Earth Independent Operations Development for NASA's Mars Campaign Office

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NASA's Moon to Mars Objectives lay out a strategic vision for the future of human spaceflight that culminates in crewed missions to the surface of Mars. The Mars Campaign Office (MCO) of the Moon to Mars Program is responsible for developing the technologies and capabilities necessary to support Mars missions. One such set of technologies supports a need for increased independence from Earth driven primarily by a communications delay between Earth and Mars that can reach twenty minutes or more each way. This paper lays out the initial strategy and approach for the MCO Earth-Independent Operations (EIO) portfolio and identifies areas targeted for investment between now and a human Mars missions tentatively planned for the early 2040s.

I. Introduction

NASA has established and released a set of high-level Moon to Mars Objectives for a human spaceflight campaign that focuses on crewed missions to cis-lunar space, to the lunar surface, and ultimately to Mars. These objectives are used both inside and outside the agency for both strategic and tactical planning. In addition to these strategic products, NASA has responded to Congressional directive by establishing a Moon to Mars Program Office with responsibility for implementing both lunar and Martian expeditions. In the Moon to Mars Program, the Mars Campaign Office (MCO) has principal responsibility for developing the technologies necessary to enable a Martian campaign. MCO utilizes a combination of in-house activities, collaborations with other technology development organizations in the agency (e.g., STMD), public-private partnerships, and international partnerships to mature these critical technologies. MCO technology development efforts are organized into portfolios of technology development activities in a given technological discipline (e.g., Environmental Control and Life Support systems - ECLSS). In the fall of 2023 MCO formally established Earth Independent Operations as a new technical portfolio with responsibility for ensuring that crew on a mission to Mars have the tools and information necessary to respond to on-board problems without the rapid response from a large number of ground support resources.

The speed of communications between the ground and space vehicles are limited by the technologies available. These delays are easily accommodated in earth orbit (nearly instantaneous) and in cis-lunar space (second-scale delay). Delay in communication between the Earth and a Mars transit vehicle will quickly approach 20 minutes. The portfolio of technologies in the EIO domain are intended to provide crew the decision support necessary to migrate additional tactical decision-making and anomaly response from Earth to the flight vehicle. This paper identifies prior research into this problem, describes NASA's planned approach to providing the necessary onboard capabilities, and outlines current and future development efforts.

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II. Overview of Prior Work

Fault Management and Failure Modes

Flight software for management of space systems is generally based on a systematic application of failure modes and effects analysis (FMEA). Selected failure modes are identified and controlled through automatic fault detection, isolation, and response (FDIR) capabilities [1], while others may be controlled through a combination of automatic actions and ground-managed procedures. Rigorous FMEA-based FDIR capabilities are crucial to managing complex space systems but are limited to controlling the set of failure modes and effects that were identified through the engineering design process.

As many as 40% of failure modes may go unidentified through KDP E, the transition from design into operations [2],[3],[4]. Many additional failure modes are identified quickly as the vehicle operates in the expected environment, but studies on current-day ISS indicate that unpredicted, unplanned, or ambiguous faults and failures occur on a regular basis [5].

Human Spaceflight Anomalies

Studies of human spaceflight anomalies during International Space Station (ISS) operations provide an initial estimate for the frequency of unpredicted, unplanned, or ambiguous faults that defeat onboard FDIR capabilities – termed anomalies. ISS operations experience an average of about 30 potential anomalies annually, of which 1 or 2 turn out to require rapid response to ensure crew health and preserve system performance [5] [6]. The majority of anomalies with crew survival implications are associated with Environmental Control and Life Support systems (ECLSS). In general, anomalies with crew survival implications are only anomalies once – procedures and monitors are developed to control a failure mode once identified. Procedures developed for any failure mode are tested and simulated extensively by ground controllers and engineers before adoption.

Anomaly Management in Low Earth Orbit

In current ISS operations, anomalies are managed almost exclusively by ground controllers. First-line responders sit in console positions at the Mission Control Center at Johnson Space Center (JSC) in Houston, Texas. Additional engineering and subject matter expertise is available in the Mission Evaluation Room (MER) at JSC, at the Huntsville Operations and Support Center at Marshall Space Flight Center (MSFC) in Huntsville, Alabama, and at supplier and contractor facilities across the world. Overall, over 200 personnel are either on staff or on call to immediately respond to an ISS emergency [6].

Any given flight control position for ISS may be expected to evaluate up to five concurrent monitors of data in the form of vehicle telemetry, timelines and plans, or operations documentation as well as multiple voice loops. In the MCC alone, there are approximately 100 screens of data being evaluated at any given time in order to ensure that the ground is able to identify and respond to problems or anomalies.

