Characterizing Self-Sufficiency and Habitability for Autonomous Deep-Space Habitat Operations

by

Sophia Anne Zaccarine

B.S., Embry-Riddle Aeronautical University, 2015

M.S., University of Colorado, 2022

M.E., University of Colorado, 2022

A dissertation submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirement for the degree of

Doctor of Philosophy

Ann and H.J. Smead Department of Aerospace Engineering Sciences

2024

Committee Members:

Dr. David Klaus, Chair

Dr. Allison Hayman

Dr. Torin Clark

Dr. Jim Clawson

Dr. Christine Fanchiang

IRB Protocol #23-0669

Zaccarine, Sophia Anne (Ph.D., Aerospace Engineering)

Characterizing Self-Sufficiency and Habitability for Autonomous Deep-Space Habitat Operations

Thesis directed by Dr. David Klaus

Deep-space human exploration will necessitate increasing operational autonomy for the crew and habitat as reliance on extensive Earth support becomes impractical. In this context, the habitat and onboard crew must effectively become an 'autonomous system' that can operate for finite periods without external intervention from outside a defined control volume, which historically has extended beyond the habitat to include ground facilities, teleoperators, and other space assets. For deep-space exploration missions, however, timely logistical resupply becomes impractical and communication with Earth is delayed, or even impossible at times from occultations. Therefore, to enable the operational autonomy needed to accomplish the overall mission objectives, additional onboard capabilities will be required to offset decreased Earth-based support and move toward self- sufficiency. These capabilities may be facilitated by emerging technologies, This thesis characterizes the required functionality needed to enable operational autonomy in deep-space and identifies other potential benefits, or improvements beyond State of the Art (SoA), that can be provided by design attributes for emerging technologies to close the gap between current Earth-dependent limitations and required (or desired) onboard capabilities.

First, the general functionality needed to enable deep-space missions is identified and categorized as nominal, off-nominal, or a blend between the two with the goal of enabling operational autonomy. These primary enabling capabilities are further broken down into operations that involve monitoring, maintenance and fault management. This dissertation identifies and examines these basic requisite capabilities using an abstraction

hierarchy process to create a visual representation of a functional decomposition, along with an information flow model as components of a work domain analysis. The effort is aimed at establishing design considerations for enabling self-sufficient deep-space autonomy, referred to as Earth Independent Systems Operations (EISO).

Second, other non-essential, but potentially beneficial, opportunities are explored for their contributions to improving habitability. Where self-sufficiency captures *required* functionality, potentially *beneficial* opportunities that can improve crew well-being can be mapped to habitability. This research proposes a process to characterize habitability by aligning it with two of the three key tenets of a human-rated spacecraft: *Accommodate* and *Utilize*, while the third tenet, *Protect*, which is focused on risk mitigation, is not addressed in this research effort. Novel stratifications of 'Attributes of Accommodate' (what the habitat does) and 'Degrees of Utilize' (what the crew does) to assess the tenets of accommodate and utilize are proposed to detail how a habitat with increasingly autonomous capabilities influences habitat and crew task allocation. Components of habitability, distilled from a broad literature review, are then aligned with proposed attributes of accommodate and applied to select examples from past missions.

Third, a triangulation method is incorporated that uses a combination of qualitative and quantitative research methods. This approach supplements the top-down functional analysis with a bottom-up, empirically derived set of data that demonstrates the utility of the work compiled from the characterization of self-sufficiency and habitability. Qualitative interviews with subject matter experts (SMEs) were conducted under CU IRB Protocol #23-0669 to identify design attributes that are deemed to be important when designing toward a maintainable ECLSS. The interview goals were derived from the broader topics of self-sufficiency and habitability to focus on 'maintenance' as an example representing one category of the general enabling capabilities needed for deep-space autonomy. These

attributes are compiled into Design Considerations and Operational Considerations and were derived using thematic analysis.

Finally, to further contextualize the attributes of maintainable ECLSS and better understand how to use them in future trade studies when designing deep-space habitats, a Likert rank-order survey was created and distributed to ECLSS professionals with a request to rank the compiled attributes as 'Not Important', 'Somewhat Important', 'Important', or 'Very Important,' with an option to select 'Unsure' for no ranking. To assess validity of the listed design attributes, these participants were also asked to contribute any additional themes they thought were missing from the analysis. The results are displayed in a diverging stacked bar chart which demonstrates the relative importance of the ranked attributes. From the survey, two additional design attributes were provided in the free-response questions, one of which was added to the overarching drivers, which resulted in a total of 24 attributes ranked for consideration when designing maintainable ECLSS. The set of 24 attributes are compared to several NASA design standards and handbooks to assess their alignment with broader topic of maintainability. Given that ECLSS is a critical subsystem tasked with keeping the crew alive, many of the derived design attributes are also extensible to a number of other critical subsystems on a deep-space habitat.

These results propose a systematic method for identifying the functionality required to enable operationally autonomous deep-space missions by characterizing self-sufficiency and/or improving habitability as underlying design drivers. The process presented demonstrates a combination of top-down functional analysis methods with bottom-up qualitative and quantitative experimental data.

Acknowledgements

First and foremost I must thank my advisor, Dave Klaus. Dave is well-known and respected in our field for his impressive accolades, professional achievements, and talent as a professor. In addition to this, I am grateful to have worked with him because he is a genuinely caring and good person. It is rare to have the chance to learn from someone with his caliber of skill and also kindness and humility. Thank you for giving me positive and constructive feedback and teaching me to understand the power of cohesive storytelling for a complex topic. You always made time to meet with me for reviews of my research and for this I am grateful. Thank you for choosing to mentor me through this process even though part of how I pitched my application was by asking you to attend my conference talk that was scheduled after 9:00pm at Big Sky!

I want to also thank my committee for their time spent reviewing my comprehensive exam and now dissertation, for answering niche questions about statistics, and for helping teach me the importance of rigorous science and constructing a thesis.

To my colleagues, friends, and support system Dr. Rollock, Michael, and Patrick. Thank you Annika for your wisdom, athletic inspiration, and cheering me on through this process. Thank you Michael for supporting my moments of self-doubt with long conversations, empathy and pizza. Thank you Patrick for the hot takes and reality checks, reminding us that grind culture is great but rest is equally important. You three have been so kind, incredibly intelligent and creative in your work and I am proud to have been included alongside you in our cohort. You have made me a better person and researcher.

To Dr. Sam Eshima, Dr. Jacob Kintz, and Ulubilge Ulusoy (our honorary Buff). We began the HOME journey together I'm so glad to have worked closely with you. I want to also extend my thanks to the broader HOME community – all the friends I have made and everything I have learned from the variety of expertise across the STRI has been a wild ride and it's bittersweet to see it coming to a close with our final review this year.

I have been fortunate to be a part of various support groups in the aerospace engineering department at CU Boulder. I want to thank the entire CU Boulder Bioastronautics program. The genuine support each student has for the others makes this a healing and unbelievably supportive culture I'm grateful to have been a part of. I want to extend my gratitude to the aerospace advisors and staff – Joanie Wiesman, Lydia Pinkham, and Nicole Simmons, thank you for helping me ensure all my paperwork and deadlines were met to completion. You are the best! I extend my gratitude to Misty White, our IRB manager, for always being kind and meeting with me to help ensure I completed my projects with attention to detail and comprehension.

During my time at CU, I was able to learn about far more than the research topic I investigated. During my dual MS process, I took many different classes for my engineering management degree, and I am grateful for how much I learned from these classes that were fun and expansive. I am grateful for the CU Women's club soccer program that gave me the opportunity to have a collegiate soccer experience and compete at a national level in the sport I love. I was also a part of various design and mentoring groups for social justice where I learned about social justice and equity research, how to be a more effective ally, and how much I can continue learning.

To the land that I was on for graduate school and the mountains that have given us peace and contentment each day in our surroundings. I want to acknowledge these are unceded lands of the Cheyenne, Arapaho, and Ute nations and wish to acknowledge their

communities, elders and future generations (Garcia, F., 2018; University of Colorado at Boulder, n.d.). This research also cites behavioral studies that are over 100 years old, and I want to acknowledge the animal subjects who were unwittingly a part of these and adjacent studies.

To my colleagues and friends from NASA Goddard – you all inspired me to pursue this journey in the first place and showed me that a career in spaceflight can come with a supportive, inclusive, and empathetic community. And especially to my mentor Doug, the chance to travel to the north pole, launch hardware into space, and be on NASA TV will forever remain a life highlight and provided the content for the conference presentation that was part of why I was accepted into this program.

To all my friends that I've met in graduate school all the way back to my friends from where I grew up, thank you for helping me pick my head up from my work and retain perspective. To my sunflower women and friends, our continued friendship and your support through this entire process means so much to me.

To my family, near and far (mostly far). I am fortunate to have been born into a big family that thrives on overwhelming love, energy, and fun. I am who I am today because of the inspiration I have taken from my aunts, uncles, cousins, grandparents, siblings, and parents, including those who are not here to see the conclusion. My parents are the most honest, hardworking people I have ever known and are the people that instilled in me an entrepreneurial spirit, realism, a personal ethos, and the work ethic that I've relied on to bring me to the finish line. Thank you for filling our home with safety, warmth, home cooking and endless books that spurred my dream to pursue learning and curiosity. My siblings Sarah and David have, among endless support, sent me numerous cat videos and have kept my feet on the ground through our lives. Mae and Juno, your antics, midnight

yowling, ceaseless desire to play fetch, top-tier biscuit making and purring have made us laugh daily and your unconditional love brightens our world.

To Alexander. We met the first day of this journey and haven't been apart since. You've been there through the late nights and very early mornings, the times leading up to milestones where I subsisted on matcha, smoothies, emotional support popcorn, and of course the many nutritious meals that you prepared for us, and every day in between. Your endless support of my mental, physical, and emotional health with goofiness, affirmations, dance parties and an unwavering belief in me have been the foundation of this entire effort. To quote Finding Nemo, "I look at you, and I'm home" (Stanton, A. & Unkrich, L., 2003).

And finally, to my past self, 20+ years ago. Your dreams, wonder and enchantment with the natural world, why things work they way they do, black holes, faraway galaxies and magic will be questioned, prodded, doubted and you will even grow to almost completely doubt yourself. But you will find yourself again. Filter the noise, bet on your inner strength, and choose the path that surrounds you with humble, caring, hardworking people who will hold you up through the journey. I'm proud to say that I did.

"I had an experience...I can't prove it, I can't even explain it, but everything that I know as a human being, everything that I am tells me that it was real! I was given something wonderful, something that changed me forever. A vision of the universe that tells us, undeniably, how tiny, and insignificant, and how rare and precious we all are! A vision that tells us that we belong to something that is greater than ourselves, that we are not, that none of us are alone!"

– Jodie Foster (Robert Zemeckis, 1997).

Film adapted from 'Contact' written by Carl Sagan (Sagan, 1985).

Funding

This effort was supported by NASA under grant number 80NSSC19K1052 as part of the NASA Space Technology Research Institute (STRI) Habitats Optimized for Missions of Exploration (HOME) 'SmartHab' Project. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

This effort was also supported by the funding provided for a Teaching Assistant position in the Fall Semester of 2019 for ASEN 3112 – Structures in fulfillment of the PhD Teaching Practicum requirement.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

It is well recognized that deep-space human exploration missions will require increasing levels of autonomy. The NASA Moon to Mars (M2M) Habitation Considerations Technical Memorandum emphasizes the use of autonomy in lunar surface and Mars transit operations and states autonomy must be assumed to enable long-duration, uncrewed missions (Harris, et al., 2022). Predictions for future deep-space missions assume an average mission length of ~914 days, while the NASA M2M estimates a ~1,200 day mission without resupply (Drake, 2009; Harris, et al., 2022). Operational autonomy onboard a deep-space habitat implies the habitat and crew, collectively forming an autonomous system, can function with a high level of self-sufficiency without the extensive Earth-based support needed for current operations (Rollock & Klaus, 2022). To achieve the higher levels of autonomy needed for deep-space exploration, emerging technologies introduce potentially enabling solutions to the trade space (Pischulti et al., 2024). A technology is considered 'emerging' if it is novel, fast-growing, and if its most prominent impacts exist in the future (Rotolo et al., 2015).

Emerging technologies offer potential to fill the gaps between the current low Earth orbit (LEO) State-of-the-Art (SoA) capabilities, represented by ongoing operations such as those conducted on the International Space Station (ISS), and the required and desired needs for deep-space exploration. However, by definition, these technologies are low-

Technology Readiness Level (TRL), and therefore not yet sufficiently developed for use in spaceflight. Exploring the potential of promising new technologies capable of enabling deep-space 'Smart Habitats' is the focus of the NASA 'Habitats Optimized for Missions of Exploration' (HOME) Space Technology Research Institute (STRI).

To meet the demands of deep-space operations, future 'Smart Habitats' can be assessed based on their ability, by way of humans and/or machines, to complete required functions autonomously without relying on external support or intervention. A boundary of external support (i.e., capabilities with respect to contributing agents) is established to define the control volume, which for this research, encompasses only the habitat such that all operations during a finite mission period can be completed independent of Earth support, allowing the habitat systems and/or crew to act autonomously, displaying self-sufficiency, in critical situations. A self-sufficient system is informed by self-awareness and possesses the necessary onboard abilities to complete all mission-enabling and critical functions for a specified duration of time, where self-aware systems have knowledge of their internal and external environment, previous states, actions and consequences which inform future decision-making (Rollock & Klaus, 2022).

For the deep-space work domain of human exploration, physical context is marked by extreme distance from Earth, which impedes communications due to signal transmission time delays and periodic occultations. Additionally, timely resupply flights become impractical due to extended transit times from Earth. The resultant impacts to communication and logistical support in turn drives the need to increase onboard autonomous capabilities in order to achieve mission objectives with reduced Earth-reliance.

Additionally, human spaceflight is fundamentally complex and hazardous, demanding rigorous risk mitigation approaches enabled by the social dynamics of the onboard crew and ground team in order to respond to life- or mission-threatening situations

in a time-critical manner if anomalies occur. Together, these elements form a 'sociotechnical system' as defined by Vicente (Vicente, 1999). Cognitive work analysis of sociotechnical systems is particularly useful for revolutionary, or emerging, systems that may present novel functionality (Crone et al., 2003). Emerging technologies that have been integrated successfully to cope with 'real world problems' typically result from proactive cognitive analyses done by developers to understand the user's work environment (Deal & Hoffman, 2010b). Additionally, creating intelligent systems to be used in future domains has historically triggered unanticipated effects on cognitive work, emphasizing the importance of conducting these cognitive analyses early (Hoffman et al., 2010).

Therefore, identifying and analyzing those tasks that must be completed onboard to enable self-sufficient operations are necessary precursors before specific technologies can be developed to accomplish them. This research focuses on determining, categorizing, and analyzing those deep-space habitat functional needs using a combination of top-down functional analysis and bottom-up qualitative and quantitative experimental data which lays the groundwork for later technology development, including for emerging technologies.

A systematic method is proposed for identifying required functions of operationally autonomous deep-space habitats by characterizing self-sufficiency and habitability as design drivers. The compiled design criteria leveraging best practices and lessons learned from past missions can guide designs for future deep-space habitats that will need to accomplish unprecedented operational autonomy.

Chapter 2

Background and Literature Review

2.1 Autonomy and Self-Sufficiency

2.1.1 Levels of Autonomy

Characterizing autonomy into discrete levels was originally proposed by Sheridan and Verplank (Sheridan & Verplank, 1978), who contrasted levels of a computer's autonomy relative to a human's level of control. Additional levels of autonomy have been proposed by the Society of Automation Engineers (SAE) for self-driving vehicles which define levels of vehicle autonomy versus control and decision-making offered by the human driver for driving-related tasks such as braking, assessing road conditions, and steering (SAE International, 2018). Aviation Autonomy Levels have also been defined, referencing the SAE automotive levels to capture autonomy of pilot tasks, as there is growing interest in incorporating increasingly advanced flight systems and eventually full autonomy (Anderson et al., 2018). Proposed space-trusted autonomy levels were generated by Hobbs et al. (Hobbs et al., 2022) by contrasting Technology Readiness Level (TRL) with operator trust, resulting in an augmented set of Trust Readiness Levels (TrRLs) that guide selection of an appropriate autonomy level based on technology readiness and human trust.

2.1.2 Emerging Technologies as Potential for Enabling Self-Sufficiency

Emerging technologies in areas such as human-autonomy teaming, additive manufacturing, and machine learning can potentially decrease the need for Earth support by providing necessary onboard functions and increasing self-awareness, with the ultimate

goal of enabling self-sufficient operations (Klaus et al., 2022). Most emerging technologies are predominantly intended for terrestrial settings and/or are in low-TRL design stages, thus may offer potential, but not yet feasible spaceflight applications, as summarized in Pischulti et al. (Pischulti et al., 2024) . The creation of intelligent technologies to fit within future work systems is a documented challenge especially in spaceflight as there is a tendency to avoid low-TRL options (Deal & Hoffman, 2010a). Self-sufficient systems rely on self-awareness and must have adequate cabilities onboard to complete mission-critical functions for a specified time duration, while self-aware systems have knowledge of both their internal and external environment as well as their previous states, actions and consequences to inform future decision-making (Rollock & Klaus, 2022). The ability to reach a requisite level of self-awareness for space habitats, and subsequent self-sufficiency, may be aided by incorporating emerging technologies that provide an adequate level of autonomy for sustained operations. Identifying the capabilities that must be onboarded to enable self-sufficient operations, however, is a necessary precursor before specific technologies can be developed to meet these needs.

2.1.3 'Automation' vs. 'Autonomy'

It is important to distinguish between the terms 'automation' and 'autonomy' as enablers of self-sufficient operations. NASA's Autonomous Systems group describes automation as containing pre-planned steps requiring command and control, thus is not self-directed (Fong, 2018). Automation is also represented by technology that seeks data, controls processes, and can transform information to make some decisions in a narrowly defined task, and effectively takes control of this action because a human no longer wants to (Lee & See, 2004). This does not mean that a human user is eliminated, however, as their role typically changes to that of a supervisor or operator of the automation

(Parasuraman & Riley, 1997). Autonomy, on the other hand, is characterized by an ability to reach goals without relying on external control (NASA, 2020a; Vagia et al., 2016). Key attributes include an ability to be goal-directed with an ability to direct its own actions, the ability to adapt to changing demands, and a level of self-governance (Endsley, M., 2011, 2015). This translates into establishing decision-making and control authority roles. Similar to self-sufficiency, autonomy is defined with respect to a given set of boundaries (i.e. autonomous with respect to what?). In this setting, a deep-space habitat must be adequately self-sufficient to operate autonomously with respect to ground communications and logistical support during time-critical operations (Rollock & Klaus, 2022).

2.2 Monitoring, Maintenance and Fault Management as Enabling Functions of Self-Sufficient Operations

In addition to conducting activities for accomplishing the primary mission objectives, the general supporting functions needed to sustain habitat operations categorically consist of monitoring key parameters, performing planned or reactive maintenance, and employing fault management strategies. Onboarding these critical capabilities that have traditionally heavily relied on ground support offers one approach for increasing habitat self-sufficiency by reducing reliance on ground communications and/or logistics. NASA has identified the migration of ground expertise to onboard autonomous and automated systems as an agency-wide need for deep-space research objectives in their 2023 SBIR Solicitation (Manu, Samidha, 2023). Nominal operations, those occurring as expected on a day-to-day basis, transition to off-nominal operations as a result of an anomalous behavior being detected. State-of-the-Art (SoA) and historical spaceflight examples for transitioning between nominal and off-nominal operations, however, are predominantly reliant on input from a group of subject matter experts in NASA's Johnson Space Center mission control center and

can occur concurrently with some operations continuing nominally while others are addressing off-nominal scenarios. These experts typically task switch seamlessly between nominal and off-nominal operations by following protocols assigned to each scenario and applying real-time troubleshooting and anomaly response tasks, while also navigating a number of machine-machine, human-machine, and human-human interactions (Wang & Caldwell, 2003). Operations include both scheduled and unplanned maintenance or repair, including verification of completion. Additionally, autonomous completion of scheduled maintenance was identified as a requirement for deep-space exploration (Harris, et al., 2022).

Monitoring of critical subsystems and using the data to perform fault management, including planned and corrective maintenance, occupy extensive time for the onboard crew and ground team. Modeling of these activities provides insight on operator task demands, the knowledge they use to structure their decision-making, and knowledge interchanges between these critical subsystems.

2.3 Monitoring – Active and Passive

Monitoring of relevant data streams enables effective operations and provides a means to differentiate between operating states, which is a critical function of the work domain of deep-space operations. This capability relies on a sensor suite to collect data, including observations reported by the onboard crew, which on the ISS, is used to inform ground operators for real-time situation assessment and subsequent data trend processing and analysis (Wallace et al., 2017). These data streams also support numerous research efforts ranging from payload operations to human performance testing. Various types of monitoring approaches exist that describe subfunctions needed to enable overall performance monitoring, with relevant spaceflight examples described below.

2.3.1 Satellite Monitoring

Satellites rely on telemetry data recorded by sensors local to subsystems, attitude control, and any relevant payloads. This housekeeping, or system health, data is monitored to ensure functionality of the onboard operations. Examples of relevant data streams include pressure, temperature, current, on/off status signals for redundant systems, and tracking of mechanism deployment. Modern communication satellites typically contain thousands of these telemetry streams (Fillery & Stanton, 2011) . This information stream adheres to the following flow proposed by Carlton et al. (Carlton et al., 2018):

1. Telemetry is received from components
2. Event detection algorithms are applied
3. Events from the component level (1-N components) are monitored
4. Subsystem level events are monitored
5. System level events are monitored
6. Environment level events are monitored

2.3.2 System, or Vehicle, Monitoring

System, or vehicle, monitoring for a human spacecraft includes telemetry and housekeeping data as well as data streams from subsystems (e.g., air and water quality, gas pressure and constituents, thermal conditions, acoustics, radiation, structural status, etc.), and terrain dust contamination, if applicable. Monitoring of air quality includes sensors that detect volatile organic compounds and airborne aerosols in microgravity (Limero & Wallace, 2017); surfaces and water are monitored to detect microbial growth and pathogens in the crew's environment (La Duc et al., 2004); internal and external charging events are also monitored to avoid static shock to the crew or short circuiting critical avionics (Bogorad et al., 1995).

2.3.3 Crew Health Monitoring

In addition to the habitat, crew physiological health is also monitored. Monitoring of crew health began during the first human spaceflight of Yuri Gagarin in 1961 and is typically collected and then downlinked to ground control including data streams such as heart rate, ECG signals, EMG electro-oculagram, galvanic skin response, and thermography (Cermack, 2006). Additionally, the central nervous system can be monitored due to the psychosocial and physiological stressors associated with spaceflight. While terrestrial imaging techniques like positron emission tomography (PET) scans, magnetic resonance imaging (MRI), and computerized tomography (CT) are limited to terrestrial applications, different imaging options like functional near-infrared spectroscopy (fNIRS), ultrasound and electroencephalography (EEG) are candidates for use in deep-space (Dinatolo & Cohen, 2022). Cognitive performance is another category of interest, as stressors from spaceflight can increase the risk of mental impairment and declined performance (Manzey, 2000). Ideally, crew health data is collected using non-intrusive sensors to monitor health risks and identify concerning trends in the wearer's health (Cermack, 2006). However, given the failure potential of miniaturized electronics due to the increased radiation environment of deep-space, e.g. single-event upsets, current commercially available wearable sensors may be limited in their utility for this application.

2.3.4 Monitoring Effectiveness

Elements of sensors, sensor density, node density, and network deployment influence the effectiveness of a monitoring regime (Garetto et al., 2007). These sensor suites are affected by the physical location, sensitivity, and fidelity of each individual sensor, as well as their ability to network with one another. ISS contains approximately 350,000 sensors that monitor station and crew health (Mark Garcia, 2023). To function in deep-

space, these sensor suites must be small, radiation hardened, ideally easily maintained, and able to remain calibrated for long periods of time (Limero & Wallace, 2017). Additionally, latency and occultations affect the ability to downlink and uplink data streams and prevent real-time responses that are inherent to current spaceflight operations.

2.4 Maintenance

As part of fault management responses, 'maintenance' of components is also a critical function of the work domain that has continued challenges. Large amounts of crew time are spent completing maintenance aboard the ISS, performing tasks ranging from doing a simple filter replacement to responding to a potentially life-threatening emergency situation (Keeter, Bill, 2021d). Typically, these repair, maintenance, and inspection tasks are completed by onboard crew but need support from ground controllers throughout the process (Ulusoy & Reisman, 2022). An analysis of ISS crew time found that Environmental Control and Life Support Systems (ECLSS) maintenance took more time for crew to complete than was designed into their schedule, impeding their ability to productively achieve other mission objectives (Russell & Klaus, 2007). Completing this maintenance often relies on the usage of spare or replacement parts that are brought to ISS from a resupply launch, indicating the logistical reliance present in current operations. Furthermore, the broad category of 'maintenance' does little to capture the detailed tasks that comprise these actions. Similar to crew health monitoring, crew maintenance also extends to ensuring physical and mental health through use of various design features and countermeasures.

2.5 Fault Management

When a failure, degradation or anomaly is detected in the data stream, fault management ensues. This process analyzes the monitored data streams and applies algorithms and decision-making to isolate failed components before performing appropriate maintenance (D. M. Johnson, 1996). The primary fault management functions are detection, diagnosis, decision, and response. These exist within a defined system boundary that separates who/what is in control of the system and who/what is external from control, called the environment, in which the system operates. System states and behaviors are used to characterize changes that occur, particularly if a system exits a nominal state to an off-nominal one (NASA, 2012). This habitat function is effectively paralleled for a crewmember dealing with an illness or injury in terms of providing in flight medical treatment capabilities.

2.5.1 Limitations of Current Fault Management Methods

Robotic spacecraft use onboard fault detection techniques that respond to severe faults and contact ground control to perform diagnosis. This onboard detection method may switch the spacecraft to a 'safe mode' that, while waiting for ground analysis and response, typically prevents completion of mission objectives. Further, these onboard processes are typically 'brittle' as they are mission-specific and thus difficult to update after launch (Kolcio & Fesq, 2016). Additionally, achieving self-sufficiency for deep-space missions necessitates less reliance on ground teams for solutions, reduction of service interruptions, and improved system reactivity, exacerbating the difficulty of onboarding these critical operations (Tipaldi & Bruenjes, 2014). These issues become increasingly complex as additional subsystems are incorporated for human space habitats.

A study targeting automated fault management for a simulated self-sufficient spaceflight crew found increased accuracy of fault diagnosis, lowered operator workload, and shortened fault identification time, but unexpectedly found potential threats to operator situation awareness (Lorenz et al., 2002). An associated study investigated out-of-the-loop unfamiliarity and its effect on operator use of intelligent fault management for an atmospheric control system. The results indicated that involving intelligent fault management can decrease operator workload, but this is affected by the specific level of autonomy (Lorenz et al., 2001). More recently, model-based systems engineering (MBSE) methods were used to create a fault management system for off-nominal state isolation and detection which resulted in no false positives for the nominal test data but did not test for spontaneous faults or off-nominal data (Kolcio & Fesq, 2016).

Furthermore, 'unknown unknown' anomalies present additional complexity beyond established methods used to proactively mitigate 'known unknowns'. Attempting to automate components of fault management remains a challenge in current spaceflight operations where ground control is readily available to provide their expertise, which will not always be available in deep-space. Enabling the crew to independently respond to 'unknown unknown' anomalies is a needed area of research that may rely on novel tools such as digital twins, onboard autonomous agents such as large-language models (LLM's) that can help with corrective maintenance and repair, systems designed from their inception to be easily repairable by onboard crew, and others (Gratius et al., 2024; Ulusoy & Reisman, 2022).

2.6 Task Completion Options and Function Allocation

An additional consideration for the functions mentioned above is defining who the operator can or should be. The intended purposes of adding higher levels of autonomy to

deep-space habitats, including the addition of emerging technologies, include leveraging increased autonomy to augment/assist the crew, performing tasks for the crew when the habitat is inhabited, performing tasks for the crew when uninhabited, performing the role of the ground team, improving existing capabilities, and adding new capabilities (Klaus et al., 2022). Incorporating emerging technologies into a deep-space habitat to achieve these desired purposes affects how function allocations will be conducted, as the traditional options for task completion on a spacecraft can increase as these technologies are added. To perform a function allocation evaluation, attributes of the various operation methods for a task (i.e., manual completion of a maintenance task by either the crew or a robot) and criteria for selecting an operator (i.e., time to complete the task, accuracy of task completion, workload needed to complete task, etc.) must be generated. These criteria are applied to evaluate the effectiveness of each operation method, and the demonstrated effectiveness can aid in deciding which tasks are allocated to which operator. Additionally, there is a temporal criticality concern involving *when* these tasks need to be completed that must also be captured by the criteria.

Traditional function allocation methods include HABA-MABA (Humans-Are-Better-At, Machines-Are-Better-At, previously MABA-MABA, Men-Are-Better-At…) and Levels of Automation (LOA) frameworks. Originally published by Fitts in 1951, the HABA-MABA framework has received marked criticism in more recent times. Among other issues, the breakdown assumes fixed strengths and weaknesses of humans and machines, which is not applicable to all situations and negates the possibility of skill development (Dekker & Woods, 2002). The framework also separates capabilities of machines and humans entirely, disregarding the ability of machines to perform increasingly complex tasks or added benefits from human-machine teaming. The NASA Human Integration Design Handbook (HIDH) advises against assigning functions to a computer solely because the computer is

capable of completing them. Instead it provides an updated approach and suggests the use of tasks analysis and human reliability analysis, where possible, as a means to identify which tasks are more suited to humans or computers, to be assessed throughout the design lifecycle.

