NASA/TM–20240011157

Determining Simulation Fidelity Necessary for Evaluating Onboard Vehicle Capabilities and Crew Roles on Long Duration Exploration Missions Beyond Low-Earth Orbit

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August 2024

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Acknowledgments

Research behind this report was supported by the Human Factors and Behavioral Performance Element of NASA's Human Research Program. We thank Joel Lachter and John Karasinski for comments and suggestions on an earlier draft of the report.

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Acronyms and Definitions

ACC	Altitude Chamber Complex
ANSMET	Antarctic Search for Meteorites
AR	Augmented Reality
ART	Anomaly Resolution Team
CAMS	Cabin Air Management System
CDRA	Carbon Dioxide Removal Assembly
CHAPEA	Crew Health and Performance Exploration Analog
DoD	Department of Defense
DRM	design reference mission
ECLSS	Environmental Control and Life Support System
ESA	European Space Agency
ETCS	External Thermal Control System
EVA	Extravehicular Activity
FAROUT	Foul Air Removal Operation Untitled Tournament
FMARS	Flashline Mars Arctic Research Station
FMS	Flight Management System
GPS	Global Positioning System
HERA	Human Exploration Research Analog
HESTIA	Human Exploration Spacecraft Testbed for Integration and Advancement
HI-SEAS	Hawai'i Space Exploration Analog and Simulation
HOME	Habitats Optimized for Missions of Exploration
HSIA	Human Systems Integration Architecture
IFI	Items for Investigation
ISS	International Space Station
LEO	low-Earth orbit
MAT	Multi-Attribute Task
MATB	Multi-Attribute Task Battery
MCC	Mission Control Center
MER	Mission Evaluation Room
MOD	Mission Operations Directorate
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Lab
NDRC	(U.S.) National Defense Research Committee
NEEMO	NASA Extreme Environment Mission Operations
OGA	Oxygen Generation Assembly
ORU	Orbital Replacement Unit
OSRD	Office of Scientific Research and Development
R&R	removal and replacement
RATS	Research and Technology Studies

RETHi....................................Resilient Extra-Terrestrial Habitats
ROI ....Research Operation and Integration
RPC..remote power controller
SMA.......................................Safety and Mission Assurance
SME ....subject matter expert
SSAT......................................System-wide Safety Assurance Technologies
SSTF ....Space Station Training Facility
SVMF ....Space Vehicle Mockup Facility
VR..virtual reality

Determining Simulation Fidelity Necessary for Evaluating Onboard Vehicle Capabilities and Crew Roles on Long Duration Exploration Missions Beyond Low-Earth Orbit

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Executive Summary

Identification of onboard vehicle capabilities and crew roles and responsibilities necessary for achieving effective human-systems collaboration will require iterative cycles of concept development and empirical evaluation of human performance in complex operations. This report presents the results of an effort to lay the groundwork for determining the level of fidelity of simulated environments most suitable for validating concepts and evaluating implementations of a new Human Systems Integration Architecture (HSIA) that will support the flight crew on long duration exploration missions beyond low-Earth orbit. To do that, we conducted a literature review on simulation fidelity and surveyed simulation capabilities inside and outside of NASA used in NASA-sponsored research. We also analyzed two International Space Station (ISS) vehicle anomalies to identify the types of scenario events and crew activities that may need to be simulated. Our survey findings reveal that most NASA simulation facilities are designed to achieve high physical fidelity while HSIA risk mitigation requires simulation emphasizing task and functional fidelity aspects. A trade analysis shows that, for standard and requirement development, evaluation conducted using synthetic task environments with inexperienced participants will support testing a wide variety of conditions and yield findings robust enough to be generalized to a wide variety of designs on which developed standards and requirements might be levied while allowing human performance standard measures to be collected using consistent methods across tasks and conditions. For technology/tool development, because findings will only need to be generalized to the actual target environment in which the technology/tool will be used, it is more suitable to evaluate the prototypes in a scaled world that preserves functional relationships present in the actual target environment with intended user populations. To wrap up, we give an overview of a well-known synthetical task environment in the space domain and discuss what it takes to construct a synthetic task environment.

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1 Introduction

> *"The root of these problems lies in the inability to handle complexity. In field research, there is often too much of it to allow for any more definite conclusions, and in laboratory research, there is usually too little complexity to allow for any interesting conclusions"* (Brehmer & Dörner, 1993, p.172)

> *"This leaves us in the invidious position that what is interesting is not explained and what is explained is not interesting. Simulation in its many guises may offer an excellent compromise"* (Ward et al., 2006, p.243)

The likelihood of an unanticipated major vehicle malfunction in all Design Reference Mission (DRM) categories is estimated to be greater than 10% for a 30-day mission, based on analysis of extended low-Earth orbit (LEO) and Lunar human spaceflight mission data (Vera et al., 2022). The consequences of such unanticipated major vehicle malfunctions become more significant with increasing Distance from Earth as the primary countermeasures currently available rely on support from experts at mission control on the ground (e.g., providing guidance and oversight, troubleshooting, commanding the vehicle directly, etc) delivered through real-time communication. The possibility of adverse performance outcomes given decreasing real-time ground support during future exploration missions, most consequentially that flight crew is unable to adequately respond to unanticipated major vehicle malfunctions and execute safety-critical procedures, is characterized as a Human Systems Integration Architecture (HSIA) risk (Buckland et al., 2022). Successful mitigation will require seamless collaboration between flight crew and onboard vehicle capabilities to enable effective and efficient responses to the aforementioned situations. Identification of onboard vehicle capabilities and crew roles and responsibilities necessary for achieving such human-systems collaboration will require iterative cycles of concept development and empirical evaluation of human performance in complex operations.

While methodologies have been developed to study human performance in complex operations in situ through observation and analysis (e.g., Pew, Miller, and Feehrer (1981) on the decision-making process of nuclear power plant operators during off-nominal accidents), empirical evaluation of human performance in complex operations is mostly carried out in simulated environments. In certain cases, that choice is made due to necessity, when the actual operating environments are not easily accessible (e.g., airplane cockpits, space vehicles). In others, it is made based on preference. Simulated environments provide researchers the freedom and ability to vary fidelity and thereby the means to manage the dimensions and degree of complexity in simulated operational tasks. Even though the natural desire is often to simulate environments as closely as possible to the actual (or the conceptualized) ones, the costs of constructing a high-fidelity environment as well as running simulations and collecting data in it are often prohibitive. The presence of realistic but unrelated factors could also interfere with evaluating behaviors of interests.

The purpose of this work was to lay the groundwork for determining the level of fidelity of simulated environments most suitable for validating concepts and evaluating implementations of a new HSIA that will support the flight crew on long duration exploration missions beyond LEO. This report presents the results of that effort and is organized as follows. It begins with a discussion of the use of simulation for evaluating human performance in complex operations, focusing on determinants of fidelity (Section 2). We then present the results of a survey of existing and planned simulation capabilities inside and outside of NASA that were used in NASA-sponsored research to evaluate crew performance (Section 3). Next, we present an analysis of two vehicle anomalous events that occurred on the International Space Station, focusing on identifying crew behaviors of interest, scenario features that elicit them, and simulator components that may be needed to enable the scenarios (Section 4). Lastly, we present a trade space analysis of HSIA simulation objectives and fidelity considerations (Section 5), followed by a discussion of recommended simulation solutions for validating new HSIA concepts and evaluating HSIA implementations (Section 6).

2 Use of Simulation for Evaluating Human Performance in Complex Operations

Conducting applied research to understand and improve human performance in complex operations has always been a difficult problem (Brehmer & Dörner, 1993; Ward et al., 2006). Though born out of necessity in some cases, such as when the actual task environments are not easily accessible (e.g., spaceflight), simulation offers an excellent compromise. Not only do simulations afford scalable and thus manageable levels of complexity in their emulation of the actual task environments, but they can also be made to provide better support for the assessment of performance. It follows that, in identifying simulated environments for validating new HSIA concepts and evaluating HSIA implementations, one needs to not only consider whether they provide a suitable level of fidelity (*simulation for fidelity*) but also how well they support research activities (*simulation for research*).

2.1 Simulation for Fidelity

Simulation fidelity refers to the extent to which a simulated environment replicates the actual environment it is intended to emulate (i.e., the real world). One of the first devices that can be regarded as a simulator was possibly the 1910 Antoinette trainer, a synthetic flight training device (Huddlestone & Harris, 2016). The issue of simulation fidelity was, however, not rigorously considered until the mid-20th century. At that time, the urgent need to solve practical problems in World Wars I and II, combined with desires of psychologists to contribute to the wartime effort, inspired many of the research topics in the field of applied psychology; among them was the design of training methods (Hoffman & Deffenbacher, 1992). The high cost and often slow initial distribution of complicated weapons created a training problem and fueled the development of synthetic trainers (Wolfle, 1946). In a technical report written while serving as a member of the Applied Psychology Panel of the U.S. National Defense Research Committee (NDRC) of the Office of Scientific Research and Development (OSRD) (Hoffman & Deffenbacher, 1992; Hunter, 1954), Wolfle (1946) discusses in detail three essential characteristics of a good trainer: validity, knowledge of results, and satisfactory physical features. In Wolfle's terminology, validity concerns the degree to which skills acquired from practice on the trainer can transfer to performance on real equipment. Wolfle defines what he calls the true validity of a trainer – determined empirically by comparing the performance in using the real equipment of subjects who practiced on the trainer to those who practiced on the real equipment. Wolfle contrasts true validity with what he calls the face validity of the trainer – the apparent or superficial similarity of the trainer to the real equipment. Wolfle warns of the potential dangers of relying on face validity: while it brings a greater sense of realism and, therefore, may improve students' motivation, face validity does not necessarily predict true validity. Rather, of greater importance than superficial similarity is the similarity in terms of the psychological processes and skills required for proficiently using the real equipment. The second essential characteristic, knowledge of results, refers to the incorporation of a means to inform the student of their progress; in other words, assessing performance and providing feedback. The third essential characteristic, satisfactory physical features, concerns whether the trainer can be easily maintained and is designed as simply as possible while still achieving its intended validity.