Figure 1: Infographic regarding ISS Anomaly Management

Impact of Communications Delay

The impact of communications delay on spaceflight operations has been studied frequently but has not consistently considered realistic delays [7][8]. As delay increases, tasks currently managed on the ground must be shifted onboard to ensure that they can be performed efficiently and with access to reliable and timely data. At a delay of 3 seconds or greater, it is expected that crew will execute any task requiring immediate feedback. At delays of 1-5 minutes, oversight and direct guidance roles will shift on-board. For time delays over 10 minutes, it is expected that crew will be responsible for the initial triage and response to onboard problems – either expected or unexpected [9][10]. In addition to the shift of responsibility to onboard crew, communications delays broadly impact crew health and well-being, and individual and team performance [11][12].

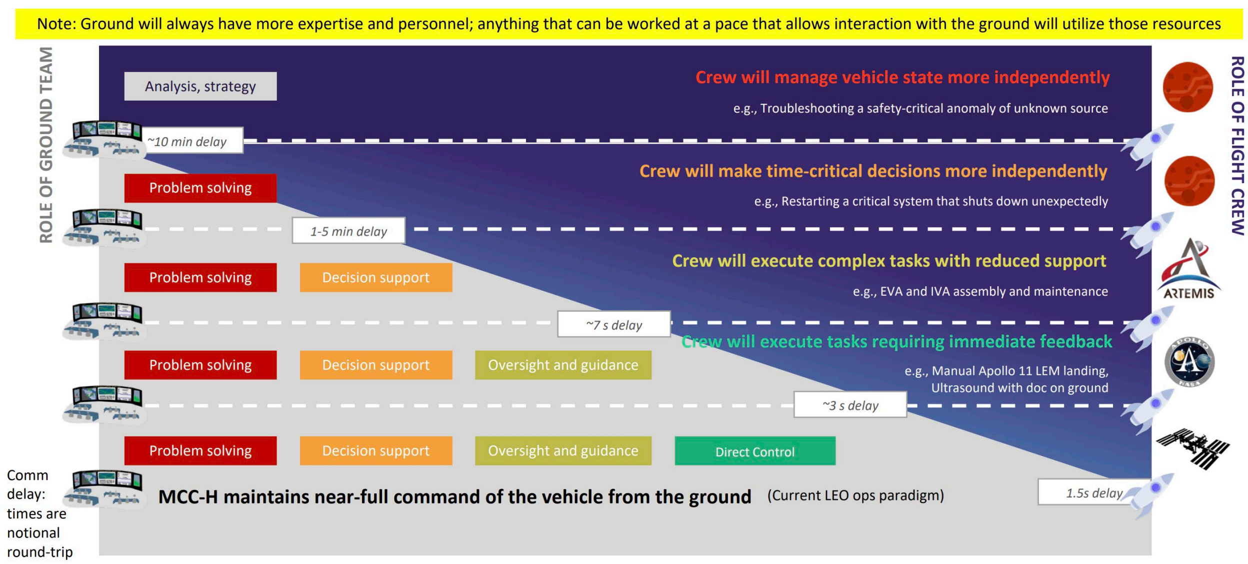

Figure 2: Infographic describing Transition of Mission Command under Time Delay

III. Approach and Development Considerations

The MCO EIO Domain sponsored a summit in the summer of 2023 to identify the necessary capabilities to implement crew decision support tools as they respond to on-board anomalies. Three products were developed as a result of the summit – a set of considerations and constraints for use in identifying and prioritizing technology investments, a logical decomposition of the technologies needed, and a set of initial work plans to describe a time-phased investment schedule based on a Mars mission in the early 2040s.

A. Considerations and Constraints

Minimum Earth Independence

The principle of "minimum Earth independence" states that any capability that can reasonably be left on the ground, will be. Ground-based capabilities will have the benefit of both heritage technologies and the full set of domain experts and engineering teams currently used in human spaceflight operations. Limiting the scope of Earth independence capabilities allows for more focused technology development and represents a measured approach to the adoption of advanced compute capabilities like artificial intelligence and machine learning.

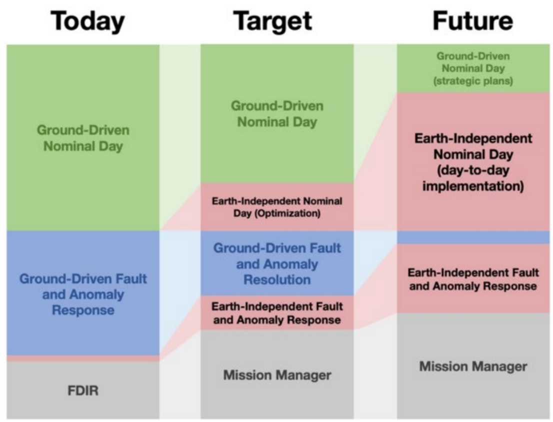

Figure 3: Infographic describing Earth Indepdendence Targets

Crew Survivability

The set of hazard controls currently utilized for human spaceflight rely heavily on real-time ground support, rapid abort, and resupply from Earth – all of which will be unavailable during a Mars mission. Without new sources of hazard mitigation, the risk to crew is likely to exceed reasonable targets. The focus of the EIO domain is to provide a source of mitigation that increases overall agency confidence that a crewed Mars mission can return safely. Once a path to the crew survival capability has been established, domain research will pivot to preventing loss of major mission objectives and then to optimizing nominal operations.