LOA frameworks attempt to separate the cognitive performance of humans into discrete steps and then match these steps with associated levels of automation (Roth, 2019). An early LOA framework proposed by Sheridan and Verplank created a one-dimensional set of levels of automation, starting from Level 1 where a human has all control and the automation, in the form of a computer, contributes nothing. The levels proceed up to a Level 10 where a computer acts autonomously to complete a task and the human contributes nothing to the task completion (Sheridan, 1978). Despite criticisms that Sheridan and Verplank's levels of automation/autonomy only display situations where increased autonomy comes at the expense of human involvement, these levels have been used for function allocation and are widely cited in much of the following research and taken more seriously than the original creators predicted (Shneiderman, 2020). Attempts to generate levels of automation where higher autonomy does not come at the expense of operator involvement have been created with a focus on human-centered automation (Endsley & Kaber, 1999), including a model which attempts to unite human information processing with Sheridan and Verplank's levels by equating human information processing with types of actions that can be automated (Parasuraman et al., 2000) . However, LOA frameworks as a whole have been criticized for lacking ordinal levels, not addressing the functional differences or context of the situation, and not being capable of addressing current and future issues (Bradshaw et al., 2013).

Requirements for effective function allocation have been proposed instead of prescribing a single method for accomplishing all types of operations, as edge cases

repeatedly demonstrate that a one-size-fits-all method for allocating functions proves impractical (Feigh & Pritchett, 2014). Subsequent work used the five requirements for function allocation and generated a framework to model the effectiveness of function allocation early in the design process (Pritchett et al., 2014b). A follow on companion study proposed a set of metrics derived from the model, used to measure the tradeoffs when evaluating types of function allocation (Pritchett et al., 2014a).

Function allocation methodologies have seemingly evolved from a mindset of choosing either humans or machines, which can be ineffective, to a mindset of attempting to automate as much as possible, which can add unforeseen complications, to current research suggesting human-automation and human-autonomy teams may bring out the best of both options. Others have pointed out the benefits, including increased reliability, of using human-machine teaming instead of a 'this or that' mentality (Bye, 1999; Christoffersen & Woods, 2002; Dekker, 2011). This work does not address the creation of a new function allocation framework, rather it offers considerations specifically related to habitability by analyzing the fundamental tenets of a human-rated spacecraft.

2.7 Human-Automation and Human-Autonomy Teaming

Human-automation interaction (HAI) and human-automation teaming (HAT) are extensively documented in the literature as completion methods for complex tasks. Automation predominantly involves ways in which to conduct pre-programmed, supervised tasks for a human user (de Visser et al., 2018). Human-automation teaming has occurred continuously on the ISS since operations began. The average mission length is ~6 months (~182 days) (NASA, 2011), however, and crews are typically rotated for each mission, therefore data do not exist for how effectively human-automation teaming will perform over the longer, single-crew durations expected for deep-space missions.

Unique from HAI is an emerging technology that describes when a human and a semi-autonomous or fully autonomous agent operate together toward a common goal. HAT is marked by dynamic learning of autonomous agents, which can enable trust rebuilding during teaming and increased perception of the autonomous agent as a teammate rather than a tool (de Visser et al., 2018; Hancock, 2017; O'Neill et al. 2020). Limitations in current AI capabilities suggest that for the foreseeable future, AI and autonomous systems will need to operate jointly with humans to accomplish tasks, making HAT a particularly relevant emerging technology for this work (Endsley et al., 2022). Trust, situation awareness, and workload of the human operator as well as explainability of the autonomy (or explainable artificial intelligence, xAI) are cited as challenges when forming effective human-autonomy teams (Endsley et al. 2022). Research has been conducted into understanding the importance of trust in human-autonomy teaming, finding that ethical norms affect the trust relationship between the human and AI (Textor et al., 2022) and performance, explainability, and perceived utility of the autonomous system are factors in establishing trust (Dorton & Harper, 2022). Visual cues of the autonomous system have been shown to improve performance by increasing the human perception of the autonomous system as a 'teammate' (Tokadl & Dorneich, 2022). Applications of improved human-autonomy teaming include operations conducted in autonomous vehicles (Garcia et al. 2022), and in revolutionizing health care (Alam & Mueller, 2022; Czaja & Caruso, 2022; Salwei & Carayon, 2022).

Earlier predictions for future deep-space missions assumed an average mission length of ~914 days, while the NASA M2M estimates a ~1,200 day mission without resupply (Drake, 2009; Harris et al., 2022). To effectively integrate and leverage HAT and other emerging technologies in deep-space habitats, further research is needed to characterize the effects of this teaming over longer durations. For this research, HAT and

HAI literature was consulted for the characterization of habitability presented in this thesis.

2.8 Cognitive Engineering Methods for Modeling Complex Systems

Cognitive engineering is a field that leverages principled approaches for modeling human cognitive functioning to inform system design, including in complex sociotechnical systems (Miller et al., 2017). Deep-space habitats, which will likely leverage HAT and need to conduct function analysis to understand the dynamics of humans working with automation and possibly autonomous agents, are complex sociotechnical systems which can benefit from incorporating cognitive engineering methods. Typically, these methods define a work domain, or the system being controlled independent of operator (e.g. human, automation), and achieve this by performing a work domain analysis that identifies the functional structure of the work domain (Vicente, 1999). This analysis is similar in principle to a function decomposition which identifies 'what' must be achieved to support successful system operation without defining a technological means for achieving said function.

The envisioned world problem describes the challenges associated with conducting work domain analyses for work domains that do not yet exist, like deep-space habitat operations (Woods & Dekker, 2000). Cognitive engineering tools are relevant for addressing this problem and provide a framework for how to envision these work domains by using analytic tools to explain functionality and constraints of the workspace (Lintern, 2013).

To analyze how autonomy will factor into the crew's cognitive work demands in the future of deep-space exploration, the work domain of deep-space operations can be described for its physical context and description of work goals (Roth & Bisantz, 2013). In this case, the physical context is represented by far distances from Earth which alter the

frequency and format of Earth-based communication and logistical support, and the work goals are described by self-sufficient operations. However, the enabling functions of self-sufficient operations must be decomposed into more detail to fully describe the work domain of deep-space operations.

2.9 Designing for Deep-Space Functionality: ECLSS

As NASA and commercial agencies investigate solutions for the Artemis and Gateway programs, robust ECLSS is a necessary component of these architectures and provides a use case that represents the habitat as a whole since the entirety of ECLSS is critical to crew survival. Closed-loop ECLSS capabilities in a transit habitat that maintain habitable conditions for crew and payloads for up to 1,100-day missions are requested, with 10 days of non-regenerable water and air supply present for contingency (Harris, et al., 2022). Previous conceptual studies by NASA Johnson Space Center for long-duration, partially regenerable ECLSS have been proposed to support near-Earth object (NEO) asteroid missions, but cited reliability concerns as the highest priority for future work (Curley et al., 2012). Next-generation CO2 removal beds such as CDRILS are seeking to increase robustness and reliability of these critical systems over long-duration flights (Kamire et al., 2021). ECLSS robustness is defined as "ability to maintain habitable conditions for crew survival and productivity over the mission lifetime under a wide range of conditions" (C. M. Escobar et al., 2017) and represents one of the top design priorities for a reliable ECLSS in deep-space.

However, functional needs are designed to describe *what* needs to be accomplished, and not *how* the function should be met, i.e., functional requirements should be defined independently from a proposed solution. Once these requirements are given a performance goal, designers can then generate solutions. Understanding how to create designs to meet

the demands of deep-space requires an understanding of what functional needs exist for self-sufficient operations, and, an understanding of how the decision-making process is typically conducted by engineers.

2.10 Triangulation: Combining Qualitative and Quantitative Research

Finally, a method for experimental demonstration that combines each of the areas of research described above is needed. Qualitative research is used in fields such as exercise science, medicine, and psychology to capture and generate knowledge resulting from the human experience (Nowell et al., 2017). Qualitative analysis, including thematic analysis as a subset of this type of inquiry, has been used in a range of disciplines including sport and exercise research, medical applications, and aerospace science (Almand et al., 2023; Braun, V. et al., 2016; Kintz & Palinkas, 2016; Laws et al., 2022; Malterud, 2001a; Willms et al., 1990). Though qualitative research has grown in popularity for its flexibility and ability to capture the complexity associated with 'real-world' data and scenarios, it has been critiqued for its trustworthiness, particularly when detailed descriptions of the methods used were omitted by researchers in publications (Attride-Stirling, 2001; Tuckett, 2005). The rigor and use of these methods was also questioned when qualitative health research surfaced as a pronounced method in the field in the 1980's, primarily due to the assertion that these methods are not objective and therefore cannot yield generalizable results (Sandelowski, 1997; Sandelowski, 2004).

However, since then the growing perceived importance of practical knowledge in the medical sector has prompted increased emphasis on qualitative research and on developing tools for assessing the datasets in a rigorous manner (Sandelowski, 2004). However, it has also been argued that quantitative research alone has shortcomings in describing complex datasets. In a paper written to investigate the nature of clinical medicine knowledge,

Malterud proposes qualitative research as a method to close some of the gaps associated with only relying on quantitative data (Malterud, 2001b).

This approach of combining qualitative and quantitative methods can increase validity or confidence in the data collection and is one form of 'triangulation' which combines and compares the data collected and analyzed from two or more different methods (Mays, 2000). Using both qualitative and quantitative approaches has also been described as complementary rather than incompatible given that underlying principles for textual interpretation and statistical analysis are similar (Malterud, 2001a). Qualitative methods, such as semi-structured interviews, can be used to investigate relevant variables and can increase the accuracy of follow-on quantitative approaches (Willms et al., 1990). The method of triangulation is not necessarily a pure test of validity, but rather can be leveraged to ensure comprehensiveness of the data collected (Mays, 2000). Further, triangulation seeks to improve comprehension of complex topics by combining multiple sources of information, i.e. qualitative and quantitative datasets, rather than relying solely on criteria-based validation (Miles & Huberman, 1994). The goal is to select multiple triangulation sources that have varied strengths that complement each other, even if this sometimes results in reliability rather than validity information (Miles & Huberman, 1994; Mathison, 1988).

Practicing medicine is influenced and informed by patient interactions, opinions, and communication, all of which are not necessarily quantitative but serve to enhance the study and practice of the discipline in combination with quantitative methods (Malterud, 2001b). Attempting to describe human decision-making for something as complex as designing and operating a human-rated spacecraft is an apt place for applying triangulation given the importance of documenting opinions and communication between engineers designing these systems and operators on the ground and onboard.

2.11 Summary

Proposed levels of autonomy and distinctions between automation and autonomy as unique terminology have been described in various research efforts. These influence the development of HAT which is one promising emerging technology, among others, for deep-space habitats. Incorporating HAT, and potentially other emerging technologies, will require detailed function allocation and cognitive analyses to understand the implications for how the crew, habitat, and distant ground teams will work together to achieve the necessary functions of monitoring, maintenance, and fault management for self-sufficient operations. By combining top-down functional and cognitive analysis methods and bottom-up triangulation investigating maintainable ECLSS as a use case, this dissertation contributes to these research areas by proposing characterization of self-sufficiency and habitability as a method for contextualizing and categorizing enabling capabilities and other potential benefits that emerging technology can bring.

Chapter 3

Problem Statement

Not all existing SoA technologies are feasible for use under the unique constraints of long-duration deep-space missions as described above. To address the identified shortcomings, improvements must be made that advance the self-sufficiency needed to autonomously accomplish all required operations. Additionally, improvements to habitability can also be considered. Emerging technologies offer great potential in meeting these needs; however, adding autonomous capabilities without assessing functional need and performance is cited as a common pitfall of integrating these systems (Bradshaw et al., 2013). A method for contextualizing and classifying enabling capabilities and other potential benefits that emerging technology can bring is proposed here as a means of avoiding this concern and preventing the addition of unnecessary complexity to the habitat.

Therefore, the overarching research goal of this thesis is to:

Identify and define trade study criteria needed
to determine where emerging technologies can provide benefit
(i.e., gaps where SoA is insufficient) on a deep-space habitat
by increasing self-sufficiency and/or habitability,
mapped to categorized functional needs.

An important caveat to note is that this research is not based on meeting the specific needs of a particular mission. Rather, the focus is to create a mission-agnostic process that

can be applied in the design of any future habitat by determining where emerging technologies are required, as well as where they might provide a desired benefit, to accomplish a given mission goal.

Research topics were generated to address this research goal, as summarized in the following five Specific Aims (SA).

- SA1 - Characterize and differentiate representative nominal and off-nominal onboard operational scenarios for a deep-space habitat
- SA2 – Identify attributes of select *(and other needed)* emerging technologies capable of supporting, performing or improving nominal operations in contrast to SoA approaches
- SA3 – Identify opportunities and assess potential benefits of incorporating emerging technologies with a focus on nominal operations
- SA4 – Define method for analysis and summarize recommendations for strategically prioritizing implementation of emerging technologies in a deep-space habitat
- SA5 – Demonstrate the prioritization method by utilizing HOME Demo results and/or conceptual scenarios

Chapter 4

Monitoring, Maintenance and Fault Management Considerations for Self-Sufficient Deep-Space Habitat Operations

4.1 Objectives

The processes that constitute real-time decision-making and response for current human spaceflight nominal and off-nominal scenarios, be it data monitoring or managing emergency responses, comprise a complex work domain that contains gaps for deep-space utilization. While monitoring, maintenance and fault management processes are supported by current spaceflight operations, they require extensive Earth-based support from mission control. Additionally, these methods are limited in their efficacy even with the ongoing support of ground teams. Operational autonomy is needed to enable self-sufficient deep-space operations where ground teams are not always available to help during time-critical operations, and one way to direct work development for an undefined, future system like deep-space operations is to define a work domain using cognitive engineering methods (Vicente, 1999).

The objectives of this Chapter are to describe the enabling general functions of the work domain of self-sufficient deep-space operations by analyzing the monitoring, maintenance and fault management tasks as functional categories using the methods of an abstraction hierarchy and information flow model. Before these categories can be analyzed, however, delineations between nominal and off-nominal scenarios, operations, conditions, and operating states, as compiled from the referenced fault management literature, are provided to clarify the operational context of the general functions. By proactively scoping

the work domain of deep-space exploration using the initial steps of a work domain analysis, this Chapter aims to provide a framework to serve as a baseline for the development of quantitative methods for assessing the potential benefits provided by emerging technologies toward operationally autonomous deep-space mission.

4.2 Methods

4.2.1 Function Decomposition of a Deep-Space Habitat

A common pitfall when integrating autonomous systems or pursuing a higher 'level' of autonomy is to do so without referencing functional needs (Bradshaw et al., 2013). Therefore, a joint effort was conducted in previous research to draft a mission-agnostic deep-space habitat operational framework using function-driven design (Klaus et al., 2022). This work began by defining a generic Design Reference Mission (DRM) and Concept of Operations (ConOps) to describe a high-level mission profile for deep-space habitat operations. This work incorporated principles used in design reference architecture, engineering handbooks, human research roadmap, and technology roadmaps created by NASA and other industry experts for anticipated future lunar and Martian missions (Badger, J. et al., 2018; Drake, 2009; Fong, 2018; Harris, et al., 2022; Manu, Samidha, 2023; NASA, 2007, 2023; Wu, S & Vera, A.H., 2019). This representative ConOps was not constrained by specific mission objectives, however, as the intent of the research is to inform any future deep-space mission needs, independent of their goals. The ConOps defined phases of flight somewhat chronologically and separated them into intermittent uncrewed and crewed scenarios to align with ConOps for NASA's Lunar Gateway station that estimate there could be uncrewed periods up to 9 months in duration (Manu, Samidha, 2023).

These phases of flight were referenced to perform a functional decomposition process which identified 'what' must be completed on a mission-agnostic deep-space habitat without specifying 'how' this function is completed, i.e. using specific technologies. The phases were decomposed into functional objectives and then subsequently decomposed into functional requirements. Once these requirements are identified, standard engineering practices can then be used to create systems that accomplish the required functions. An example from this functional decomposition process is displayed in Figure 1.

5. Crewed Operations	5.1 Provide Pressurized Structure		
	5.2 ...		
	5.7 Maintain Vehicle Health	5.7.1 Monitor habitat health and status (H&S) parameters	5.7.1.1 Monitor O2 level
			5.7.1.2 Monitor Ptotal
			5.7.1.3 Monitor TC's
			5.7.1.4 Monitor for fire detection
			5.7.1.5 Monitor habitat external shielding
			5.7.1.6 Monitor water quality
			5.7.1.7 Monitor habitat avionics (temperature, data rates)
			5.7.1.8 Monitor sensor outputs
			5.7.1.9 Monitor habitat power usage
			5.7.1.10 Monitor habitat internal temperature
			5.7.1.11 Monitor habitat external temperature
			5.7.1.12 Monitor habitat attitude control
			5.7.1.13 Monitor habitat ephemeris
			5.7.1.14 Monitor radiation levels
			5.7.1.15 Verify expected operational conditions
			5.7.1...
		5.7.6 ...	
		5.7.7 Conduct necessary maintenance / repair operations	
	5.19 ...		
	5.20 Provide Logistics Management		

Figure 1: Section of deep-space habitat function decomposition (used with permission from Klaus et al., 2022).

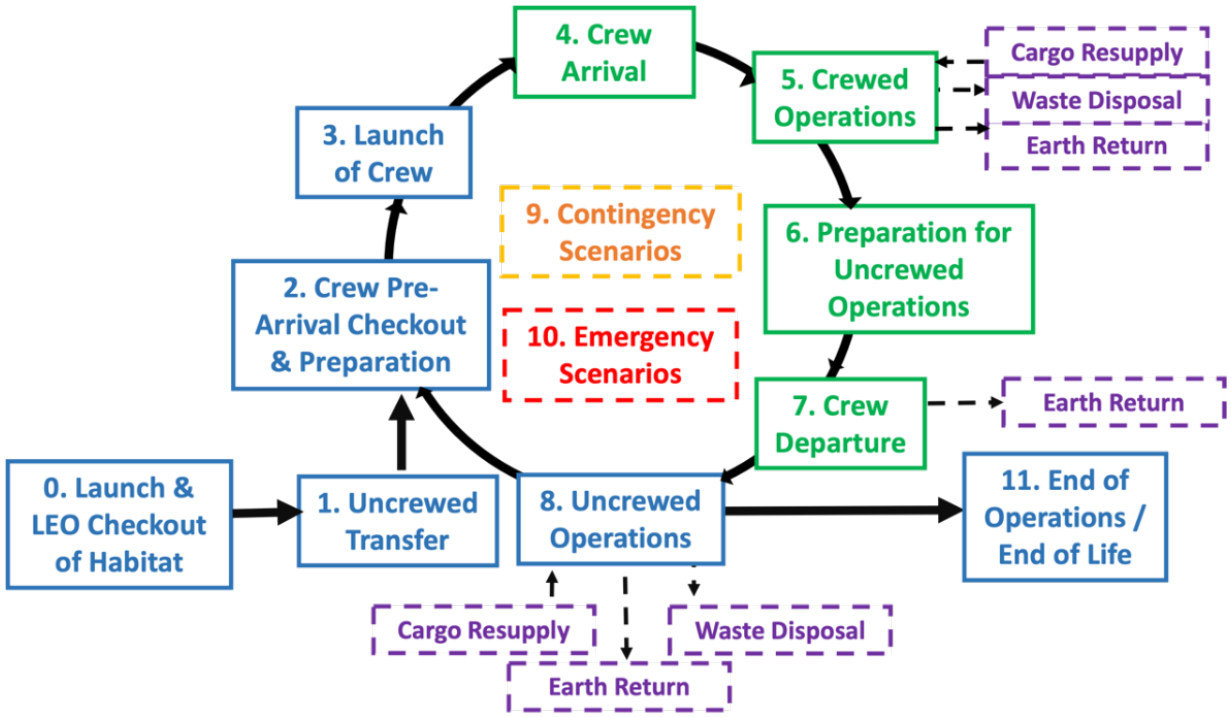


Figure 2: Mission-agnostic ConOps created for a deep-space habitat (used with permission from Klaus et al., 2022).

Separating 'nominal' and 'off-nominal' operations from a ConOps and functional perspective using this decomposition process became difficult, as considerable overlaps were identified between scenarios, which is documented in the literature as a challenge (J. C. Day & Johnson, Stephen B., 2014; S. Johnson et al., 2011; S. Johnson & Day, 2010) and is further examined in this work.

4.2.2 Defining Nominal and Off-Nominal from Function Decomposition

At first glance, it might appear that differentiating nominal from off-nominal activities would be straightforward. Nominal scenarios are defined as situations which provide expected, satisfactory performance and achieve this performance within anticipated bounds (NASA, 2012). NASA defines off-nominal as deviating from acceptable and expected performance limits, also described as unsatisfactory or anomalous (NASA, 2022). However, the transition from nominal to off-nominal conditions is not uniformly documented and is

difficult to characterize (J. C. Day & Johnson, Stephen B., 2014; S. Johnson et al., 2011; S. Johnson & Day, 2010). Enabling a deep-space habitat to delineate between nominal and off-nominal scenarios requires more specificity regarding which operations belong in each paradigm, and/or clarity regarding if any are unique to either scenario. These separated definitions might not have been explicitly needed when differentiating between the two was implicit in mission operations for experts in ground control, but given the desire to automate certain operations, defined demarcations between nominal scenarios, operations, conditions, and operating state are needed to thoroughly characterize design goals for an autonomous system where decision-making and control authority roles involve more than just humans.

This work incorporated existing references and the functions derived from the functional decomposition described in Section 4.2.1 to define nominal scenarios, operations, conditions, and operating state to clarify how these terminologies contribute to ongoing operations. Additionally, a state diagram and state transition matrix were created using terminology and references from fault management literature to distinguish between habitat-level nominal and off-nominal operating states and demonstrate operational transitions between the two states, shown in Figure 3 and Table 2, respectively.

4.2.3 Cognitive Engineering Work Domain Analysis

Utilizing each of the five tools that comprise a cognitive work analysis is not necessary to successfully scope a domain, rather, appropriate pieces can be selected for a given system (McIlroy & Stanton, 2012; Read et al., 2015; Sanderson & Carroll, John M., 2003). For this paper, a work domain analysis, the first step of a cognitive work analysis, was conducted using the following processes.

Identifying and categorizing the functional needs for self-sufficient deep-space operations into monitoring, maintenance and fault management was done by examining the functions generated in the function decomposition described in Section 4.2.1. These functions and their associated constraints were then combined in an abstraction hierarchy which defines the functional landscape of operational autonomy for deep-space operations and distills the function decomposition into a prioritized hierarchy. The abstraction hierarchy follows a flow from the high-level 'functional purpose' down to the physical form needed to achieve each function.

To analyze the interaction between the physical functions derived in the abstraction hierarchy, an information flow model was created to provide operational context for self-sufficient operations. This tool can also provide a baseline for comparison and contrasting the addition of emerging technologies (Miller et al., 2015; Miller & Feigh, 2019).

4.2.4 Summary

Monitoring, maintenance, and fault management are areas that require advancement toward operational autonomy before they are ready to support a deep-space paradigm. This is represented by their current reliance on near-instantaneous communications and post-processing by ground teams, as well as logistical resupply. When targeting improvements of these enablers of self-sufficiency and exploring the tangential benefits provided by improved habitability, a framework using the cognitive engineering principles of a work domain analysis can be used. This process includes an abstraction hierarchy and information flow model to determine the functional needs landscape of self-sufficient deep-space operations.

4.3 Results

4.3.1 Defining Nominal Scenarios, Operations, Conditions, and Operating State

The nuanced complexity of the concepts of 'nominal' and 'off-nominal' and how they affect decision-making to enable continued operations is important to note. Furthermore, these need to be described early in the envisioning process to assist in defining the functional structure of the domain (Miller & Feigh, 2019; Vicente, 1999). The terms 'nominal scenarios, operations, conditions, and operating state' are summarized in Table 1 and described further in the following sections.

Nominal Scenarios	Provide expected, satisfactory performance and achieve this performance within expected bounds (NASA, 2012)
Nominal Operations	Tasks that must be done to keep a system operating within a nominal scenario
Nominal Conditions	Predetermined design features and performance limits that distinguish a nominal operating state
Nominal Operating State	Describes the set of physical and logical variables of a habitat constrained by pre-determined nominal operating conditions (J. Day & Ingham, n.d.)

Table 1: Separation between nominal scenarios, operations, conditions and operating state.

4.3.2 Nominal Scenarios and Operations

As noted in the table, nominal scenarios provide expected, satisfactory performance and achieve this performance within expected bounds (NASA, 2012). Nominal operations describe the accompanying tasks and actions that must be completed to sustain operations within the predetermined performance bounds associated with a nominal scenario. These operations include monitoring of the systems to verify expected performance, certain types of maintenance needed to keep the systems functioning and performing the activities that

accomplish mission goals. The monitoring and maintenance process informs proper fault management, which is discussed further in Section 5.8.

Modes of operation, in this case nominal operations, are labels used to describe the capabilities needed to satisfy the objective of the state (Wasson, 2005). Colloquially, these operations are needed to keep the crew alive, healthy, happy and productive (Klaus, 2017), and can include routine checks of life support systems, medical checks for the crew, and scientific research, among others. When an anomaly is detected, the responsive operations enter the anomaly response domain. According to Johnson et al. (S. Johnson et al., 2011), an anomaly is defined as "the unexpected performance of the intended function" (p. 1965). Clarifying which operations are nominal is important, as different success criteria will be applied to assess nominal performance vs. anomaly responses in deep-space. The transition from nominal operations to anomaly response is challenging to define for some operations, particularly for monitoring and prescribing different types of maintenance, as monitoring is conducted in both nominal and off-nominal scenarios and different types of maintenance are also performed in both situations, as was found in the functional decomposition effort described in Section 4.2.1. Providing clarity by examining classifications of monitoring and maintenance types can help describe this nuance.

4.3.3 Nominal Conditions and Operating State

Where nominal operations are actions that must be taken or functions that must be completed, the nominal operating state includes the overall physical and logical variables that describe the condition of a habitat. A state is described as the mode or condition of existence that a system, in this case a habitat, is in (J. Day & Ingham, n.d.; Wasson, 2005). This operational state is constrained by pre-determined nominal operating conditions. Nominal operating conditions are defined by designers as what features and performance

the systems should demonstrate to provide desired, nominal performance. NASA defines off-nominal as deviating from acceptable and expected performance limits, which can also be described as unsatisfactory or anomalous (NASA, 2022). The three transitions to off-nominal states are categorized as failures, anomalies, and degradations. Where anomaly was referenced as the unexpected performance of the intended function, Johnson et al. (S. Johnson et al., 2011) defined a failure as "the unacceptable performance of the intended function" and a degradation as "the decreased performance of the intended function" (p. 1965).

Notably, unique cases exist where a system can experience an anomaly but not enter an off-nominal state – such as if the performance of a component is unexpected but still deemed to be acceptable (J. Day & Ingham, n.d.; S. Johnson & Day, 2010). As an example from monitoring crewmember state, if bone mass was found to be constant or even increased during a mission, this would likely be unexpected and considered anomalous, since historically bone loss has been observed in spaceflight (Sibonga et al., 2015). However, since adequate bone mass is maintained, they would remain in a nominal state. Occurrences such as this must be considered for the crew as well as habitat subsystems to fully address the nature of anomalies in which unexpected events do not map to a clearly defined off-nominal state, therefore, do not bring a system outside of its predetermined nominal limits (J. Day & Ingham, n.d.; S. Johnson & Day, 2010).

4.3.4 Nominal vs. Off-Nominal Operating States

4.3.4.1 Anomalous Events

In addition to characterizing nominal and off-nominal operating states, the variety of situations that anomalies can present must also be described. For example, an anomaly may cause a system to transfer to an off-nominal state, but it also may not be recognized as

an anomaly if the performance of the system remains within predetermined nominal limits (S. Johnson & Day, 2010).

Anomalous events that are unexpected but deemed acceptable must still be captured and documented in case they do escalate to an unacceptable, off-nominal event. In the event of a benign anomaly where the event is unexpected yet still acceptable, the response action is to 'accept' the anomaly, document this instance if additional analysis is warranted, and update the definition of the nominal state to reflect the new conditions, as required. The escalation from an anomaly can manifest as a degradation, a failure, or can directly become an off-nominal state. Additionally, a degradation can precede an anomalous event if the initial degradation is expected before the anomaly occurs. For example, an antenna that transmits data at a slower than optimal rate due to atmospheric disturbance is classified as a degraded operation if the designers predicted the transmission would be slower and is off-nominal unless the reduced data transmission is deemed acceptable for the intended operation. If the slowed transmission is unexpectedly followed by a complete blackout, the event is then anomalous. It is important to clarify that an anomalous event is not an operating state, rather a distinct event, or cascade of events, that prompts a series of actions to be taken to return the habitat to a nominal operating state within predetermined nominal conditions. Visualizing the recursion between these states and resultant actions can be useful in explaining the nuances between them, as demonstrated in a concept diagram proposed in Johnson et al. (S. Johnson et al., 2011). An additional way to visualize the relationship between the habitat-level states of nominal and off-nominal and resultant actions is illustrated below in Figure 3 using a basic state diagram of the habitat-level state and as a state transition in Table 2.

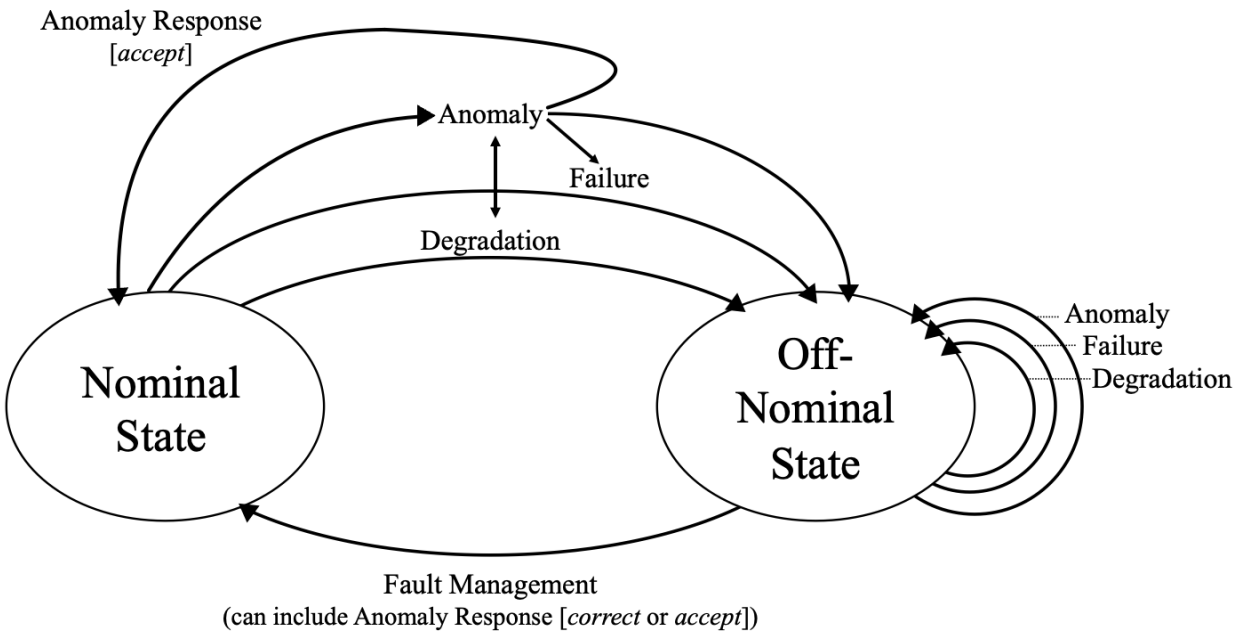


Figure 3: State diagram for a space habitat, with arrows used to represent transitions between the states.