Praised for his major role in initiating the systematic thinking about research problems related to the design of training devices (Gagné, 1954), Wolfle (1946) arguably introduced many of the core concepts in the discussion of simulation fidelity in the literature despite never using the word fidelity. On the one hand, what Wolfle called face validity is effectively what is later considered ***equipment or physical fidelity*** (Kinkade & Wheaton, 1972), the degree to which a simulator duplicates the appearance and "feel" of the operational equipment. A closely related concept is ***environmental fidelity***, which refers to the total sensory stimulation context which the simulator tries to duplicate (Hays, 1980; Kinkade & Wheaton, 1972; Wheaton et al., 1976); for example, the sensory stimulation (excluding haptic feedback) that arises from an actual task situation (e.g., motion cues and a three-dimensional dynamic visual presentation of road conditions). Environmental fidelity is sometimes extended to include ***stimulus fidelity*** or ***functional fidelity***, the degree to which training equipment duplicates stimuli present in the operational environment and provides opportunities to realistically respond to them (Fink & Shriver, 1978). More simply put, whereas physical fidelity concerns the degree to which a training simulator "looks like" or "feels like" the actual equipment, functional fidelity concerns the degree to which it "acts like" the actual equipment (Allen et al., 1986; Baum, Riedel, et al., 1982; Baum, Smith, et al., 1982; Hays, 1980).

On the other hand, the similarity of the psychological processes and skills that Wolfle called attention to is often referred to as ***psychological fidelity*** (or realism), the degree to which a simulated work environment elicits the same behavior on the part of the operator as the actual operational environment (Matheny, 1978). Psychological fidelity has on occasion been taken to mean the degree to which a simulator is perceived as being a duplicate of the operational equipment and the task situation, emphasizing the subjective experiential aspect of physical fidelity (Kinkade & Wheaton, 1972). In the former sense, psychological fidelity can be far removed from physical fidelity (for example, guiding the trainee on what to do in the operational environment using only verbal descriptions), so long as transfer of response occurs that enables the job to be performed correctly (Miller, 1954). In fact, Gagné (1954) notes that more effective training may result when an "exact simulation" of a job situation is sacrificed if changes made to the job situation allow critical aspects to be emphasized in the training situation.

Subsequent discussions of fidelity in the literature have more or less coalesced along these themes and converged on three broad dimensions: physical fidelity (how simulation looks, sounds, and feels), functional fidelity (how simulation acts and behaves), and psychological fidelity (whether simulation triggers the same mental processes required in performing the job in the real environment) (see Hays, 1980 for an early review; and Liu et al., 2008 for a more recent review). As Alluisi (1978) notes that, although physical and functional fidelities can and perhaps should be viewed as separate dimensions, they are moderately correlated. Additionally, Elliott, Dalrymple, Regian, and Schiflett (2001) proposed a dimension called construct fidelity, which is set at a level beyond individual responses and refers to the degree to which performance constructs of interests (e.g., planning, teamwork, situation awareness, decision making, problem solving, workload, tempo, information ambiguity, etc.) are inherent in the simulated environment. While discussion of simulation fidelity strives to clearly define how to qualify similarity or realism in various dimensions, paradoxically the real issue is the departure from fidelity that can be undertaken in simulation that will still lead to a particular level of performance (Baum, Smith, et al., 1982).

In addition to individual dimensions, simulation fidelity can also be considered globally at the simulated environment level. Gray (2002) classified simulated task environments into five types:

> **High-fidelity simulation of complex systems**: Attempt to mimic the complexity of the real world but in a fail-safe environment. Examples include commercial flight cockpit simulators, nuclear power plant simulators, and simulators used by the military.
>
> **High-fidelity simulation of simple systems**: High fidelity does not necessarily imply complexity. This is the case when one subsystem of a more complex system is built as a stand-alone simulator. Examples include the simulation of a Global Positioning System (GPS) or Flight Management System (FMS) interface. In singling out one subsystem, the simulation sacrifices context-of-use (and consequently some real-world complexity) to focus on elements specific to the subsystem (e.g., its user interface).
>
> **Scaled worlds**: Attempt to preserve a subset of the functional relationships found in a complex target task environment in the real world while paring away others. Because the functional relationships preserved and simulated would retain some of the complexity originally present in the real world (albeit limited to the specific functional relationships simulated), performance in a scaled world environment typically requires prior extensive experience with the target task environment. Researchers choose to utilize scaled worlds when they are interested in generalizing findings back to the target task environment in the real world because the similarity between the two worlds (real and scaled) would readily support it.
>
> **Synthetic environments (or microworlds)**: Allow abstraction of functional relationships from one or more complex task environments in the real world to be studied in a less complex make-believe world. Performance in a synthetic environment typically requires little to no experience with the target task environment on which it is based.
>
> **Laboratory tasks**: Simple laboratory environment that supports investigation of fundamental cognitive mechanisms.

To give an example that illustrates the differences among these five environments, simulating the whole Environmental Control and Life Support System (ECLSS) of the International Space Station (ISS) can be regarded as a high-fidelity simulation of a complex system. Isolating and simulating only the Carbon Dioxide Removal Assembly (CDRA) can be regarded as a high-fidelity simulation of a simple(r) system (Sherif & Knox, 2005). Building a simulation of ECLSS preserving only the core operation components (pump, heat transfer, flow path) but still requiring expertise to operate can be regarded as a scaled world. Abstracting CDRA operations down to simple physics principles in a game setting (say, in a fictitious game named Foul Air Removal Operation Untitled Tournament, FAROUT), where naïve participants compete for the most carbon dioxide removal with different types of procedure aids (e.g., paper, AR, VR), can be considered a synthetic environment. Studying how mental models affect the operation of engineered devices by comparing the mental models of winners and losers in FAROUT can be done with laboratory tasks.

Gray's (2002) framework will be used as the guiding framework for the trade space analysis discussed in Section 5.

2.2 Simulation for Research

Regardless of what level and type of fidelity is adopted for the design of a simulated environment, ultimately the goal of running a simulation is in part to assess human performance (recall the second essential characteristic of a good trainer, knowledge of results, Wolfle, 1946). In the context of human spaceflight risks, that means the ability to measure crew performance on tasks in operations. Presently, NASA utilizes a set of spaceflight standard measures for monitoring human system risks experienced by astronauts on International Space Station (ISS) missions (Clement et al., 2021). Within this set, the only measure that directly relates to crew performance is Cognition, which includes a battery of 10 neurocognitive tests that cover a range of cognitive domains relevant to spaceflight: reaction time, learning, working memory, abstraction, spatial orientation, emotional recognition, abstract reasoning, visual tracking, risk decision making, and attention. Results of the Cognition battery can offer an assessment of crew's general cognitive capacity but do not necessarily predict how that capacity manifests in task performance in operations that depend on contextual factors such as the specific task and operation and human-system capabilities provided (Wenzel, 2021). Even though NASA's space programs currently utilize two additional human factors standard measures designed specifically to capture insights into crew's operational performance — Crew Notes (jotted down by crewmembers while working a procedure) and Crew Comments (verbal answers to questions related to specific activities or events happening during mission, collected in post-flight debriefs) — both are anecdotal in nature and have the potential to underreport performance problems, not to mention that they require a great deal of effort to transcribe, analyze, and interpret (Wenzel, 2021).

To remedy this situation, Wenzel (2021) was tasked by the Space Human Factors and Habitability Element of the Human Research Program to identify a core set of valid and reliable human factors performance measures (i.e., standard measures) that can be used in research to assess crew state and readiness to perform. Performance assessments obtained from research can then inform system design (e.g., adapting system functions to crew capabilities) and operation design (e.g., adapting schedules and task allocation to crew state). These measures can also be used during spaceflight missions to monitor crew state and performance in real time and track changes over time. The effort included a literature review to evaluate the state-of-the-art human performance measures and interviews with NASA and Department of Defense (DoD) subject matter experts (SMEs) to solicit recommendations. The results identified four basic human factors standard measures:

Accuracy – can be measured by focusing on successes (e.g., task completion, percent or number correct) or failures (e.g., error rate, absolute error, root-mean-square error)

Time – can be measured as time on task, task completion time, response time or duration, recognition time, movement time, etc. on tasks with a well-defined beginning and end

Workload – can be assessed using accuracy and time measured, or by way of task load, degree of expended effort, perceived workload, etc.

Situation awareness – can be assessed using objective measures such as probe technique or subjective measures such as rating scales

Of particular relevance to this task, Wenzel (2021) notes that NASA and DoD SMEs uniformly recommended that the collection of such data be built into onboard systems for all future NASA crewed missions, including long-duration exploration missions (LDEMs), so that their implementations and interpretations can be better tailored for individual tasks, operations, systems, etc. Wenzel (2021) continues that future HERA (Human Exploration Research Analog) and other analog missions should prioritize implementing such measures in any technological infrastructure utilized in ground-based experiments and simulations.

3 Survey of Existing and Planned Simulation Capabilities Around NASA

We conducted a survey of existing and planned simulation facilities inside and outside of NASA used in NASA-sponsored research for evaluating crew performance[4] to see what capabilities may be available to meet the needs of HSIA concept and countermeasure development and evaluation (for a comprehensive review of existing analogs not limited to NASA, see Heinicke & Arnhof, 2021). The survey included 12 research analogs, 2 academic research efforts, and 3 mockup and training facilities, and for comparison, the International Space Station (which serves as an analog for LDEMs) (see Appendix). Surveyed categories included facility details (e.g., location, environment features, hazards tested), mission parameters (for research analogs), available research support capabilities (e.g., hardware, software, ground simulation, telemetry flow), and the level of emulation of the five human spaceflight hazards identified by NASA's Human Research Program (Buckland et al., 2022). These categories correspond to increasingly Earth-independent design reference mission (DRM) elements contributing to the HSIA risk. The survey primarily used publicly available information as input data (e.g., descriptions provided by the facilities and projects on the internet, published research papers, etc.). The survey only included physical simulators and mockups; virtual and hybrid or mixed reality environments (e.g., Baughman et al., 2022) are beyond the scope of the survey. Table 1 presents a quick summary of the surveyed facilities.