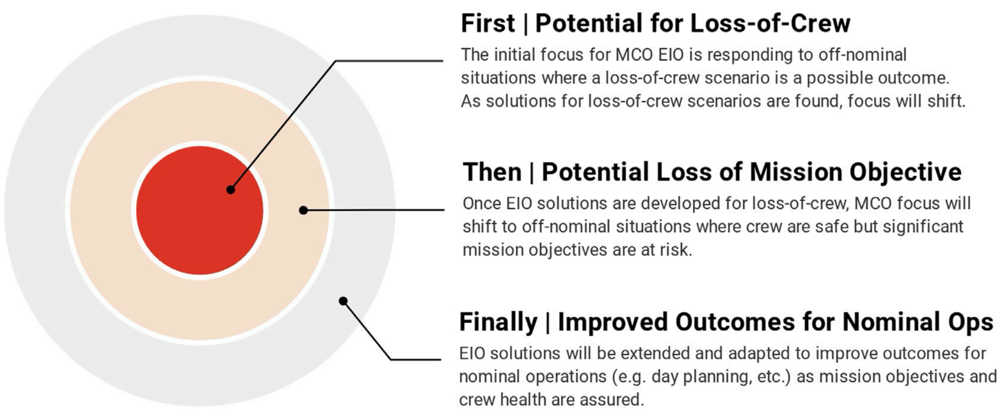

Figure 4: Infographic Describing EIO Focus Areas

Time-To-Effect

In human spaceflight operations, faults are prioritized by the speed with which the overall vehicle state is degrading. A fault with a long time to effect can be effectively managed by the ground even in the context of a communications delay, but faults with a more rapid time to effect must be handled on-board. The driving use cases for EIO technology development focus on unknown or ambiguous faults with a time-to-effect less than 8 hours. Research into ISS failure modes confirms that the majority of faults in this category stem from ECLSS systems.

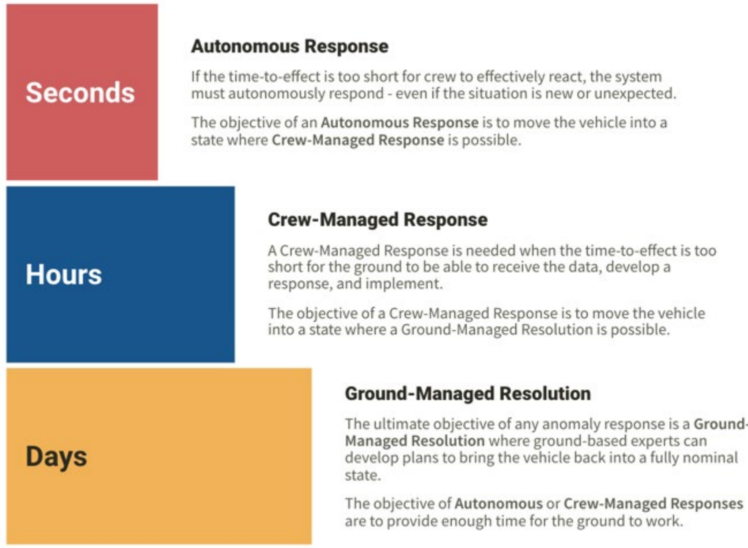

Figure 5: Infographic describing Time-To-Effect Implications for EIO

Development Timeline

Plans released in 2020 by NASA propose a crewed mission to Mars as early as 2039, and agency procedures generally require new technologies to be in an injectable state by the Preliminary Design Review (PDR) of the relevant element [13]. Current NASA estimates indicate that PDR for a 2039 Mars habitation element would occur in late 2027. As a result, EIO capabilities must be carefully scoped and prioritized to be effective.

B. Logical Decomposition of EIO Technologies

The logical decomposition of EIO needs is comprised of a number of either physical or logical hardware elements that are considered necessary to execute anomaly response. Five initial categories of technology were identified based on functional similarity (multiple technologies meeting related needs). Figure 6 below shows the current decomposition as of June 2024 and known relationships between technology categories.