Starting State	Input	Next State	Output
Nominal	Degradation	Off-Nominal	When a degradation occurs, the system enters an off-nominal state
	Anomaly	Nominal	If an anomaly occurs and is accepted, the system remains in a nominal state
	Anomaly	Off-Nominal	If an anomaly occurs and is linked to a failure, the system enters an off-nominal state
	Failure	Off-Nominal	When a failure occurs, the system enters an off-nominal state
Off-Nominal	Degradation	Off-Nominal	None
	Anomaly	Off-Nominal	None
	Failure	Off-Nominal	None
	Fault Management	Nominal	When fault management or anomaly response is successful, the habitat is returned to a nominal state

Table 2: State transition table to accompany state diagram of a space habitat

The diagram shown in Figure 3 indicates that a failure, anomaly and/or degradation each present possible deviation from a nominal state. Furthermore, the visual reflects the logic that it is possible for states to exist that are both failed and anomalous, not failed but anomalous, and failed without being anomalous (S. Johnson et al., 2011). These diagrams indicate the feedback loop of knowledge gained through component-level fault management and anomaly response that informs operators and may prompt them to update acceptable conditions for the nominal state at the habitat-level.

It is important to note that the space habitat may physically enter an off-nominal state that is not observed or detected. This is due to the limitations of observability of systems, or the ability to fully reconstruct the internal state of a system from system outputs. These output variables are typically constrained by sensor readings and generating a complete quantitative model of a complex system of systems, like a space habitat, is intrinsically limited by the outputs (Liu et al., 2013). For anomaly response actions to commence, the anomaly itself must be observable enough to be detected by active monitoring. This is discussed further in Section 4.4.1.

4.3.4.2 Redundancy and Fault / Failure Tolerance

Redundant systems uphold functionality if there is a failure that is resolved without operator involvement, which is classified as a type of fault tolerance. Fault tolerance and failure tolerance provide a system with the ability to complete a necessary function when faced with a specific number of simultaneous, independent failures. Fault tolerance and corresponding redundancy have limitations, and defining the boundaries of what is captured by the redundancy is crucial to avoid higher level failures later (S. Johnson et al., 2011).

4.3.4.3 Flowing Habitat-Level States into Component-level Analysis

There are a vast number of potential anomalies, failures, and degradations that result in transition from a nominal state to an off-nominal one in a deep-space habitat. To provide insight into the design and to implement effective fault management strategies, habitat systems can be analyzed using systems engineering tools such as a failure mode and effects analysis (FMEA) and applied to fault detection, isolation, and recovery (FDIR) processes. These methods serve to couple the habitat-level nominal and off-nominal states to detailed component functionality as the design matures.

Given a deep-space habitat is a highly complex and integrated system-of-systems, these component-level analyses will likely not be trivial. Though no criticality analysis or component-level fault management analysis was conducted in this work, it is recognized that after the habitat-level states are defined, their utility also applies to the decomposition of the systems.

4.3.4.4 Operational States

High-level system states can be categorized into four basic space habitat operational states, as adapted from Klaus et al. (Klaus et al., 2022).

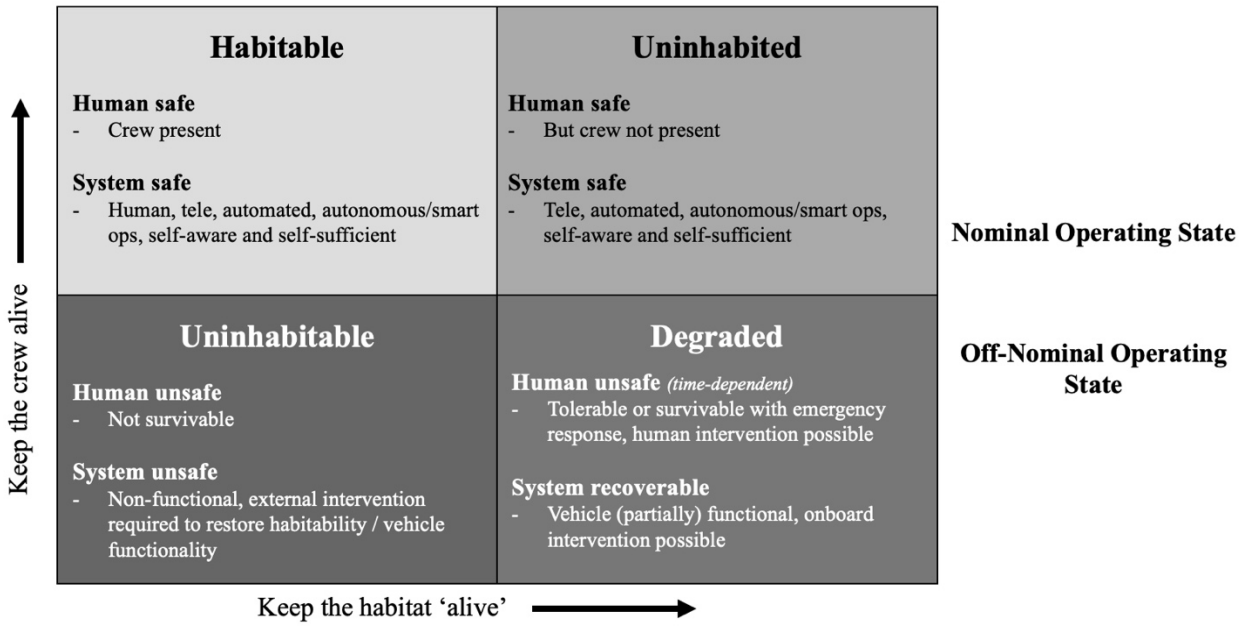


Figure 4: Basic Space Habitat Operational States (adapted from (Klaus et al., 2022)).

These modified operational states provide more detail to what situations may be present in nominal and off-nominal operating states on a deep-space mission. Additional clarity is provided by next creating an abstraction hierarchy to begin the work domain analysis.

4.4 Proposed Abstraction Hierarchy of Deep-space Habitat Functional Needs

To capture the work domain of deep-space operations, a diagram shown in Figure 5 is organized in an abstraction hierarchy, the primary model format for work domain analysis, and models this representation using Naikar (Naikar, 2017) and Naikar et al. (Naikar et al., 2003) as a basis.

The general functions in this abstraction hierarchy were abstracted from the functional decomposition conducted in previous work which defined the necessary functionality of a mission-agnostic deep-space habitat, an example of which is shown in

Figure 1 (Klaus et al., 2020, 2022). Functions such as 'provide a habitable atmosphere' are needed to 'accomplish mission objectives', where 'monitoring' is necessary to characterize the health and status of the systems and crew. Proactive 'fault management' strategies implemented to prevent failures and 'maintenance' as needed to prevent failures or repair systems identify operations that also must be done to sustain safe human spaceflight. Currently, each of these functions relies heavily on ground-based support and, therefore, represent capabilities that must be performed onboard to support deep-space exploration missions. Onboarding general functions such as these increases operational autonomy and moves toward self-sufficiency of the habitat. Additional design choices that are made to enhance crew quality of life are indicated separately, as these serve a different function, and are captured as improvements to habitability.

The physical functions that enable self-sufficiency were derived from further analysis of monitoring, maintenance, and fault management as described in Sections 4.4.1, 4.4.2, and 4.4.3, where habitability was simplified to personal elements for desirable 'nice to have' additions beyond requirements for self-sufficiency. Priorities and values are proposed from comparison of NASA's stated goals and mission statements of spaceflight industry leaders, and the functional purpose is proposed based on the rationale provided in the Introduction and Background of this Chapter.

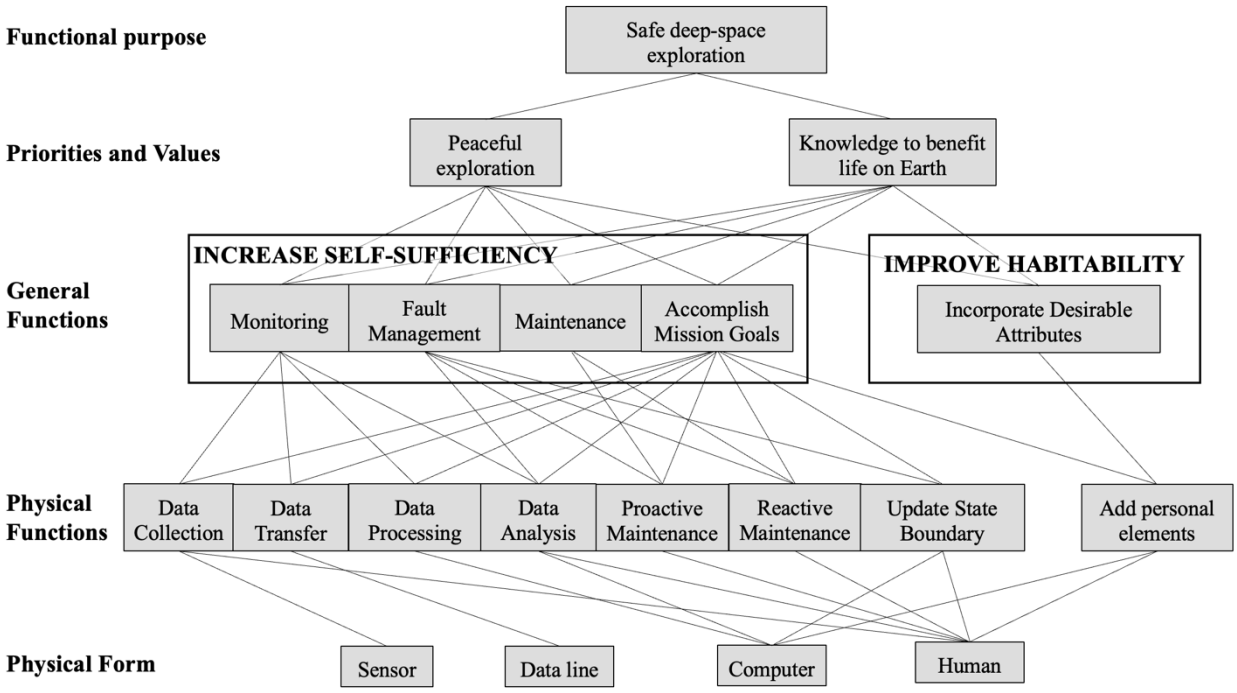


Figure 5: Abstraction hierarchy of functional needs onboard a deep-space habitat, independent of specific mission architecture and requirements.

The relationship between layers of an abstraction hierarchy uses means-end logic. By looking at one layer of this hierarchy, the rationale for why the function is performed is linked above, and the rationale for how the function is achieved is detailed in the layers below. The ultimate functional purpose is sade deep-space exploration, with emphasis placed on peaceful exploration and gathering knowledge to benefit life on Earth. The top three tiers of Functional Purpose, Priorities and Values (or Abstract Functions) and Generalized Functions remain consistent regardless of which technology is used in the work domain (Miller & Feigh, 2019; Naikar, 2005, 2017).

Reaching self-sufficiency requires technology improvements be made to accomplish the general functions of monitoring, maintenance and fault management, needed to ultimately achieve mission objectives. Desired improvements made to habitability extend beyond the 'need to have' requirements imposed by self-sufficiency can be optionally

incorporated to improve living conditions and/or provide performance aids for the crew. Improving habitability can also facilitate accomplishment of mission goals through enhanced well-being of the crew, as indicated by the connecting line. However, these 'nice to have' additions offered by improving habitability are out of focus for this work, and the emphasis here is instead placed on enabling the general functions required for self-sufficiency. The physical functions represent what is required to enable the general functions, as well as what processes are afforded by the physical forms displayed along the bottom row (Tokadlı & Dorneich, 2018). These proposed physical functions and their capabilities are defined in further detail in the following sections, which also informed the creation of their physical form.

The abstraction hierarchy diagram illustrated in Figure 5 provides a high-level snapshot of deep-space habitat functional needs. However, this diagram does not fully capture the complexity of interactions between monitoring, maintenance, and fault management, which is discussed further in the following sections and includes an information flow model to further depict the sub-function interchanges in an operational context.

4.4.1 Monitoring

Through the functional decomposition conducted in previous work, the general functions of 'monitoring' and 'maintenance' were not clearly able to be binned into nominal or off-nominal and lacked specificity regarding subtypes of each function (Klaus et al., 2022).

4.4.1.1 Proposed Categories of Monitoring

Across the different types of monitoring discussed in the Background, there is a pattern that emerged regarding the typical flow of how data collection works for spaceflight.

This flow is captured in Table 3 by separating the associated needs into the four functional categories of data collection, data transfer, data processing, and data analysis.

Monitoring Category	Characteristics
Data Collection	Reliant on sensor network, node density, and the physical sensor placement for a given subsystem (Garetto et al., 2007).
Data Transfer	Data is sent from a sensor to a processing location, either local or remote.
Data Processing	Raw signals must be converted (e.g., from a voltage reading to a temperature) to be understandable in the given context.
Data Analysis	Reliant on onboard crew or systems (e.g., Digital Twins) and/or ground teams to examine the data, observe trends, and make meaningful connections to inform future decision-making.

Table 3: Functional categories of Monitoring .

Each category of Monitoring can be considered nominal or off-nominal based on situational context. Broadly, these capabilities are continuous in nominal operations and inform off-nominal responses. This activity is further explored in the description of the information flow model proposed in Figure 7.

4.4.2 Maintenance

As a general function, 'maintenance' captures a wide range of activities that vary in complexity and intended purpose. Understanding the separation between types of maintenance in nominal and off-nominal scenarios will inform where emerging technologies could provide benefit, whether their addition is to improve existing maintenance techniques or to offload the time burden imposed on the crew.

In a review of maintenance types, a taxonomy of maintenance is split into two overarching groups. These are separated into reactive, or unplanned, maintenance and proactive, or planned, maintenance (Kothamasu et al., 2006). These groups are then split into increasingly specific types of maintenance for system health. However, these groups and maintenance types are not mapped to a spaceflight scenario or categorized as either

nominal or off-nominal. Therefore, the types of maintenance found in the literature were organized into nominal, off-nominal, and a blend or transition point between the two as seen in Figure 6.

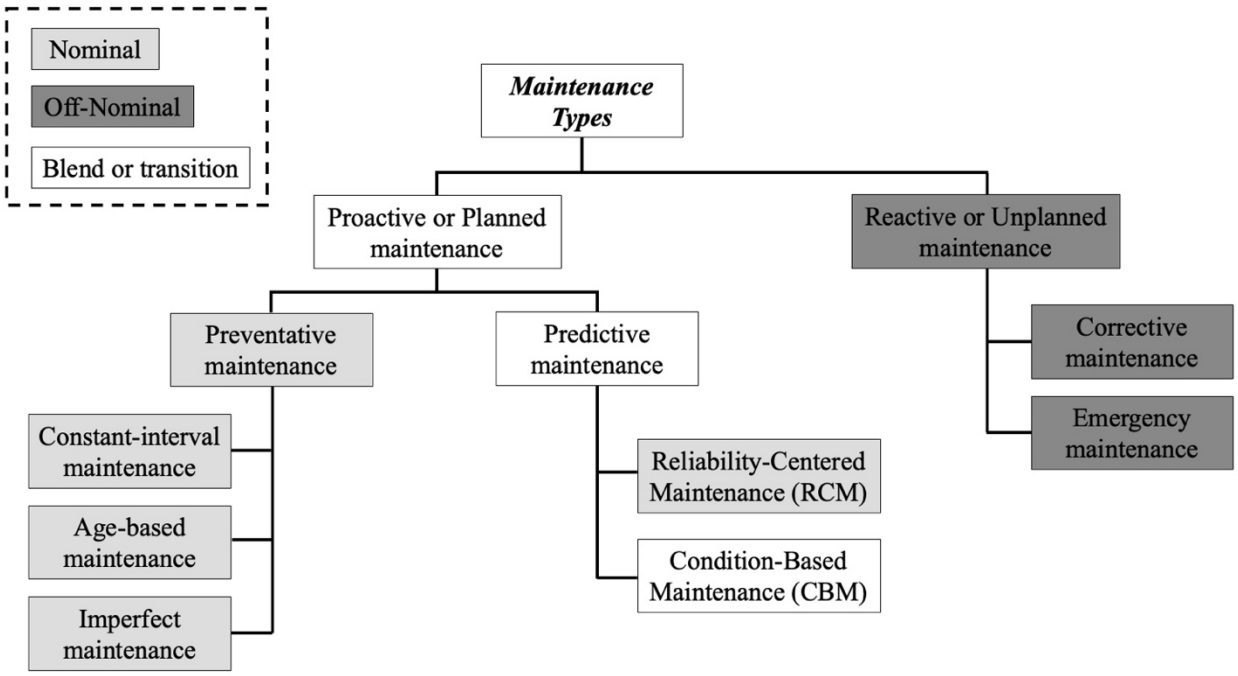


Figure 6: Categorization of maintenance types, adapted from Kothamasu et al. 2006.

4.4.2.1 Preventative Maintenance

Within the category of proactive maintenance, preventative maintenance includes subcategories of constant-interval, age-based and imperfect maintenance and is categorized as a nominal operation. Constant-interval encompasses scheduled maintenance done at regular time periods. Age-based maintenance is conducted after a component has reached a certain age. Imperfect maintenance considers the uncertainty associated with preventative strategies and does not assume a system is restored to original condition after maintenance (Kothamasu et al., 2006). This is categorized as nominal because the uncertainty is factored in as a part of the preventative planning, rather than as a responsive action. Examples of

preventative maintenance include the preventative filter removal, replacement and cleaning of the Potable Water Dispenser (PWD) and the regularly scheduled quarterly maintenance of the Advanced Resistive Exercise Device (ARED) which examines any wear on the hardware and verifies nominal operation, both completed in November 2021 (Keeter, Bill, 2021c). In September 2021, during regular maintenance activities, the ISS crew replaced a brine filter in the Urine Processing Assembly (UPA), an activity that occurs every 60 days (Keeter, Bill, 2021b). The PWD filter removal and replacement is an example of age-based maintenance, the quarterly ARED maintenance combines constant-interval maintenance with knowledge informed by imperfect maintenance, and the filter replacement of the UPA is an additional example of age-based maintenance.

4.4.2.2 Predictive Maintenance

Predictive maintenance is generally classified as a blend between nominal and off-nominal with the subcategory of reliability-centered maintenance (RCM) categorized as a nominal operation. Developed for the aircraft industry, RCM uses reliability estimates from a system to generate cost-effective maintenance schedules. Used predominantly for safety-related tasks, typically a failure modes and effects analysis (FMEA) is used to assess the impacts of scheduled maintenance on system reliability. The use of condition monitoring to establish an optimal maintenance schedule is what bins RCM as predictive rather than preventative maintenance (Kothamasu et al., 2006). Reliability engineering is a field expected to benefit from machine learning, an emerging technology, particularly by way of advancing reliability for better accident prevention and enhanced decision-making (Xu & Saleh, 2021).

Separate from RCM, condition-based maintenance (CBM) is categorized as a blend between nominal and off-nominal. CBM relies on live monitoring of a system to create a

realistic operational curve and can use adaptive control to increase failure prediction (Kothamasu et al., 2006). Thus, CBM is a blend because it relies on continuous monitoring, a nominal operation, to generate higher accuracy in failure prediction. Live monitoring can occur either as a nominal or off-nominal situation. If the characteristics of reliability and failure rates are provided from previous performance data, appropriate maintenance schedules are created as a nominal operation. However, if unexpected failures are detected during regular use and inform an updated characteristic profile, this would be considered off-nominal as it would likely require anomaly response to return the habitat to a nominal state. CBM is enabled by effective remaining useful life (RUL) predictions, which might be aided by deep learning and nonstationary Gaussian process regression (DL-NSGPR), as was done in a study conducted for a turbofan engine with data from NASA's prognostics repository (Xu et al., 2022). This prognostics-focused approach, aided by the emerging technology of deep learning, is useful for deep-space missions where anomaly response will benefit from advanced warnings of impending failures.

4.4.2.3 Reactive or Unplanned Maintenance

Reactive maintenance or repair, including corrective and emergency maintenance, is classified as off-nominal. This includes situations where an anomaly occurs, either a 'known unknown' or an 'unknown unknown', and the crew or system must respond rapidly. Corrective maintenance occurs after a failure has occurred and restores the system to nominal operations. Emergency maintenance must occur immediately to prevent severe consequences (Kothamasu et al., 2006). Both corrective and emergency maintenance would ideally rely on pre-written procedures designed to address 'known unknowns'. However, by definition, procedures cannot pre-exist for 'unknown unknown' anomalies that are unexpected. In this case, additional fault management methods are required to supplement

the knowledge gap and assist crew in performing reactive maintenance, especially in time-critical scenarios where they must rapidly respond to a failure in less time than it would take to solicit and receive guidance from the ground.

Examples of reactive maintenance include the anomaly experienced on the ISS on July 29, 2021, where unplanned activation of the Multipurpose Laboratory Module thrusters occurred and moved the station out of the intended flight path (Keeter, Bill, 2021a). With support from ground, the onboard crew was able to rectify the anomalous situation and return the ISS to nominal orientation through corrective maintenance after initially using emergency maintenance strategies to safe the system.

4.4.2.4 Proposed Separation of Maintenance Types

The following table summarizes the separation of maintenance types with operational examples indicated.

<table>
<tr><th colspan="3">Type of Maintenance</th><th>Spaceflight Examples</th></tr>
<tr><td rowspan="4">Proactive or Planned

(Blend)</td><td rowspan="3">Preventative

(Nominal)</td><td>Constant-interval

(Nominal)</td><td>Quarterly maintenance of Advanced Resistive Exercise Device (ARED) (Keeter, Bill, 2021c)

60 day replacement of brine filter in Urine Processing Assembly (UPA) (Keeter, Bill, 2021b)</td></tr>
<tr><td>Age-based

(Nominal)</td><td>Filter removal and replacement of Potable Water Dispenser (PWD) (Keeter, Bill, 2021c)</td></tr>
<tr><td>Imperfect

(Nominal)</td><td>Informs quarterly maintenance of ARED (Keeter, Bill, 2021c)</td></tr>
<tr><td rowspan="2">Predictive

(Blend)</td><td>Reliability-centered

(Nominal)</td><td>Machine learning, predictive analytics, prognostics (similar to applications mentioned by Xu & Saleh (Xu & Saleh, 2021)) included in a deep-space habitat</td></tr>
<tr><td>Condition-based

(Blend)</td><td>Deep learning, prognostics (similar to turbofan example by Xu et al. (Xu et al., 2022)) applied to deep-space habitat</td></tr>
</table>

Type of Maintenance		Spaceflight Examples
Reactive or Unplanned *(Anomaly Response)*	Corrective *(Anomaly Response)*	Return ISS to nominal orientation with support from mission control (Keeter, Bill, 2021a)
	Emergency *(Anomaly Response)*	Respond to MLM misfiring, communicate with mission control to diagnose anomaly (Keeter, Bill, 2021a)

Table 4: Summary of maintenance types and spaceflight examples.

Categorizing maintenance types as nominal, off-nominal, or a blend of the two separates the functional needs of the space habitat and aids in the work domain analysis by breaking the general function of 'maintenance' into specific subfunctions needed to establish an autonomous operational paradigm.

4.4.3 Fault Management

The state diagram shown in Figure 3 indicates how fault management is used to return a system to a nominal operating state from an off-nominal state. The fault management process is used to isolate failed components, a necessary step before performing appropriate maintenance (D. M. Johnson, 1996). Improved monitoring and maintenance capabilities for deep-space missions, two of the categories identified in this paper, influence fault management. These processes are interconnected and affect the success of spaceflight operations by conveying what issues have occurred to onboard crew and ground teams, as well as an understanding of why the failure occurred, what the current system behavior is, and what corrective actions must be taken. Fault management is also typically indicated by redundant system and software design that offer increased failure tolerance. This can affect caution and warning (C&W) events and how they are classified (J. Day & Ingham, n.d.; S. Johnson & Day, 2010; O'hagan & Crocker, 2011).

Target areas for autonomy include rapidly correcting software issues, automating repetitive tasks, and increasing the autonomy of time-critical responses (O'hagan & Crocker, 2011). A continuing issue with fault management includes 'brittle' (i.e., non-adaptable) designs created for single missions and use of inconsistent terminology to describe the processes (S. Johnson et al., 2011). Off-nominal or emergency situations that require unplanned responses may necessitate that the onboard crew be able respond in real-time without help from the ground (Tokadlı & Dorneich, 2018). Traditionally, fault management has housed the functions of detect, diagnose, decide and respond. However, this neglects a fundamental piece that must be considered in this framework, which is the addition of the preemptive (nominal) monitoring capabilities that enable this decision-making in the first place (S. Johnson & Day, 2010).

4.5 Proposed Information Flow Model of Deep-Space Operations

To showcase how these individual parts interact in an operational context, an information flow model is proposed in Figure 7. This follows practices used for operational flow charts by incorporating Boolean logic to capture elements of human decision-making through the process.

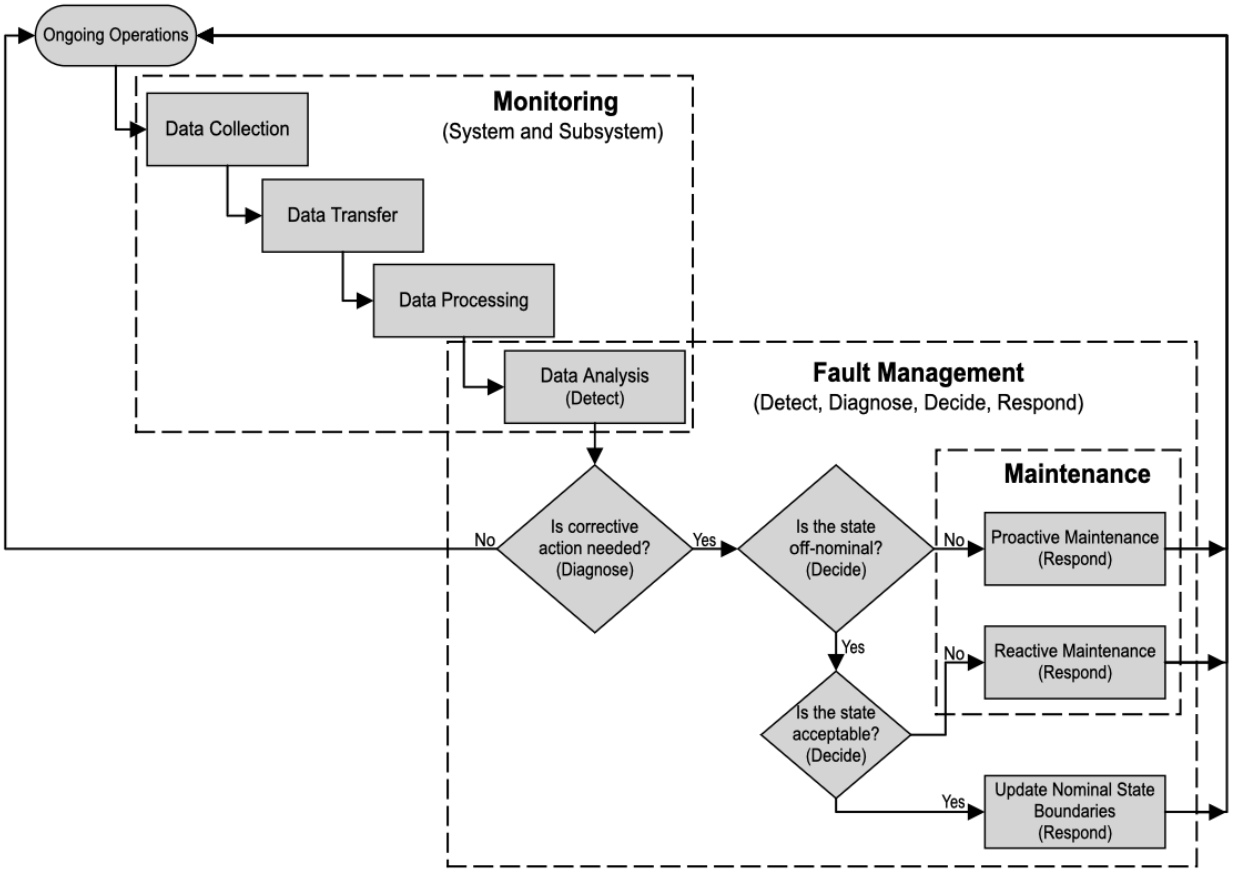


Figure 7: Information flow model of spaceflight operations represented with an operational flow diagram using Boolean logic.

This model represents how SoA operations are currently conducted on spacecraft to illustrate the interactions and constraints between the core functional categories of Monitoring, Maintenance, and Fault Management for how they enable the operations needed to accomplish mission objectives. Collecting the functions that enable the work domain of current spaceflight operations and displaying them in an informational flow model demonstrates how these operations are intertwined throughout both nominal and off-nominal operations, and indicates the steps that enable decision-making to maintain ongoing operations. Together these comprise the functional categories of self-sufficient operations and collecting them sheds insight on which pieces are gaps that enable self-

sufficiency. Additionally, this information is displayed in a control loop to reflect the influence of control logic on the ability to return a system from an off-nominal state to nominal using control methods, a concept that traces back in the literature (Albert et al., 1995; J. C. Day & Johnson, Stephen B., 2014; S. Johnson et al., 2011; S. Johnson & Day, 2010). The following subsections describe each step, including how these may be affected in deep-space.