[4] We would like to acknowledge the contribution of Dr. Donna Dempsey, who created and conducted the initial analog research facility survey on which the current survey expanded.

Table 1
Existing Simulation Capabilities

Summary of Existing Simulation Capabilities			
	Facility / Program / Vehicle	**Hazards Tested**	**Years Active***
Operations (1)	International Space Station (ISS)	Isolation, Microgravity	23
Research Analogs (12)	Human Exploration Research Analog (HERA)	Isolation	9
	NASA Extreme Environment Mission Operations (NEEMO) in Aquarius	Isolation, Distance from Earth, Microgravity	18 (ended in 2019)
	Human-Related Altitude Chamber Complex (ACC)	Environmental hazards and isolation	8
	Crew Health and Performance Exploration Analog (CHAPEA)	Isolation	<1
	Hawai'i Space Exploration Analog and Simulation (HI-SEAS)	Isolation, dark and light cycles, distance from Earth (20 min. delay)	10
	NEK Ground-based Experimental Complex	Isolation, dark and light cycles, distance from Earth	16
	Haughton-Mars Project (HMP) Flashline Mars Arctic Research Station (FMARS)	Isolation	22
	Desert Research and Technology Studies (RATS)	Distance from Earth	26
	McMurdo Station	Hostile environment, isolation	68
	Palmer Station	Hostile environment, isolation	55
	Antarctic Search for Meteorites (ANSMET)	Hostile environment, isolation	47
	Concordia Station	Hostile environment, isolation	18
Academic Research Efforts (2)	Habitats Optimized for Missions of Exploration (HOME)	N/A	
	Resilient Extra-Terrestrial Habitats (RETHi)	N/A	
Training Facilities (3)	Space Station Training Facility (SSTF)	N/A	27
	Space Vehicle Mockup Facility (SVMF)	N/A	35
	Neutral Buoyancy Lab (NBL)	Hostile environment	21

*Years active is estimated as of 2023, using the year of the first human analog mission/campaign as the starting year

Specific capabilities at each facility varied and often depended on research projects running at the time, but a few notable observations emerged. First, the survey revealed that most simulation facilities are designed to emulate the physical attributes of the space environment, particularly isolation and confinement, and in general not to simulate complex space mission operations. Except for the Space Station Training Facility (SSTF), which utilizes high fidelity flight control software models for training, very limited software realism was found in the facilities surveyed. Software utilized is often provided by the individual research projects and, therefore, not typically integrated with the hardware of the facilities.

Second, except for equipment used in field studies designed to test engineering and design concepts for surface operations, such as Extravehicular Activity (EVA) space suits tested in Desert Research and Technology Studies (RATS) (Graziosi et al., 2006; Ross et al., 2013), the survey found limited hardware realism built into simulation facilities. Even when a facility advertises capabilities to simulate actual vehicle hardware, research integration often proves challenging. For example, the documentation for Human Exploration Research Analog (HERA) describes a simulated Environmental Control and Life Support System (ECLSS) and other space vehicle systems for supporting complex operational activities (Research Operation and Integration (ROI) - Flight Analogs, Human Research Program, 2019). Crewmembers of HERA analog missions use them to perform maintenance and housekeeping tasks designed to simulate activities of actual missions (Jordan, 2017). A researcher who has attempted to utilize those capabilities for research purposes reported many architectural and logistical limitations (D. Selva, personal communication, 2022) that required a substantial amount of further development to expand and update the simulator and its database to meet project needs (Milstead & Wilson, 2020). The Human-Rated Altitude Chamber Complex's (ACC's) Human Exploration Spacecraft Testbed for Integration and Advancement (HESTIA) is another exception to the observation that there is limited hardware realism in simulation facilities. Integrated into the HESTIA chamber are a real Environmental Control & Life Support System, portable CO2 and O2 sensors, a human metabolic simulator, an electrolyzer, and an air revitalization system (Wright & Hansen, 2016). However, efforts to build the chamber into a habitation facility are not complete, and it is unclear if human performance testing relevant to the HSIA Risk is included in future facility plans, as current human performance research focuses on the effects of environmental exposure (e.g., elevated CO2 levels) (Mitchell, 2023).

Given the limitations in current simulation facilities, the ISS is often noted and used as a "high fidelity" analog for long-duration exploration missions, but the constraints posed by conducting simulated tasks in a real operational environment limit its effectiveness. For example, Kintz and colleagues studied crew member task completion under communication delay on the ISS, but concerns raised by the Mission Operations Directorate (MOD) necessarily resulted in limitations to the study (Kintz et al., 2016; Kintz & Palinkas, 2016). The tasks allowed for the study had to be negotiated with the MOD to address the concern that higher complexity tasks could be dangerous or life threatening (Kintz & Palinkas, 2016). Further, telemetry from the ISS continued to flow in real time during task execution despite the focus on transmission delays (Kintz et al., 2016).

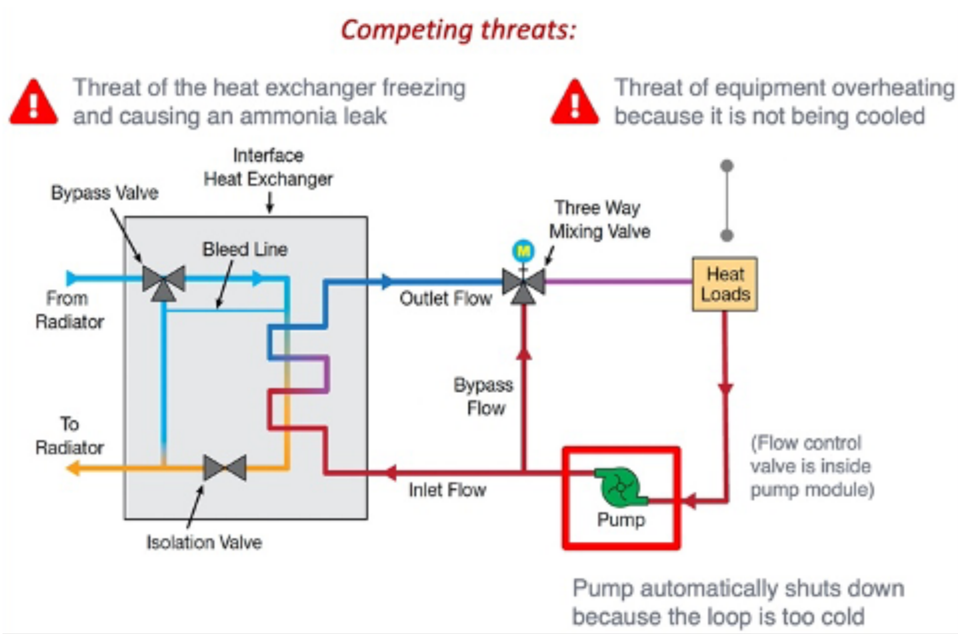
4 Analysis of Potential Simulation Research Needs

To identify potential simulation research needs, we analyzed two ISS anomalous incidents to identify features present in real spaceflight anomaly response scenarios. Our analysis was informed by ISS IFI (Items for Investigation) documentation, MCC artifacts (including procedures and flight rules), Mission Evaluation Room (MER) artifacts (including Anomaly Resolution Team (ART) and Flight Investigation Team (FIT) meeting summaries), and ISS daily summaries, as well as available publications (Dempsey, 2018; JSC SMA Flight Safety Office, 2019). These anomaly scenarios are described in further detail in the companion report "Human Systems Integration Architecture Needs Analysis: Anomaly Response Analysis Mapping to Operations Beyond Low-Earth Orbit" (Panontin et al., 2023), as well as in Valinia et al. (2022).

4.1 External Thermal Control System (ETCS) Loop A Pump Module Failure

On December 11, 2013, software automatically shut the pump module inside one of the two external cooling system loops (designed as active thermal control systems) onboard the ISS (Loop A) after the loop became too cold to operate safely. Six alarms sounded in the first minute of the failure (four of which were heard onboard), and over the next 30 minutes, over 30 alarms would sound. The Mission Control Center (MCC) ground team had to move quickly, as this fault posed competing threats (Figure 1). On one hand, ISS's two cooling loops (A and B) are not fully redundant, so many onboard systems were suddenly in danger of overheating. On the other hand, too much cooling – as the anomaly indicated – also posed a potentially catastrophic risk due to the potential of freezing and the heat exchangers which could result in a breach of toxic ammonia entering the cabin (Dempsey, 2018; JSC SMA Flight Safety Office, 2019; Panontin et al., 2023; Valinia et al., 2022).

Figure 1
Competing Threats Illustrated Using Schematics of An Active Thermal Control System (adapted from Dempsey, 2018, Chapter 11, Figure 2)



When the first alarms sounded, the crew was immediately informed that the ground was aware and responding, and the crew was instructed to continue with nominal operations. The ground team then immediately began procedures to restart Loop A's pump module. Pump recovery procedures were time-constrained and had to be initiated within minutes to restore the required cooling and redundancy. Simultaneously, based on documentation of thermal system constraints, the ground team triaged the impacted systems to determine which systems needed to be moved to Loop B and which ones should be safely powered down.

Although it had been restarted in full bypass mode (no ammonia flowing), the temperature in the loop remained too low to be used safely. During the next few hours, the ground team commanded various flow control valve positions to characterize the loop response and understand the continuing fault. At the same time, the ground was analyzing and redistributing heat loads. The crew assisted in powering down certain equipment onboard the ISS at the end of their day but otherwise maintained nominal operations.

Over the next seven days, the team attempted numerous interventions, all commanded from the ground, including utilizing line heaters, power cycling the pump, adjusting other valves, etc. Ultimately, the nominal operation could not be recovered, and the pump module had to be replaced through an EVA.

