmembers must make do with resources more akin to a single laptop display. This contrast in visual real estate further complicates the efficient monitoring and management of spacecraft operations, demanding innovative solutions to present critical information in a clear, concise, and accessible manner.

Research to Inform Design Requirements

Our research into historical anomalies revealed characteristics that make anomalies particularly difficult to resolve, including imperfect sensor data, complex causal relationships, and limited intervention options (Panontin, McTigue, Parisi, & Wu, 2023). For missions extending beyond LEO, onboard systems need capabilities that support the crew's ability to engage in creative and critical problem solving to overcome those challenges.

Building upon our previous work, this paper introduces new insights into the methods that expert problem solvers use and discusses how these best practices can be distilled into systems that support problem solvers with less system knowledge. Through a comprehensive literature review and interviews with expert problem solvers from NASA and analogous domains, we present preliminary recommendations for the organization and integration of information to facilitate efficient problem-solving processes. We also present a case study of anomaly response on the International Space Station (ISS), highlighting key decision points where an enhanced onboard data system could significantly augment the crews' mental model of the vehicle.

How Do Experts in Mission Control Manage Information Today?

Expert Problem Solvers of NASA's Mission Control Center (MCC)

In today's Mission Control Center (MCC) for ISS operations, 15-20 flight controllers work around the clock in three shifts, continuously monitoring real-time data for their specific subsystems. They are supplemented by Back Room and Mission Evaluation Room (MER) engineers. Together, they detect failures, assess their impact, devise troubleshooting strategies, identify workarounds, and oversee procedure execution. This comprehensive responsibility requires a deep familiarity with a vast array of engineering and procedure information, as well as system build, test, and configuration documentation.

Flight Controllers are each system experts who specialize in one vehicle subsystem. Before earning their certification, ISS Flight Controllers are trained for an average of two years through a series of courses and simulations. During this period, Flight Directors evaluate them on a set of core skills including their ability to recognize and respond to problems (Dempsey, 2017). This training builds upon their prior education and experience, typically in aerospace engineering. Our past research estimates the average ISS Flight Controller on console has 12 years of relevant experience, including over 7 years of on-console experience managing their system of expertise (Vera, 2021). This experience enables controllers to rapidly make connections while parsing vast quantities of information, intuitively identify information that is relevant to the situation, and contextualize that information within the broader picture of the vehicle state. Flight Controllers develop an advanced mental model of their system, allowing them to make informed decisions swiftly and effectively resolve issues.

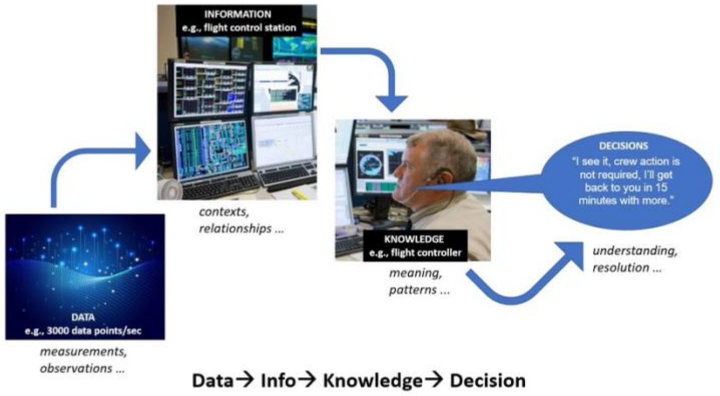


Figure 1: Notional Depiction of Information Processing by a Flight Controller

Problem-Solving Model

Flight Controllers are trained to respond to faults using the “failure, impact, workaround” (FIW) response (O'Hagan & Crocker, 2006). This involves pinpointing the failure, assessing the downstream system-wide impacts, and generating workaround options that will mitigate those impacts before further damage can occur (Schmidt, et al., 2011).

The Problem-solving Model in Figure 2 synthesizes the Flight Control approach with similar models from industry and literature (Brooks, 2022) (Federal Aviation Administration, 2023), and breaks it down by the critical questions problem solvers in complex domains must answer to make a decision. Table 2 provides examples of the types of information they analyze to answer these questions.