4.5.1 Data Collection

Data collection provides insight used in ensuing steps through fault management, maintenance, and eventual return to nominal operations. This process is ongoing throughout operations and does not terminate unless an operator creates the change. Typically, this operation is completed via a sensor suite that collects data continuously or at a specified interval. This relies on a useful and effective sensor suite that has both the proper placement and density of sensors to collect the desired information. Sensor degradation or falling out of calibration are concerning limitations when targeting deep-space operations.

Additionally, the onboard crew can function as 'multisensors' (e.g., vision, smell, sound, etc.) to collect feedback on system functionality throughout the environment. Their mobility and ability to examine systems directly, in addition to using their senses to detect issues, make them a valuable contributor for data collection within the sensor suite.

4.5.2 Data Transfer

Once the data has been collected, it is transferred to a processor, which is either an onboard computer and/or a downlink to ground teams, via hardwired or wireless connections. The time delay, signal-to-noise ratio and latency inherent to deep-space

operations can impede the ability to downlink data to accommodate processing demands, discussed further below.

4.5.3 Data Processing

After transfer, the data is processed. Also referred to as signal processing, this step converts the relevant raw data signals to a useful form, e.g. converting a reading from voltage to a temperature. Performing data processing on the ground by downlinking collected data is a growing inhibitor to spaceflight research. There is a demand for increased performance of spaceborne processing systems due to evolving instrument precision and computation speed which incurs higher demands on the processor. Typically, high data rate instruments will restrict data collection to 10-20% of the mission duration to adhere to bandwidth limitations for downlink. Onboarding processing, or making use of local processing, allows for preprocessing of the data to compress the downlinked data stream and potentially allows for more autonomy of decision-making onboard (Petrick et al., 2014). Additionally, all monitors require computing power to analyze the data taken from the intended sample, in addition to health checks of the monitor itself (Limero & Wallace, 2017).

4.5.4 Data Analysis

The final step of this Monitoring process is data analysis and trend monitoring. Collecting, transferring and processing data in the preceding steps is most useful when appropriate analysis is taken to understand what is occurring. This process makes use of ground controllers and is highly reliant on teams of humans working together to troubleshoot and diagnose the proper issues. Data analysis represents a key area where emerging technologies could be used to reduce analysis time and increase correctness. In a review of ECLSS environment monitoring, Limero & Wallace (Limero & Wallace, 2017)

describe how even with the use of advanced computers, accurately identifying 'unknown unknowns' is extremely difficult and can take weeks for expert ground teams to analyze the data. Data analysis is where the fault management function of 'detection' occurs and may be aided by algorithms used to improve trend analysis and predictive capabilities.

4.5.5 Decision: Is corrective action needed?

This decision represents the 'diagnose' function of fault management, where the operator onboard or on the ground diagnoses any potential faults, failures, or anomalies that may have been detected during data analysis. If the data appears nominal, operations continue as normal. If the data appears off-nominal, this prompts the next decision. Algorithms could take ownership over this decision by informing the human operator of whether data appears to be trending in an off-nominal pattern.

4.5.6 Decision: Is the state off-nominal?

This decision is the first portion of the 'decide' function of fault management. In this decision, the responsibility of the operator or algorithm is to determine if the data is out of scope for projected nominal bounds of expected performance. If the state is nominal, proactive maintenance ensues as a response. If the state is off-nominal, the process continues to the next decision.

4.5.7 Proactive Maintenance

The 'response' step for fault management in the case of a nominal state is to perform proactive maintenance. In both categorizations of predictive maintenance, emerging technologies such as machine learning, deep learning, prognostics, and predictive analytics could benefit a deep-space habitat. Examples include residual-life distributions that model component degradation, prognostic models for cataloguing spare parts inventory, and using neural networks to inform condition-based maintenance (Elwany & Gebraeel, 2008;

Gebraeel et al., 2005; Wu et al., 2007). Similarly, preventative maintenance may also benefit from these capabilities, as increased prognostics may inform future constant-interval, age-based, or imperfect maintenance schedules.

4.5.8 Decision: Is the state acceptable?

If the decision is the state is off-nominal, the next decision is whether this state is acceptable or not. In reference to the state diagram shown in Figure 3, this constitutes deciding which route of anomaly response to take, either 'correct' through reactive maintenance or 'accept' by updating the nominal state boundaries.

4.5.9 Reactive maintenance

Corrective and emergency maintenance (repairs) are captured as the 'correct' portion of anomaly response. In this situation, the crew or agent must perform maintenance via corrective action to return a system or subsystem to a nominal state. Given the time criticality associated with types of emergency maintenance, this section is an additional area that needs improvement before it is achievable in deep-space. Improvements can include sensor-actuator systems like robots, where the physical actuator at the end location achieves the reactive action. Furthermore, coordination among nodes can present emergent behavior such as swarm intelligence (Garetto et al., 2007). These actions could also benefit from enhanced predictive and prognostic capabilities to reduce the time needed to diagnose issues before responding, and ideally to reduce the amount of emergency maintenance needed. These added capabilities may assist in identifying and diagnosing any 'unknown unknown' issues that arise over a mission lifetime and are not fully understood or addressed during the initial design.

4.5.10 Update Nominal State Boundaries

This process ensues from the decision that the state is acceptable but was previously determined to need corrective action. This step is the 'accept' portion of anomaly response where an anomaly occurred but after analysis was determined to be acceptable with a state change. For example, if a redundant component fails but does not affect overall mission performance, the nominal state can be updated to operate as expected with one less component, but likely will be flagged for continued monitoring if an associated anomaly, failure, or degradation occurs.

The level of contextual understanding needed to process and respond to the subsystem and system-level interactions present in spaceflight is representative of the sociotechnical system of deep-space operations. By decomposing the work domain into this information flow model, this section unites the standard functions within fault management with the two types of maintenance that are represented as possible response actions and ties the proposed monitoring categories into the diagram as necessary precursors to decision-making.

4.5.10.1 Monitoring, Maintenance and Fault Management for Habitat and Crew

The monitoring, maintenance and fault management categories of nominal operations are predominantly used to address system health of the habitat and assess how this contributes to overall self-sufficiency. These categories must also be discussed for how they pertain to ensuring crew health and treatment of illness or injury. For example, regular exercise is one method of maintaining physiological health of the crew, which lowers the likelihood of a failure associated with physiological health decrements later in the mission. Quantifiable methods of monitoring and maintaining crew health are beyond

the scope of this work and addressed by the field of space medicine, but it is acknowledged that operations holistically encompass both habitat and crew health. High performance in deep-space will likely be achieved by a crew that can monitor and perform fault management, including maintaining the habitat, autonomously during blackout periods or occultations. Conversely, this will also be facilitated by a habitat that can assist monitoring and maintenance of the crew (Shelhamer & Gersh, 2023).

4.5.11 Accomplishing Mission Objectives

The motivation for human spaceflight operations is driven by the mission objectives. Mission objectives, in turn, are derived from the desired research, exploration or other goals of a human spaceflight program. The objectives, along with their constraints, then lead to decisions made for required number of crew, mission duration, and destination, followed by the detailed engineering design. Successful implementation of the generalized monitoring, maintenance, and fault management capabilities discussed here serve to support successful completion of the specific mission objectives. Future government and commercial deep-space missions will pursue unique exploration and science objectives, as well as experience anticipated periods where the habitat will remain operational but unoccupied. As such, the purpose of this research is not to propose a specific mission architecture to meet these as-of-yet unspecified objectives, rather to provide mission-agnostic design and operational considerations for autonomous monitoring, maintenance and fault management functions that are applicable to any future deep-space program.

4.6 Discussion

The capabilities needed for autonomous monitoring, maintenance and fault management are proposed as key enabling functions for self-sufficient deep-space missions. These are generated in an abstraction hierarchy and demonstrated in an information flow

model to scope the work domain of deep-space operations and provide operational context for the decision-making processes needed to sustain self-sufficient operations. These design considerations are supplemented by updated terminology defined for nominal vs. off-nominal scenarios, operations, conditions, and operating state, which needed clarification before the enabling functions could be characterized.

Reaching an adequate level of self-sufficiency enabled by monitoring, maintenance and fault management facilitates the onboard decision-making and control authority needed to accomplish mission objectives in deep-space. Additionally, although not emphasized here, potential improvements to habitability can enhance crew quality of life, which can also influence accomplishment of mission objectives in the isolated confined environment of long-duration deep-space travel. Forming an integrated, overarching framework with an abstraction hierarchy as proposed in this work, which incorporates cognitive engineering work domain analysis methods, can be used to identify where operational autonomy is necessary and provide a pathway for achieving it.

4.7 Outcomes

4.7.1 Research Objectives

This work completes the proposed analysis for the following objectives.

SA1 – Characterize and differentiate representative nominal and off-nominal onboard operational scenarios for a deep-space habitat

- O1.1 – Summarize key functional needs for deep-space habitat operations
- O1.2 – Differentiate between nominal and off-nominal (including anomaly response) operations
- O1.3 – Differentiate between nominal and off-nominal operating states

- O1.4 – Define and characterize self-sufficiency attributes in the context of nominal scenarios
- O1.5 – Define and characterize habitability attributes where emerging technologies offer potential benefit

SA2 – Identify attributes of select *(and other needed)* emerging technologies capable of supporting, performing or improving nominal operations in contrast to SoA approaches

- O2.1 – Survey the literature for relevant existing emerging technology attributes
- O2.2 – Document and characterize the need for emerging technologies for adding novel capabilities, or in comparison to SoA nominal operations, as applicable

SA3 – Identify opportunities and assess potential benefits of incorporating emerging technologies with a focus on nominal operations

- O3.1 – Identify enabling attributes of emerging technology relevant to increasing self-sufficiency and/or improving habitability
- O3.3 – Map emerging technology capabilities to categorized benefits for increasing self-sufficiency and/or improving habitability

4.7.2 Publications and Presentations

Sections of this work are included in the following publications and presentations.

1. *Zaccarine, S. and Klaus, D. (2023) Characterizing the Trade Space for Incorporating Emerging Technologies into Deep-Space 'Smart' Habitats: Needs and Opportunities. International Conference on Environmental Systems (ICES). Poster.*
2. *Zaccarine, S. (2023) Collecting, Surveying, and Assessing Criteria for Self-Sufficiency in Deep-Space Habitat Operations. HOME Seminar Series.*
3. *Zaccarine, S. and Klaus, D. (2023) Attributes of Habitability for Self-Sufficient Deep-Space Habitat Operations. NASA HRP Investigator Workshop. Poster presentation.*

4. *Zaccarine, S. and Klaus, D. (2022) Autonomous System Capabilities and Attributes for Nominal Operation Task Allocation of a 'Smart' Deep Space Habitat. International Conference on Environmental Systems (ICES). Poster.*
5. *Klaus, D., Pischulti, P., Rollock, A. and Zaccarine, S. (2022) Functionally Aligning Emergent Technologies for Deep Space Smart Habitats, ICES-2022-120*
6. *Zaccarine, S. (2021). Identifying Smart System Capabilities and Attributes for Nominal Operations in a Deep Space Habitat. HOME Seminar Series.*
7. *Klaus, D., Zaccarine, S., Pischulti, P., and Rollock, A. (2020) Establishing assessment criteria for intelligent infusion of smart systems into a space habitat, ICES-2020-419.*
8. *Zaccarine, S. (2020). Intelligent Infusion of Smart Technologies into a Space Habitat. Bioastronautics Seminar Series.*
9. *Zaccarine, S. (2020). Intelligent Infusion of Smart Technologies into a Space Habitat. Smead Aerospace Researchpalooza. Awarded Honorable Mention.*

This work is in preparation for the following publication.

10. *Zaccarine, S. and Klaus, D. (2024). Monitoring, Maintenance and Fault Management Considerations for Self-Sufficient Deep-Space Habitat Operations. In review.*

Chapter 5

Increasing Habitability Considerations for Autonomous Deep-Space Habitat Operations

5.1 Objectives

Increasing self-sufficiency of deep-space habitats is a necessary enabler for autonomous deep-space missions. However, additional considerations can include incorporating emerging technologies for opportunities beyond meeting the functional needs mapped to self-sufficiency. This captures 'desirable' attributes that can make the habitat 'nicer' beyond meeting what is required to keep the crew alive at a minimum. Discussing the concept of incorporating desirable attributes becomes increasingly important when considering crew venturing to deep-space and facing extreme isolation. Additionally, how crew will interact and accomplish purposeful, meaningful work in teamwork with an autonomous deep-space habitat that can handle vast functionality on its own is an interesting design and psychological problem.

5.2 Background

Beyond meeting the required functionality needed for self-sufficient operations, other applications for autonomy that potentially improve general crew health, well-being or efficiency can also be considered in the context of increasing overall habitability. Improving habitability (i.e., quality of life) beyond the minimum requirements needed to enable a habitable (i.e., livable) environment generally encompasses aspects of human health and performance, including physiological and psychological health, and is included for completeness in the abstraction hierarchy presented in Chapter 4. Many of the attributes of

habitability overlap with, and are addressed by, the functional needs inherent to a self-sufficient habitat, including life support and operability to enable mission objectives. However, other design elements and choices made to enhance the social, cultural, or personal environment for the crew constitute potentially 'desirable' attributes that can be optionally incorporated beyond the necessary elements directly needed for self-sufficiency, if deemed acceptable in the overall trade process.

Currently, definitions for what habitability encompasses vary, particularly when targeting long duration missions. Additionally, the terms 'habitable' and 'habitability' are often interchanged, when their actual meanings differ.

5.2.1.1 Distinguishing Between a Habitable Environment and Habitability

In the fields of planetary science, geoscience, and astrobiology, a habitable environment is defined as one that can sustain a living organism, and conversely an uninhabitable environment cannot sustain a living organism. Similarly, the habitability of a planet is distinguished by its ability to support life (Cockell et al., 2016). In the context of human spaceflight, a given vehicle is considered habitable if it provides the basic life support functions needed to keep a human being alive. This need is typically met by ECLSS, which serves the purpose of maintaining a breathable atmosphere within an adequate temperature range, and providing sufficient food, water and waste management on a spacecraft. These functions fulfill the minimal requirements of keeping the crew alive. The ECLSS can also aid in enabling crew health, happiness and productivity to aid in achieving mission objectives, but this is not a requirement (C. Escobar et al., 2019). Beyond these base life support functions, habitability of a spacecraft is broadly used to describe the living conditions of the spacecraft and how well these conditions enable the crew to perform their duties, essentially serving as a 'quality of life' indicator.

5.2.1.2 Human-Rated Spacecraft and Flight Operations

Understanding the needs and requirements for human-rated spacecraft offers additional insight into habitability. NASA's Systems Engineering Handbook describes flight operations as actions that are performed by crew, onboard systems, or ground control (NASA 2007). Typically, the flight crew conducts research or experiments in flight and assists in anomaly responses as needed (Keeter 2021). Vehicle automation is used extensively through ascent and for many ongoing station-keeping activities, such as temperature control, orbit maintenance, and other applications (Sivolella 2014). The ground team can initiate changes to the vehicle, uplink telemetry, downlink data for long term changes, and partake in a large amount of decision making and task scheduling for the mission and crew.

Flight operations were defined by former director of NASA JSC's Mission Operations Directorate and Apollo 11 flight director Eugene Kranz as the level a flight system can enable a balance of minimal risk, minimal operating costs, and maximal mission success (Kranz 1985). At that time, planning, training and implementation of operations were completed by the Mission Operations Directorate. In the future, most operations will likely still be designed and considered by ground teams before the spacecraft is launched for a deep-space mission. However, the role of ground operators may be taken over, at least partially, by the crew and autonomous systems onboard the habitat.

The fundamental tenets of a human-rated spacecraft are to accommodate crew needs, utilize their skills and capabilities to accomplish mission objectives, and protect the crew, ground, and uninvolved public. Rephrasing, 'accommodating' the needs of the crew is provided by habitat functionality, 'utilizing' the crew's capabilities is summarized as crew operations, while 'protect' is addressed by risk mitigation approaches (Klaus et al. 2014).

5.3 Methods

To characterize habitability, inspiration was taken from the various levels of autonomy proposed throughout the literature for terrestrial applications as a way to visualize how varying amounts of habitability would appear in an operational setting to the crew. Attributes of accommodate and degrees of utilize were created by referencing and aligning with the tenets of a human-rated spacecraft, 'accommodate', or what the habitat provides the crew, and 'utilize', or what the crew provides the habitat. Attributes of accommodate were mapped to various level of autonomy frameworks to compare what an autonomous deep-space habitat might provide to the crew. Degrees of utilize, designed to capture how humans can effectively make use of an autonomous habitat, were proposed and incorporate items from the theories of human workload and an ideal 'flow' state represented by the Hebb version of the Yerkes-Dodson theory.

5.4 Results

5.4.1 Combining Elements of Habitability

Habitability considerations are extensive, as many of these elements intersect with personal preference. Celentano et al. (1963) asserts that habitability implies an environment akin to a comfortable situation on Earth (Celentano et al., 1963). The Celentano Curve represents three states of habitation: optimal, the performance limit, and the tolerable limit. These correspond to an associated habitable volume per crewmember and the estimated mission duration in months. Based on heuristic data, these curves provide an estimate for what longer duration missions may require to support the three states of habitation. Testing of this curve in 2008 concluded that mission duration is the primary driver for habitat size, with crew size and functional operation potentially providing secondary effects (Cohen, 2008). This testing also supported the hypothesis that

small vehicles are fundamentally different than large vehicles, and that volumetric requirements for capsules such as the Orion Crew Exploration Vehicle, built to accommodate four crew for lunar missions, fit in a unique data set separate from much larger and longer duration habitats (Sherwood & Capps, 1990).

In 1967, NASA's Deputy Administrator George Mueller recruited Raymond Loewy, an industrial designer, to serve as a 'Habitability Consultant' for the Skylab space station. Inclusions of a viewing porthole and a triangular table, so no crewmember was ever at the 'head' of the table, demonstrated the psychological and social concerns that a physical environment can have on a crew (Mohanty et al., 2006). Currently, NASA has a habitability team as part of their Human Health and Performance Directorate that create effective systems, architecture, and products for use in spaceflight. These individuals combine experience in human-centered design, industrial design, architecture, aerospace engineering, industrial engineering, and systems engineering (Lewis, 2021).

Other attempts to describe habitability include a definition from the Human Factors and Ergonomics Society (HFES), which is extensive and nests habitability as one part of human systems integration. In this definition, habitability includes physical, social, and cultural environments, as well as personal services and living conditions (HFES, 2021).To add clarity for deep-space missions which present unique challenges to crew, the NASA Human Exploration of Mars DRM 5.0 asserts that habitability goes beyond basic life support and must address crew emotional and physiological stressors to maximize productivity (Drake, 2009). Additional performance factors of habitability include availability of certain items in a given vehicle layout, cleanliness of the environment, inventory management capability, and level of sensory stimulation (Mindock, Jennifer, 2012). These definitions and descriptions are summarized in Table 5 to capture the many facets of habitability in a human spaceflight context.

Habitability Considerations	Source
Akin to a comfortable situation on earth	(Celentano et al., 1963)
Contains optimal, performance and tolerable limits of **habitable volume**	
Physical environment (lighting, ventilation and physical space)	(HFES, 2021)
Social environment (interpersonal relationships, personal support network, interpersonal interactions)	
Cultural environment (behaviors, beliefs, customs)	
Personal services (medical, religious)	
Living conditions (breathable atmosphere, personal hygiene)	
Habitability describes the relationship between habitat design and crew **psychology**	(Mohanty et al., 2006)
Layout including shape, dimensions, orientation, décor, interfaces, and contingency and emergency spaces	
Psychological issues can include environmental, individual, interpersonal, maladaptive, performance, and altered states of consciousness	
Unites principles from human-centered design, industrial design, architecture, aerospace engineering, industrial engineering, and systems engineering	(Lewis, 2021)
Environment must minimize physiological and emotional stress to **maximize crew productivity**	(Drake, 2009)
Availability of personal items, medical care, recreation, private space, i.e. layout of the habitat	(Mindock, Jennifer, 2012)
Cleanliness of environment	
Inventory management capabilities of habitat	
Sensory stimulation of habitat	

Table 5: Habitability definitions and considerations.

As indicated in these references, increased habitability enables an environment that promotes physiological and mental health beyond basic life support. This is especially important for longer duration missions given the unique physiological and psychological stressors that will be placed on the crew.

Further characterization of habitability is now explored by aligning the elements identified in Table 5 with the fundamental tenets of a human-rated spacecraft, accommodate and utilize.

5.4.2 Considerations for Vehicle Accommodation

5.4.2.1 Historical Examples and Temporal Concerns

In the context of this research, *habitat operations* are more specific than spaceflight operations and address uniquely what the habitat does for the crew as an accommodation metric (Klaus et al., 2014). Examples of past missions with varying amounts of accommodation include the Personal Rescue Enclosure (PRE), which was developed as a crew survival system that could be used in an emergency evacuation to quickly transfer crew from one Space Shuttle to another (David, 2009). This mission provides basic life support for a short period of time. In contrast, the Space Shuttle for short durations (~weeks) and the ISS for short to long duration missions (~months) provide capabilities beyond basic life support. Inclusion of design choices such as crew quarters, windows, and workstations can provide these capabilities, among other additions. These environments allow for productivity in research duties and potentially satisfaction in work depending on the crew member. These missions provide varying levels of 'what the vehicle does for the crew' and promote different aspects of habitability.

The temporal nature of different missions is important to note. The average length of an ISS mission is six months or 182 days (NASA, 2020b), far lower than the 1,200-day mission specified in the M2M without resupply from Earth or the ideal 914 day estimate for an example mission by the Mars Architecture Steering Group at NASA (Drake, 2009; Harris, et al., 2022). Reaching an optimal level of habitat accommodation will likely vary depending on unique mission objectives and duration of the mission, and design choices made for ISS may not be as applicable for deep-space habitats.

5.4.2.2 A Need for Attributes of Accommodation

The existing definition of *accommodate* as a tenet of a human-rated spacecraft, or 'what the vehicle does for the crew', does not account for habitats that will contain increasing levels of autonomy and higher degrees of self-awareness and self-sufficiency. A proposed hierarchical breakdown of attributes of accommodate that the habitat provides the crew as follows. Note that the use of 'autonomous system' can include the crew in the loop, e.g., the crew and the habitat together can function as an 'autonomous system'.

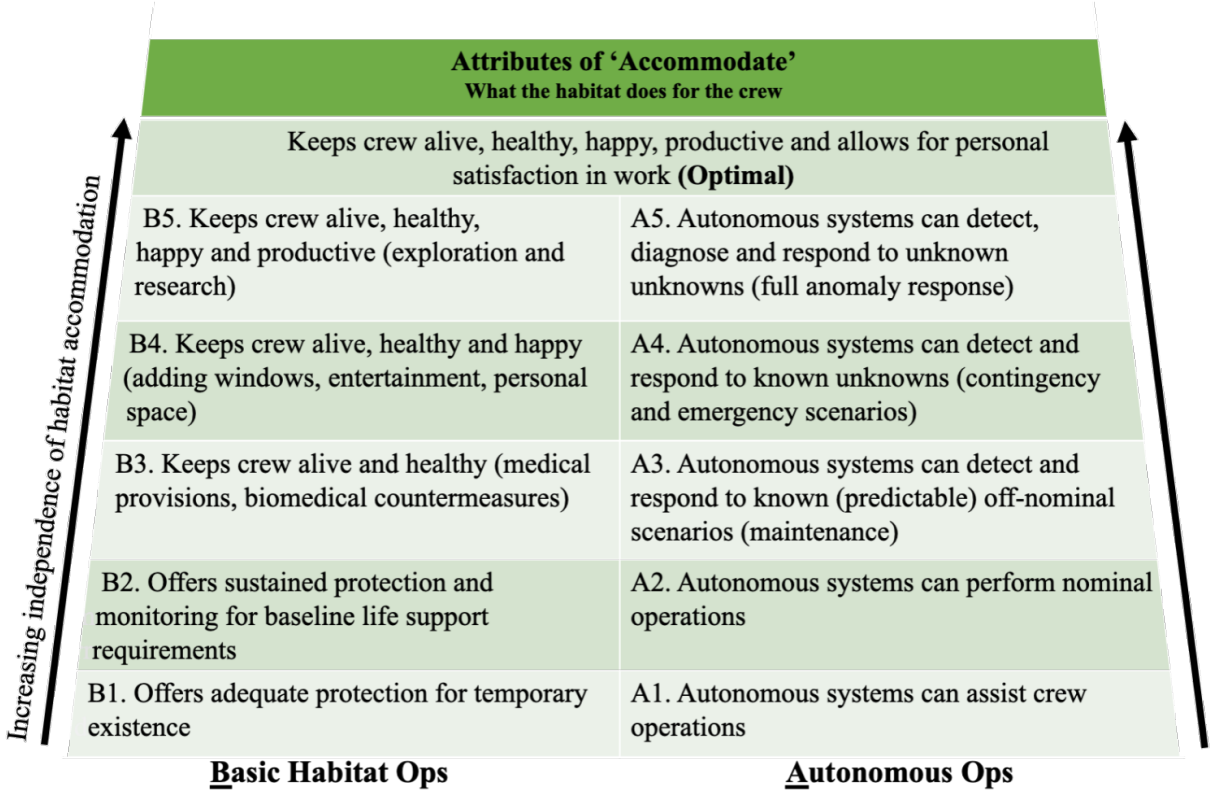


Figure 8: Proposed hierarchy for attributes of habitat accommodation.

Examples of past missions that fit on this diagram include the Personal Rescue Enclosure (PRE), meets the standards of a number 1 habitat. The PRE was developed as a crew survival system that could be used in an emergency evacuation to quickly transfer crew from one Space Shuttle to another (David, 2009). The Space Shuttle for short durations (~weeks) meets the standards of a number 5 habitat, and the ISS for long

duration missions (~weeks – months) also meets the standards for a number 5 habitat. SpaceX's Inspiration4 all-civilian mission served as an example of a number 7 habitat given the habitat was highly automated for nominal operations but saw a predictable off-nominal WMS failure where the crew needed to repair a fan system with coaching from the ground team (Hamilton, I.A., 2021). The goal standard for any habitat is written across the top as the Optimal point. This reflects the notion that optimal missions could be reached either via basic vehicle operations, or by adding enhanced autonomous operations.

The temporal nature of different missions, as discussed for a number 5 habitat, is important to note. The average length of an ISS mission is six months or 182 days (NASA, 2020b), far lower than the 1,200-day mission specified in the M2M without resupply from Earth (Harris, et al., 2022). Reports from past spaceflight missions indicate too high of a workload in some cases (Scheuring et al., 2007; Stuster, 2010; Uri, 2020). Increasing the attributes of accommodation by strategically implementing autonomous systems could help offload the crew and provide a sustainable work balance during their mission.

However, offloading too many crew responsibilities could pose problems as well, as studies have shown the negative results of either too low or too high a workload (Stuster, 2010). To find the correct balance of workload for the crew, a proposed metric for degrees of utilize is discussed next.

5.4.3 Considerations for Human Utilization

Even if desired amounts of accommodation can be achieved, concerns can arise if the crew is not being *utilized* properly. For example, reports from historical short-duration missions indicate too great a workload in multiple cases. On Skylab 4, astronauts and mission managers acknowledged that scheduling in the first half of the mission was too high (Uri, 2020). Reports from Apollo missions include mentions of extreme mental and

physical fatigue from long work hours during surface operations (Scheuring et al., 2007). On the ISS, crew reported making minor mistakes caught by the ground team that were attributed to mental fatigue and inadequate scheduled time for task completion (Stuster, 2010). Increasing accommodation of a habitat by strategically implementing autonomous capabilities could help offload the crew and provide a sustainable work balance during their mission. However, offloading too many crew responsibilities could pose problems as well, as studies have shown the negative results of either too low or too high a workload (Stuster, 2010).To aid in finding a correct balance of workload for the crew, the term *utilize* is discussed.

5.4.3.1 Human Information Processing Theories and Workload

Human information processing is described by numerous theories including information processing theory, rational decision and signal detection theory, information acquisition and Bayes theory, or naturalistic decision making (Vidulich et al., 2010; Wickens & Carswell, 2021; Wickens & Hollands, 2000). Uniting these theories with human performance can ideally be used to enhance human-machine interaction or human-autonomy teaming. Causes for human error during performance can include inexperience of the human operator, lack of training, stress, or misleading displays, among other human factors issues. Additionally, there may be limited attention resources by crew that account for suboptimal performance.

Physiological and cognitive limitations exist for human operators as well. Hypoxia, shifts in perception due to vestibular stimulation, and gravity-induced loss of consciousness (G-LOC) are some of the issues reported from human operators using aerospace vehicles (Wickens & Hollands, 2000). Several spaceflight-induced physiological adaptations also exist when transitioning to and from a microgravity environment. Some of these changes

include loss of muscle mass, loss of bone mass, the cephalic fluid shift, and a number of other effects that can alter human performance (Buckey, 2006). Long-duration, continued presence in a micro-gravity environment may also alter the performance of the crew.

Finding a balance in workload for human operators is highly desirable. The NASA Human Integration Design Handbook (HIDH), Revision 1, discusses an ideal balance between situation awareness and workload that allows the human operator to remain attentive and involved without being overwhelmed (NASA, 2014). The effects of "clumsy automation" have been researched, which indicate that too much automation can lead to a redistributed workload instead of a reduced one (Parasuraman et al., 2000; Wiener, 1988). Similarly, too low of a workload could lead to a lack of purpose and decreased mental health of the crew. Both underworked and overworked crew are undesirable for achieving mission objectives.

Challenges in defining workload include that it is a highly individualized metric, and measurement metrics are either direct, indirect, and/or subjective (Casner & Gore, 2010). Several options for evaluating workload subjectively include the Instantaneous Self-Assessment (ISA), NASA Task Load Index (TLX), and the Bedford Workload Scale, each of which have unique advantages and disadvantages (Casner & Gore, 2010).