Table 2 below lists the activities carried out by ground teams during the first three days of the actual incident that the crew would need to complete given a Mars-like communication delay (e.g., 20 minutes one-way). The scenario features and operational constraints associated with each activity were identified. The activities, scenario features, and operation constraints inform expedition tasks (cf. Munson & Holden, 2021; Stuster et al., 2018) and characteristics relevant to the HSIA risk that may be needed to study crew response to anomalous events.

Table 2

Activities and Associated Scenario Features and Operational Constraints for the ISS Cooling Loop Anomaly in 2013

Activity	Scenario Features	Operational Constraints
Manage alarms	• Multiple, cascading alarms	• Parsing competing alarms • Challenge of isolating the initiation
Find correct procedures	• Complex procedures (linked to alarms)	• Time pressure
Execute procedure	• Complex procedures • Complex hardware (that can be manipulated) • Interface (for inputting commands) • Telemetry at the task site (linked to hardware/user actions)	• Time pressure
Understand downstream impact (of failure + corrective actions)	• Multiple connected systems	• Complex sub-system interactions • Causal relationships are not immediately understood • Systems thinking required to perform risk assessments
Shed heat loads	• Engineering data onboard • Complex hardware • Interface for commanding/controlling • Telemetry at the task site	• Time pressure • Simultaneous efforts required
Realize the heat loop is still too cold	• Telemetry at the task site	• Procedure has unexpected outcomes • Causal relationships not understood • More analysis required to gather data
Manually test flow control valve	• Interfaces for commanding/controlling • Telemetry at the task site (tied to user actions)	• Challenge of safety perturbing the system to gain understanding
Asynchronously communicate with the ground	• Comm platform • Ground team	• Documentation under time pressure

4.2 Oxygen Generation Assembly (OGA) Hydrogen Dome Orbital Replacement Unit's (ORU) Cell Stack High Voltage Failure

On July 5, 2010, the OGA Hydrogen Dome ORU's cell stack experienced a high voltage failure, causing the OGA to shut down (Carpenter et al., 2012; Jones, 2016; Takada et al., 2015). The shutdown prevented O2 production in the U.S. Orbital Segment and forced reliance on the Russian Elektron. Initially, continued use-as-is of the H2 ORU was explored by the ground team; however, there was a concern that compromised membranes could leak H2 into an O2 circuit and lead to fire/explosion that could damage other ORUs.

Investigations into past OGA water samples also revealed a lower pH than expected. Two days after the initial failure, following considerable work on procedures and analyses, the ground team decided to move ahead with the Hydrogen Dome ORU removal and replacement (R&R) using a spare unit already onboard and remediation of the recirculation loop. On the day the R&R and recirculation were attempted, the crew completed the physical setup necessary for flushing the recirculation loop, but the flushing itself was commanded entirely from the ground. The teams planned to complete the R&R immediately after the recirculation, but recirculation operations halted when a fault (remote power controller (RPC) trip) caused the OGA to unexpectedly shut down. After the ground unsuccessfully performed several reactivation attempts and workarounds, they advised the crew to return to nominal operations while the ground continued investigating the fault.

Analyses of an OGA data dump revealed a "Math Fault" (i.e., a math operation shutdown indicator) that caused the system to shut down. The ground team and crew proceeded with the remediation procedure the next day, but the MER needed to investigate the fault further before performing the higher-risk R&R. Analyses determined unusual sensor data values during the remediation caused the fault and subsequent OGA shutdown. Experts on the ground determined the fault was unlikely to take place again and successfully moved forward with the R&R. The failed ORU was later returned to Earth for in-depth failure investigation.

Table 3 again provides the time-critical activities the crew would need to complete if this anomaly happened during Mars transit with a 20-minute one-way communication delay. The scenario features and operation constraints associated with each activity are identified.

Table 3

Activities and Associated Scenario Features and Operational Constraints for the OGA Hydrogen Dome ORU Cell Stack High Voltage Failure in 2010

Activity	Scenario Features	Operational Constraints
Execute OGA activation procedure	• Complex hardware • Complex procedure • Telemetry at the task site	
OGA unexpectedly shuts down; wait for ground input	• Comm platforms • Ground team	• No perfect information • Causal relationship not understood
Reactive OGA in standby mode	• Complex procedure • Telemetry at the task site	
Demate O2 hose	• Complex hardware • Procedure	
Sees moisture onboard after O2 disconnect (unexpected)	• Complex hardware you can interact with • Off-nominal hardware state	• Specific expertise required (to know this is unusual) • Causal relationship not understood
Begin OGA remediation procedure	• Procedure • Telemetry at the task site	
Notice flush is slower than expected	• Telemetry at site of task • Complex hardware that's responding to use actions	• Specific expertise required • Causal relationship not understood
Alarm that RPC is tripped	• Alarms	
Crew waits for ground input	• Comm platform • Ground team	
Attempt ground instructions, but each time RPC is tripped still	• Complex hardware • Alarms • Comm platform • Ground team	• Procedure has unexpected outcomes • Causal relationships not understood • Imperfect data; diagnosis required
Deactivate OGA	• Procedure • Hardware	
Re-attempt remediation procedure (successful)	• Complex procedure • Hardware • Telemetry at the task site	
Conduct hydrogen dome ORU R&R	• Complex procedure • Complex hardware • Tools	

These two scenarios were analyzed to abstract high-level activities common to anomaly response (Table 4). The activities identified can help craft the simulation characteristics and research tasks needed to validate new HSIA concepts and countermeasures.

Table 4
High-Level Activities (Abstracted from Tables 2 and 3) that a Mars Crew May Need to Complete during Anomaly Response with Associated Scenario Features and Operational Constraints

High-Level Activity	Scenario Features	Operational Constraints
Managing alarms	• Multiple, cascading alarms	• Parsing competing alarms • Challenge of isolating the initiation
Finding correct procedures	• Complex procedures that are linked to alarms	• Time pressure
Executing procedures	• Complex procedures • Complex hardware that can be manipulated • Interface for inputting commands & controlling systems • Telemetry at the task site, linked to hardware and user actions	• Time pressure • Procedure has unexpected outcomes
Commanding	• Engineering data onboard the vehicle • Interface for inputting commands & controlling systems • Telemetry at the task site	• Time pressure • Simultaneous efforts required
Monitoring	• Telemetry at the task site • Complex hardware that responds to user action	• Procedure has unexpected outcomes • Causal relationships not understood • More analysis required to gather data • Specific expertise required
Troubleshooting	• Interface for inputting commands & controlling systems • Telemetry at the task site	• Challenge of safety perturbing the system to gain understanding • Specific expertise required
Asynchronously communicating with the ground	• Comm platform • Ground team	• Documentation under time pressure

5 Simulation Objectives and Fidelity Requirements Trade Space Analysis

As discussed in Section 2, simulation fidelity can be assessed for individual dimensions (Hays, 1980; Liu et al., 2008) or a whole environment (Gray, 2002). The question remains how to choose the level of simulation fidelity appropriate for the study. For an individual dimension, the answer is relatively straightforward: the fidelity should be set at a level that supports the effective investigation of research questions. For example, suppose the research studies the effect of alerting and hypothesizes that different alert sound frequencies differ in their ability to draw attention when played at the same volume against background environment noise. In that case, the simulation should accurately reproduce the alert sounds at specified frequencies and volumes and the background noise level for adequate experimental control (in other words, high audio fidelity). Conversely, if the research studies troubleshooting and the alert sounds simply serve as the trigger to the troubleshooting process, impulses to raising the fidelity of the alert sounds (e.g., visual-audio) should be tempered by considerations for whether and how the effect of hearing higher fidelity alert sounds (e.g., the visceral responses they elicit) could impact the effective investigation of troubleshooting behavior.

According to Gray (2022), which type of simulated environment would best support studies validating new HSIA concepts and evaluating HSIA implementations? For guidance, we turn to the debate on the level of fidelity best suited for training simulation. Recall the discussion of the origin of synthetic trainers in Section 2.1. The purpose of a training device is to facilitate the acquisition of skills required to use the actual device in operations. The desired level of fidelity of a training device (i.e., simulator) should, therefore, be determined by what characteristics of the simulator (e.g., functions, tasks) bring about the most rapid and efficient acquisition of those skills (Gagné, 1954). In other words, the level of fidelity should be determined by the desired outcome of training simulation: transfer of learning.

Early research on training simulation tended to assume and find that higher fidelity produces superior transfer of learning (e.g., Allen et al., 1986; Miller, 1954). However, Ritter, Yeh, McDermott, and Weyhrauch (2023) caution that what was considered high fidelity between the 1950s and 1980s, when most of those studies were conducted, may reflect a lower fidelity ceiling on par with representative technology at the time. Furthermore, Ritter et al. note a growing body of research showing higher fidelity does not always lead to better learning (for more in-depth reviews, see also Doozandeh, 2021; Doozandeh & Hedayati, 2022; Doozandeh & Ritter, 2019). For example, Noble (2002) found that the pilot's skill level and, consequently, their learning stage interacts with simulation fidelity to produce differential learning outcomes — e.g., with novice pilots benefiting from lower fidelity simulators that do not overburden the learner with details. Dahlstrom, Dekker, van Winsen, and Nyce (2009) found that a mid-fidelity simulation (consisting of a laptop computer, printer, and a tabletop) that captured sufficient and salient aspects of reality was effective in helping student pilots develop the competence required to manage situations involving underspecified problems, time pressure, and complex group interactions. It also incited a surprisingly high level of engagement reflected in the intensity of communication, cooperation, and decision making. Doozandeh and Hedayati (2022) found that, based on the results of a meta-analysis of reports from 1960-2021 that studied training of troubleshooting or problem-solving tasks with simulations of different levels of fidelity or realism, trainees with high prior skills benefitted from training simulation of high fidelity. However, none of the low-, medium- or high-fidelity simulations demonstrated a universal superiority.