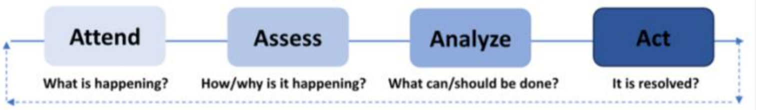


Figure 2: Flight Controller Problem-solving Model

What is happening?	**How/why is it happening?**	**What can/should be done?**	**It is resolved?**
• Detection/ recognition • Configuration/ system status • Consistency of observations • Confirmation	• Anomaly description • Pattern recognition • Timeline of events • Impacts, risks, hazards, system capabilities • Urgency/priority needed to resolve issue • Identify differences and changes (e.g., config) • Probable (proximate) causes • Rationale	• Objectives, outcomes • Options • Assumptions • Tests • Prioritization, decision • Dissenting opinions • Plan	• Effects, feedback • Triggers • Contingencies • Verification • Ops, rule changes

Table 2: Problem-solving Model broken down into critical questions and the data used to answer them

How do expert problem-solvers construct and access their mental models of complex systems?

Mental Models

Mental models are representations of specific domains or situations that support understanding, reasoning, and prediction (Gentner, 2001). To uncover the knowledge and skills necessary for successful problem solving, we explored mental models through interviews with expert problem solvers operating under time-constrained contexts in various safety-critical sectors, including space exploration, healthcare, and nuclear power. Additionally, we conducted a literature review on information management strategies across different domains and examined artifacts pertaining to training and operations, including interfaces.

Our analysis reveals key themes common across these safety-critical domains, including common best practices that experts employ to construct and manipulate their mental models, organize and integrate information, and support decision making:

Construction and manipulation of the mental models:

- Developing personalized **heuristics** through past experiences that guide their processes.
- Learning to recognize patterns in advance to be **proactive** rather than reactive.
- Investing effort in **background work**, memorizing the details of the domain and environment.
- Using the **apprentice model** to learn: assisting experts and observing them in operations.
- Learning from **mistakes** in simulations, guided by feedback and **iterative evaluation** by experts.
- Practicing hands-on troubleshooting to build an understanding of **systems integration.**

> *"First, you're building a mental model of how the system works, and then you're building a mental model of how the system works with other pieces. And then you're building a mental model of how do I coordinate and choose what to do when things get complex?"* - ISS Flight Control Trainer

Processes to organize and integrate information:

- Ensuring important "**rules**" are drilled into the culture through repetition (verbal and written) and memorable slogans (e.g., "train like you fly," "Crew safety, vehicle safety, mission success").
- Presenting information **hierarchically**: starting from big picture, and then **drilling down** into detail.
- Documenting **rationale for actions**: reminders of *why* an action is necessary, and the consequences of an action or inaction.
- Promoting shared **situational awareness** of team: shared workload, checking for mistakes.

> *"So ... the navigation is about how can you keep [launch controllers] in context of the problem at hand while allowing them to explore the data that's hanging off of each of these elements during that exploration."* - Artemis Data System Engineers

Approaches that are used to support decision making:

- Using **alerting capabilities** and analytics to help with problems before they grow.

- Using **tools** to support decision-making based on past experiences.
- Using **benchmarks** and industry best practices to give a good foundation for where to start (goals).

Case Study: ISS Training Simulation Fault Scenario

At NASA's John Space Center, the Space Station Training Facility (SSTF) equips new Flight Controllers with the skills to become expert problem solvers by applying their core system knowledge in mission simulations. In full-scale integrated simulations, trainees from different console disciplines all work together as a Flight Control Team to respond to a series of increasingly difficult problems, which are dynamically generated by instructors.

Figure 3 outlines the sequence of events in a specific training simulation (Dempsey, 2017), highlighting the gaps in the mental models of the flight-controllers-in-training that ultimately led to adverse outcomes. This simulation, like most training simulations, introduced multiple failures across different systems with interrelated impacts. The initial conditions (starting point) of the simulation included a failure of one of two redundant Internal Audio Controllers (IACs), a transient failure of External Thermal Control System (ETCS) Loop B which shut the pump down, and a configuration of the Lab 1 Internal Thermal Control System (ITCS) to "single loop mode". This mode joins two segments, with either the low-temperature loop (LTL) or moderate-temperature loop (MTL) pumps circulating fluid throughout the whole system.