5.4.3.2 Workload and the Yerkes-Dodson Theory

The Yerkes-Dodson theory, colloquially referred to as the Yerkes-Dodson law or Yerkes-Dodson observation, empirically describes a relation between workload, or pressure, and performance on a combination of simple and complex learning tasks (Yerkes & Dodson, 1908; Yerkes & Morgulis, 1909). In 1954, Schlosberg proposed a theory that emotional behavior can be used to describe all behavior, regardless of task complexity (Schlosberg, 1954). Shortly thereafter, Hebb created a curvilinear version of the arousal-performance

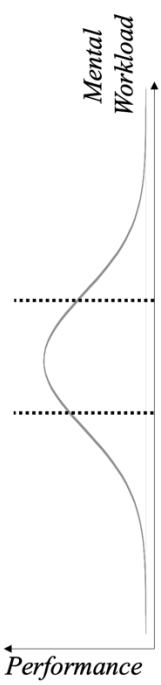
connection in a bell curve shape that has been commonly misattributed as the original Yerkes-Dodson theory. Hebb asserted that arousal is synonymous with motivation, and this 'drive' is what causes the relationship between arousal and performance, in agreement with Schlosberg's idea of emotional behavior. Hebb attributed the drop in learning for any task to strong anxiety surrounding higher performance, and therefore decreased motivation (Hebb, 1955a, 1955b). This Hebb version of the Yerkes-Dodson theory formed the broadly recognized inverted-U relationship that describes that there is an optimal learning point that is generated by a level of stress, causing motivation, that is not too high or too low.

A study published in 2006 found a curvilinear relationship between cortisol release and memory performance consistent with the proposed shape of the Hebb version of the Yerkes-Dodson theory and, at the time of publication, claimed these findings represented the first demonstration of the inverted-U relationship between human memory and endogenous stress hormones (Andreano & Cahill, 2006). Though the Hebb version of the Yerkes-Dodson theory has been contested in cognitive psychology literature, it has been accepted more broadly in behavioral neuroscience and attempts have been made to assess its feasibility. There is a growing interest in identifying and achieving a 'flow state', where a person is devoid of distraction and instead entirely focused, energized, and enjoying a task at hand, which is related to the observations of Yerkes and Dodson (Khazaei et al., 2021; Peifer, 2012).

5.4.3.3 Proposed Degrees of Utilize

Similar to habitat accommodation, the existing definition of *utilization*, or 'what the crew does for the vehicle', lacks granularity. Past studies of typical crew operations are likely not representative of how crew will interact with increasingly autonomous habitats. An ideal amount of utilization would enable crew satisfaction by providing enough

meaningful work to the crew. This workload would ideally model a 'flow state' and prevent constant, highly stressful situations that could reduce performance, and would also balance low pressure situations by maintaining the crew's ability to complete their tasks and respond to off-nominal situations. A proposed 'Degree of Utilize' assessment framework is outlined below as a baseline for further consideration and refinement.



	Degree of 'Utilize' What the crew does for the habitat	
9	Crew capabilities are overextended/habitat unable to assist	***Over-utilized (Overworked)**
8	Crew is needed for emergency anomaly response (without help from ground)	
7	Crew is needed for emergency anomaly response (with help from ground)	
6	Crew can utilize habitat for personal satisfaction or enjoyment	***Optimal (Satisfied)**
5	Crew has adequate time for research and exploration activities	
4	Crew is needed for many operations	
3	Crew is needed for some operations with optional habitat assistance	
2	Crew can perform some tasks - habitat capable of performing nominal and off-nominal operations	
1	Crew not needed - habitat monitors H&S and performs all nominal and off-nominal operations, humans are only passengers (space tourism)	***Under-utilized (Bored)**

Figure 9: Proposed degrees of crew utilization to assess an optimal workload for the crew.

The Degree of Utilize diagram incorporates a superimposed inverse-U Hebb version of the Yerkes-Dodson theory on top of a spectrum of crew operations. The Hebb version was adopted because complex tasks are likely more representative of a high stress spaceflight operating environment than monolithic simple tasks. In Figure 9, the crew responsibilities range from very little as a passenger/tourist at number 1, up to the crew having to maintain nearly all flight operations at a number 9. An example of a Degree 1 of Utilize would

theoretically be a fully autonomous habitat that supports the inhabitants without requiring them to perform any operational roles. An analogous terrestrial example of this is transporting passengers in a fully autonomous self-driving car. Actual spaceflight operational scenarios detailed in 5.4.2.2 from Skylab, Apollo, and ISS showcased examples of work overload as would be seen in a Degree 9 of Utilize (Scheuring et al., 2007; Stuster, 2010; Uri, 2020). The optimal range in the middle of the diagram allows for crew satisfaction where the crew has enough meaningful work to complete without constantly being in a high-pressure situation that could reduce performance. This table is intended to characterize a general trend that emphasizes crew workload conditions as the scale increases, with more research needed to refine, demonstrate and the validate specific roles at each level.

An interesting caveat to note is the individuality associated with concepts like workload particularly for the evolving demographic of astronauts. The 'Optimal' range in the middle is highly dependent on an individual's unique work style and preferences. Furthermore, the limited demographic representation in historical astronauts, and datasets resulting from these limited participants, do not necessarily represent the increasingly diverse astronaut classes hired for government and commercial missions. Stratifying the desired utilization of the habitat, or what the crew does for the overall mission, should account for the individual nature of each crew member and be tailored as such. For example, one crew member may thrive on having more periods of working stress than another in order to remain satisfied and ready to respond to the demands of the mission.

Furthermore, in an autonomous deep-space habitat, operations relying on decision-making such as maintenance, monitoring and spacecraft reconfiguration could be achievable by either the crew, the habitat, or a combination of the two working together, as demonstrated in Figure 10 which incorporates autonomous systems into function allocation

which has typically been reliant on human or automation. Note that an autonomous system in this work can be comprised of a human, a human and automation, or a human, automation, and autonomous behaviors.

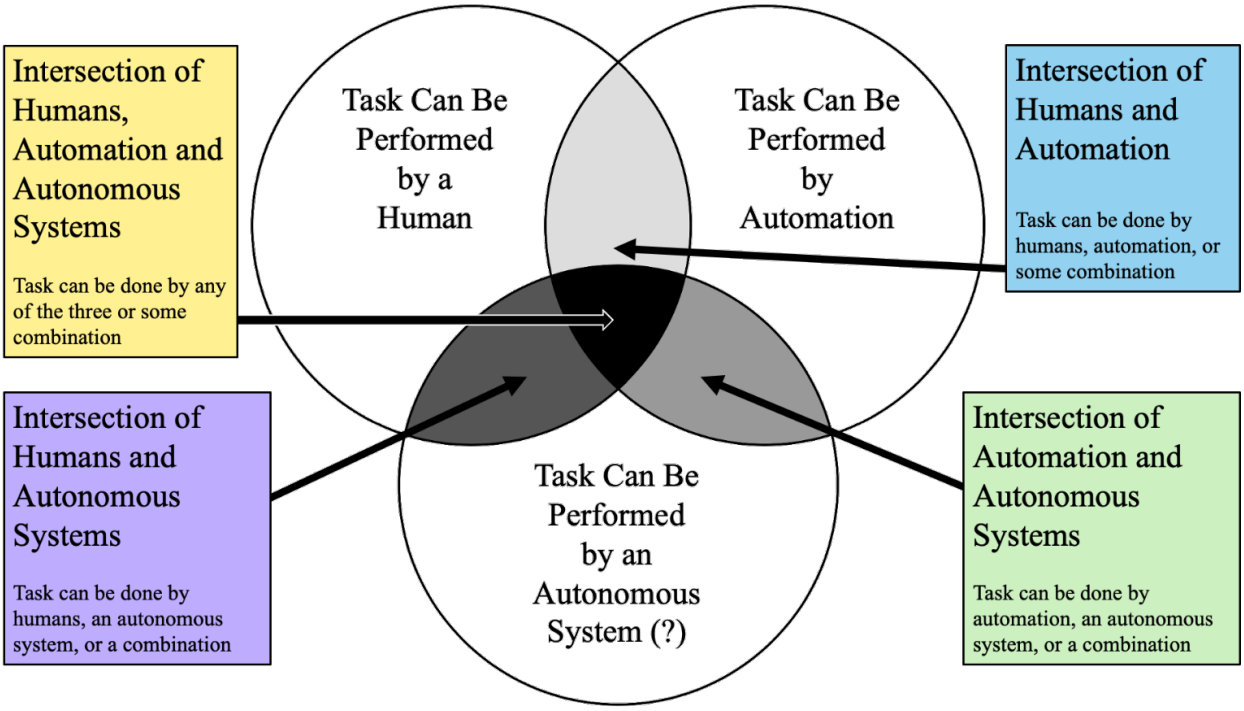


Figure 10: Figure visualizing function allocation between humans, automation, and autonomy.

Operational autonomy implies a given crew and habitat can survive and respond to time-critical emergency scenarios without ground support, as this will be required for future deep-space missions due to the time delay and lack of ability to send rapid logistic resupply. Depending on the given mission this could be achieved by a number of configurations of crew and automation that enable the behavior of the crew and habitat to resemble an 'autonomous system'. Assessing which operation completion type is ideal for a given mission and unique operator may be aided by stratifying the terms *accommodate* and *utilize*.

5.4.4 Aligning Tenets with Habitability

The proposed attributes of accommodation and degrees of utilize can be aligned with the habitability considerations captured in Table 5 and applied to vignettes of past missions.

Vehicle	Duration of Life Support	Additional Design Elements, Habitability Improvements
Personal Rescue Enclosure (PRE)	Hours	None – only life support
Space Shuttle	Weeks	Workstations, galley
International Space Station (ISS)	Months*	Windows, workstations, crew quarters, leisure activities, entertainment

*Has been continuously occupied since November 2000, but is resupplied every ~3 months and average mission length for one crew is 182 days (NASA, 2020b)

Table 6: Comparing vehicle accommodation by analyzing habitability elements from historical missions.

Combining the proposed attributes and tenets with vignettes provides context for how habitability has evolved over time and may need to continue evolving as the demand placed on crew changes for deep-space missions.

5.5 Discussion

Attributes of accommodate (what the habitat does for the crew) and degrees of utilize (what the crew does for the habitat) are compiled and proposed as a way to characterize habitability. Identifying the design features that future deep-space habitats may include to facilitate positive interaction with the crew directs analysis beyond what functionality habitats *need* to do to support life and includes considerations for the crew psychology. In combination with the analyses conducted in Chapter 4 to characterize self-sufficiency, these analyses can provide context for which operations may benefit from incorporating emerging technology.

It is important to note certain operations may foster a sense of purpose, motivation, or enjoyment, and tending astronauts' mental health is an important component of mission design since the humans will be expected to live in a physically, mentally and emotionally difficult situation for potentially years at a time. Psychological well-being directly impacts performance and must be included in the trade space when considering the impact of incorporating emerging technologies. As written in the NASA M2M, the habitat must accommodate meaningful work for the crew to enable purpose-driven personal and social activities (Harris, et al., 2022).

Additional considerations include adaptable and adaptive autonomy with corresponding implications to how the crew will interact with the autonomy and if these teaming opportunities include dynamic control authority over 'who' decides to make mission-level decisions. Incorporating user preference and individuality in these designs will likely be important as well as certain crew may trust the autonomous teammate more or in different situations than other crew.

As operational autonomy is pursued to enable safe deep-space mission, both 'need to have' solutions encompassed by self-sufficiency and 'nice to have' (potential 'needs' depending on a given crew and mission) additions included to improve habitability are important factors of the design. These findings highlight where emerging technologies could improve on current SoA solutions and enable deep-space operations.

5.6 Outcomes

5.6.1 Research Objectives

This work completes the proposed analysis for the following objectives.

SA1 – Characterize and differentiate representative nominal and off-nominal onboard operational scenarios for a deep-space habitat

- O1.5 – Define and characterize habitability attributes where emerging technologies offer potential benefit

SA3 – Identify opportunities and assess potential benefits of incorporating emerging technologies with a focus on nominal operations

- O3.2 – Characterize attributes of accommodation and utilization in terms of habitability in the context of nominal operational scenarios

5.6.2 Publications and Presentations

Sections of this work are included in the following publications and presentations.

1. *Zaccarine, S. and Klaus, D. (2023) Characterizing the Trade Space for Incorporating Emerging Technologies into Deep-Space 'Smart' Habitats: Needs and Opportunities. International Conference on Environmental Systems (ICES). Poster.*
2. *Zaccarine, S. and Klaus, D. (2023) Attributes of Habitability for Self-Sufficient Deep-Space Habitat Operations. NASA HRP Investigator Workshop. Poster presentation.*
3. *Zaccarine, S. and Klaus, D. (2022) Autonomous System Capabilities and Attributes for Nominal Operation Task Allocation of a 'Smart' Deep Space Habitat. International Conference on Environmental Systems (ICES). Poster.*
4. *Zaccarine, S. and Klaus, D. (2021) Autonomous Systems for Enhancing Human Performance and Vehicle Operations in Deep Space Habitats, AIAA Rocky Mountain Annual Technical Symposium (ATS).*
5. *Zaccarine, S. (2021). Identifying Smart System Capabilities and Attributes for Nominal Operations in a Deep Space Habitat. HOME Seminar Series.*

This work is in preparation for the following publication.

6. *Zaccarine, S. and Klaus, D. (2025). Characterizing Habitability for Deep-Space Habitat Operations. Forthcoming.*

Chapter 6

Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats

6.1 Objectives

The cognitive engineering functional analysis conducted in Chapters 4 and 5 of this dissertation proposes general functional categories for increasing self-sufficiency and improving habitability to enable deep-space missions. To accompany this top-down analysis, a bottom-up analysis is conducted in Chapters 6 and 7 to collect data in a rigorous manner by using human-subject testing. The following analysis focuses on qualitative investigation of the general function of 'maintenance' identified in the abstraction hierarchy proposed in Figure 5, with rationale provided below. The experimental methods described in this chapter were approved under CU IRB Protocol #23-0669.

6.2 Background

Crew time in space is a valuable asset. An analysis of crew-time utilization aboard the International Space Station (ISS) and Skylab found actual crew time spent on scheduled and unscheduled maintenance exceeded design expectations and hindered their ability to complete other mission objectives. Further, a major component of this time resulted from maintenance of the environmental control and life support systems (ECLSS) (Russell et al., 2006). ECLSS is a critical subsystem for human spaceflight that enables and supports the functions needed to keep the onboard crew alive and healthy. Therefore, ensuring its functionality, both by increasing likelihood of successful operation and, when

anomalies occur, allowing for crewed maintenance to restore nominal functioning, is necessary to support safe mission operations.

When designing these systems, a series of decisions are made by the design teams to satisfy a host of criteria, often set by the high-level goals, ConOps, and subsequently derived requirements for the mission. Making design decisions to satisfy requirements is a multi-variable decision. In many cases, there is no single 'right answer', but rather a set of mission drivers that constrain which design attributes are highest priority for a given mission. For NASA, these include high levels of reliability and maintainability (Groen et al., 2015). Understanding which design attributes are typically employed when designing maintainable ECLSS could potentially inform cost-saving best practices to be used by future designers. Similar retrospective investigations using various methods have been conducted to derive best practices and compile 'lessons learned' from past space missions to increase likelihood of mission success in future architectures for topics including space logistics, cerebral blood flow regulation in microgravity, structural analysis using finite element analysis (FEA), and habitability (Blaber et al., 2013; Evans et al., 2006) (Baggerman et al., 2004; Smith et al., 2020).

ECLSS subject matter experts (SME's) such as engineers and astronauts have a wealth of knowledge related to designing ECLSS and performing maintenance on these systems in-flight. Documenting the design knowledge used to inform these practices is challenging, as capturing the nuance and experience afforded from years of experience is difficult to succinctly summarize. There are compiled sets of design recommendations in the NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health NASA-STD-3001 Volume 2 Revision C, the NASA Human Integration Design Handbook (HIDH), the Human Spaceflight Mission Analysis and Design (HSMAD), the NASA Systems Engineering Handbook, and the NASA Reliability and

Maintainability (R&M) Standard for Spaceflight and Support Systems, which are analyzed in depth in Chapter 7 (Larson & Pranke, 2000; NASA, 2007, 2014, 2017, 2022). This effort seeks to contribute to these standards by identifying which of these are considered by the interviewed participants for the specific use of maintainable ECLSS for deep-space. The summarized results intend to contribute actionable themes that can be implemented into future ECLSS designs to target maintainability improvements by collecting detailed verbal responses from SME's using qualitative methods. This represents a potential way to save significant crew time on future missions and aligns with the design goals set forth by NASA to improve maintainability and reliability for future missions (Groen et al., 2015; Harris, et al., 2022; NASA, 2017).

6.2.1 Qualitative Research and Interviews

Qualitative research is used in fields such as exercise science, medicine, and psychology to capture and generate knowledge resulting from the human experience (Nowell et al., 2017). The rigor and use of these methods was questioned when qualitative health research surfaced as a pronounced method in the field in the 1980's, primarily due to the assertion that these methods are not objective and therefore cannot yield generalizable results (Sandelowski, 1997; Sandelowski, 2004). However, since then the growing perceived importance of practical knowledge in the medical sector has prompted increased emphasis on qualitative research and on developing tools for assessing the datasets in a rigorous manner (Sandelowski, 2004).

This work focuses on a contextual research question, 'what are design attributes to consider for improving ECLSS maintainability in deep-space missions?' This type of qualitative research question seeks to understand the nature of what already exists by

querying individuals or groups to understand real-world problems (Barroga & Matanguihan, 2022).

6.3 Methods

6.3.1 Deductive and Inductive Approaches

This study is unique from recent human spaceflight applications of qualitative investigation because it uses primarily a deductive approach rather than primarily inductive (Almand et al., 2023; Laws et al., 2022). This approach was chosen because it allowed the researchers to generate targeted interview questions on the specific topic of ECLSS maintainability for deep-space operations. The research team could not reasonably claim to be unbiased to the interview topics given their previous experience, so a deductive approach was more suitable and allowed for a deeper analysis into the topic of ECLSS maintainability.

Though the analysis was primarily deductive, inductive elements were also incorporated by allowing the list of themes to evolve and shift from the hypothesized attributes, generated prior to conducting interviews, as coding analysis progressed (Braun, V. et al., 2016). This list of hypothesized design attributes for highly maintainable ECLSS was drafted and benchmarked by the interview team before beginning interviews and served as the code book for the thematic analysis. This served as the reference point from which interview responses were compared for augmentation, whether by validating the existing attributes or introducing attributes the interview team did not previously consider. The participants were told the interview team compiled their thoughts previously and were seeking opinions and augmentation from the interview responses, but the participants were not given the list of attributes, with the exception of ‘fault tolerance’ and ‘accessibility’ (renamed Ease of Access) provided as examples to provide context. These two attributes, or

themes, were selected to provide context because the researchers thought they were likely to be mentioned regardless. At the conclusion of each interview, the participants were asked to provide any other thoughts or feedback regarding ECLSS maintainability that were not captured in the interview questions or their previous responses. This was meant to capture any remaining knowledge that may not have been prompted from the interviewer questions.

6.3.2 Eligibility and Pre-Screening

After participant recruitment was conducted via email and interested participants replied, pre-screening eligibility questions were sent and filtered participants for 4+ years of ECLSS-relevant experience and spaceflight-relevant experience. These inclusion criteria ensured participants had a level of knowledge suitable for an SME. The benchmark for 4+ years was referenced from the upper end of NASA's required training time to become a flight operator (Hutt, 2012). The inclusion criteria were split into 'ECLSS-relevant' and 'spaceflight-relevant' experience to allow for a hypothetical participant with flight experience, a unique and limited characteristic, that may have 4+ years of spaceflight experience but not 4+ years ECLSS experience, that was desirable to interview given astronauts are few. However, all participants for this study met both inclusion criteria. The participants were also asked to self-identify their experience as academic research and development, engineering design, ground operations (launch or mission control), and/or in-flight operations (astronaut), and were asked to select all experience types that applied. These experience identifiers were created by the research team to guide the interviews appropriately and avoid asking participants irrelevant questions. These experience identifiers were not exclusion criteria, rather, helped guide the interview questions.

Previous studies have emphasized the importance of including human factors principles early in the lifecycle of designing space vehicles (Baggerman et al., 2004). By interviewing SME's with experience spanning the lifecycle of engineering development, this study documents SME knowledge gathered from the end user to inform future systems design.

After confirming their eligibility, participants were provided a consent form and pre-interview project background. The participants were asked to review these documents prior to their interview, and the documents were reviewed at the start of each interview to ensure their understanding. The 2-page pre-interview project background contained definitions for ECLSS robustness, deep-space missions, operationally autonomous, self-sufficiency, and emerging technologies as relevant topics for the interview. The research objective was stated, and the structure of the interview was described. The participants were asked to verbally provide their consent before beginning the interview questions.

6.3.3 Semi-Structured Interviews

Semi-structured, qualitative interviews were conducted for data collection. This method was selected due to its ability to capture verbal responses from participants in a 'stream of consciousness' style. The pre-written script was referenced and served as a guide for each interview. The semi-structured method allowed the interviewer to expand on certain participant responses even if they deviated from the pre-written script – for example, the interviewer could ask follow-up questions on a participant response even if the follow-up questions were not pre-written. Apart from ensuring the interview was more conversational than rigid, this was also helpful because it allowed for clarification on certain participant responses, but also on interview questions if the participant requested

more detail. The interviews were targeted to take 45 minutes – 1 hour, with a hard cutoff at 1.5 hours.

The interview questions were split into 3 sections of general event description, detailed experience-specific questions, and a final 'open-ended' question where participants were invited to share any relevant topics that were not captured in the pre-written interview guide. The event description questions focused on ECLSS maintenance experience in any capacity and invited the participants to share their experience with ECLSS maintenance or maintenance for other subsystems. The experience-specific questions were compiled to reflect the four areas of experience collected in the interview pre-screening eligibility form. Specific questions pertaining to each experience type were written by the primary researcher, and during interviews, the interviewer would ask only the questions in the appropriate experience type for each participant.

6.3.4 Reflexive Thematic Analysis

Thematic analysis was used to analyze results, which allows a researcher to investigate and deduce patterns from large qualitative datasets. Thematic analysis offers a robust and flexible framework to researchers, making it an applicable method to a range of research inquiries (Braun, V. et al., 2016). This method has recently been applied to human spaceflight by querying astronauts on their preference for exercise devices in spaceflight (Laws et al., 2022), to derive primary risk considerations and contributing factors for complex medical evacuation (MEDEVAC) procedures (Almand et al., 2023), and in post-mission interviews to assess communication delay impacts to behavior on ISS (Kintz & Palinkas, 2016). Both semantic and latent themes were identified in this analysis. Semantic themes are identified by capturing directly stated ideas, i.e., if a participant mentions 'robustness is important', then the theme of 'robustness' can be directly coded. Latent

themes represent the ideas or concepts underlying the directly stated ideas. The thematic analysis used a deductive approach given the list of theorized concepts that were generated before beginning the interviews. Inductive elements were still incorporated by allowing the content to guide the evolving list of themes, which aligns with most thematic analyses that incorporate both semantic and latent, deductive and inductive elements .

Thematic analysis was conducted by a single researcher using NVivo qualitative analysis software by analyzing the interview data to compile 'codes' which summarize important phrases or ideas shared from participants and are meant to 'evoke' the section of data without needing to read the interview transcript (Braun, V. et al., 2016; Laws, J.M. et al., 2020). These codes are then grouped into high-level 'themes' which represent the key findings from the dataset in a condensed and more readily shareable way (Almand et al., 2023; Suedfeld et al., 2015).

The stopping criteria for data collection was 'coding saturation', defined when one participant interviewed didn't present novel codes to the analysis. Coding saturation does not inherently imply 'meaning saturation', however, and factors such as saturation, the purpose of the study, study population, and complexity and stability of the codebook are identified as parameters to inform an appropriate stopping criteria (Hennink et al., 2017). Given the limited number of potential participants who could qualify for this study, an a priori estimate for saturation ranged from 7 to 15 participants. Furthermore, these participants were asked to identify objective design attributes specifically for ECLSS maintenance, not to recount their opinions of their relative importance. This simplified and stabilized the interview topic, questions, and resultant complexity of the codebook and reinforced confidence in the stopping criteria.

To identify coding saturation, participant response transcripts were analyzed to determine if any novel codes were found. When 1 participant interview didn't present novel

codes to the analysis, testing concluded. This stopping criteria was reached after 7 SME's. Though this sample size is small, given the narrow question asked and the limited subject pool of appropriate SME's for this topic, this sample size fulfilled the goals of this research study.

6.3.5 Data Analysis

The flexibility associated with thematic analysis as a method must also come with transparent reporting. Systematically conducting data analysis supports transparent reporting of the research methods used (Malterud, 2001a; Sandelowski, 1995). Methodological rigor was modeled after the trustworthiness criteria of credibility, dependability, and audit trails by requesting internal and external review of the interview design and analysis throughout the study and by recording the study design in the IRB protocol and this chapter (Nowell et al., 2017).

Internal validity was sought by independently coding a section of the interviews between the research team members. A section of one participant's deidentified, transcribed interview was reviewed in a joint session between the research team. Each member of the research team conducted the coding analysis independently using the jointly created code book, and when each member completed their analysis, the team compared results to discuss any discrepancies between interpretation of participant responses and what code book element should be assigned to them. After reaching consensus, the remainder of the 7 interviews were analyzed by one researcher.

Given that this data is a collection of subjective opinions regarding design attributes, and the analysis is a subjective interpretation of these opinions, a true external validation effort which attempts to creative objectivity from subjective data is inappropriate for this study. However, an attempt at modified external validity was conducted by asking

an external researcher with experience conducting aerospace-relevant qualitative interviews to review the data in the following ways. The external collaborator was asked to review 2 sample interviews in full, selected to incorporate all 4 participant identifiers and chronologically diverse from a interview timeline perspective. Only the transcription was provided and not the audio recording to uphold participant privacy. The collaborator reviewed the transcribed interviews and then examined the coding analysis conducted by the primary researcher for the 2 interviews. The primary researcher then met with the collaborator to discuss consistency of codebook application and to compare interpretations of the data and determine comparison of interpretation of the thematic analysis.

6.3.6 Data Confidentiality

Each interview was recorded using the university-affiliated, password protected Zoom account of the primary researcher. Each individual meeting was password protected to prevent non-research personnel from entering the meeting. Only the audio was recorded from each meeting to protect participant confidentiality and encrypted transcription was used from the audio-only recording. After each interview was completed, the primary researcher listened to the audio recording and updated the transcript to align erroneously transcribed words with participant responses. Additionally, the primary researcher inserted proxy numeric codes for potentially identifiable names or events mentioned by participants, i.e. the mention of a colleague's name would be replaced with a proxy code of '211' and recorded on a separate key document. This key document is only accessible to the research team, is the only record of potentially identifiable information that arose from the interviews and will be destroyed when the IRB protocol is closed.

6.4 Results

In total, 7 SME's were interviewed for this research. Their experience types are documented in the table below. These experience categories were identified by the research team as unique perspectives regarding the design of highly maintainable ECLSS. Most participants self-identified experience in more than one area.

Area of Experience	Number of Participants
Academic Research and Development	4
Engineering Design	4
Ground Operations (Launch or mission control center)	5
In-flight operations (Astronaut)	2

Table 7: Number of participants with self-identified experience types.

Over 83,000 words and over 7.5 hours of audio were recorded. From this dataset, 23 themes of maintainable ECLSS were derived in this analysis, with 6 themes identified as mission drivers for deep-space habitats as a whole and are not unique to ECLSS. These results are displayed in Table 8.

Overarching Mission Drivers for Deep-Space	Maintainable ECLSS Drivers	
	Design Considerations	**Operational Considerations**
Functional Needs	Reliability	Ease of Access
Mission Duration	Resiliency	Explainability
Mass, power, volume	Adaptability	Ease of Maintenance
Cost	Observability	Integrated Systems
Project Schedule	Commonality	Complexity
Vendor Availability	Redundancy	Maintenance Time
	Regenerability	Repairability
	Fault Management	Capability
	Risk Management	Operator Safety
	Material Properties	Onboard Control Authority
	Consumable Margin	
	Spare Parts Provision	
	Survivability	

Table 8: Summary of prominent themes identified through thematic analysis.

Each theme does not imply positive or negative association – for example, including 'complexity' as a theme does imply that a participant mentioned it is positive or desirable for systems to have complexity. These themes represents design attributes to be considered during the design phase of creating ECLSS that can be easily maintained by crew in deep-space when anomalies arise.

In total, these interviews presented 10 novel themes to the list the researchers compiled prior to conducting interviews, which included resiliency, adaptability, observability, commonality, survivability, ease of maintenance, integrated systems, maintenance time, repairability, and onboard control authority. 3 additional themes – fault management, risk management, and capability – were condensed from theorized themes.

These compiled themes were presented to 2 external researchers with experience in human spaceflight engineering, not to assess the completeness of the list, but to verify the organization and categorization into 'Design Considerations' and 'Operational Considerations' accurately captured the identified themes.

6.4.1 Theme Definitions and Representative Participant Statements

Some of the themes can be referenced to existing definitions in the literature and these references are displayed with each theme. However, other themes are captured with proposed definitions to accurately represent the participant responses. Additionally, as mentioned in the experimental design section, the themes of fault tolerance and accessibility – renamed Ease of Access – were given to participants as a representative example of a design attribute, or theme.

6.4.1.1 Themes - Design Considerations

Reliability: "The probability of a product performing its intended function under stated conditions without failure for a given period of time" (Hutchison, Nicole, 2023).

- Demonstrated performance relies on ground or in-flight testing.
- Mentioned by participants often in conjunction with simplicity of the design.
- Reliability was one of the most-mentioned themes during the interviews and was described as highly desirable, but not a failsafe.

Representative participant statements:

"Never had a failure in it on my 4 flights, never even heard of a failure in that system."
"When you assemble components on the ground, you go through an extensive verification test to make sure it's working so that you go launch it."
"On low Earth orbit, you know, there's a push to try to test out…different technologies…it helps narrow your scope down of what could we use for a future mission that's recommended."