What would be the desired outcome of simulations for validating new HSIA concepts and evaluating HSIA implementations? We argue that it is the generalizability of findings. The required level of generalizability differs depending on how the findings will be used, that is, the category of deliverables. The Human Research Program Integrated Research Plan lists category options for deliverables (Milstead et al., 2022 Table 1). Results from simulations for the HSIA risk mainly support two categories of deliverables:

> **Standard/Requirement/Guideline**: Results from simulations can serve to provide information that is relevant to a higher-level standard or requirement (or requirements set), which feeds the design of the vehicle and its sub-systems
>
> **Technology/Tool**: Results from simulations can serve to validate prototype hardware, software, systems solutions

Increasingly higher correspondence of a simulated environment to one system increases the applicability of findings to that system but reduces generalization to others (Alluisi, 1967; Gray, 2002). Therefore, the required level of generalizability of findings therefore determines the required level of simulation fidelity. The trade space based on these findings and utilizing Gray’s characterization of simulated environments is shown in Table 5.

Table 5

A Summary of Types of Simulated Environment of Varying Fidelity, Goals They Serve, Expertise of Participants Expected, and Conditions for Their Use

Type	High fidelity Complex Sys	High fidelity Simple Sys	Scaled world Functional relationships	Synthetic Make believe	Simple lab
Goal			For generalization to the target task environment	For generalization to many different task environments	For theory development/ evaluation
Expertise level	Requires prior (extensive) experience with the target task environment			Requires little to no experience with any of the target task environments	
Good for		Validating specific concept/application with intended user population		Testing range and limitation of observed principles/patterns	Evaluating causal relations and mechanisms
Deliverable (Use)	Verification & Validation		Technology/tool, Countermeasures	Standards/ Requirements/ Guidelines	

This trade space can be analyzed to determine the fidelity needed for the deliverable categories above. For standards/requirements/guidelines to apply to a wide range of design solutions, they need to be developed based on behavioral patterns that are valid and reliable across a wide range of situations. In this case, the evaluation conducted using a synthetic, simulated environment with inexperienced participants will better support testing a wide variety of conditions and deriving valid and reliable behavioral patterns from them. For technology/tool development, because findings will only need to be generalizable to the actual target environment in which the technology/tool will be used, evaluating the prototypes in a scaled world that preserves functional relationships with intended user populations would be most suitable (see Table 5 for a summary).

6 Discussion

The goal of simulations is often to recreate the actual operational environment to maximize realism or physical fidelity, whether in parts (e.g., a piece of equipment) or in full (e.g., a habitat analog). This is evident from our survey of existing simulation facilities and analog missions inside and outside of NASA: most of them are designed to achieve high physical fidelity, i.e., to look and feel like the actual space environment, whether vehicle or habitat. It is perhaps also due to this implicit belief that most people readily accept simulators or analogs that look and feel like space environments to be of high fidelity. However, as discussed in Section 2, simulation fidelity can be assessed from multiple dimensions, regarding how the environment looks, sounds, and feels like, how the equipment acts (functional fidelity), and how the tasks elicit psychological and cognitive processes (psychological fidelity). The HSIA risk concerns the crew's ability to resolve vehicle anomalies. Simulation for HSIA risk mitigation must consider task and functional (ergo, psychological) fidelity aspects. As Suedfeld (2018) argues, after failing to find evidence that Antarctica stations are truly analogous to space environments in terms of isolation and confinement, analogies should be based on similarities of experience, not necessarily the environment.

Because different deliverables require simulated environments of different levels of fidelity (Gray, 2002), going forward, HSIA simulation needs would be best served by an environment that can scale and support varying levels of fidelity across multiple dimensions and collection of human performance standard measures. In simulation facilities that emphasize physical fidelity, such as those NASA-operated or -sponsored simulation facilities reviewed in Section 2, researchers are limited in their ability to control or alter the simulation and the performance measures they can derive from it because simulations often replicate the environments at the expense of their utility as a research tool (Cooke & Shope, 2017). The most feasible and versatile solution is to develop a synthetic task environment (i.e., a make-believe microworld) that supports the simulation of anomaly response research tasks constructed by systematic abstraction from real-world anomaly responses. Synthetic task environments are computer-generated environments that simulate conditions encountered in the real world while providing researchers with a level of experimental control as well as accuracy and efficiency of data collection typically only found in laboratory research (Alluisi, 1967; Brehmer & Dörner, 1993; Difonzo et al., 1998). In a typical synthetic task environment, tasks are made just complex enough to allow studying complex human performance in a semi-realistic setting but easy enough so that they can be performed by participants with limited training (Manzey et al., 2008).

Moreover, Brehmer and Dörner (1993) note that, unlike problems used in the classical psychology of thinking, an important characteristic of microworlds is that they present participants with several different problems simultaneously rather than a single well-defined task. To solve problems, participants must engage in goal analysis, formulating subgoals below the global goal given by the researcher. Then, participants must learn about the microworld and use their knowledge to form expectations, make prognoses, and decide actions and alternatives, while maintaining situation awareness of important variables and the effects of their actions and reconsidering and reevaluating their strategies. Last but not least, participants must also organize all those activities into some coherent whole; for example, they need to decide when they have collected enough information and must begin responses. In other words, microworld scenarios require combined and coordinated use of skills like thinking, problem solving, planning, or decision making, befitting what Elliott et al. (2001) conceived as having construct validity. In using microworlds, researchers knowingly trade physical fidelity for more experimental control and a larger participant pool. However, if the goal is to deliver standards (or requirements, guidelines), synthetic task environments may be the highest level of fidelity that can still produce findings generalizable to a wide range of situations.

Multi-Attribute Task (MAT) Battery (or MATB) is a synthetic task environment developed by NASA (National Aeronautics and Space Administration, 2014). Comstock and Arnegard originally developed it as a DOS-based experimental platform (Comstock & Arnegard, 1992). MATB became MATB-II when it was subsequently ported to Windows and upgraded with a graphical user interface (Santiago-Espada et al., 2011). Its development is currently supported by NASA's System-wide Safety Assurance Technologies (SSAT) project. MATB was designed to provide a benchmark set of tasks for studying operator performance and workload. It incorporates tasks analogous to crewmembers' activities in flight while providing a high degree of experimental control, supporting the collection of performance data on subtasks, and allowing the use of non-pilots as test participants. Tasks supported include system monitoring, manual target tracking, scheduling, communication, and resource (fuel) management. It has been used to study the effects of sleep deprivation (Caldwell & Ramspott, 1998), automated decision support (Rovira et al., 2002), effects of automation reliability on monitoring performance (Oakley et al., 2003), and management of multiple concurrent tasks (Gutzwiller et al., 2014).

Cabin Air Management System (CAMS) is arguably the most well-known and widely used microworld in the space domain. Hockey, Watsell, and Sauer (1998) developed CAMS as part of the European Space Agency's effort to advance space-related human factors research (Sauer, 2003). CAMS simulates an automated process control task based on a simplified life support system for human spaceflight. System operators carry out four tasks: system control, fault diagnosis, acknowledgment of alarms, and tank level recordings (Sauer et al., 2000). CAMS incorporates an alarm subsystem and allows a range of fault conditions to be preprogrammed to occur at various times during an experimental session. It uses simple schematics to represent the air management system visually. CAMS is built with a data-gathering capability that automatically records system states at 10s intervals and supports the reconstruction of the experimental session in its entirety. Those data support the measurement of a large number of performance measures: task performance, system interrogation and intervention, and subjective operator state (mental effort, anxiety, fatigue). The initial CAMS environment was written in MS Visual Basic, and participants used a mouse to interact directly with the displayed components of CAMS. Subsequent development and expansion added decision aid functionality (AutoCAMS, Lorenz et al., 2002) and ported the environment to Java (AutoCAMS 2.0, Manzey et al., 2008). CAMS has been used to study the effects of sleep deprivation (Hockey et al., 1998), training (Hockey et al., 2007), effects of levels of automation in fault management (Lorenz et al., 2002), isolation and confinement (Sauer et al., 1999), and more recently impacts of communication delays (Fischer & Mosier, 2014; Gonzalez et al., 2015; Mosier & Fischer, 2021).

How does one develop a synthetic task environment/microworld like MATB or CAMS? Although detailed steps might vary, developing a synthetic task environment typically begins with understanding the real tasks. Information that could inform this step includes documentation, interviews with experts, examination of other analog work environments, and behavioral and cognitive task analysis (Cooke & Shope, 2017). For example, Sauer, Wastell, and

Hockey (1996) analyzed space missions completed by NASA, ESA, and the Soviet space program and identified seven generic crew activity categories: management/planning, system control, payload operations, maneuvering, EVA, communications, and onboard training. Cognitive task analysis then helps identify the goals, cognitive demands, and resources required for the tasks and the high-workload, high-skill portion of the tasks (Martin et al., 1998). What comes next after task analysis varies, partly depending on the developer's approach. For example, Sauer et al. (2000) took what they describe as a theoretical approach to microworld design. Sauer et al. theorized how humans complete certain tasks and made specific predictions about how certain variables would impact the performance of those tasks. They then built conditions into the microworld that made it easier for the behavior to emerge. A specific example is that they predicted a decrement in human performance in low priority tasks (secondary tasks) is more likely to occur than primary task decrement under high workload. They implemented that hypothesis in the simulation model by incorporating several tasks, each with different priority gradients. The result is a simulated task environment that supports realistic representation and operation of the task domain and investigation of theoretical hypotheses. Unlike Sauer et al., Cooke and Shope (2017) simply worked to identify aspects of the actual task that they planned to emphasize (or exaggerate) according to their research objectives. For example, their interest in team cognition led to the abstraction of features such as distributed knowledge and information, knowledge and information sharing, planning and dynamic replanning, which then became features of conditions and events built into the synthetic task environment.