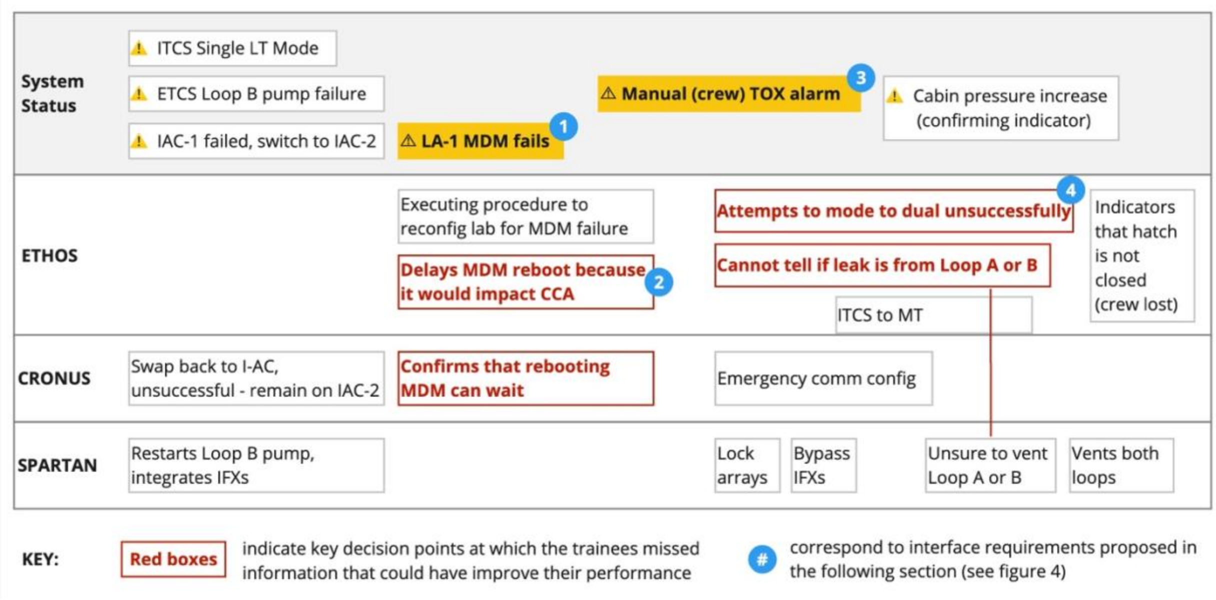


Figure 3: The Multiplexer/DeMultiplexer (MDM) failure scenario

The configuration of the ITCS presented a significant roadblock to the inexperienced ETHOS flight controller when the Lab 1 Multiplexer/DeMultiplexer (MDM)—responsible for transmitting sensor data—failed, cutting off data transmission to the Primary Command and Control MDM. This failure left the Flight Control Team effectively blind to the performance of the LTL, which provides cooling to critical internal systems within the Laboratory Module. The trainees did not grasp the significance of the failure and opted to delay rebooting the MDM, leaving the system in a vulnerable state in which a toxic atmosphere would be undetectable. To drive home the criticality of this error, the instructors then simulated an ammonia leak on board. The trainees, hindered by the MDM failure, were both unable to see any data characterizing the leak and unable to isolate it to a specific loop due to the configuration of the ITCS. They had no choice but to vent both loops to reduce the ammonia exposure, which would damage the vehicle irreversibly; and the crew's survival remained unlikely.

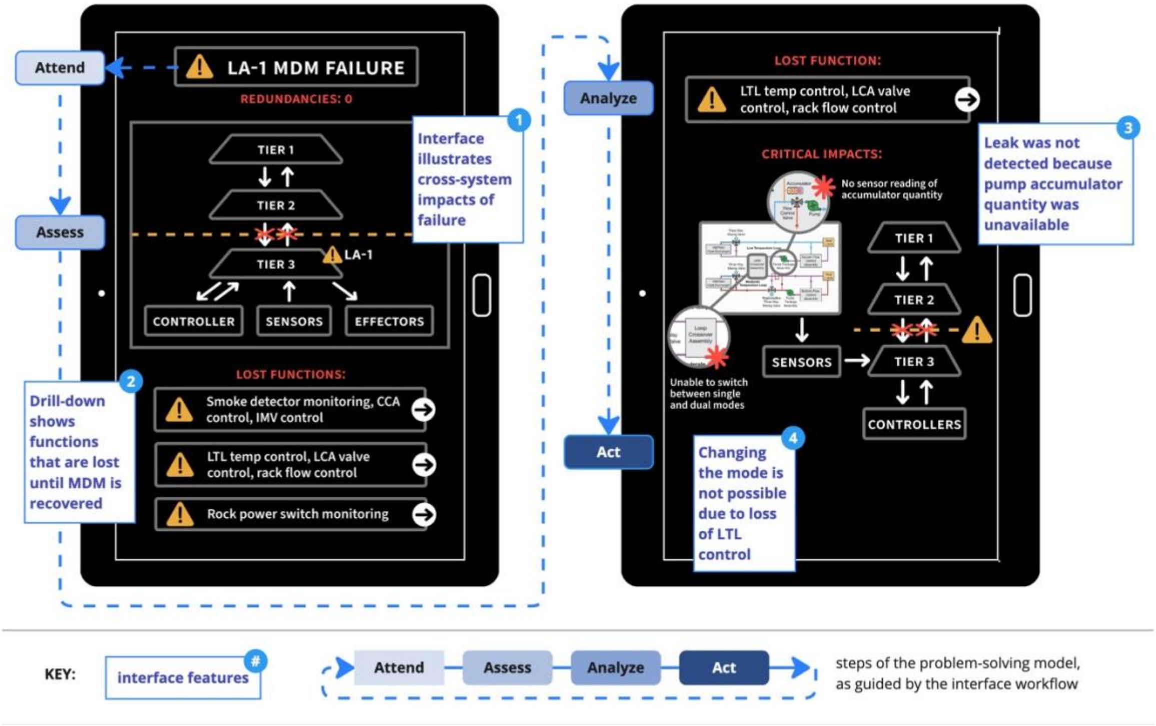
How can we enable crew members to think like expert problem solvers?