"I don't know what the number is of hours tested on the ground versus hours in space – but it's a pretty big number. And so their whole philosophy is, if it's gonna die, let's let it die while we can just change it out with a tech rather than in orbit"

""So, having that philosophy of test early, you know, test quickly, early, and close by before integrating into a vehicle for transit to Mars is, I think, a really great philosophy."

Resiliency: The elastic or flexible ability to withstand unexpected failures and recover functionality after failure. Includes the concept of graceful failure modes (C. M. Escobar et al., 2017, p. 20)".

- Includes connection with cascading failures and lack of redundancy
- An ideal, resilient system might suffer a failure but can self-recover in a given period of time

Representative participant statements:

"You really have to have the ability to replace just a sensor…whatever might fail at the lowest possible level, so that your spares volume and mass is as small as possible. Yet you can survive multiple failures"

"So even if it's saturated or goes into a regime where it can no longer perform…its function. Ultimately, it's recoverable. And it will self-recover once the scenario is corrected."

Adaptability: How easily a system can be redesigned to achieve updated functionality if mission objectives change.

- Describes a system that is designed to allow crew to easily modify components, rather than a design that can only achieve the original design objectives

Representative participant statements:

"Being able to introduce sensors or new components that might ultimately be required without a massive redesign of the entire system."
"Designing for these kind of 'what if' scenarios to be able to accommodate them…it may lead to capabilities that never get used, but if they were needed, could be crucial."

Observability: The ability to fully reconstruct the internal state of a system from system output variables (Liu et al., 2013)

- Includes ability to improve fault management responses
- Relies on sensor density, calibration, and accuracy in the flight environment
- Participants also mentioned that more sensors could potentially lead to more false readings or failures, but generally the desire of the SME's was to include more sensors for more observability

Representative participant statements:

"For a rapid depress, for example. We have access to…all the cabin pressure sensors. And we can see that data on the plot, so it's easy to visualize."

"So wherever feasible, as long as it doesn't alter the process, or alter it significantly, I want sensors."

"Having having sensors everywhere is great. So, having that information at your fingertips in order to provide a more well-rounded troubleshooting approach is awesome. So, having redundant sensors all over the place is fabulous."

Commonality: The reuse of identical design elements, including systems and components, in multiple places throughout an architecture (Crawley, E et al., 2010)

- Includes commonality of tools
- Was referenced as a way to simplify maintenance activities, reduce maintenance time, and improve logistics and reduce inventory tracking of specialty parts
- Mentioned in conjunction with 3D-printing – specifically, that allowing the printing of common parts implies 3D-printed components must be integrated before launch
- Mentioned as a method to reduce the amount of spares needed for a mission

Representative participant statements:

"Parts that didn't have the clearance for hand access or regular tool access you needed a special tool."

"It's really a philosophy of designing for the maintenance with that in mind…that logistic train from both the tools and the replacement parts is fairly small."

" Having common parts such that … you don't have unique parts for every different piece of hardware. Therefore you could…have a limited sort of spares logistics which will help in terms of the mass remission."

Redundancy: Whether a habitat, system, or component has a secondary, duplicate ability to achieve a given function

- Was mentioned by participants in the context of function, system, and component-level redundancy
- Participants mentioned if commonality is also implemented, then redundancy can be easier to achieve by using the same spares for multiple systems

Representative participant statements:

"You need backups for those systems if they're the kind that are gonna keep you alive to give you time to fix the first system."

"2 is no good. So 3 is a good number, and 4 is a better number."

"A lot depends, from a maintenance standpoint, on how many redundant systems you have. And that, of course, gets driven by the entire architecture of the system design during the design phase."

Regenerability: The ability of a system to recapture or recycle byproducts and make use of them.

- Often mentioned in conjunction with the of consumables required or allowable for a given mission
- Often mentioned as the ideal goal, but also mentioned as being complicated and less reliable than single-use counterparts
- CO2 removal and water provision were mentioned most frequently as examples

Representative participant statements:

"Do you use very simple lithium hydroxide canisters that are that are almost fail-safe … or a very complicated carbon dioxide removal system, you know, like a CDRA?"

"That's where your emerging technologies are gonna come in. Where you have ability to, with minimal consumables, scrub that CO2. Now you can get it out and you get the O back out of it…the carbon, you can dump overboard, or maybe you can use it in your 3D printer."

Fault Management: The proactive design strategies used to "preserve or maximize [a] system's ability to achieve its goals in the face of current or prospective failure" (S. Johnson et al., 2017).

- Captures a host of terminology including fault tolerance, failure modes, fault containment, fault isolation, cascading failures, mean time between failure, and safing
- Also mentioned in conjunction with operational concerns in terms of how the faults can be resolved, if not with resilient designs, then with crew in-flight
- Relies heavily on ground team support currently
- Mentioned in reference to known and unknown failure modes – e.g., fault management strategies are employed for any kind of fault

Representative participant statements:

"Fault tolerance. Just having 2 systems talking to each other doesn't help you because you don't know which one's right."

"We would call it unplanned maintenance…remove and replace is something where we do not plan on doing this type of an activity on orbit."

"There was a requirement that you can't have cascading failures. You can't have failure of one component fail a downstream component. Well, that was happening all over CDRA."

Risk Management: Likelihood of risk coupled with the severity of the consequence should it occur (paraphrased from (NASA, 2019)).

- Likelihood of risk and failure mentioned often in conjunction with dormancy periods anticipated for deep-space missions
- High-severity consequences mentioned with regard to oxygen provision, CO2, and water

Representative participant statements:

" Concentration on, in terms of development, on parts that maybe are more prone to failure is something that's necessary."

"If I'm gonna have…5 pumps for coolant versus, you know, 3 filters. The pumps are probably gonna weigh more, but maybe they're more likely to break."

"What we could do… based off the failures we've seen in the past is try to test out…this hose is known to break often. Can we develop a better hose for that? Can we test it out…maybe in Low Earth orbit, and see how it holds up functionality-wise?"

"Because these holes got clogged, there was no place for the water to go, and so the water, essentially just built up inside the vent loop and just got redirected into the helmet."

Material Properties: Unique physical or chemical properties of components in a design that can assist in maintenance or pose a hazard to the crew.

- Incorporates considerations of contamination effects and hazardous materials
- Conversely, can also represent helpful or useful material properties in a design that assist in maintenance

Representative participant statements:

"If you drag any into the vehicle with you by accident, because you were outside, and you got sprayed with ammonia, you can kill everybody in the vehicle. A piece the size of your thumb would be enough to kill the people in the vehicle."

"Have locations on the component that crew members can touch without needing special gloves or special attention to where they're putting their hands."

" Shape memory of items is always appreciated. So for wires and hoses and everything, especially if something needs to be routed in a particular way, having that shape memory helps crew members put things back together correctly."

Consumable Margin: How much volume of a consumable material is accessible for onboard operations.

- Also includes considerations for the limiting consumable on a given mission
- Is interconnected with regenerability where recycling is involved

Representative participant statements:

"Everything leaks. It's just how much… you can stand and how much you plan for on a logistic resupply."

"You can reduce the … robustness, because there's almost that assumption of we're always gonna be able to maintain it or or fix … and so doesn't need to be that robust as long as we have enough consumables"

Spare Parts Provision: Number and type of spare parts that are provided or manufacturable onboard.

- Mentioned in conjunction with commonality and consumable margin
- 3D-printing, and its limitations, was mentioned by several subjects as an option for providing a variety of spares

Representative participant statements:

"One thing I think about often…is you have to think about sparing. And that could be, for like any piece of equipment…do you have enough components to fully replace…basically all of it? If you don't, what are you gonna prioritize for those components that you could replace?"

"Issues that we've seen are components breaking…the crew member picks up a a scrubber and it's cut in half, or it's like sliced down the side, and you're like, well, now, I need a backup."

Survivability: "The ability of a system to minimize the impact of a finite disturbance on value delivery, achieved through either (1) the satisfaction of a minimally acceptable level of value delivery during and after a finite disturbance or (2) the reduction of the likelihood or magnitude of a disturbance." (Richards et al., 2007)

- Mentioned with respect to contamination effects, particularly for water systems, during dormancy periods in deep-space operations, regarding whether systems can be expected to be brought back online

Representative participant statements:

"There is some concern right now for periods of either spacecraft quiescence, or when the crew is not present…the plans are maybe 30 days at a time, and then the whole year in between…. and so when you turn those systems on…it'll be similar to when things are sort of dormant when you leave them, because it wouldn't have been operating. Now you're gonna operate it."

"If you take an ECLSS system…particularly this affects most likely those systems that contain water, because that's probably the fluid that probably has the greatest chances for issues, corrosion or bacteria to build up or fouling to occur…this is an area that we've not studied at all."

6.4.1.2 Themes - Operational Considerations

Ease of Access: How easily a crew member can physically maneuver to reach a component or system to perform a maintenance task.

- Different from the maintenance task itself, this refers to how easily a crew member can access the location they need to

Representative participant statements:

"So you would occasionally have to remove some items to get to another item, and that caused more work and risk and, and things like that. But in general it would be great if everything you needed to get access to was directly accessible by a crew member."

"And then another issue sometimes that can happen is…if astronauts are trying to remove a piece of equipment and they can't get it out. Or they're trying to install a new piece of equipment, and they can't install it in."

"Access to things is critically important… even if you don't ever expect to have to access particular parts or pieces of a piece of equipment."

Explainability: How easily the data presented to the crew can be understood. Includes easily interpretable procedures and human factors design.

- Includes maintenance procedures and how simple or easy they are to understand
- YouTube videos were mentioned by several participants as an example of explainability.
- Videos mentioned as a tool to consider for future procedures in place of written ones

Representative participant statements:

"The adage of a picture is worth a thousand words is so so true…don't send up a gazillion words, just sent up a picture with arrows pointing to things… it made it way easier for anybody to execute."

"And so I can see us moving to a direction where we have basically a YouTube channel of just 'how to fix it' type videos."

"Testing of procedures in the real environment and making sure that things are are absolutely correct in the procedures, is very, very important."

"There were sometimes things that were not covered by procedure that required troubleshooting, required a good bit of interaction with the ground control team."

Ease of Maintenance Action: The relative simplicity of the required maintenance action.

- E.g. replacing a filter versus soldering a replacement PCB
- Captures the ideal of simplicity in design and maintenance which is effectively the inverse of complex, integrated systems

Representative participant statements:

"Don't make any system that you design in the vehicle…so complex that a person can't, with a … reasonable amount of tools, dig into it and fix it."

"We have color-coded hoses. And that helps out the crew…the simple things really do pay dividends."

"The other thing is ease of maintenance…I don't know how many screws, or a hundred screws could have been 4, and it could have been 2 in microgravity, and it would have been just fine."

Integrated Systems: Number of interfaces – functional, physical, logical, or otherwise - between components.

- Separate from complexity, integrated systems are those which have a high number of connections to other components or systems in the vehicle
- This can decrease the ease of maintenance and increase risk of coupled or cascading failures

Representative participant statements:

"Unfortunately, that system is all encapsulated in this one, basically one piece of equipment. And so we had a failure…and it essentially brought down the entire unit."

"And so you have all these these issues that come up that you have to deal with that you never intended, just because you wanted to change out the mass spec…that's just one of a thousand examples."

Complexity: Number of components within a system.

- Separate from integrated systems, in the context of these themes, complexity refers to the number of components present within a given system
- Complexity was mentioned predominantly as a negative, undesirable feature due to its effect on maintenance time, difficulty, and failure modes

Representative participant statements:

"They're complicated systems. You know, they have lots, a lot of parts, lot of functions, some things you can jury-rig, some things you can't."

"If the engineers are trying to come up with this complex, super sophisticated design with multiple failure modes - the hair on the back of your neck ought to be standing up, says timeout, this is not right. That's my speech."

Maintenance Time: How long it takes to perform a given maintenance task.

- Separate from how easy it is to access and maintain a given component, maintenance time captures the total time taken to complete a maintenance task
- Maintenance time can be extensive even if the maintenance is easy to access and simple to perform

Representative participant statements:

"Any routine maintenance you should think about packaging and those sorts of things to make sure that that, it's not an unnecessary time required to do things."

"So in reality, some systems - I don't think we've ever spent a maintenance man hour on, and they're fantastic, it's been over 20 years, and they're working great. Other things, we blew the maintenance man hour per year allocation in the first activity."

Repairability: A system designed to allow for component-level or 'intermediate-level' (I-level) maintenance.

- The counter of this is the ORU-model which uses pre-built, pre-packaged insertable units
- Repairable systems allow crew to access the component-level to replace a sensor, for example, instead of an entire system

Representative participant statements:

"And then a lot of the inside smaller parts weren't intended to be accessed by crew, so the only the parts on the outside had to have hand clearance and tool compatibility with the toolkit"

"Maintenance in deep space has to be I-level maintenance concept from the start."
"The parts that are the component parts have to be accessible, which means…having the build-up such that maybe parts are more separated, so you can get wrenches or other things in there."

"Each component that you think you're gonna maintenance, make sure that each one of them is independently accessible versus having an entire system or housing system."

Capability: Current ability and actions of the unique operator based on their training and available equipment (adapted from (Easter, B., 2023).

- Combines caregiver actions, knowledge inputs, required activities as mentioned in the NASA SDLO Medical Model, and also includes the current ability of a crew member based on their available energy, cognitive abilities, and other reserves (Easter, B., 2023)
- Relies on the individual in question and captures that individual capability varies over time

Representative participant statements:

"How the crew has to interact with those computers required an immense amount of training, just an immense."

"It was pretty critical that you kept your met rate low because if you let your heart rate get up and your respiratory rate get up you're gonna be expelling more CO2 and the MedOx is gonna saturate sooner than not. And a number of EVAs have been terminated."

"The procedure needs to be so user friendly because you're not gonna be able to ask the ground, what do you mean by step 3? I don't understand that. And you probably weren't trained on it. If you were trained on it, it might have been 3 years ago."

"They're human, right? We want to make sure they can function normally, and they're not overloaded."

"The crew is trained to run all the emergencies without [ground control] help. So I would expect them to do that and not, maybe, have as much communication with [ground control]."

Operator Safety: Systems designed to mitigate unnecessary hazards from affecting the crew.

- Mentioned often with respect to complicated procedures that made operations hazardous that didn't need to be
- Though spaceflight is inherently hazardous, this theme was mentioned as a goal to enable with well-tested and designed systems that incorporate human factors and avoid hazardous materials when possible

Representative participant statements:

"The only way to know for sure which one was right, you had to follow the tubes that went from the valve to the different port locations. So it was a truly hazardous operation, just because of the lack of labeling."

"And so the person could pick up the procedure, and with the help of another person, and execute it without making a mistake. There's nothing in that situation you can't make worse by throwing the wrong switch, cutting the wrong wire."

"Because the last thing [crew] wanna do is basically wear latex gloves so that they don't touch an O ring, but they have to put their hand there in order to manipulate it to get that filter into a particular spot."

Onboard Control Authority: Whether there is the ability to make time-critical decisions onboard the habitat.

- Mentioned in reference to the fact that ground control cannot have instantaneous communications with crew in deep-space
- Automation and autonomy and their interactions with crew were mentioned, but this theme predominantly captures the ability for crew to make decisions in time-critical situations when needed in deep-space, and how maintainable designs can support that

- It was mentioned that current crew potentially have more ability to be autonomous in their decision-making, and will need to for deep-space critical operations

"If you design it simple, then someone on their own, maybe even without a whole lot of documentation, can do something about it."

"[Crew] didn't really need ground support for that. They just looked at, they're like, 'Oh, looks [like] it's a loose nut. I'm just gonna tighten it'. So…having that training before they go up of just basic mechanical skills probably will take care of a lot of issues."

"I think, having having the pictures…videos and procedures, we have…having all of those items available to the crew, I think is extremely helpful and gives them a certain amount of autonomy."

"I think in a lot of ways we … kind of cut the legs off under…crew in terms of autonomy because we make them so reliant on [ground control]."

6.4.2 Themes Mentioned per Participant

One tool for analyzing this data is to compare frequency of responses. However, reporting the number of times each participant mentioned a given theme could be misleading and imply themes mentioned more frequently are more important. This could be misleading given that recording the count of mentioning a term removes context with which the theme was mentioned, and, this relies on the thematic analysis of the researcher. Oftentimes an entire paragraph of text is assigned to a theme, and if instead the paragraph was broken into constituent sentences and assigned a code, the frequency of the term would be higher.

Instead of reporting a frequency plot, this analysis was conducted by reporting whether or not a participant mentioned a theme and does not report the number of times the theme was mentioned. This is captured in Table 9.

	Participant Number	011	012	013	014	015	016	017
Design Considerations	Reliability	X	X	X	X	X	X	X
	Resiliency		X	X		X	X	
	Adaptability						X	
	Observability	X	X	X		X	X	X
	Commonality		X		X	X	X	
	Redundancy	X	X	X	X	X	X	X
	Regenerability	X	X		X	X	X	X
	Fault Management	X	X	X	X	X	X	X
	Risk Management	X	X	X	X	X	X	X
	Material Properties	X	X	X	X	X	X	X
	Consumable Margin	X	X	X	X	X	X	X
	Spare Parts Provision	X	X	X	X	X		X
	Survivability					X	X	
Operational Considerations	Ease of Access		X	X	X	X	X	X
	Explainability	X	X	X	X	X	X	X
	Ease of Maintenance Action	X	X	X	X	X	X	X
	Integrated Systems	X	X				X	X
	Complexity	X	X	X	X	X		X
	Maintenance Time	X	X	X	X	X	X	
	Repairability	X	X	X	X	X	X	X
	Capability	X	X	X	X	X	X	X
	Operator Safety	X	X	X	X	X	X	X
	Onboard Control Authority	X			X	X		X

Table 9: Plot of participant responses per theme. Note that frequency does not imply relative importance or the context in which themes were mentioned.

This chart uses Boolean 'yes or no' logic and indicates with an 'X' if a participant mentioned a given theme. This plot does not demonstrate frequency of responses as this does not accurately represent the relative importance of each theme mentioned without displaying the context in which the theme was mentioned. Additionally, this table does not capture the saliency of each participant response per theme. To provide the interpreted importance each participant assigned to themes, Section 6.4.5 highlights the high-level takeaways listed from each participant with representative quotes.

The themes mentioned by all 7 participants include reliability, redundancy, fault management, risk management, material properties, consumable margin, explainability, ease of maintenance action, repairability, capability, and operator safety. The themes mentioned by the least number of participants included resiliency, commonality, integrated systems, and onboard control authority which were mentioned by 4 out of the 7 participants, survivability which was mentioned by 2 participants, and adaptability which was identified by 1 participant.

6.4.3 Participant Experience Type Compared to Themes Mentioned

Participants were asked in a pre-screening eligibility form to identify their experience so the primary researcher could attempt to glean if there were trends between experience type and identified themes. After analyzing Table 9 and comparing this to the participant experience types, the following trends emerged. The themes of survivability, adaptability, and commonality were uniquely mentioned by participants with engineering design experience, which appears reasonable given these themes were all grouped as engineering considerations given their applicability to the design phase of an ECLSS subsystem. The theme of onboard control authority was only mentioned by participants with either academic research and development and/or flight operations experience.

Interestingly, there were no unique themes identified by participants with flight operations or ground operations experience, meaning participants without ground or in-flight operations experience mentioned all 23 themes in their responses. This indicates that for the participants who were interviewed, having self-identified operations experience was not a precursor for knowledge of both engineering and operational considerations.

6.4.4 Discussion

These themes were captured to represent the important design attributes that influence the design and use of an ECLSS subsystem in a hypothetical deep-space habitat. Effort was placed on distilling these themes and separating them into unique contributors to system design and operations. However, given they comprise factors across a complicated and highly integrated system, there is an understanding that each of these terms are inherently related and are all important. The intention of this analysis was not to derive which themes are more important than the others. Rather, it was to scope the design trade space by capturing factors from experts with different experience in a guided, stream-of-consciousness forum that is aided by qualitative interview methods to supplement the knowledge captured in existing standards (Larson & Pranke, 2000; NASA, 2007, 2014, 2017, 2022).

6.4.5 Saliency of Participant Responses and Representative Quotes

To add additional context to the analysis and form key takeaways, each interview was reviewed for the most salient responses provided by each participant. These represent statements made by participants that indicated very high importance.

Multiple participants spoke of a mission design philosophy of incorporating regenerable systems as the primary option for ECLSS functionality but also including a 100% reliable system on-demand if needed as a redundant option.

"If there is a need for a maintenance or repair activity on the primary system…is there an appropriate standby system … perhaps less reliable or less lower performance, or perhaps requires more consumables, or has other deficits. But it's known that it will work on demand with 100% confidence."

"I would plan for regenerable or recycling type systems that would minimize mass… But I would also want to have backup system that was extremely simple, safe, and ex and extremely extremely reliable."

Participants also repeated a thread about the simplicity of the design and how this can impact the overall reliability, robustness, and safety of the mission. An emphasis was placed on simplifying designs to reduce the required training a crewmember would need to perform maintenance actions.

"The simpler the system, likely the more robust it might be."
"And so if I was designing something for deep space… my number one design criteria would be make it simple."

"Make it simple, and then manual so that a person can take over for psychological reasons, if necessary."

"And so those are design concepts, I think that you need almost need to take a step backwards in capability, and the most important thing being reliability and maintainability as key aspects. And if you lose an automatic feature, so be it. That's why you got humans on board."

Multiple participants also mentioned that no matter how much reliability analysis and testing is conducted, anomalies will still arise, and there is a need to design highly maintainable systems to allow the crew to correct these anomalies when – not if – they occur.

"But don't make any system that you design in the vehicle, and including ECLSS, so complex that a person can't, with a … reasonable amount of tools, dig into it and fix it."
"And things they never expected to replace still had to be replaced. So it shows that you can't really base your access and maintainability on reliability numbers that you don't have real experience with it based on predictions or analysis. Just expect everything to break and need to get access to everything."

"So things like reliability. Yeah, that's really important. You wanna have reliable equipment, but you can't depend on that. So you gotta have maintainability so that you can fix stuff."

"That makes it harder… trying to develop the technologies and verify…. it's not gonna break. Because you never know the different ways it will."

Finally, participants mentioned the importance of designing systems that crew can access at the component level, or 'intermediate level maintenance, rather than using high-mass spares or ORU's. This implies the capabilities of the crew should include crewmembers that are able to dig into a complex system and perform component level repairs rather than using ORU's.

"When I think about future maintenance and repair activities of future ECLSS systems, that ability to actually get to the component level at where the fault occurs likely would be very, very important."

"And what that underscored to me was, when you go outside of low Earth orbit, you can't possibly use the ORU model… So where does that put us. Maintenance in deep space has to be I-level maintenance concept from the start."

"Crew members should actually assemble… the initial hardware on the ground at the factory that they're gonna have to maintain in-flight if their life depends on it."

In conclusion, the goal of this work was to record what engineers and operators consider important attributes and other considerations when designing and maintaining ECLSS. Capturing the thoughts of the SME participants and using thematic analysis to organize their thoughts into actionable design features provides a qualitative assessment of the end-to-end lifecycle of ECLSS, starting with the design principles used by engineers creating the design, through to the astronaut who utilizes the system.

Though this analysis was targeted for ECLSS maintenance, the findings can be modified for application to other critical spacecraft subsystems. Less critical subsystems can likely benefit from incorporating many of these design principles as well. A detailed analysis comparing these attributes to referenced design standards can be found in the Discussion of Chapter 7, along with additional attributes derived in the follow-on study presented next.

In the words of one of the participants, *"I hope that this turns into something that could be useful for folks to remind them of the key important things while designing these critical systems for a spacecraft."*

6.5 Acknowledgements

Gratitude for the work compiled in this chapter is extended to all participants who volunteered their time and expertise and agreed to be interviewed; to Austin Almand for his reviews of the interview design, deductive approach, and thematic analysis methods; to Dr. Jonathan Laws for his consultation regarding inductive vs. deductive approach and qualitative analysis methods for this chapter; and to University of Colorado at Boulder PhD Candidates Patrick Pischulti and Michael Zero for their internal review of the results summarized in Table 8 and their overall support of this work.

6.6 Outcomes

6.6.1 Research Objectives

This work contributes to the proposed analysis for the following objectives.

SA4 – Define method for analysis and summarize recommendations for strategically prioritizing implementation of emerging technologies in a deep-space habitat

- O4.1 – Create prioritization scheme for incorporating emerging technology based on results from Specific Aims 1-3 and an established methodology
- O4.2 – Summarize key benefits for increasing self-sufficiency and/or improving habitability

SA5 – Demonstrate the prioritization method by utilizing HOME Demo results and/or conceptual scenarios

- O5.2 – Define success criteria for assessing the methodology proposed in SA4
- O5.3 – Demonstrate the methodology

6.6.2 Publications and Presentations

Sections of this work are included in the following publications and presentations.

1. *Zaccarine, S. and Klaus, D. (2023) Characterizing the Trade Space for Incorporating Emerging Technologies into Deep-Space 'Smart' Habitats: Needs and Opportunities. International Conference on Environmental Systems (ICES). Poster.*
2. *Zaccarine, S. (2023) Collecting, Surveying, and Assessing Criteria for Self-Sufficiency in Deep-Space Habitat Operations. HOME Seminar Series.*

This work is in preparation for the following publication.

3. *Zaccarine, S., Almand, A. and Klaus, D. (2024). Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats. In work.*

Chapter 7

Survey of Ranked Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats

7.1 Background

The SME interview study conducted in Chapter 6 sought to increase the reliability and context of a set of design attributes that are used by designers to create maintainable ECLSS by collecting thoughts from SME's across a range of experience backgrounds using semi-structured qualitative interviews. The resultant design attributes, deduced using thematic analysis that was both internally and externally reviewed, were used to generate and increase the sensitivity and accuracy of survey questions sent out to participants with ECLSS experience for this chapter. This survey allows for the use of descriptive statistics to quantitatively describe the dataset. Taken together, these chapters present a use of triangulation by combining qualitative and quantitative methods to increase confidence in and comprehensiveness of the data collected. The results of the derived interview attributes and survey results are compared to existing design handbooks in the discussion of this work to demonstrate how they can be decomposed into trade study criteria, and to examine the alignment between the results and the referenced standards. The referenced handbooks are the NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health NASA-STD-3001 Volume 2 Revision C, the NASA Human Integration Design Handbook (HIDH), the Human Spaceflight Mission Analysis and Design (HSMAD), the NASA Systems Engineering Handbook, and the NASA Reliability and

Maintainability (R&M) Standard for Spaceflight and Support Systems (Larson & Pranke, 2000; NASA, 2007, 2014, 2017, 2022). The experimental methods described in this chapter were approved under CU IRB Protocol #23-0669.

7.2 Methods

Methodological rigor is modeled following the trustworthiness criteria of credibility defined by Nowell (Nowell et al., 2017). Credibility is attempted by applying data collection triangulation and uniting the survey design with the results found in the previously conducted reflexive thematic analysis. Additionally, a modified version of member checking, asserted as the most essential method for establishing credibility, is applied by disseminating the survey to several of the participants who took part in the SME qualitative interviews summarized in Chapter 6 (Lincoln & Guba, 1985). The approach is modified because the survey was designed to be entirely anonymous such that it is unknown to the researchers if these participants chose to take the survey. The final portion of the survey provided an open-ended question to solicit participant feedback which allowed for participants of the interviews to assess the intentionality of their responses and the interpretation of their interview data.

Following the contextual research question posed in Chapter 6 which sought to understand 'what are design attributes to consider for improving ECLSS maintainability in deep-space missions?', this chapter uses a descriptive research question to discern 'what is the relative importance of the attributes of maintainable ECLSS collected by interviews with SMEs'? A descriptive research question follows a contextual research question, as was addressed in Chapter 6, and seeks to describe the phenomenon in greater detail (Barroga & Matanguihan, 2022).

7.2.1 Likert Survey Design

Likert surveys have been used across a host of psychology studies as documented in a review of Likert scale developments completed in 2021 (Jebb et al., 2021). Likert surveys have also been applied in aerospace, including a study that characterized time and effort drivers for aerospace product development and a survey conducted to determine student retention in aerospace engineering when entering full-time employment (Butler, 2015; Jaifer et al., 2021; Weigel, 2010). For this work, originally the primary researcher considered asking participants to simply rank all the criteria from most to least important. However, this potentially could have been overwhelming because there are 23 attributes. It also would not have easily allowed participants to give the same value to different attributes that they might find equally important. Presenting participants with the research team's proposed order and asking them to move attributes where they thought appropriate was also considered. However, this might have biased the participants to agree with the proposed rankings simply because they were presented in that order. Ultimately, using a Likert-scale for each attribute was selected to allow participants to bin their responses and consider each category of attributes, 'Design Considerations' and 'Operational Considerations'.

This survey is different from referenced 5- or 7-point bipolar Likert scales ranging from 'Strongly Disagree', 'Disagree', 'Neutral' or 'Neither Agree nor Disagree', 'Agree', to 'Strongly Agree' (Sullivan & Artino, 2013). Instead, a unipolar 4-point scale shown in Section 7.2.2 was developed with an option to select 'Unsure' for any theme participants did not have experience with, knowledge of, or did not want to rank.

5- or 7-point bipolar scales did not suit the questions in this study because there were no proposed statements for participants to agree or disagree with. Additionally, it was expected there would be a positive bias for responses because the researchers assumed that all attributes would receive at least an 'Important' ranking, hence why the unipolar scale was chosen.

7.2.2 Qualtrics Survey Design

A password-protected University version of Qualtrics was selected to design and administer this survey. In the interest of protecting participant confidentiality and privacy, the survey was administered using an anonymous Qualtrics link that can be taken from a laptop, phone, or tablet and does not record respondents' IP Address, location data, or contact info. Participants were provided a copy of the consent form in the body of the recruitment email. The survey used 'click to consent' where participants were asked to review the written consent provided in the email before opening the survey link as opening and completing the survey indicated their consent to participate.

After completing a reCAPTCHA 'I'm not a robot' response, participants were provided project background summarizing the work conducted in Phase 1, Chapter 6, of this study including a copy of Table 8 which displays the derived design attributes from the interviews grouped into 'Design Considerations' and 'Operational Considerations'.