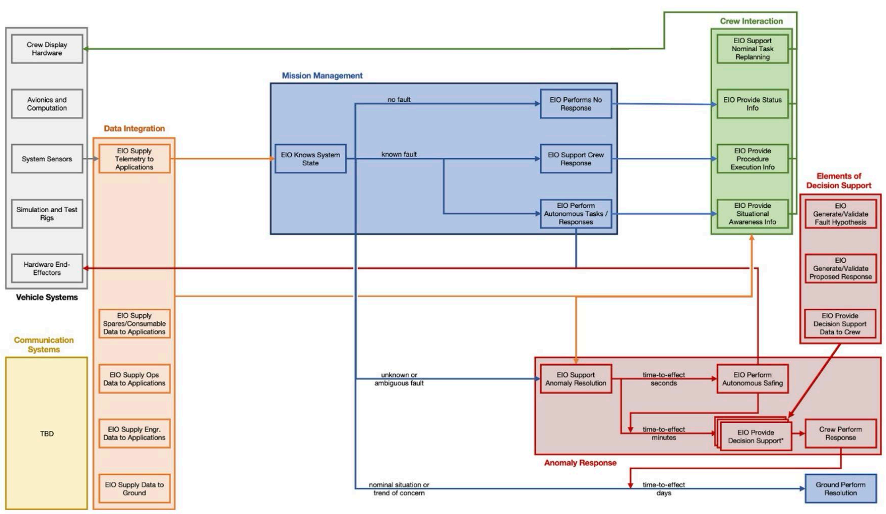

Figure 6: FFBD describing the logical decomposition of EIO needs.

1. Vehicle Systems

Vehicle Systems is a category of technology development that focuses on the physical components that must be integrated into a flight system in order to enable the various software applications to operate; additionally, it provides both hardware-in-the-loop and hybrid testbeds necessary to validate software technology concepts. There are five specific technology areas in the Vehicle Systems activity.

Avionics

Avionics technology development seeks to develop and integrate computers, data storage, data acquisition units, and other avionics hardware capable of both supporting advanced compute methods and surviving the radiation environment in deep space or Mars. Initial efforts focus on establishing the viability of the High Performance Space Computer architecture [15] and studying the necessary changes to flight software development and verification that will be required to fully utilize HPSC capabilities for human spaceflight use cases.

Sensors

Early research being performed by NASA researchers into state variance (further described in Section 4) indicates that developing machine intelligence for Mars applications will require significantly more sensor data than currently collected as well as sensor fusion capabilities that can help bridge gaps where sensors cannot be reasonably added. Sensor technology development focuses on determining what new sensor technology can be applied to the diagnosis of space system faults, how to most efficiently provide system state data to EIO applications, and how to mitigate the mass impact of additional sensors with wireless sensor technology or data transfer protocols that reduce the mass of the wiring harness.

Hardware End-Effectors

Hardware end-effectors are a potential area of future development in the event that existing controllers are inviable for Mars applications. ECLSS systems represent one bounding case for end-effectors; development of an ECLSS-focused test facility will allow for component testing and help identify any development or research work necessary to enable remote commanding of flight systems.

Crew Display Hardware

Display technologies for terrestrial or low-earth-orbit applications are not necessarily viable for deep space use cases, and potential implementation of augmented or virtual reality technologies will drive additional development. Technology development in this area focuses primarily on the development of radiation-tolerant display drivers.

Test Platforms

The Vehicle Systems activity manages test platform development for the EIO domain. The two principal test platforms currently in development are described in Section 4 below.

2. Mission Management

Mission Management encompasses the set of conventional FDIR technologies historically implemented on space vehicles. In general, these capabilities are robust and on track for a mission to Mars in the 2040s. Technology development work under this activity focuses on ensuring FDIR applications and anomaly response capabilities can integrate effectively, especially with the There are three specific development areas in the Mission Management activity.

State Determination

State determination seeks to establish whether the flight system is in a known or or unknown state and whether that state requires autonomous or crew-involved responses. In general, this is a robust capability and is not in need of significant development; Moon to Mars implementation programs (notably Gateway) are continuing to mature and extend that capability. There is a need for technology development in the related crew interaction technology area (status information) described below.

Planned Autonomous Response

Matching autonomous responses to known states is a similarly robust technology and is not targeted for significant additional technology investment at this time. There is a need for technology development in the related crew interaction technology area (situational awareness) described below.

Planned Crew-Involved Response

Matching crew-involved responses to known states is a similarly robust technology and is not targeted for significant additional technology investment at this time. There is a need for technology development in the related crew interaction technology area (procedure execution) described below.

3. Crew Interaction

Crew Interaction encompasses a number of research and development efforts on the human-computer interface, focused on ensuring that crew are able to understand vehicle status, maintain awareness of autonomous vehicle responses, and execute procedures. The scope of work covers both the data reduction and analysis tasks necessary to identify high-priority data for crew as well as the display and formatting of data onscreen in an effective way. Task replanning and adjustment applications will also be adapted from these capabilities.

Status Information

Technology development into status information display will focus primarily on data analysis and data reduction methods to dramatically reduce the amount of data that a crew member would need to consume in order to understand the current state of their vehicle. Future development work may establish recommended display methods for status information, focused on the evolving use case of "crew member as flight controller".