7 Conclusions

Mitigation of the HSIA risk requires an environment that can scale and support varying levels of fidelity across multiple dimensions and collection of human performance standard measures. Existing NASA simulation facilities focus on physical fidelity while simulation for HSIA risk mitigation requires capabilities to support task and functional fidelity aspects. A synthetic task environment (i.e., a make-believe microworld) that supports simulation of anomaly response research tasks constructed by systematic abstraction from real-world anomaly responses presents the most feasible and versatile solution. The present report describes anomaly response activities observed in two actual incidents on the ISS. Further work is needed to survey anomaly response scenarios and conduct cognitive task analysis on anomaly response activities. Abstract features can be built into the microworld to support realistic task experiences and research and development agendas by studying the goals, cognitive demands, and resources associated with these activities,

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Appendix:
Survey of Existing and Planned Simulation Capabilities Around NASA

We conducted a survey of existing and planned simulation facilities around NASA for evaluating crew performance. The survey was based on prior work by Dr. Donna Dempsey and updated to include more recent analogs, with a particular focus on capabilities relevant to validating concepts and evaluating implementations pertaining to the HSIA Risk. A total of 18 facilities were included in the survey under 4 categories:

Operations

- International Space Station (ISS)

NASA-Operated and/or Participated Research Analogs

- Human Exploration Research Analog (HERA)
- NASA Extreme Environment Mission Operations (NEEMO) in Aquarius
- Human-Rated Altitude Chamber Complex (ACC), including Human Exploration Spacecraft Testbed for Integration and Advancement (HESTIA)
- Crew Health & Performance Exploration Analog (CHAPEA)
- Hawai'i Space Exploration Analog and Simulation (HI-SEAS)
- Nezemnyy Eksperimental'nyy Kompleks (NEK) Ground-Based Experimental Complex
- Haughton-Mars Project (HMP) Flashline Mars Arctic Research Station (FMARS)
- Desert Research and Technology Studies (RATS)
- McMurdo Station
- Palmer Station
- Antarctic Search for Meteorites (ANSMET)
- Concordia Station

NASA-Sponsored University-Led Analog Environments and Research Facilities

- Habitats Optimized for Missions of Exploration (HOME)
- Resilient Extraterrestrial Habitats Institute (RETHi)

NASA Training Facilities

- Space Station Training Facility (SSTF)
- Space Vehicle Mockup Facility (SVMF)
- Neutral Buoyancy Lab (NBL)

The following details HSIA-relevant parameters for each facility.

International Space Station (ISS)

General Description

The International Space Station is a large spacecraft in orbit around Earth. Human research on ISS crew has made significant advances in understanding of the effects of physiology on human health in space missions, but ISS has traditionally not been as suitable for research on other hazards of human spaceflight such as isolation and communications delay.

Because ISS shares many similarities with interplanetary spaceflight, astronaut missions on ISS afford two major types of research capabilities for understanding space flight in low Earth orbit and beyond. The first is the ability to study the long-term effects of spaceflight factors (e.g., microgravity, radiation, etc.) on astronaut health and performance. ISS also allows the opportunity to simulate the isolation and autonomy that occurs in missions beyond low Earth orbit, thought the demand to prevent simulation activities from introducing real life dangers limits its practical simulation capabilities.

Hardware

- Environmental Control and Life Support System
- Medical capabilities
- Propulsion
- EVA hardware
- Electrical power system
- Thermal control system
- Payload dependent research equipment

Software

- Research software is payload dependent.
- Crew has access to caution & warning system, procedure viewers / execution, and system schematics and data (though not to the same extent as the ground) via laptops onboard the ISS.

Ground Simulation

- Mission Control Center (MCC) at Johnson Space Center consists of Front Room, Multi-Purpose Support Rooms (MPSRs), and Mission Evaluation Room (MER).
- Real communication with MCC.
- Can simulate communication delays, though past research (e.g., Kintz et al., 2016) has not delayed vehicle telemetry.

Telemetry

- Data exchanged between ISS and ground.
- Flight controllers in the Front Room are monitoring telemetry from all major systems.

Applicability to Lunar and Mars DRMs

- High fidelity hardware and software for Lunar and Mars simulation studies.
- Comm delay studies are possible, but the real danger posed by operating at a comm delay on ISS missions limits study capabilities.

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Human Exploration Research Analog (HERA)

General Description

NASA's Human Research Program utilizes the Human Exploration Research Analog (HERA) to conduct a series of analog missions. HERA, located at Johnson Space Center, is a unique 650-square-foot habitat split among two floors and a loft, designed to serve as an analog for isolation, confinement, and remote conditions in exploration scenarios. These simulated missions may include up to 45 days spent living and working isolated inside of the HERA habitat. Studies suitable for this analog include behavioral health and performance assessments, communication and autonomy studies, human factors evaluations, and medical capabilities assessments.

Hardware

- Virtual reality
- Laptops for crew
- Tablets for crew
- Simulated stowage
- Exercise equipment
- Simulated Environmental Control and Life Support Systems (ECLSS)
- 3D Printer

Software

- Mission-like timelines
- Software for studies is researcher dependent
- Flight simulators

Ground Simulation

- Mission Control Center (MCC) for real-time interaction with HERA crew members
    - 24/7 mission video surveillance with audio, recorded during mission
    - Voice communication recordings between HERA and MCC during the mission
    - Communication delay, voice and/or text, up to 20 minutes each way
    - Simulation of Acquisition of Signal/Loss of Signal (AOS/LOS) of varying duration

Telemetry

- Video feeds within habitat
- Data retrieved over internet
- Crew health data (e.g., heart rate, actigraphy)

Applicability to Lunar and Mars DRMs

HERA is capable of simulating communication delay, isolation, confinement, emergencies, and remote mission scenarios. VR does allow for simulated EVA tasks.

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NASA Extreme Environment Mission Operations (NEEMO) in Aquarius

General Description

The NEEMO analog mission uses the world's only operating undersea laboratory, Aquarius, to mimic the isolation, constrained habitats, harsh environments, and reduced gravity that challenge space exploration missions. Operated by Florida International University (FIU), Aquarius is located 5.6 kilometers (3.5 miles) off Key Largo in the Florida Keys National Marine Sanctuary. It was deployed next to deep coral reefs 62 feet (19 meters) below the surface. The Aquarius habitat and its surroundings provide a convincing analog for space exploration. NEEMO crew members, known as aquanauts, experienced some of the same challenges there that they would on a distant asteroid, planet or moon. During NEEMO missions, the aquanauts were able to simulate living on a spacecraft and test spacewalk techniques for future space missions. Working in space and underwater environments requires extensive planning and sophisticated equipment. The underwater condition had the additional benefit of allowing NASA to "weight" the aquanauts to simulate different gravity environments. The annual two- to three-week missions provide NASA aquanauts an opportunity to train crew; conduct behavioral, physiological, and psychological experiments; test hardware configurations; test exploration operations; and perform a host of other exploration-related activities.

NEEMO missions were discontinued in 2023.

Hardware

- Telerobotics
- Diving suits
- Vehicle mockups
- Rovers
- ETags

Software

- Lab/science supporting software

Ground Simulation

- Aquanauts are supported by a MCC.

Telemetry

- Direct communication, teleoperation of robots, medical data

Applicability to Lunar and Mars DRMs

NEEMO simulates a harsh exterior environment, lower gravity conditions, isolated conditions long duration missions of up to three weeks.

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Human-Rated Altitude Chamber Complex (ACC)

General Description

Located at Johnson Space Center, the ACC consists of eight chambers that can simulate characteristics of the space environment. Originally designed to test life support systems, the ACC can also be used to simulate isolation and other aspects of long-duration space flights. Two of the chambers are used primarily for human testing and can be modified to simulate different atmospheric pressure, lighting, and other conditions. ACC studies tend to focus on life support systems, long duration spaceflight, and psychological effects of confinement.

The ACC chambers have been used to simulate long-duration space flight, including a 56-day Skylab mission simulation and a 91-day Lunar Mars Life Support Test Project. During these simulations, investigators make every effort to limit supply replenishment and face-to-face contact with the crew, and the on-board team is responsible to attend to all interior upkeep and repairs.

Hardware

- EVA hardware
- Life support systems
- Programmable pressurized chamber
- Programmable temperature controlled enclosures
- "Canned man" (i.e., machine that simulates human systems such as metabolism)

Software

- No references to software and/or interfaces inside the analog (though could be brought in)

Ground Simulation

- No information about whether there is ground support offered as part of the ACC, but specific studies (e.g., the lunar Mars Life Support Test Project in the 1990s) had individuals monitoring the study.

Telemetry

- Suit data
- Chamber diagnostic info
- Data from "canned man
- Data from hardware being tested

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Human Exploration Spacecraft Testbed for Integration and Advancement (HESTIA)

General Description

HESTIA is a 3-story 20-foot diameter closed-loop habitat in the ACC used to support ongoing research in environmental control and life support systems, habitation systems, and human health and performance related to elevated carbon dioxide exposures. HESTIA can operate at reduced pressure and elevated oxygen environments (Pressure, CO_2 / O_2 Composition + Trace Gases). Data acquisition, power, fluids, and other facility resources are available.

Hardware

- ECLSS system consisting of:
    - 1) Air Revitilizaiton System which has 4 subsystems: fan, condensing heat exchanger, trace contaminant removal system, and reactive plastic lithium hydroxide unit (removes CO_2).
    - 2) Human metabolic Simulator.
    - 3) Electrolyzer.
- More technologies to be added to increase fidelity; existing components can be replaced.

Software

- No references to software and/or interfaces inside the analog

Ground Simulation

- No current ground component, though may be part of development plans

Telemetry

- ECLSS data

References

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Crew Health & Performance Exploration Analog (CHAPEA)

General Description

CHAPEA is a series of analog missions that aim to simulate year-long stays on the surface of Mars. The missions are conducted inside a 1,700 square foot 3D printed habitat, known as Mars Dune Alpha. The habitat includes private crew quarters, a kitchen, and dedicated areas for medical, recreation, fitness, work, and crop growth activities, as well as a technical work area and two bathrooms. Each mission will consist of four crew members. During the mission, the crew will conduct simulated spacewalks and provide data on a variety of factors, which may include physical and behavioral health and performance.

Hardware

3D printed hab with the following hardware:

- Dedicated workstations
- Medical station
- Food growing station
- Galley
- VR for EVAs

Software

- Lab/science supporting software related to simulated spacewalks (e.g., VR software) and robotic operations

Ground Simulation

- Crew supported by MCC. Supports Mars like communication delay.