After reviewing the background material and derived themes the participants were first asked to rank the attributes for 'Design Considerations' on one page and then asked to rank 'Operational Considerations' on the next page. Each theme was presented with a proposed or cited definition and a deidentified representative statement from SME responses from Phase 1 of the research. The representative statements add clarity to each definition to allow participants in Phase 2 of the research to have insight into how the

analysis was conducted for Phase 1. If at any point in the survey participants wanted to navigate back to this page, they were able to. The summary tables are provided below in Tables 10 and 11.

Design Considerations		
Theme	**Definition**	**Representative Statements**
Reliability	"The probability of a system or system element performing its intended function under stated conditions without failure for a given period of time." (Hutchison, Nicole, 2023) Often relies on ground or in-flight testing.	"I don't know what the number is of hours tested on the ground versus hours in space - but it's a pretty big number. And so their whole philosophy is, if it's gonna die, let's let it die while we can just change it out with a tech rather than in orbit."
Resiliency	The elastic or flexible ability to withstand unexpected failures and recover functionality after failure. Includes the concept of graceful failure modes (paraphrased from (C. Escobar et al., 2019))	" So even if it's saturated or goes into a regime where it can no longer perform…its function. Ultimately, it's recoverable. And it will self-recover once the scenario is corrected."
Adaptability	How easily a system can be redesigned to achieve updated functionality if mission objectives change.	"Being able to introduce sensors or new components that might ultimately be required without a massive redesign of the entire system."
Observability	The ability to fully reconstruct the internal state of a system from system output variables (Liu et al., 2013)	"For a rapid depress, for example. We have access to…all the cabin pressure sensors. And we can see that data on the plot, so it's easy to visualize." "Wherever feasible, as long as it doesn't alter…it significantly, I want sensors."
Commonality	The reuse of identical design elements, including systems and components, in multiple places throughout an	"Having common parts such that … you don't have unique parts for every different piece of hardware. Therefore you could…have a limited sort of spares logistics."

	architecture (Crawley, E et al., 2010) Includes commonality of tools	
Redundancy	Whether a habitat has a secondary, duplicate ability to achieve a given function	"You need backups for those systems if they're the kind that are gonna keep you alive to give you time to fix the first system."
Regenerability	The ability of a system to recapture or recycle byproducts and make use of them.	"Do you use very simple lithium hydroxide canisters that are that are almost fail-safe … or a very complicated carbon dioxide removal system, you know, like a CDRA?"
Fault Management	The proactive design strategies used to 'preserve or maximize [a] system's ability to achieve its goals in the face of current or prospective failure' (S. Johnson et al., 2017)	"Fault tolerance. Just having 2 systems talking to each other doesn't help you because you don't know which one's right." "There was a requirement that you can't have cascading failures. You can't have failure of one component fail a downstream component."
Risk Management	Likelihood of risk coupled with the severity of the consequence should it occur (paraphrased from (NASA, 2019))	"Concentration on, in terms of development, on parts that maybe are more prone to failure is something that's necessary."
Material Properties	Unique physical or chemical properties of components in a design that can assist in maintenance or pose a hazard to the crew	"If you drag any into the vehicle with you by accident, because you were outside, and you got sprayed with ammonia, you can kill everybody in the vehicle." "For wires and hoses…if something needs to be routed in a particular way, having…shape memory helps crew members put things back together correctly.
Consumable Margin	How much volume of a consumable material is accessible for onboard operations	"Everything leaks. It's just how much… you can stand and how much you plan for on a logistic resupply."
Spare Parts Provision	Number and type of spare parts that are provided or manufacturable onboard	"For…any piece of equipment…do you have enough components to fully replace…it? If you don't, what are you gonna prioritize for those components that you could replace?"

Survivability	"The ability of a system to minimize the impact of a finite disturbance on value delivery." (Richards et al., 2007)	"There is some concern right now for periods of either spacecraft quiescence, or when the crew is not present…systems…wouldn't have been operating. Now you're gonna operate it."

Table 10: Design Considerations derived from the qualitative interviews conducted in Chapter 6, provided to participants as context for the survey response questions.

Operational Considerations		
Theme	**Definition**	**Representative Statements**
Ease of Access	How easily a crew member can physically maneuver to reach a component or system to perform a maintenance task	"So you would occasionally have to remove some items to get to another item, and that caused more work and risk and, and things like that. But in general it would be great if everything you needed to get access to was directly accessible by a crew member." "Access to things is critically important… even if you don't ever expect to have to access particular parts or pieces of a piece of equipment."
Explainability	How easily the data presented to the crew can be understood. Includes easily interpretable procedures and human factors design.	"The adage of a picture is worth a thousand words is so so true…don't send up a gazillion words, just sent up a picture with arrows pointing to things… it made it way easier for anybody to execute." "And so I can see us moving to a direction where we have basically a YouTube channel of just 'how to fix it' type videos."
Ease of Maintenance Action	The relative simplicity of the required maintenance action. E.g. replacing a filter versus soldering a replacement PCB	"Don't make any system that you design in the vehicle…so complex that a person can't, with a … reasonable amount of tools, dig into it and fix it." "We have color-coded hoses. And that helps out the crew…the simple things really do pay dividends."
Integrated Systems	Number of interfaces – functional, physical, logical, or otherwise - between components	"Unfortunately, that system is all encapsulated in this one, basically one piece of equipment. And so we had a failure…and it essentially brought down the entire unit."

Complexity	Number of components within a system	"They're complicated systems. You know, they have lots, a lot of parts, lot of functions, some things you can jury-rig, some things you can't."
Maintenance Time	How long it takes to perform a given maintenance task	"Any routine maintenance you should think about packaging and those sorts of things to make sure that that, it's not an unnecessary time required to do things.
Repairability	A system designed to allow for component-level or 'intermediate-level' maintenance. The counter of this is the ORU-model.	"And what that underscored to me was, when you go outside of low Earth orbit, you can't possibly use the ORU model…maintenance in deep space has to be I-level maintenance concept from the start." "The parts that are the component parts have to be accessible, which means…having the build-up such that maybe parts are more separated, so you can get wrenches or other things in there."
Capability	Current ability of the unique operator based on their training and available equipment (Based on NASA SDLO Medical Model (Easter, B., 2023))	"So that's very complex. How those interact and how the crew has to interact with those computers required an immense amount of training, just an immense."
Operator Safety	Systems designed to mitigate unnecessary hazards from affecting the crew.	"The only way to know for sure which one was right, you had to follow the tubes that went from the valve to the different port locations. So it was a truly hazardous operation, just because of the lack of labeling."
Onboard Control Authority	Whether there is the ability to make time-critical decisions onboard the habitat.	"If you design it simple, then someone on their own, maybe even without a whole lot of documentation, can do something about it. "I think in a lot of ways we we … kind of cut the legs off under our crew in terms of autonomy because we make them so reliant on [ground control]."

Table 11: Operational Considerations derived from the qualitative interviews conducted in Chapter 6, provided to participants as context for the survey response questions.

The participants were then provided the Likert survey response question with a request to rank each attribute listed above as:

0 – Not Important
1 – Somewhat Important
2 – Important
3 – Very Important
Unsure

Answers were required for each attribute on a given page, e.g., responses were not recorded for ranking 'Design Considerations' if all attributes included for design considerations were not ranked. The survey was designed throughout with forward and back arrows so participants could navigate back to responses if they wished to revisit or change their answers.

The survey concluded with a free response text box with the prompt *"Are there any attributes of maintainable ECLSS for deep-space that you want to contribute to this analysis, for either Design or Operational Considerations? Please share your thoughts and details for your rationale, or skip this question if not applicable. The survey will end after you submit this question."* This question was meant to increase the validity of the analysis conducted in Chapter 6 and to provide participants a chance to provide feedback on the survey itself.

The participants were able to exit the survey at any time and Qualtrics did not retain partial responses if the participants did not click 'submit'.

7.2.3 Participant Population

Participants with any number of years of professional spaceflight and/or ECLSS experience were sought for this phase of research. Example populations drew from astronauts, engineers, mission control operators, and graduate researchers. Key differentiators of these cohorts included direct interaction with designing or operating

ECLSS hardware and/or software, and/or experience observing or supporting ECLSS maintenance in a spaceflight mission.

7.2.4 Quantitative Statistical Analysis: Descriptive vs. Inferential Statistics, and Parametric and Non-parametric statistics

Descriptive statistics were used to summarize the characteristics of the dataset including measures of central tendency, variability, and frequency.

Inferential statistics, including parametric and non-parametric testing, were postulated as a possibility when drafting this survey, but were determined to not be appropriate for this dataset due to the number of responses received. Since Likert data is ordinal, inferential statistical tools depend on the underlying normality of the dataset, which relies on the number of participants who complete the survey. An Anderson-Darling test can be used to determine normality but typically needs 20-30 datapoints to be performed accurately (Sullivan & Artino, 2013). If a dataset is normally distributed, then parametric statistics can be performed for an analysis. If the dataset is not normally distributed, nonparametric analysis can be performed. However, 9 responses were received for this survey, and the decision to use inferential statistics relies on receiving 20 or more responses. For this analysis, descriptive statistics were the most appropriate method for reporting findings.

7.2.5 Qualitative Analysis: Free-Response Questions

Additionally, qualitative analysis is performed to supplement the quantitative analysis. A free response question was provided at the end of the survey for participants to contribute any additional thoughts they had after completing the survey. For example, if a participant writes in the free-response question that one theme is much more important or less important than the others, this will be taken into consideration along with the

quantitative results. The free-response question is offered at the end of the survey and is meant to capture these qualitative results.

7.3 Results

In total, 10 survey responses were received. However, one response did not include ranking data, so 9 participant responses were used in the evaluation. The survey was designed to take approximately 20 minutes to complete, and the average completion time was 20.5 minutes.

Table 12 displays the anonymized raw results from the data. A link to this anonymized dataset, available through Open Science Framework (OSF), is included in Appendix C, with a copy of the data shared on OSF also included. The first column includes the design attributes for maintainable ECLSS that participants were asked to rank as 'Not Important', 'Somewhat Important', 'Important', 'Very Important', or 'Unsure' as shown in the top row for columns 2-6. The descending rows beneath columns 2-6 represent the number of times participants assigned a given value to the design attribute. Column 7 displays which questions were not answered by participants, and the furthest right two columns display the mean and mode for the values. The median and mode values were calculated using the descriptive statistics analysis function in Microsoft Excel Version 16.83 and selecting the importance values. For 'Reliability', this meant selecting '1,2,3,3,3,3,3,3,3', ignoring where value corresponding to the 'Unsure' ranking and treated as a non-answer. An example for how these were calculated is included in Appendix C.

	Not Important = 0	Somewhat Important = 1	Important = 2	Very Important = 3	Unsure	No Answer	Median	Mode
Repairability	0	0	2	6		1	3	3
Reliability	0	1	1	6	1		3	3
Consumable Margin	0	1	2	6			3	3
Spare Parts Provision	0	1	2	6			3	3
Ease of Maintenance Action	0	1	2	5		1	3	3
Redundancy	0	1	3	5			3	3
Fault Management	0	1	3	5			3	3
Risk Management	0	1	3	5			3	3
Operator Safety	0	1	3	4		1	2.5	3
Onboard Control Authority	0	1	3	4		1	2.5	3
Ease of Access	0	1	3	4		1	2.5	3
Capability	0	1	4	3		1	2	2
Resiliency	0	2	3	4			2	3
Regenerability	0	1	6	2			2	2
Survivability	0	2	4	3			2	2
Material Properties	0	2	5	2			2	2
Explainability	0	2	5	1		1	2	2
Maintenance Time	1	2	2	3		1	2	3
Complexity	1	1	5	1		1	2	2
Commonality	1	3	3	2			2	1
Integrated Systems	1	1	5	0	1	1	2	2
Observability	0	5	4	0			1	1
Adaptability	0	5	4	0			1	1

Table 12: Anonymized raw dataset received from survey responses.

It is not known why certain attributes received no answer except that they were all a result from one participant dataset. It is possible the participant did not have time to answer the second set of questions for 'Operational Considerations', or left answers blank instead of clicking the 'Unsure' button. In any case, this data was retained because the survey was completed and submitted.

There are mixed opinions in the literature whether reporting mean and standard deviation on Likert scales is appropriate given that the data is ordinal and the average of 'Somewhat Important' and 'Important' is not 'Somewhat Important-and-a-Half' (de Winter & Dodou, n.d.; Jakobsson & Westergren, 2005). Therefore, the decision was made to only report the median and mode values for this work to avoid presenting misleading results.

To more easily visualize the responses in a transparent reporting method, a diverging stacked bar chart was created and is displayed in Figure 11. This plot was used because of its ability to convey the number of responses and their relative value in a way that makes it easy to compare responses between categories (in this case, the attributes) (Robbins, Naomi B. & Heiberger, Richard M., 2011). Similar to Table 12, this chart orders the values starting with the highest average reported first at the top.

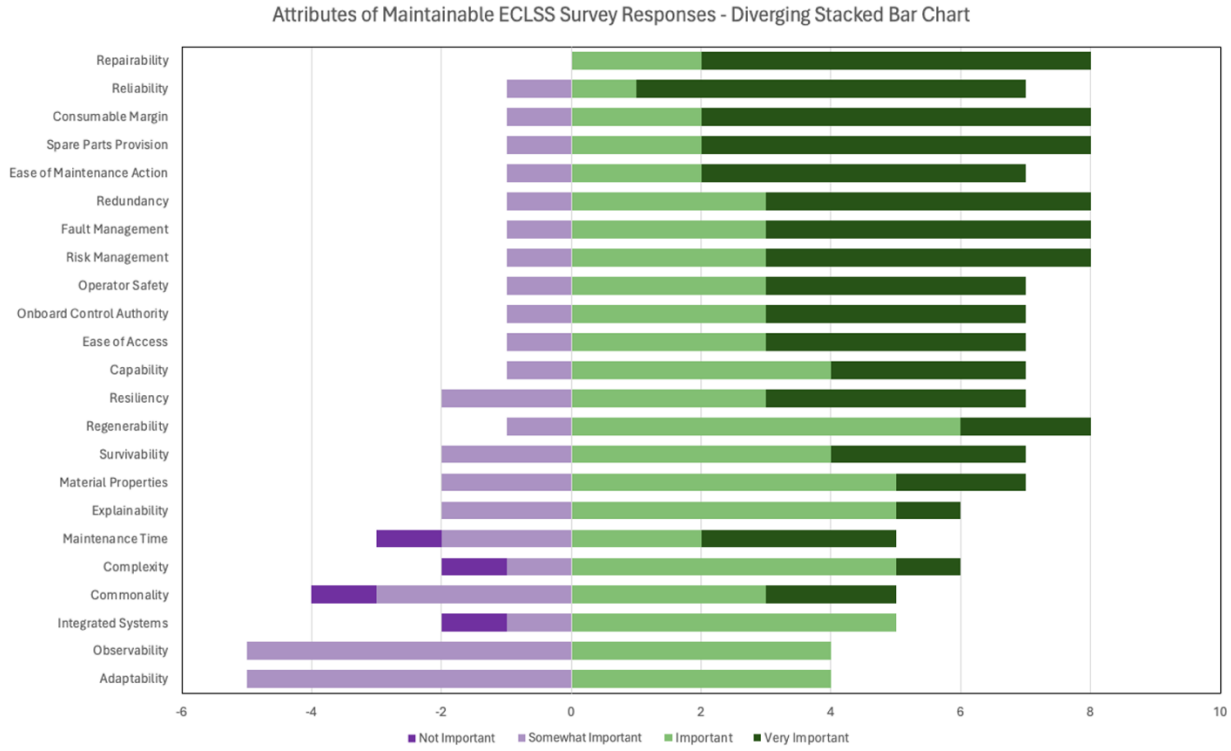


Figure 11: Diverging stacked bar chart used to visualize the Likert-style survey questions.

The results in Figure 11 provide a visualization of the number of each response type provided by participants and indicate their relative value centered about zero on the x-axis. The zero point on the x-axis does not correspond to a zero value in the average calculation, rather, it indicates whether the responses were positive ('Important' or 'Very Important') or negative ('Somewhat Important' or 'Not Important') relative to an assumption that each attribute is 'Important' as a baseline. The width of each colored bar per attribute corresponds to the number of responses received per attribute, so the widths are not equal due to the two 'Unsure' responses received and the number of attributes that were not answered. Most participant responses were either 'Important' or 'Very Important' for most attributes, which aligned with the research team's expectations that all of the attributes were important.

The sole attribute that received only 'Important' and 'Very Important' ratings is 'Repairability'. This indicates the participants had most consensus in their scoring of this attribute. Comparing the raw data from Table 12 shows that Repairability received 'Important' and 'Very Important' ratings and one 'Unsure', meaning that for those participants who answered, it was rated highly. 'Consumable Margin', 'Spare Parts Provision', and 'Ease of Maintenance Action' also received the same number of 'Important' and 'Very Important' ratings as 'Repairability', but also received a 'Somewhat Important' rating which decreases the total importance placed on them. However, these attributes also had one more reported response than 'Repairability', which affects the weighting. 'Maintenance Time', 'Complexity' and 'Commonality' received all four importance ratings indicating there was less consensus among the responses by participants for these attributes, which is easily visualized in Table. The two attributes that received only 'Not Important' and 'Somewhat Important' ratings were 'Observability' and 'Adaptability'. Several clusters emerged of attributes with identical rankings. These clusters included

'Consumable Margin' and 'Spare Parts Provision'; 'Redundancy', 'Fault Management', and 'Risk Management'; 'Operator Safety', 'Onboard Control Authority', and 'Ease of Access'; and 'Observability' and 'Adaptability'.

7.3.1 Comparison to Saliency of Responses from Chapter 6

The saliency analysis conducted in Chapter 6 indicated that complexity (or rather, designing systems to be simple and the opposite of complex), repairability by allowing crew to access the component-level to perform maintenance, and not overly relying on reliability analyses were some of the most important attributes presented by the interviewed SME's.

The relative importance of 'Repairability' seems reflected between both the interviews and the survey results given that it received solely the highest two rankings in the survey. Complexity was rated in the bottom third of attributes. It's possible that because complexity is not desirable, participants rated it lower. Or, it could be an assumption that the systems will likely be complex regardless, so emphasizing the other attributes seemed more important. Interestingly, though the participants in the interviews repeatedly mentioned that reliability values only provide an estimate and will likely fail regardless, reliability still ranked as one of the highest importance attributes in the survey. However, this still seems to align with participant responses from the interviews, who emphasized that though designers *should* strive for the highest reliability possible, those values may be misleading since it is likely that components will fail whether or not they are expected to.

7.3.2 Free-Response Answers from Participants

To allow participants to share additional thoughts on the survey, a free response question was appended at the end of the survey after participants had ranked each attribute. These responses allow for a qualitative analysis of the survey results compared

with the descriptive statistics and are captured below with analysis appended after each quote.

"Redundancy is important, but dissimilar redundancy is much better still. Also, some of these qualities were hard to evaluate without additional information. For example, a long maintenance time might be perfectly acceptable or desirable even, if the crew workload is low and the time to effect of any consequence of the failure is sufficiently long."

Dissimilar redundancy in these attributes would be included within 'Redundancy'. An example analysis for scoring a system or component's redundancy by considering whether or not redundancy exists, and then adding points if there is dissimilar redundancy. The mention of difficulty in evaluating these qualities is documented further in the Discussion.

"Complexity is a complex topic. Many systems must be complex due to their nature, but the goal of a designer should be to make systems simple. Simple systems are generally more reliable and more maintainable and repairable. One should ask if simplicity is important (it is!)."

The intention of the themes of 'Ease of Maintenance' and 'Complexity' derived in the thematic analysis conducted in Chapter 6 were to capture the concept of design simplicity. Designing for these attributes, a simplified design would ideally present an easier maintenance task through being simpler total set of tasks. Conversely, a complex system would be weighed negatively in the design considerations. The intention of the design attributes compiled in Chapter 6 was to capture distinctly different themes. From this analysis, 'simplicity' and 'complexity' were set as opposite measures of the same value, hence why both did not appear in the compiled attributes.

However, given the emphasis placed on simplicity both in the saliency analysis in Chapter 6 and the qualitative analysis here, 'design simplicity' is added as an attribute for

transparency if this table is referenced and is included in 'Design Considerations' rather than 'Operational Considerations'.

"Capability on the design side. How good is this unit/system at doing its job? For example, maybe this CO2 removal system can only get our CO2 levels down to 2500 ppm, as opposed to one that can bring it down even lower. But then you could trade this against all the other metrics such as complexity and maintainability."

This comment is noted and an attribute for 'System Performance Capability' is added. Performance of systems was included within 'Survivability' for the thematic analysis conducted in Chapter 6 to capture their performance over long time constants and through different conditions. This quote seemingly implies something different, which is the selection between systems during the design phase for their performance efficiency. This is captured as an overarching requirement driver for deep-space, since it will likely be considered along with other standard drivers such as mass, power, volume, and is not unique to ECLSS maintenance. Additionally, 'Capability' from Chapter 6 is renamed as 'Operator Capability' to prevent confusion.

"Ability to disassemble, reassemble & test functionality without need of special tooling or complex test equipment. The volume required for critical spares (defined as enough spare components to last the entire voyage) to be minimized. The extra padding and packaging for shipment/storage to be minimized yet still allow adequate protection of spare parts. The ability to replace fittings, fasteners, fluid connections in flight as multiple cycles can quickly cause failures."

This comment is noted and is addressed in the following ways. The first sentence "without need of special tooling" is capturable by the 'Commonality' attribute described in the thematic analysis conducted in Chapter 6. Similarly, the volume and required packaging for spares are captured in 'Spare Parts Provision'. Similar to the discussion for redundancy, a sample evaluation using these considerations might consider what spares are required, if any, for a given system. Then, the volume and packaging required for these

spares could also be traded. The final sentence regarding "the ability to replace fittings, fasteners, fluid connections in flight" is captured by the 'Repairability' attribute which addresses the ability for crew to perform component-level maintenance of systems in-flight rather than relying on an ORU-style model.

7.3.2.1 Additional Design Attributes Compiled from Survey Free-Response Results

Design Simplicity: The intentional design of a system to include less parts and less interactions to achieve the same functionality. Serves as a counter to 'Complexity' and 'Integrated Systems'.

- May result in increased robustness, increased ease of maintenance, and a more explainable maintenance procedure.

Representative participant statements:

"Many systems must be complex due to their nature, but the goal of a designer should be to make systems simple. Simple systems are generally more reliable and more maintainable and repairable."

System Performance Capability: How capable is a system at performing a given function, i.e. a CO2 scrubber that can reduce more CO2 volume per unit time.

- Beyond survivability, characterizes systems in the design phase for their ability to meet and potentially surpass requirements.
- Likely has ties to regenerability.

Representative participant statements:

"How good is this unit/system at doing its job? For example, maybe this CO2 removal system can only get our CO2 levels down to 2500 ppm, as opposed to one that can bring it down even lower."

These updated attributes are presented in Table 13 which modifies and completes Table 8 from Chapter 6.

Overarching Mission Drivers for Deep-Space	Maintainable ECLSS Drivers	
	Design Considerations	**Operational Considerations**
Functional Needs	Reliability	Ease of Access
Mission Duration	Resiliency	Explainability
Mass, power, volume	Adaptability	Ease of Maintenance
Cost	Observability	Integrated Systems
Project Schedule	Commonality	Complexity
Vendor Availability	Redundancy	Maintenance Time
System Performance Capability	Regenerability	Repairability
	Fault Management	Operator Capability
	Risk Management	Operator Safety
	Material Properties	Onboard Control Authority
	Consumable Margin	
	Spare Parts Provision	
	Survivability	
	Design Simplicity	

Table 13: Final set of design attributes for maintainable ECLSS derived using triangulation and a combination of qualitative and quantitative analysis.

The combined results from using triangulation resulted in an additional two attributes added, resulting in 24 total attributes for design and operational considerations for maintainable ECLSS.

7.4 Discussion

7.4.1 Synthesis and Commentary

The assumption when creating this survey was that each of these attributes are important to a design and the goal was to determine which criteria, if any, were rated as most important to least important from a set of participants with ECLSS experience. It was surprising that any of the criteria were assigned as 'Not Important', as was applied to 'Maintenance Time', 'Complexity', 'Commonality', and 'Integrated Systems' once each. Given the emphasis placed on creating simple systems observed in the interviews

conducted in Chapter 6, the rating of 'Not Important' assigned to 'Complexity' and 'Integrated Systems' was even more surprising. 'Reliability' receiving solely the top two highest ratings was not surprising and aligned with the results from the interviews summarized in Chapter 6.

Additionally, 'Observability' receiving solely the lowest two ratings was surprising. Given that system observability is how sensor data is verified for accuracy and that measured outputs align with what is supposed to be measured, it was unexpected for it to have received relatively low importance scores. Observability is, in a sense, the baseline for how several of the other attributes are enabled. Without observable systems to monitor health and status datastreams for a system, it is unclear how real-time reliability, performance, and risk measurements can be captured accurately to inform prognosis analyses for updated maintenance schedules (Gratius et al., 2024).

Finally, 'Adaptability' receiving solely the lowest two ratings, combined with it only being mentioned by one participant in the interviews summarized in Chapter 6, indicates that for these participants, it was among the least important of the attributes. Adaptability was defined for this study as *"how easily a system can be redesigned to achieve updated functionality if mission objectives change"* to capture the participant description from the qualitative interviews, as captured in Table 10. However, more research indicates it can contain more definitions. A study by Collins Aerospace as part of NASA's Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement (BAA) solicitation was conducted to investigate adaptable ECLSS to support in-flight maintenance. A summary of this work was conducted to derive lessons learned and described adaptable systems as including elements of *resiliency, evolvability, affordability, modularity*, and *intelligence*, which captures a broader definition than was used for 'adaptability' for this survey (Clawson et al., 2023). Attempts were made to capture the

participant responses from the qualitative interviews as accurately to their statements as possible, and to not infer or bias a response based on the interviewer's perception of terminology. Therefore, it is possible that adaptability was ranked lower on the Likert scale due to the definition used for this survey.

Possible reasons for the surprising results include that only 4 responses indicated 'Not Important', and all other responses for attributes were ranked as at least 'Somewhat Important', meaning that overall, most attributes were given 'Important' or 'Very Important' by most participants. Additionally, it is possible that the definitions provided were not fully clear, as was indicated by one participant in the free-response question section. The survey was designed to strike a balance between including detailed information but also not being unreasonably time-intensive for participants. This intention was to keep the survey from being prohibitive for participants and to encourage more participant responses. However, it is possible that adding more detail would have generated different rankings from participants. Providing a more detailed prompt regarding a specific mission with defined mission objectives, for example, may have made the questions easier to answer by providing a use case. It is also possible that participants brought preconceived notions of definitions for terms and did not reference the definitions created that were unique to the compiled responses from the thematic analysis. Though the literature was referenced to align definitions with common use for these terms as much as possible, specific definitions were generated primarily for 'Operational Considerations' to most accurately capture participant responses.

7.4.2 Comparison to Existing Attributes and Deriving Trade Study Criteria

The compiled attributes from this research can be used to inform and support trade studies conducted by engineers designing systems for deep-space. For example, 'reliability'

as a design attribute can be characterized by measurable quantities for specific components such as mean time between failure (MTBF), number of spares needed, and maintenance requirements, among others, and used to weight components and systems against others as part of the design process.

To display how several of the attributes derived in this research can be converted to trade study criteria and further, to identify if any themes derived in these interviews are not aligned with existing design standards, several NASA design handbooks were reviewed. This includes the the NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health NASA-STD-3001 Volume 2 Revision C, the NASA Human Integration Design Handbook (HIDH), the Human Spaceflight Mission Analysis and Design (HSMAD), the NASA Systems Engineering Handbook, and the NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems (Larson & Pranke, 2000; NASA, 2007, 2014, 2017, 2022). A summary of the contents of these handbooks is provided in the following sections. These sections were identified with the key words of 'maintainability' or 'maintainable' with some related sections reviewed as well (e.g. 'Tools' is a separate section in the HIDH, but is related to this work).

Converting these attributes to trade study factors can be done by referencing these primary design handbooks for detailed guidance – e.g., for the tooling component of Operator Capability, the NASA HIDH has a detailed set of human factors criteria, summarized below. A collective look at the standards and their application to the results derived in this research is summarized at the end in Section 7.4.2.6.

7.4.2.1 NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health (NASA-STD-3001 Volume 2, Revision C)

A review of the Maintainability section of the NASA Space Flight Human-System Standard is summarized below (NASA, 2022). Each number references a section in the standard, with a summary of the requirement contents in bullet points, unless the name of the requirement itself is self-explanatory in which case there are no bullet points.

9.7 Design for Maintainability

- System-level optimization of parts
- Ergonomics
- Considering information and tools as portion of design

9.7.1.1 Design for Maintenance

9.7.2.1 Maintenance Time

- Designed for safe and efficient maintenance, that can be completed in the allotted time, while wearing most encumbering anticipated clothing

9.7.1.3 In-Flight Tool Set

- In-flight tools can be used by all crew in any protective equipment

9.7.2.2 Captive Fasteners

- Design for captive fasteners because free fasteners can become foreign object debris (FOD) and add risk

9.7.2.3 Minimum Number of Fasteners – Item

9.7.2.4 Minimum Variety of Fasteners – System

9.7.3 Accessibility

9.7.3.1 Maintenance Item Location

- Crew should not have to remove other systems to maintain an item

9.7.3.2 Check and Service Point Accessibility

- Must be available while wearing most encumbering equipment expected

9.7.3.3 Maintenance Accommodation

- Maintenance tasks should be defined and analyzed for 'worst case' scenarios, i.e., to be completed with the most encumbering clothing

9.7.3.4 Visual Access for Maintenance

- Ensure visual access is provided if it is needed for maintenance operation

9.7.3.5 Tool Clearance

The comparable derived attributes from the qualitative interviews and survey conducted in this work include 'Commonality', 'Risk Management', 'Fault Management', 'Spare Parts Provision', 'Ease of Maintenance', 'Ease of Access', 'Integrated Systems', 'Complexity', 'Maintenance Time', 'Operator Capability', and 'Operator Safety'.