Situational Awareness

Technology development into situational awareness will focus on the identification and elevation of advisories or data markers to help crew understand (and if necessary). Many of the critical questions for situational awareness are shared by either status information or procedure execution and will be met by similar research and prototyping activities into performing data reduction, determining how and under what circumstances information should be elevated for crew attention, and how best to display data so that it can be consumed without the risk of oversaturation.

Procedure Execution

Technology development into situational awareness will consider various concepts of operation for performing both pre-planned procedures and procedures developed during anomaly response operations. Current state of the art relies on real-time, step-by-step task direction from ground personnel with immediate access to visual data, telemetry, and crew responses. Research and development efforts will identify the most effective replacement for those oversight and task verification roles.

Task Replanning

Given the constant effect of communications delay on nominal operations, it may be advisable to allow for nominal replanning. Research may be conducted in future by MCO on adapting existing human spaceflight applications for this purpose, and ongoing research in NASA's Human Research Program will provide initial results on task replanning and scheduling needs.

4. Anomaly Response

Anomaly Response represents the primary focus area for EIO technology development and the most critical set of capabilities in the domain for addressing crew survivability. It seeks to provide an integrated suite of software applications based on the time-to-effect of the unknown or ambiguous fault identified. For faults with a time-to-effect of seconds or single minutes, there is considered to be insufficient time to brief crew and request a decision; as a result, a limited amount of autonomous safing under uncertainty will be necessary. Autonomous safing under uncertainty is not expected to return the vehicle to a nominal state or even necessarily to a steady state, but it is expected to take the minimum actions necessary to increase the time-to-effect sufficiently to allow crew to act. For faults with a time-to-effect measured in tens of minutes, an anomaly response capability will transition primarily into an advisory mode with the intent of providing decision support to crew. Advanced compute techniques (including machine learning techniques) will generate one or more fault hypotheses for crew and will provide an *a priori* validation capability to ensure that the hypotheses provided effectively explain system behavior; crew will identify hypotheses based on system recommendations and human observation. Advanced compute techniques (potentially including generative AI) will be employed to recommend additional diagnostic and troubleshooting steps; both crew- and computer-proposed procedures will again be validated by an *a prior* simulation to advise crew on whether the proposed steps are safe. Crew will select and perform diagnostic or troubleshooting activities with an aim to increase the time-to-effect of the relevant fault to days.

In all cases, the objective of the anomaly response capability is to help on-board crew put the vehicle into a state where ground crews have time to develop a strategy for verifying onboard diagnoses, performing root cause analyses and anomaly reports, generating a plan to return the vehicle to the highest functioning state possible, and modifying any other procedures or plans that have changed as a result of the fault.

Autonomous Safing under Uncertainty

Autonomous safing seeks to develop a real-time autonomous response that makes the minimum number of changes to system state necessary to give crew sufficient time to address the fault or anomaly in question. This capability is expected to be adapted from conventional FDIR approaches with additional system models in place to generally prioritize low-risk procedures.

Fault Hypotheses and Diagnosis Generation

Diagnosis of unexpected faults and failure modes is currently an entirely manual effort for human spaceflight operations; information is provided via telemetry, and expert ground controllers are responsible for understanding all the failure modes of their hardware systems and how they might interact. For on-board anomaly response, fault hypothesis generation seeks to emulate that creative process by identifying possible failure modes or combinations of failure modes that could result in the fault signature identified. System-generated fault hypotheses will be validated and provided to crew as part of their decision-making process.

Procedure Development

In anomaly response scenarios, crew will be expected to adapt or generate procedures for verifying fault diagnoses and for providing an initial response. ISS ground operations provide a model for that problem-solving approach but rely on expertise not available to onboard crew; procedure development research will develop methods to provide suggestions or recommendations for procedure steps for crew to incorporate into their plans.

Hypothesis and Procedure Validation

Both fault hypothesis and procedure development are expected to require synthesis of new information by advanced compute capabilities (e.g., generative AI) that are rapidly evolving and have no examples of prior use in human spaceflight. These systems are risky and unproven; validation techniques must therefore be included to ensure that synthesized information is technically valid and that agency stakeholders feel that the system can be trusted to support critical decisionmaking. Hypothesis and procedure validation development efforts seek to create *a priori* models of system behavior with that are capable of running in on-board avionics systems and accurate enough to ensure that faults and procedure steps generated by EIO applications will improve (or at least not worsen) system state.

Crew Interaction with Decision Support Systems

Human-computer teaming for procedure development is largely unresearched for space applications and is not known to be broadly used in terrestrial settings. Under this scope of work, crew interaction applications will be used as research platforms to identify effective methods and approaches to help crew understand and interact with recommendations generated by onboard systems.