Telemetry

- Direct communication, video, surveys

References

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Hawai'i Space Exploration Analog and Simulation (HI-SEAS)

General Description

HI-SEAS is an analog space research station at an isolated Mars- and Moon-like site on the Mauna Loa volcano on the Big Island of Hawaiʻi at approximately 8200 feet above sea level. HI-SEAS is unique, in addition to its setting in a distinctive analog environment, as:

1. Crew is selected to meet research needs (in serendipitous analogs, such as Antarctic stations, crew selection criteria are not controlled by researchers);
2. The conditions (habitat, mission, communications, etc.) are explicitly designed to be similar to those of a planetary exploration mission;
3. The site is accessible year round, and has very little variation in weather, allowing longer-duration isolated and confined environment studies than at other locations;
4. The Mars- and Moon-like environment provides for high-fidelity analog research tasks, such as geological field work carried out by human explorers and/or robots.

The HI-SEAS habitat itself is semi-portable, low-impact and designed to have all the desirable analog features specified in Keeton et al. (2011). It has a habitable volume of ~13,000 cubic feet, a usable floor space of ~1200 square feet and small sleeping quarters for a crew of six, as well as a kitchen, laboratory, bathroom, simulated airlock and engineering bay area. The HI-SEAS site has Mars and Moon-like geology, which allows crews to perform high-fidelity geological and astrobiological field work and add to the realism of the mission simulation. The habitat has developed high-latency communication system between the Crew and the Mission Support team with a Mars-like 20-minute delay on message reception each way (and a few second delay for lunar analog missions). Communication is solely through email. Comm latency and other mission parameters can be varied according to study requirements.

Hardware

- Virtual reality
- Space suits
- EVA equipment
- Workbench with tools for repairs
- Electrical system
- 3D printer
- Lab equipment for water & air monitoring

Software

- Dashboard for telemetry
- Experiment-specific software (e.g., robotics, 3D modeling)
- Software provided by external researchers for specific studies

Ground Simulation

- Crew supported by MCC both in analog and during EVAs.
- Can support Mars like delays (20 minutes both ways)

Telemetry

- Suit data
- Video
- Voice
- Hab telemetry
- Weather
- Crew has access to power, water, and weather data (shown in Figure A1 above)

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Nezemnyy Eksperimental’nyy Kompleks (NEK) Ground-Based Experimental Complex

General Description

Nazemnyy Eksperimental’nyy Kompleks, or NEK, is a unique, multi-compartment facility at the Institute of Biomedical Problems (IBMP) of the Russian Academy of Sciences in Moscow, Russia. NEK is used as an analog for isolation, confinement, and remote conditions in exploration scenarios. The pressurized facility can accommodate up to six crew members and operate for long-duration missions of more than one year. The crew members are physically isolated from the outside world and have limited communication beyond NEK’s walls.

Built in the 1960s, NEK has a long history of conducting isolation studies. Previous missions include the Mars-500 Project that lasted 520 days. This was an analog study involving three missions conducted between 2007 and 2011, in preparation for an unspecified future human spaceflight to Mars. The first mission of Mars-500 was 14 days, followed by a 105-day mission. The final Mars-500 mission, which simulated a 520-day human mission, was conducted by an all-male crew consisting of three Russians, a Frenchman, an Italian, and a Chinese citizen. The experiment yielded important data on the physiological, social and psychological effects of long-term, close-quarters isolation. More recently, NEK has been used in SIRIUS missions.

Hardware

- Analog spacecraft
- Virtual reality
- Storage
- Exercise equipment
- Communication
- Medical equipment
- Lab equipment
- Work stations
- EVA simulations equipment

Software

- Lab/science supporting software provided for specific studies.
- Planetary surface simulator with 3D mockups of space system
- Operations console – includes equipment for communicating with MCC and monitors that display data on the station’s life support system.

Ground Simulation

- Yes, mission control with communication delays.

Telemetry

- Video, audio, health data; hab data

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Haughton-Mars Project (HMP) Flashline Mars Arctic Research Station (FMARS)

General Description

HMP is part of a research facility located on the world's largest uninhabited island, Devon Island in Baffin Bay, Qikiqtaaluk Region, Nunavut, Canada. Devon Island's barren terrain, freezing temperatures, isolation, and remoteness offer scientists and personnel unique research opportunities. Arctic day and night cycle and restricted communications capabilities offer fitting analogs for the challenges of a long-duration space flights.

The Flashline Mars Arctic Research Station (FMARS) is an analog habitat 8.81m in diameter and 7.66m tall at the top of its domed roof, containing enough living volume for 6-7 crew members on missions ranging from one to four months in duration. The habitat contains a science laboratory, engineering space, exercise equipment, hygiene facilities and two simulated airlocks on the first floor. The second floor is dedicated to crew accommodations including desk space, kitchen facilities, a dining table, and six small staterooms. A loft above the second floor provides storage for consumables and a possible seventh sleeping area.

Hardware

- Robots, rovers, EVA suits, Automated Transfer Vehicles (ATVs), simulated patients for medical scenarios

Software

- Lab/science supporting software; selected participants are expected to have their own research protocols.
- Planning software.

Ground Simulation

Mission support team that:

- Assists crew with complex troubleshooting which does not require quick turnaround
- Provides telemedicine support
- Provides news from home

All comms are on a Mars-like delay (e.g., around 20 minutes each way).

Telemetry

- Teleoperation of rovers and other robots, EVA communications

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Desert Research and Technology Studies (RATS)

General Description

Desert RATS is a series of field tests and simulated missions evaluating technology, human-robotic systems, and EVA equipment for future human exploration missions. Simulated missions have taken place in northern Arizona and at Johnson Space Center. The Desert RATS team evaluates technology, robotic systems and extravehicular equipment for future missions in space. This analog helps engineers design, build and operate better equipment, and establish requirements for operations and procedures. Studies suitable for this analog include spacesuit equipment, robots, habitation modules, exploration vehicles, surface mapping, navigation techniques, and communication systems.

Hardware

- Habitat Demonstration Unit
- EVA Suits
- Rovers
- Studies suitable for this analog include spacesuit equipment, robots, habitation modules, exploration vehicles, surface mapping, navigation techniques, and communication systems.

Software

- Cockpit-related software inside the rover (e.g., rover hab dashboard, cameras, plans)
- Hab control computer outside the vehicle (allows for closing the hatch)

Ground Simulation

- Desert RATS has tested communications scenarios (continuous vs twice a day) between crew on EVA and ground team during traverses.
- Fully staffed Mission Control center at JSC.

Telemetry

- Field data (video, voice, photos etc.), communication, remote rover control, rover data

Applicability to Lunar and Mars DRMs

- Desert environment provides conditions analogous to lunar and Mars conditions (challenging terrain, interesting geology, and minimal communications infrastructure).
- Appears mission dependent but Desert RATS does simulate communication delays and test equipment that supports crew autonomy (robotic assistants, Extravehicular Activity Information Systems *EVAIS* etc.)

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McMurdo Station

General Description

The United States' Antarctic Program (USAP) maintains McMurdo. Scientists believe that Antarctica's climate, terrain, temperature, and isolation provide an environment on Earth that most closely parallels the conditions of isolation and stress to be faced on long-duration human missions in space. This analog provides a unique and accessible test bed to develop prototype systems and technologies for use on the Moon and Mars. Research disciplines at McMurdo include astronomy, atmospheric sciences, biology, Earth science, environmental science, geology, glaciology, marine biology, oceanography, climate studies, and geophysics.

Hardware

- The A.P. Crary Science and Engineering Center at McMurdo contains state-of-the-art instrumentation to facilitate research and to advance science and technology. It contains modern personal computers and workstations. It has laboratory space, analytical instrumentation, and staging areas for a wide range of scientific disciplines.
- Infrastructure supporting station (e.g., power)

Software

- The A.P. Crary Science and Engineering Center has computer-based geographic information system (GIS), and a local area network (ability to support software).

Ground Simulation

N/A

Telemetry

N/A

Applicability to Lunar and Mars DRMs

- Ability to conduct extended field studies that replicate conditions present on surface missions (e.g., limited resupply, harsh environment, limited comms, difficult evacuation)
- McMurdo Station itself is isolated, but doesn't contain hardware or software capabilities needed to study HSIA risk.

References

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Palmer Station

General Description

Of the three U.S. Antarctic stations, Palmer is the only one that is accessed routinely during the winter. This station has a well-equipped laboratory and provides the opportunity for study of Biological, Ornithological, Meteorological, Atmospheric, Glaciological and Marine Ecosystem science. Palmer has research focused on the Antarctic marine ecosystem, including sea ice habitats, regional oceanography and terrestrial nesting sites of seabird predators. The station maintains networks for year-round monitoring of global seismic, atmospheric, UV activity and houses a radio receiver studying lightning over the Western Hemisphere.

Hardware

- Lab/science equipment
- Infrastructure supporting station (e.g., power)
- Google trekker backpacking camera
- Boats
- Forklift

Software

- Lab/science supporting software related to biological studies of the marine ecosystem, ocean and climate systems studies, aeronomy and astrophysics, and glaciology.

Ground Simulation

N/A

Telemetry

N/A

Applicability to Lunar and Mars DRMs

- Ability to conduct extended field studies that replicate conditions present on surface missions (e.g., limited resupply, harsh environment, limited comms, difficult evacuation)
- Palmer Station itself is isolated, but doesn't contain hardware or software capabilities needed to study HSIA risk.
  - Limited resupply – resupplied by ship that makes routine science research cruises around the peninsula
  - No routine air access

References

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Palmer Station Timeline 2015-Present. Palmer Station. https://www.palmerstation.com/history/1525/1525.html

Antarctic Search for Meteorites (ANSMET)

General Description

ANSMET is a program funded by the National Science Foundation that looks for meteorites in the Transantarctic Mountains. This geographical area serves as a collection point for meteorites that have originally fallen on the extensive high-altitude ice fields throughout Antarctica. ANSMET is a field team (typically based out of McMurdo) where teams set up remote camps on the ice. Teams typically have six people (two permanent members and four visiting members, usually meterorite specialists), though they can have anywhere from four to ten, and live for 5–7 weeks on the ice field. Using snowmobiles spaced 30 m apart they scan the blue ice for meteorites.