Lessons Learned from ISS Training

The training simulation scenario in the previous section, despite its extreme nature in terms of the number of failures within a short time frame, nonetheless acts as useful case study highlighting the challenge novices face when responding to problems in complex systems. The ETHOS controller-in-training lacked an adequate mental model of the system to understand the downstream impacts of the MDM failure and the extent to which the ITCS configuration limited their intervention options. With additional decision support, the team might have given priority to restoring the MDM over other less critical systems and prepared for the "next worst failure"—a toxic leak—by proactively reconfiguring the ITCS to dual mode.

Designing to Augment the Abilities of Novices

The notional designs presented in Figure 4 illustrate how data systems can be engineered to support crewmembers in bridging the gaps in their mental models of unfamiliar systems. These designs outline the consequences of the MDM failure mentioned earlier, highlighting the critical functions that are lost, the interactions among various system components, and the downstream impacts. The design enhances high-level situational awareness of the affected system and nudges the user to further analyze the impacts of the lost functions and their implications for available intervention strategies. This flow mimics the problem-solving model used by Flight Controllers and other experts (Figure 2).



1 Interface illustrates cross-system impacts of failure

2 Drill-down shows functions that are lost until MDM is recovered

3 Leak was not detected because pump accumulator quantity was unavailable

4 Changing the mode is not possible due to loss of LTL control

Figure 4: Notional designs to support problem solving by crewmembers. The blue numbers correspond to events of the scenario illustrated in Figure 3, demonstrating how the data system might provide relevant information to improve users' understanding of the situation.

Conclusions

Drawing on our analysis of problem-solving skills across both expert and novice levels, we propose preliminary requirements for designing data representations to support crew decision making beyond LEO:

1. Fostering a Systems-Thinking-Oriented Mental Model: The interface should provide high-level situational awareness of the vehicle state and current configuration, with the ability to drill into further detail and visualize the relationships between subsystems. Novices, who may not intuitively understand the ways that subsystems connect, can become blindsided by the downstream effects of certain events, including the repercussions of their actions. By illustrating these relationships and the physical locations of components within the vehicle, the interface promotes systems thinking. This method of progressively drilling into further detail also makes efficient use of the limited screen space available onboard, preventing novice users from becoming overwhelmed by too much information at once.

2. Prioritizing Information by Risk Level: Upon detecting a fault, the interface should display information to help users assess the impacts of the event, including the loss of functionalities, any available redundancies, and the times-to-effect of those impacts. This enables novice problem solvers to rapidly assess risks and prioritize which impacts to address first, steering clear of less pertinent details. The system should organize and integrate this information to highlight the most critical impacts initially, facilitating proactive planning for addressing the next worst failure based on the current and projected states.

3. Enhancing Decision Support and Rationale: The system's fault management workflow should adopt the "attend, assess, analyze, act" problem-solving model used by experts, by providing timely access to relevant data and resources necessary at each step. The data system should have alerting capabilities and analytics to proactively anticipate and detect problems before they grow. The system should incorporate benchmarks and historical thresholds to aid users in assessing deviations from standard operations and analyze their intervention options based on how experts have responded in similar situations in the past. The system should provide recommendations for specific actions, recommend relevant resources (e.g., schematics, procedures, engineering data), and always provide supporting documentation to explain the rationale behind suggested actions and the consequences of both action and inaction.

The recommendations and notional designs presented in this section are exploratory and require additional testing and validation before they can be applied operationally. Laboratory and analog mission studies should be used to test the effectiveness of these data representation strategies in enhancing the problem-solving skills of novices, and further identify needs specific to missions beyond LEO. In the event of an unanticipated, urgent anomaly in deep space, intervention, and innovation by integrated human-system team on board will be the only recourse for preventing adverse mission outcomes.

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