5. Data Integration

Human spaceflight operations, especially in the case of anomaly response, utilize massive amounts of data from disparate domains and sources including NASA operations (e.g. flight rules, flight telemetry), safety and mission assurance data (e.g. hazard analyses, problem reports), engineering data (e.g. schematics, system specifications), and design and construction data (e.g. waivers and deviations) captured throughout the design and development process. In general, these products are designed and managed in a way that is convenient and readable for ground controllers and support teams with both domain expertise and system context. They are not designed or managed in a way that necessarily supports personnel with reduced expertise (like an on-board crew member) and are poorly optimized for computer understanding – examples today include PDFs of heritage schematics and decision flowcharts authored in Microsoft Word. The purpose of the data integration domain is first to research the types of data necessary to operate a complex space system and respond to anomalies, with an eye towards ensuring that the necessary data is captured and managed in a way that ensures the ground crew, inexpert flight crew, and advanced compute applications on board the flight system have sufficient capability to find, understand, and use data products to respond to in-flight anomalies. Technology development work in this area is expected to begin in late 2026.

6. Communications

Added to the EIO scope of work in 2024, the Communications activity works to identify how research and technology development efforts underway across the agency (principally by the Space Communications and Networking (SCaN) organization) must be factored into EIO development efforts. Logical decomposition of any MCO-managed communications technology needs is targeted to occur in FY2025.

C. Work Plan Development

For each activity described in Section 3.2, a work plan was composed to describe the categories of planned technology investment that the EIO domain intends to pursue as well as time phasing estimates and major interdependencies. While work plans are internal to NASA, the format is shown below for context.

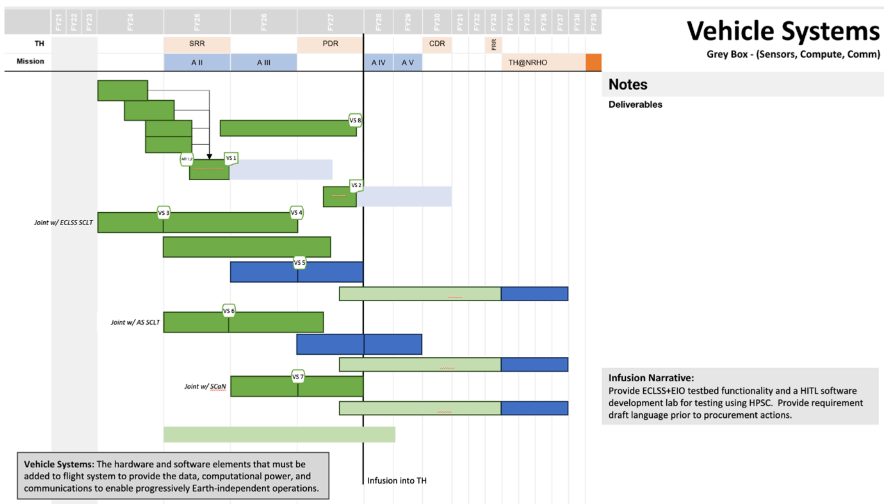

Figure 7: Sample Work Plan for EIO Development

EIO work plans will be updated annually to show both successful investments and to indicate changes in investment plans as a result of agency funding decisions. EIO work plans are distinct from advisory roadmaps provided by NASA Systems Capability Leadership Teams (SCLTs) like the ECLSS-CHP SCLT. SCLT advisory roadmaps are generally publicly available [22] and describe technology investment recommendations by technologists instead of planned investments by a funding authority.

D. Development Targets

The definition of needed functionality for a given element of the Moon to Mars campaign is crucial to the successful and timely delivery of the needed capability. As M2M technology needs are identified they will be defined from a solution-agnostic functional perspective. The result of this definition will be available for M2M implementation programs seeking to incorporate EIO capabilities at their Systems Requirements Review (SRR). Proof of capability investments will also demonstrate that the basic science and technological concepts for a defined technology need are viable at the level of TRL 3 (or equivalent). Proof of capability will not be expected to meet functional requirements but will show that the requirement can reasonably be met and that quantitative verification approaches can be identified. Proof of capability investments will be targeted for delivery prior to the Systems Requirements Review (SRR) or equivalent of a relevant M2M element. Infusible technology investments will provide hardware, software, and documentation at an injectable level of TRL 6 or equivalent. Infusible technologies will be expected to meet applicable M2M requirements and will be accompanied with infusion documentation.

IV. FY 2024 Development

The EIO domain formulated in mid 2023 and adapted a small amount of existing research to begin building the toolsets and fundamental knowledge base necessary to execute work starting in late 2024 (FY2025, described in Section 5 below).

Agency Capabilities Survey

During FY24, the EIO domain is performing a comprehensive review of existing work and capabilities that align to EIO needs as described in Section 3.1 above. The result will be used to identify areas of expertise for future technology investment and identify gaps where targeted industry and academic outreach should be performed. The result of the survey will be published as an internal NASA document under the Moon to Mars program, and outcomes from the survey will be used to inform FY25 industry and academic outreach efforts.