Hardware:

- Snowmobiles
- Scott tents
- Stove for cooking & stove for heat
- Solar panels
- Computers
- Radios

Software:

- GPS
- Personal laptop software dependent on individual.

Ground Simulation

- N/A – no simulated ground. Limited contact with McMurdo Sound (typically one call a day)

Telemetry

N/A

Applicability to Lunar and Mars DRMs

- Extreme environment, limited resupply, limited comms
- Assume that the team has to conduct in-situ maintenance and repairs
- No opportunity for experimental manipulation

References

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Graf, A. (Ed.) (August 9, 2023). *Antarctic Stations*. NASA. https://www.nasa.gov/antarctic-stations-nsf/

Concordia Station

General Description

Concordia is operated by the French Polar Institute (IPEV) and the Italian Antarctic Programme (PNRA). It is located more than 1000 km away from the coastal stations. Many researchers use this facility for psychology, physiology, and medicine. Some "crew members" perform a winter-over where they are part of research lasting the entire winter. Research performed at Concordia includes glaciology, atmospheric studies, astronomy, human related research, and some technologies.

Setup: Three building linked by enclosed walkways:

- Quiet building (sleeping quarters, labs, and hospital)
- Nosiy building (workshop, waste water treatment plant, communication room, kitchen, and cafeteria)
- Third building made up of eleven container size modules where the electric power plant, boiler room, and second workshop is located

During the Winter-over campaigns, there are around 10 participants with no resupply.

- One particular campaign makeup: four technicians for maintenance, four scientists, cook, medical doctor

Hardware

- Soyuz simulator hardware
  - Not high on physical fidelity – chair with four screens and two joysticks
  - Blanket draped over the setup
  - The simulator's hardware is a simplified version of the real Soyuz cockpit, but it features the main and necessary controls and systems that are needed to perform a rendezvous and docking procedure (propulsion, radar, communications,...). The limited space and weight to be shipped to Antarctica lead to the design of an adapted one-seater simulator, which nevertheless provided the same features for the pilot, as seen in Figure 5.
- Building infrastructure (e.g. power)
- Lab equipment

Software

- Soyuz simulator – docking and rendezvous software capabilities
  - At the Institute of Space Systems of the University of Stuttgart, a Soyuz-TMA spacecraft simulator has been used for training and research during the last decade. Different flight phases have been under focus, most especially the close-range approach and docking to the Russian segment of the ISS. The spacecraft docking simulator, a self developed set-up with a core based on the Orbiter Spaceflight Simulator is capable of recreating a realistic docking maneuver and requires a high level of skill performance from the pilot, who needs to control a 6 degrees-of-freedom spacecraft while monitoring other flight parameters displayed in the featured cockpit.

- Lab software

Ground Simulation:

N/A

Telemetry:

N/A

Applicability to Lunar and Mars DRMs

- Replicates some conditions present on surface missions (e.g., limited resupply, harsh environment, limited comms, difficult evacuation, isolation, etc.)
- Soyuz simulator – applicability for docking operations

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Habitats Optimized for Missions of Exploration (HOME)
University of California, Davis & University of Colorado Boulder

General Description

The HOME Space Technology Research Institute is a NASA-sponsored team of approximately 70 professors and students across seven U.S. universities who are engaged in fundamental and applied research to identify and develop critical technologies required for NASA to design and execute a class of deep-space human habitats unlike anything that has been fielded so far.

The five HOME research thrusts are designed to develop and validate the target technologies that will allow a deep-space habitat to function without crew for long periods, to predictably transition to and from crewed states, and to support a human crew onboard the habitat. Accordingly, autonomous systems must possess the ability to learn from experience, from directed training, and from human demonstration, allowing the SmartHab to become increasingly safer and more capable over the years-long span of its in-space mission.

The HOME mockup at the University of Colorado Boulder includes displays, docking and landing control simulators, a science station, a 6DOF robotic arm, data connections to environmental control testbeds, and day-in-the-life stations similar to those in actual space habitat designs. Researchers spread across a variety of projects use the mockup to investigate human health and performance and to develop environmental control systems.

The team also created an Aerospace Research Simulator (AReS) at the University of Colorado Boulder. The simulator evolved into a testbed that can be oriented in a vertical or horizontal configuration for assessing ascent or entry modes of flight, respectively. The facility now supports human factors testing and evaluation of cockpit layout and operations. A flight simulator system controlled by an external instructor console is currently being developed and implemented.

At the University of California Davis & Colorado Boulder, the team developed an ECLSS-focused design reference scenario with an associated mockup, called the Air Revitalization Rack (ARR). It is representative of future ECLSS hardware that will likely take on a consolidated, stacked configuration with a digital controls interface and accessible ports and interfaces. Subjects complete spaceflight-relevant tasks while receiving recommendations about actions they should take from an autonomous system. If an autonomous system can measure an operator's cognitive state and adapt accordingly, it can best aid the operator as they complete their tasks. Identical mockups are housed at UC Davis and CU Boulder.

Hardware

- ARES: cockpit mockup (2 seats + three screens + joysticks), external instructor console
- Racks: ECLSS rack mockup with parts and control interfaces
- HOME mockup: displays, docking and landing control simulators, a science station, a 6DOF robotic arm.

Software

- ARES: flight simulator software, autonomous system for recs

- Racks: ECLSS model?
- HOME mockup: display software, docking and landing simulation software.

Ground Simulation

- N/A – simulating fully autonomous ops.

Telemetry

- Presumably, ECLSS telemetry flow from rack (which is connected to HOME mockup), docking and landing simulated telemetry, and flight simulator telemetry.

References

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Resilient Extraterrestrial Habitats Institute (RETHi)

General Description

The Resilient ExtraTerrestrial Habitats Institute (RETHi) has the mission of leveraging existing novel technologies to provide situational awareness and autonomy to enable the design of habitats that are able to adapt, absorb and rapidly recover from expected and unexpected disruptions. RETHi is establishing both fully virtual and coupled physical-virtual simulation capabilities that will enable the exploration of a wide range of potential deep space SmartHab configurations and operating modes.

The team is not designing a habitat, but rather is conducting the research needed to develop the tools and techniques that will support resilience in these systems

Capabilities in development:

- Modular coupled virtual testbed: plug-and-play sim environment
    - Integrating SmartHab subsystem models in a single simulation environment
    - Includes low- to moderate-fidelity physics-based models, each with appropriate and relevant damageable/repairable subsystem properties
    - System of systems – allows team to carry out wide array of quantitative research
    - Written in MatLab – models and simulates integrated habitat as system as systems
        - Six system blocks that represent six physics based-models:
            - Structure
            - Power
            - ECLSS
            - Interior Environment
            - Health Management & Agent
            - Exterior Environment
    - Potential to model cascading events, but no human-in-the-loop component
- Cyber-physical testbed: integrates physical testing and numerical simulation to provide a modular and reconfigurable testbed
    - Physical models of key subsystems like structural system and sensors for fault detection
- Control-oriented dynamic computational modeling framework: enables us to automatically build a coarse dynamic model of the interconnected system (or generate many system models with different configurations) with the functionalities and features we intend to investigate

Hardware

- Plans to create cyber-physical testbed with physical models of key subsystems and fault detection sensors

Software

- Modular coupled virtual testbed (in dev): plug-and-play sim environment w/ SmartHab subsystem models

- Control-oriented dynamic computational modeling framework (planned)

Ground Simulation:

N/A, no human-in-the-loop component currently

Telemetry

- Simulated data in MCVT
- Planned telemetry coupled with hardware when cyber-physical testbed is developed ability to simulate all ISS system data

References

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Space Station Training Facility (SSTF)

General Description

The Space Station Training Facility is a full scale, multi-system integrated mockup that allows for the simulation of complex ISS scenarios for the purpose of flight controller training. Flight controllers in training sit console in a fully equipped Mission Control front room and respond to scenarios crafted by a team of flight controller instructors. The facility includes simulated crew and crew station mockups and trains flight controllers on full team coordination and communication.

Hardware

- Computer devices, etc. associated with Mission Control, though no hardware that would be found on the ISS

Software

- High-fidelity computer sims of all ISS and flight control systems

Ground Simulation:

- Yes; entire simulation is ground team.

Telemetry

- Yes; simulated telemetry flow for all ISS systems

References

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Space Vehicle Mockup Facility (SVMF)

General Description

Located at Johnson Space Center, the SVMF contains mockups of ISS, ORION, commercial vehicles, the Precision Air Bearing Floor, and a partial gravity simulator. The SVMF supports crew training and assessment as well as layout assessment. A major task of the SVMF is to support Engineering and Mission Operations evaluations for the International Space Station (ISS) and Orion Programs. All mockups and part-task trainers are available to support troubleshooting on the ground any time problems develop on orbit in real time.

Hardware

- Mockups of ISS, ORION, commercial vehicles, the Precision Air Bearing Floor, and a partial gravity simulator.

Software

- Control consoles for U.S. Lab modules are used for scientific payload and interface training.

Ground Simulation

- Mockups and trainers receive real-time mission support.

Telemetry

- Personnel in the SVMF are supported by video and audio.

References

Johnson Space Center. Space Vehicle Mockup Facility (SVMF).
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Neutral Buoyancy Lab (NBL)

General Description

Located at Johnson Space Center, the NBL is a facility aimed at helping astronauts prepare for spacewalks. NASA team members use the NBL to develop flight procedures, verify hardware compatibility, train astronauts and refine spacewalk procedures during flight that are necessary to ensure mission success.

Hardware

- Spacesuits
- Communication systems
- CCTV
- Medical equipment
- Remote manipulators
- ISS mockup

Software

N/A

Ground Simulation

- Crew can communicate with each other, the crew in the shuttle simulator, and with MCC at JSC.

Telemetry

- Two-way communication, CCTV for monitoring divers

References

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