Use Case Development

During FY24, researchers at Ames Research Center (ARC) and Johnson Space Center (JSC) are using a series of targeted studies of ISS anomalies to identify the set of critical functions that must be re-allocated from ground personnel to an EIO capability. The studies will describe prior ISS failure and recovery responses (e.g., for high priority IFIs) in terms of timeline (what events occurred in which order) and in terms of ownership (who performed each action), then will inject a consistent one-way twenty-minute communications delay to establish the set of activities that must be moved onboard. The results of this work will be used in FY25+ for a variety of purposes, including to inform proof of concept activities, develop requirements and verification cases for future software systems, and to explain desired EIO outcomes to management and stakeholder communities.

State Variance

During FY24, researchers at ARC and Glenn Research Center (GRC) will show that we can use telemetered data to accurately identify nominal and off-nominal states for the ISS UPA using a combination of telemetered data and synthetic data from models. We will show an ability to determine in-family vs out-of-family results based solely on telemetry readings. This capability will be extended in FY25 and adapted for anomaly response tasks, to increase accuracy, to adopt the ECLSS Ground Testbed, and to incorporate additional ECLSS elements.

Procedure Validation

During FY24, researchers at Stennis Space Flight Center (SSC) will show that we can interpret a procedure as system inputs, match that against a fault condition, and show whether it actually results in the intended outcome. This capability will be used in FY25 to test generated procedure development methods.

V. FY 2025 Development Objectives

E. Integrated Testbed Buildout

Researchers and technology developers at Marshall Space Flight Center will augment an existing ECLSS test facility and add additional test capabilities that allow Earth Independent Operation (EIO) technologies to be developed and demonstrated on ECLSS components, subsystems, and integrated systems. This activity will result in ECLSS testbeds and integrated systems that are used to develop and validate EIO technologies. These testbeds will be used to demonstrate autonomous and crew response activities to anomalies, simulating what would happen on a crewed Mars transit. Historically, ECLSS has relied on ground involvement for commanding and anomaly resolution, and this will not be possible with communication delays and black outs. ECLSS systems supply oxygen, remove CO2, and recycle water. These systems need to be reliable, and anomalies often need to be remedied quickly. In some cases, anomalies result in crew hazards such as leaking of toxic urine pretreatment from a toilet or urine processor, or hydrogen leaking from an oxygen generator.

Over the next 2 years, researchers at MSFC and Stennis Space Flight Center will augment the ECLSS Hardware Testbed with a federated model of the hardware capable of simulating fault detection, isolation, and recovery during operations, and further extended to emulate hardware and software relevant to a future Mars transit vehicle. The initial proof-of-concept will enable simulation of fault conditions that could be risky for the test hardware, allow for development of synthetic datasets for training AI/ML fault recovery models across various operational scenarios and identify interfaces needed for modeling and simulation integration.

Researchers at MSFC and the Jet Propulsion Laboratory will establish a first-in-class avionics lab with the infrastructure needed to develop, test, and operate Earth independence applications on the High-Performance Space Computer (HPSC) architecture. The HPSC architecture has several first-in-class characteristics that enable advancements in flight software and allow for limited implementation of on-board artificial intelligence and machine learning technologies. After initial buildout, the HPSC lab will be integrated into the ECLSS test facility in order to develop and test higher-fidelity prototypes of EIO applications.

F. Crew Interaction Prototypes

In 2025, researchers based at Ames Research Center and at the Johnson Space Center will perform user research and prototype development for both a situational awareness and a procedure execution capability. On board systems will be responsible for monitoring vehicle system state and providing crew with necessary situational awareness of significant vehicle state changes to enable response. This task will result in a validated, high-fidelity, interactive interface prototype that provides awareness of the following:

- Autonomous system behavior
- Off-nominal trends and behavior
- Resource and consumable levels & projections
- Mission timeline
- Data needed for problem solving and troubleshooting for time and safety-critical anomalies

Procedure execution currently relies on the real-time guidance and oversight of ground experts with access to vast datasets. This task will result in a validated high-fidelity interactive procedure execution prototype that provides:

- Guidance on nominal and off-nominal step execution
- Oversight on successful completion
- Real-time, context-specific instruction

G. Anomaly Response Research

Researchers at SSFC, ARC, and JSC will perform research and technology development focused on development of foundational capabilities that support the ability to respond to a short time-to-effect unanticipated or ambiguous fault in a critical system, including anomaly detection, machine learning and data fusion technologies. Development will also create tools that provide higher-level inference on the nature of the fault, work to disambiguate unclear faults, and support successful fault resolution.

Researchers at ARC, SSFC, and JSC will execute research and development of a prototype application that provides recommended steps to resolve an injected ambiguous fault, allowing the EIO system to suggest a procedure to crew. This activity includes the development of a solution that can create a new procedure for an unknown fault condition using existing FMEA and procedures as inputs, implementation in an HPSC, and limited human-in-the-loop testing. Research will continue towards development of an application that can simulate the execution of a synthesized procedure in an a priori model based on integrated habitat simulations, identifies whether the procedure is dangerous to the vehicle and whether the procedure is able to return the vehicle back to a safe state, and then assess the synthesized procedure. This work is built upon FY24 activities that demonstrate a procedure can be interpreted as system inputs, match that input against a fault condition, and then demonstrate whether input results in intended outcome.

H. Industry and Academic Outreach

Plans for industry and academic outreach will be developed following the conclusion of the agency capability assessment and are anticipated to begin in early 2025. Initial focus areas will focus on industries with similar use cases, sensor fusion capabilities, and industries that have worked to establish autonomous diagnostics capabilities for terrestrial applications.

References

[1] Architecture Design Document (ADD) D684-10504, "Failure Detection, Isolation, and Recovery (FDIR)," February 22, 1994, International Space Station Alpha Program, National Aeronautics and Space Administration.

[2] Final report of the performance-based operations aviation rulemaking committee / commercial aviation safety team flight deck automation working group (Docket No. SA-537, Exhibit No. 14-E). National Transportation Safety Board. (2013).

[3] Prokop, L.E. Considerations for Software Fault Prevention and Tolerance. NASA Engineering and Safety Center Technical Bulletin No. 23-06. NTRS DOCID 20230013383.

[4] Prokop, L.E. Software Error Incident Categorizations in Aerospace. NASA Engineering and Safety Center NPP-22-01775. NTRS DOCID 20230012154

[5] Vera, A., AI for Progressive Earth Independence. Conference Proceedings, Humans to Mars Summit 2024.

[6] Panontin T, Wu SC, Parisi M, McTigue K, Vera A. Human-Systems Integration Architecture Needs Analysis: Onboard Anomaly Resolution During Autonomous Operations. NASA Human Research Program Technical Report. 2021.
[7] Fischer U, Mosier K, Orasanu J. The impact of transmission delays on mission control-space crew communication. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 2013;57:1372–6.
[8] Mosier KL, Fischer UM. Meeting the challenge of transmission delay: communication protocols for space operations. Human Factors. 2023;65:1235–50.
[9] Rader SN, Reagan ML, Barbara Janoiko, Johnson JE. Human-in-the-loop operations over time delay: lessons learned. Proceedings of the 43rd International Conference on Environmental Systems. 2013.
[10] Kintz NM, Chou CP, Vessey WB, Leveton LB, Palinkas LA. Impact of communication delays to and from the International Space Station on self-reported individual and team behavior and performance: a mixed-methods study. Acta Astronautica. 2016;129:193–200.
[11] Vera, K. R. McTigue, T. L. Panontin, M. E. Parisi, & S. . Wu (2022) Risks from Decreasing Ground Support, Presented at the 1st International Workshop on Interdisciplinary Paradigms for Semi-Autonomous Deep-Space Habitation (SMARTHAB WORKSHOP 2022), San Antonio, Texas, October 13-14
[12] Marquez JJ, Hillenius S, Deliz I, Zheng J, Kanefsky B, Gale J. Enabling communication between astronauts and ground teams for space exploration missions. IEEE Aerospace Conference. 2019.
[13] NASA Space Flight Program and Project Management Requirements. NPR 7120.5F. Released August 03 2021.
[14] Kessler P, Prater T, Nickens T, Harris D. Artemis Deep Space Habitation: Enabling a Sustained Human Presence on the Moon and Beyond. IEEE Aerospace Conference. 2022.
[15] Powell W. High-Performance Spaceflight Computing (HPSC) Program Overview. Space Computing and Connected Enterprise Resiliency Conference. Released June 8 2018.
[16] M. E. Parisi, K. R. McTigue, T. L. Panontin, S. . Wu, & A. H. Vera (2022) Extreme Problem Solving II: How Can 4 Astronauts Do the Jobs of 80 Experts?, In Proceedings of SpaceCHI: Human-Computer Interaction for Space Exploration (CHI '22). May 2022
[17] Meshkati N, Khashe Y. Operators' improvisation in complex technological systems: successfully tackling ambiguity, enhancing resiliency and the last resort to averting disaster. Journal of Contingencies and Crisis Management. 2015;23:90–6.
[18] McTigue K, Parisi M, Panontin T, Wu SC, Vera A. Extreme Problem Solving: The New Challenges of Deep Space Exploration.
[19] M. N. Russi-Vigoya, D. L. Dempsey, B. . Munson, A. H. Vera, B. D. Adelstein, S. . Wu, & K. . Holden (2020) Supporting Astronaut Autonomous Operations in Future Deep Space Missions, Advances in Intelligent Systems and Computing, vol 1212., pp. 500-506.
[20] Broyan, J. Environemental Control and Life Support Systems – Crew Health and Performance (ECLSS-CHP) Future Research Needs and Alignment. Biological and Physical Sciences Research Fall Committee Meeting, National Academies of Sciences, Engineering, and Medicine. 2022.