Additionally, though they are not included directly in the Design for Maintainability section, some considerations from Section 5: Perception and Cognition, Section 6: Natural and Induced Environments, Section 7: Habitability Functions, Section 10: Human Performance and Crew Interfaces, and Section 11: Spacesuits are relevant as they influence 'Operator Capability' as defined for this work. Additional considerations from Section 8: Architecture and Section 9: Hardware and Equipment affect the 'Ease of Access' and 'Operator Safety' defined in this work. 'Redundancy' is included in several sections, tegenerable water provision is mentioned once as part of 6.3.1.4 Water Quality Monitoring, and 'Consumable Margin' is primarily mentioned for EVA and spacesuits, though these were not directly included in the section for maintainability. Taken together, the design

principles imply taking effort to design for simplicity and limit complexity where possible (NASA, 2022).

7.4.2.2 NASA Human Integration Design Handbook (HIDH)

The NASA HIDH was also reviewed, and yielded the following relevant sections, summarized the same as above (NASA, 2014). This reference provides a plethora of specific design guidance. These primarily apply to the Operational Considerations derived in the interviews and survey given the emphasis in this standard of human factors design.

- Feedback from ISS crews indicates maintainability may not have been prioritized in initial design

9.3 Maintainability

- Goals are to reduce need for specialized tools, reduce crew time spent on maintenance, reduce cognitive workload, and assure crew safety while performing maintenance

9.3.3 Accessibility

- Consider limited mobility in different clothing
- Make components visible and physically accessible

9.3.3.1 Physical Access

- Priority of access – based on criticality or those that require rapid maintenance
- Access dimensions – includes recommendations for design
- Component removal – should not need to remove a component to maintain another
- Access covers should self-support in an open position
- Check and service points should be away from hazards
- Cables – routed for easy inspection and repair, and have sufficient slack

9.3.3.2 Visual Access

- Includes labeling and direct visible access requirements

9.3.4 Failure Notification

- Automatic alert to crew when flight-critical equipment has failed

9.3.5 Efficiency

- Maintenance should take as little time as possible

9.3.6 Tools and Fasteners

- To minimize tools, must also minimize fasteners

9.3.7 Circuit Protection

- Circuit breakers are preferable to fuses for their ease of maintenance

9.3.8 Fluids

- Hazardous fluids should be isolated

9.3.9 Research Needs

- Could be two-handed or one-handed operations by crew

Additionally, many of the other sections in this handbook are related to maintainability, though they are not contained within the 'Maintainability' section. Section 9.4 is reviewed in more detail below, to demonstrate how trade study criteria can be identified in this standard by referencing the detailed design guidance and component-level considerations provided in the handbooks. For this example, assessing 'Commonality' and a portion of 'Operator Capability' can be done by including the following trade study criteria.

9.4 Tools

- Should include multipurpose tools, standardized tools, and a minimal common toolset

- Human factors guidance provided for tool design and use including power tools, handgrip size and shape for tools, tool handedness, actuation forces and their direction of action, packaging and stowage, a tool carrier, and appropriate labeling

Other relevant sections to maintainability include 9.5 Drawers and Racks, 9.6 Connectors, 9.8 Cables, 9.10 Closures and Covers, 9.11 Fasteners, 9.12 Safety Hazards, 9.13 Design for Training, and considerations included throughout Section 10: Crew Interfaces and Section 11: Extravehicular Activity (EVA).

The comparable derived attributes from the qualitative interviews and survey conducted in this work include Commonality, components of Risk Management, Fault Management, Material Properties, Spare Parts Provision, Ease of Maintenance, Explainability, Ease of Access, Integrated Systems, Complexity, Maintenance Time, Operator Capability, and Operator Safety.

Additional terminology was mentioned, not directly for how it pertained to maintainability, but included in the following contexts. Reliability is mentioned in reference to reliable measures of human workload and exercise equipment; resiliency is described as a capability provided by humans for complex problem solving; bioregenerative systems are mentioned for food provision; consumable margin is mentioned specifically for long-duration hardware; spare parts are mentioned as relevant for logistics, but not specifically for maintainability. Section 5.8.4.4.5: Tools to Support Autonomous Operations describes how crew will need simpler access to procedures in order to complete operations autonomously, and Section 10.14.6: Operational Constraints and Considerations describes a locus of control requirement that crew must have direct control over machine activity. Additionally, HAI is discussed for the sake of maintaining crew situation awareness by having the crew periodically disable automation. The handbook also mentions a higher level of crew

autonomy is needed due to communication delays and discusses how crew will need to work together to socially support each other in an autonomous environment. These concepts address the attribute of 'Onboard Control Authority' for how it relates to deep-space maintenance. 'Survivability', as captured in this work, was mentioned by SME's as concerning for periods of dormancy or quiescence in deep-space missions. Of particular concern is microbial growth in water systems or areas where humidity can condensate, as detailed in Sections 6.3.5.5 in the HIDH, which recommends filtration and air monitoring to ensure environment safety. Section 6.3.8 closes with a recomemdation for further research to characterize microbial concentration and organisms specifically when more crew autonomy is required, as will be the case in deep-space.

Observability was mentioned in reference to human capabilites such as their attention and cognition as it relates to 'Operator Capability', but not with respect to system design. Adaptability was described as a valuable skill of human response with respect to system design. Similar to the Space Flight Human-System Standard, the design principles outlined in the HIDH imply designers should strive to design for simplicity and limit complexity where reasonable (NASA, 2014).

7.4.2.3 Human Spaceflight Mission Analysis and Design (HSMAD)

In the HSMAD, Chapter 28 – Space Logistics Support, Section 28.4.1: Developing a Maintenance Concept was referenced (Larson & Pranke, 2000). This section describes a maintainability function for determining the Mean Time to Repair (MTTR) to estimate when systems will need maintenance to inform design practices to lengthen this time. The function compiles elements of safety, accuracy, economy, and ease of maintenance, and is referenced below.

$$Expected\ number\ of\ failures\ for\ elements\ of\ type\ i = n_i \lambda_i T_i$$

$$MTTR_{function} = \sum_{i=1}^{n} \{(n_i \lambda_i T_i) MTTR_i\}$$

Where

n_i $= the\ number\ of\ elements\ of\ type\ i\ in\ the\ design$
λ_i $= the\ estimated\ failure\ rate\ of\ the\ elements\ of\ type\ i\ expressed\ in\ failures/hour$
T_i $= the\ mission\ duration\ for\ subsystem\ i\ (taking\ into\ account\ duty\ cycles)$
$MTTR_i$ $= the\ Mean\ Time\ To\ Repair\ element\ i$

This section further describes a Mean Time between Maintenance Actions (MTBMA) and Mean Logistics Delay Time (MLDT). In summary, this section provides a useful exercise for estimating the logistics planning problem for maintenance, but does not discuss in depth design or operational considerations as identified in the interviews and survey section of this research. The work collected in this research, as well as criteria summarized from the other design handbooks, could contribute additional variables to update this function or apply it to design considerations in addition to logistics.

The handbook was reviewed for mention of the other design and operational considerations, which yielded more returns, though these were not directly associated with maintainability. For example, adaptability is mentioned with respect to human physiology when entering space, but not with respect to hardware design (Larson & Pranke, 2000).

7.4.2.4 NASA Systems Engineering Handbook

The systems engineering handbook offers a definition for maintainability, paraphrased as the ability of a component or system to be retainable or restorable to identified conditions when maintenance is conducted by crew with identified skill levels, using predetermined procedures, for each required level of maintenance (NASA, 2007). Appendix C: How to Write a Good Requirement Checklist also contains mention of maintainability and poses two questions. The first, are requirements specified for system

maintainability in a measurable, verifiable manner? And second, are requirements designed to minimize 'ripple effects', e.g., requirements without high coupling. The handbook also suggests that maintainability should be detailed in the systems engineering management plan (SEMP).

The emphasis of this handbook is not to provide specific design guidance, as identified in the Space Flight Human-System Standard and HIDH, but rather to compile lessons learned and provide high-level guidance for effective systems engineering (NASA, 2007).

7.4.2.5 NASA Reliability and Maintainability (R&M) Standard For Spaceflight and Support Systems NASA-STD-8729.1A—2017-06-13

The R&M standard addresses ways to plan for and evaluate reliability in NASA programs (NASA, 2017). Subobjective 1 describes ways to ensure a design meets its original intent. Subobjective 2 emphasizes ensuring functionality for the intended lifetime by incorporating reliability criteria of the system, a strategy for addressing common cause failures, and designing for nominal and extreme loads. Subobjective 3 describes elements of fault and failure tolerance, including anomalous external and internal events, by using fault management strategies such as planning for nominal and off-nominal activities and incorporating dissimilar redundancy.

Finally, Subobjective 4 describes elements of maintainability as a set of design objectives, summarized below.

Objective 4.A.1: Design for systems that are maintainable with available resources of cost and time

- Reduce maintenance time
- Use common set of tools and procedures

- Incorporate reliability centered maintenance to optimize maintainability design

Objective 4.A.2: Systems must provide effective health and status indication

- Incorporate fault detection, isolation, and recovery at lowest feasible level
- Include test-point-design strategies that minimize access time
- Design assemblies to include self-diagnostics

Objective 4.A.3: Systems should allow for reconfiguration throughout the mission

- Systems should be able to accommodate future technology or application updates throughout mission
- Should be physically and functionally interchangeable with other components and assemblies
- Modular designs facilitate remove-and-replace maintenance

Objective 4.A.A: Systems can retain operational history for maintenance to validate and optimize future maintenance procedures

- Ensure health status, diagnostic, maintenance, and degradation data can be captured and stored
- The data should be periodically tested and analyzed to update maintenance activities
- Dataset should be available for future programs and projects

This standard addresses the attribute of 'Adaptability' captured in this research in Objective 4.A.3 by recommending designs that are physically and functionally interchangeable with other assemblies should the mission update. Additionally, the basis for Objective 4.A.2 is 'Observability' which provides the basis of effective state monitoring and is required to understand system health and status to inform maintenance timelines (NASA, 2017). These objectives also address elements of 'Reliability', 'Fault Management',

'Risk Management', 'Material Properties', 'Spare Parts Provision', 'Ease of Access', 'Ease of Maintenance', 'Integrated Systems', 'Complexity', 'Maintenance Time', and 'Operator Capability'.

7.4.2.6 Comparison of Attributes from Interviews and Survey

Maintainability is a multi-faceted, highly interconnected and complex issue. The referenced design handbooks contain great depth of information for ways to consider and apply maintainability practices to design, particularly the Space Flight Human-System Standard, HIDH, and R&M Standard. The emphasis when designing and conducting the interviews and survey in this research was not to imply the individual terminology or design practices are novel, as the knowledge base of the participants likely provided influence to, or was influenced by, directly or indirectly, the same standards referenced in this work. Rather, the intention was to collect experience with maintainability and design in a unique way by using methods of triangulation with specific application to ECLSS for deep-space and attempt to capture a prioritized list using a survey.

With that in mind, upon review of these design handbooks, 'Repairability' merits further discussion and analysis. Though 'Repairability', or the ability to maintain systems at the component-level (i.e. replace a faulty sensor instead of the entire unit), as a concept is not novel, the emphasis placed on its importance for future deep-space missions by the SME's interviewed in this work represents opinions regarding design philosophy. The R&M standard recommends remove and replace units, and the HIDH references ORU's as components in Section 9.3.3.1 (NASA, 2014, 2017). The results from the interviews in this work, however, described 'Repairability' as effectively the opposite of the ORU model. This work does not comment on either of these design philosophies as more correct than the other, rather, highlights an interesting and complex issue that merits further research. The

complexity of integrating these design 'ilities' in a streamlined and effective way is evidenced by the amount of data captured in the referenced design handbooks. The primary effort in the survey done for this research was to gain insight into what this specific participant pool rated as more or less important than others but is not a conclusive set of design requirements.

7.4.3 Summary of Work

Drawing from techniques that are more typically applied in medical and social sciences domains toward an aerospace-oriented trade study practice, the work demonstrated in Chapters 6 and 7 combine qualitative and quantitative tools to describe a set of data, known as 'triangulation'. The results in this chapter provide a ranked list of design attributes important for generating maintainable ECLSS to be considered in the design phase. The collected attributes represent considerations for all phases of a design, from initial engineering design through to operational considerations when performing ECLSS maintenance. Ranking these attributes using a Likert survey assigns a weighted and ranked level of importance for these criteria relative to one another and provides a quantified way to visualize the outcome of the survey results. The attribute of 'Repairability' represents a design philosophy preferred by several of the SME's interviewed for this work which, upon review of the design handbooks noted above, implies a difference in opinion and merits further consideration between experts when designing ECLSS and habitats as a whole for deep-space. The results compiled from these interviews provide a set of prioritized design attributes, compared against existing design standards and handbooks, to help future designers prioritize their decision-making when conducting trades between different technologies or vendors for ECLSS integration. However, these are to be used for guidance, not as requirements, as was stipulated in several of the referenced handbooks

(Larson & Pranke, 2000; NASA, 2007, 2014, 2017, 2022). The dataset represents the perspectives and opinions of a limited subject pool and is therefore recommended to be considered as an example process that can be used along with other relevant sources of information and engineering best practice.

Furthermore, taken together, this process provides a structured framework and systematic method that can be applied for other subsystem trade spaces in the vehicle, adaptable beyond ECLSS maintainability. This process demonstrates how to incorporate these methods to determine weighted trade criteria based on SME input and compare them against an existing knowledge base relevant to the needs of any particular subsystem.

7.5 Acknowledgements

Gratitude for the work compiled in this chapter is extended to all participants who volunteered their time and expertise and completed the survey; and PhD Candidates Michael Zero, Patrick Pischulti and Dr. Annika Rollock for their feedback on analysis methods and review of the results compiled in Figure 11.

7.6 Outcomes

7.6.1 Research Objectives

This work completes the proposed analysis for the following objectives.

SA4 – Define method for analysis and summarize recommendations for strategically prioritizing implementation of emerging technologies in a deep-space habitat

- O4.1 – Create prioritization scheme for incorporating emerging technology based on results from Specific Aims 1-3 and an established methodology
- O4.2 – Summarize key benefits for increasing self-sufficiency and/or improving habitability

SA5 – Demonstrate the prioritization method by utilizing HOME Demo results and/or conceptual scenarios

- O5.2 – Define success criteria for assessing the methodology proposed in SA4
- O5.3 – Demonstrate the methodology

7.6.2 Publications and Presentations

Sections of this work are included in the following publications and presentations.

1. *Zaccarine, S. and Klaus, D. (2023) Characterizing the Trade Space for Incorporating Emerging Technologies into Deep-Space 'Smart' Habitats: Needs and Opportunities. International Conference on Environmental Systems (ICES). Poster.*
2. *Zaccarine, S. (2023) Collecting, Surveying, and Assessing Criteria for Self-Sufficiency in Deep-Space Habitat Operations. HOME Seminar Series.*

This work is in preparation for the following publication.

3. *Zaccarine, S. and Klaus, D. (2024). Survey Designed to Rank Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats. In work.*

Chapter 8

Discussion

8.1 Summary of Work

The overarching research goal of this dissertation is restated below, as was proposed in the Comprehensive Exam in December 2022, with minor modification.

Research Goal: Identify and define trade study criteria needed to determine where emerging technologies can provide benefit (i.e., gaps where SoA is insufficient) on a deep-space habitat by increasing self-sufficiency and/or habitability, mapped to categorized functional needs.

Two updates were made as the work evolved from the proposed research goal in the comprehensive exam. First, the word 'emerging' replaces the previously used 'emergent' to align with more commonly used definitions, where emerging *technologies* can be classified for emergent *behaviors* they display. Second, the phrase 'to a nominal operations scenario' following the parenthesis was removed as the scope of this work extended beyond nominal to include both nominal and off-nominal considerations.

The word 'determine' also replaced the word 'describe' in the second line. This clarification is made because the emphasis of the dissertation work was ultimately placed on identifying, categorizing, and empirically assessing the trade study criteria that can be used to evaluate a set of emerging technologies for their contribution to future deep-space

habitats. The cognitive engineering functional analysis conducted in Chapters 4 and 5 of this dissertation proposes general functional categories for increasing self-sufficiency and improving habitability to enable deep-space missions. The original language of the research goal was written when it was thought that assessing specific emerging technologies would be relevant. By design, future and some emerging technologies don't yet exist for spaceflight and likely will be different from current options in the future when these habitats are being actively designed. However, the emphasis was shifted to focus on the functionality driving the trade space being complete and inclusive for a wide set of future trades evaluated by designers regardless of the technology chosen for comparison and evaluation. This decision is supported by the decision to support the analysis with empirical data collection and analysis as described in Chapters 6 and 7. The phrase in parenthesis was added to clarify the use of 'benefit' in this research as it represents the ability for any to surpass the current SoA solutions in spaceflight for the categorized functional categories of self-sufficiency and habitability as described in this dissertation.

The measurable completion of this research goal is now described by explaining rationale for each specific aim (SA) and subsequent work objectives and describing the work completed. The descriptions are followed with two tables detailing the publications and presentations resulting from the work.

1. SA1 - Characterize and differentiate representative nominal and off-nominal onboard operational scenarios for a deep-space habitat

- **O1.1 – Summarize key functional needs for deep-space habitat operations**

Any spacecraft with humans onboard has a unique set of functional requirements regardless of the operating environment and mission objectives. This objective was

completed in RT1.1 group work by conducting a functional decomposition, developing a design reference missions for surface and micro-gravity environments and a concept of operations relevant to any future deep-space habitat mission architecture. These documents helped lay the foundation for the HOME research projects by aligning the emerging technologies being developed with functional needs of a deep-space habitat, in particular those involving the need for autonomy.

- **O1.2 – Differentiate between nominal and off-nominal (including anomaly response) operations**

Although the distinction between nominal and off-nominal operations seemed obvious at first, the referenced literature indicated that there is considerable nuance when differentiating between these two states. It becomes increasingly important to describe these differences to enable deep-space crew for autonomous decision-making and operations. To provide additional clarity, proposed definitions were generated from the referenced literature, most notably influenced from existing FM research.

- **O1.3 – Differentiate between nominal and off-nominal operating states**

Decision-making regarding the monitored health and status parameters on a spacecraft often relies on state information of the vehicle. In addition to providing clarity for operational scenarios in O1.2, habitat state information was compiled and presented as a habitat-level state diagram to augment existing flow charts found in the fault management literature. State transitions comprise a feedback loop between nominal and off-nominal states, as captured in the state diagram. This state diagram was accompanied by a state transition matrix to explain how different events trigger state transitions.

- **O1.4 – Define and characterize self-sufficiency attributes in the context of nominal scenarios**

In order to begin designing space habitats to be operationally autonomous, it is necessary to derive the driving general functions that enable these operations for deep-space. The function decomposition conducted in group work for O1.1. provided a list of over 375 functions. These functions were reviewed and grouped into sub-categories derived from the Phases of Flight ConOps diagram shown in Figure 2. All phases of flight except contingency and emergency scenarios were reviewed and converted to a prioritized abstraction hierarchy to glean the general function drivers of self-sufficiency and habitability. The drivers for self-sufficiency were captured as 'monitoring, maintenance, and fault management' as demonstrated in the abstraction hierarchy and have applicability to contingency and emergency phases of flight.

- **O1.5 – Define and characterize habitability attributes where emerging technologies offer potential benefit**

In addition to the necessary drivers within self-sufficiency, there are also 'nicer' attributes that make a space habitat more habitable. These comprise 'desirable' components that could make the isolation of deep-space more livable for future crews by enabling elements of human comfort beyond the requirements needed to sustain life addressed by self-sufficiency. The characterization of habitability was completed by deriving the general functions from the abstraction hierarchy completed as part of a work domain analysis resulting from the functional decomposition conducted in group work.

2. SA2 – Identify attributes of select *(and other needed)* emerging technologies capable of supporting, performing or improving nominal operations in contrast to SoA approaches

When this dissertation began, ChatGPT, DALL-E, and other large language AI models did not yet exist in an open-source format. The evolution of AI technology in the last 5 years globally demonstrates the rapid growth that some sectors of emerging technology may see, and it is likely that a number of these technologies will become applicable at some point for use in human spaceflight. Beyond the literature, from experience gained throughout this study and from presenting this work at conferences and professional growth, it became increasingly apparent that there is seemingly no clear consensus on what 'autonomy' means in an operational context and with respect to human-autonomy teaming. Autonomous vehicle language has also begun distinguishing between 'automated' and 'autonomous' to clarify that today's self-driving cars are not (yet) 'autonomous' without human oversight and intervention.

For this dissertation work to be applicable and useful for future designers, the focus was placed on identifying the functional needs that will not fundamentally change for deep-space travel.

- **O2.1 – Survey the literature for relevant existing emerging technology attributes**

This specific aim was intended to determine which attributes are needed to address the gap between the current SoA and what is required for self-sufficient habitats rather than surveying the literature for the technology itself. Additionally, identifying some of the current SoA technologies for these functions examines the potential contribution for emerging technologies in each functional category. By definition, emerging technologies do not yet exist or are not in practice especially in the spaceflight domain. This work was focused more on gap analysis of SoA solutions used in current practice to identify where the emerging technology development can be guided toward.

This objective was completed by aligning the general functions for 'self-sufficiency', derived in SA1, with relevant emerging technologies to identify examples of what could potentially fill the gap in the current SoA.

- **O2.2 – Document and characterize the need for emerging technologies for adding novel capabilities, or in comparison to SoA nominal operations, as applicable**

As the work progressed, it became clear that identifying the driving need for these technologies as compared to the SoA baseline was more relevant than identifying the currently available emerging technologies. While the bulk of this work emphasized identifying gaps within SoA operations, select emerging technologies were introduced in Chapter 4 to provide potential application to monitoring, maintenance, and fault management as general functions required for self-sufficient operations. Overall, the value from this work is applied to the functions that need to be met rather than comparing specific emerging technologies that, for the most part, do not yet exist in human spaceflight.

As such, the intent of this objective were met by identifying the general functions needed to enable operational autonomy captured in Chapter 4, 'monitoring, maintenance, and fault management', determined by using an abstraction hierarchy and displayed using and information flow model that detail the functionality associated with each phase of operations. Each phase of operations represent gaps between SoA and what is needed, through development of emerging technologies, to enable self-sufficient operations. A limited set of emerging technologies were then addressed in this chapter for their potential application to monitoring, maintenance, and fault management in the human spaceflight sector.

3. SA3 – Identify opportunities and assess potential benefits of incorporating emerging technologies with a focus on nominal operations

- **O3.1 – Identify enabling attributes of emerging technology relevant to increasing self-sufficiency and/or improving habitability**

Similar to the rationale driving the work completed in SA1 and 2, where the gaps exist in the SoA drives where developing technologies is needed to enable functionality for operational autonomy. For this objective, the emphasis was placed on self-sufficiency and not habitability.

An information flow model for self-sufficient habitat operations, which is a component of a work domain analysis which comes from cognitive engineering, was created to align attributes of emerging technologies with specific operations. The information flow model serves the purpose of displaying the functionalities in an operation flow diagram which is key for demonstrating where they fall in time relative to one another. The function of 'maintenance' for nominal and off-nominal states was aligned with a taxonomy of maintenance types proposed for system health monitoring and prognostics. In the information flow model which proposes an operational flow diagram using Boolean logic, monitoring was split into the operational phases of 'Data Collection', 'Data Transfer', 'Data Processing', and 'Data Analysis'. Fault management principles of 'detect', 'diagnose', 'decide' and 'respond' were displayed chronologically and mapped to two types of responses: proactive or reactive maintenance, or updating state boundaries.

- **O3.2 – Characterize attributes of accommodation and utilization in terms of habitability in the context of nominal operational scenarios**

Much of the analysis conducted in SA1 and SA2 and the remainder of the analysis in SA4 and SA5 emphasize self-sufficiency, or what is 'needed' to enable human life in deep-

space. However, this does not factor in the 'nice to have' options represented by habitability attributes and desirements. These may become more important for crew facing extreme isolation in transit to deep-space.

To characterize habitability, a breakdown of habitability concerns were summarized in Table 5. To visualize how different levels of habitability might function in an operational setting, attributes of accommodate and degrees of utilize were designed to align with the tenets of a human-rated spacecraft. 'Accommodate' encompasses what the habitat provides the crew, and 'utilize' encompasses what the crew provides to the mission and habitat operations. Attributes of accommodate took inspiration from level of autonomy frameworks and compare what a SoA habitat supports as compared to an autonomous deep-space habitat. Degrees of utilize were proposed to represent how crew can effectively use and interact with an autonomous habitat. These referenced research involving theories of human workload including the Hebb version of the Yerkes-Dodson theory.

Presentation of this material was met with positive feedback at the NASA HRP IWS from NASA engineers and researchers who have conducted habitability analysis and are generating a habitability analog.

- **O3.3 – Map emerging technology capabilities to categorized benefits for increasing self-sufficiency and/or improving habitability**

As with the rationale compiled for SA1 and 2, the gaps in the SoA highlight where emerging technologies and their capabilities are needed. The categorized benefits for self-sufficiency and habitability are captured in the abstraction hierarchy, and a set of emerging technologies were aligned with the operational phases of the information flow model. This work is also captured and elaborated on in SA2.

With the completion of SA1-3, the latter half of the dissertation research goal is fulfilled by characterizing self-sufficiency and habitability as the general functional goals for operational autonomy that need improvement beyond SoA methods. The remaining sections of research in SA4-5 were constructed to fulfill the former half of the research goal by identifying the trade study and decision-making criteria that can be used when designing a deep-space habitat, which is the intended use of the research results compiled in Chapters 4 and 5. The remainder of the PhD research became combined in the approach, so each objective from SA4 and SA5 is reorganized to match the flow of the work.

In order to incorporate any emerging technology in a strategic manner, a prioritization method for including them into a design can be generated to assist designers when making decisions regarding which technologies to use in a mass and volume-constrained human spacecraft design.

To accompany the top-down analysis conducted in Chapters 4 and 5 which addressed SA1-3, a bottom-up analysis was conducted in Chapters 6 and 7. The goal was to collect SME feedback on the general functions proposed in Chapter 4 to assess their validity in a formal method using empirical data collection through human-subject testing rather than relying solely on top-down methods and proposed results from Chapters 4 and 5. However, it became clear that assessing all of self-sufficiency and habitability presented too wide a scope to be reasonable and would not support meaningful data collection from participants. Therefore, the following analysis focuses on qualitative and quantitative investigation of the general function of 'maintenance' identified in the abstraction hierarchy proposed in Figure 5 as a representation of how triangulation and a combination of qualitative and quantitative methods can be applied to understand and direct decision-making for designing future deep-space habitats.

4. SA4 – Define method for analysis and summarize recommendations for strategically prioritizing implementation of emerging technologies in a deep-space habitat

5. SA5 – Demonstrate the prioritization method by utilizing HOME Demo results and/or conceptual scenarios

- **O4.1 – Create prioritization scheme for incorporating emerging technology based on results from Specific Aims 1-3 and an established methodology**

The functional categories resulting from the work conducted in SA1-3 provide a baseline for evaluating technologies by identifying what 'needs' to happen on a space habitat to be self-sufficient. Understanding decision-making processes that humans employ during a multi-factor trade study, such as the ones used when designing human-rated space habitats, can be done by compiling the relevant variables that are weighed and traded against one another, as well as their relative importance.

A two-fold study was designed by first collecting the design attributes, or variables, needed to describe the decision space by using qualitative interviews and then employing a survey to have participants rank the attributes. This employs empirical data collection in an experimental demonstration of the work compiled in SA1-3.

The experiment was designed in two phases. Phase 1 employed qualitative interviews with a small participant pool of SME's who possess breadth and depth of knowledge across a range of experience. Phase 2 employed a Likert survey with a slightly larger participant pool disseminated to individuals with ECLSS experience. The investigation was constructed this way to first collect data on the design attributes, or variables, that SME's use when conducting design trades for ECLSS and spacecraft development. Collecting this data in a comprehensive way seemed infeasible by way of a text-based survey, so longer-form spoken

interviews were conducted. It was also of interest to determine relative importance for these attributes, and this seemed suitable for use of a Likert survey circulated to a broader participant pool.

- **O5.2 – Define success criteria for assessing the methodology proposed in SA4**

When collecting any form of data, it is valuable to understand how much data is 'good enough' to draw meaningful conclusions. Given that the interviews are part of a qualitative research study driven by a research question and not a hypothesis, a typical power analysis cannot be performed to determine how many participants are needed to reject a hypothesis. Rather, the participant number was formed by estimating how many participants could reach the desired experience identifiers from an overall limited subject pool. Though the survey allowed for quantitative description of the dataset, it still represented a research study driven by a research question and not a hypothesis, so similar estimates were formed for desired participant numbers.

Additionally, the success criteria used for the interviews was 'coding saturation'. Though this method is flexible, criteria from the literature were used to ensure a rigorous analysis, and interviews commenced after one participant presented no new novel themes.

- **O5.3 – Demonstrate the methodology**

Once the methodology was defined and the study designed, data collection could proceed. The interviews resulted in data collection from 7 SME's with over 83,000 words transcribed and over 7.5 hours of audio recorded. NVivo software was used to perform thematic analysis which was both internally validated and externally checked throughout to ensure methodical and rigorous application of data collection and analysis. The result is a set of 23 design attributes to be considered when creating deep-space ECLSS that can be maintained by onboard crew.

Once the attributes were compiled from the interviews, a survey was disseminated to participants with ECLSS experience resulting in a set of 9 participant responses. These results were presented and analyzed from a diverging stacked bar chart which provides a ranking of these attributes. The free-response question was analyzed and, in comparison with the results compiled from the interview, resulted in 2 more attributes being added, with one as an overarching driver, to complete a total set of 24 design attributes specific to ECLSS maintenance. These compiled attributes were compared to several design handbooks and standards and found 'Reliability' merits further investigation before implementation, as it seemingly represented a different design philosophy than was seen in the handbooks.

- **O4.2 – Summarize key benefits for increasing self-sufficiency and/or improving habitability**

Summarizing the outcomes from the research study describes the utility of the dataset and completes the research goals set forth in this dissertation. SA4-5 compiled and ranked the design attributes used during decision-making when creating maintainable ECLSS, extensible from current and past missions to future deep-space architectures. This resulted in 24 design attributes to be leveraged in ECLSS designs for deep-space, summarized in Table 13. These design attributes represent the benefits that can be provided, potentially by emerging technologies, by enabling functionality beyond the SoA that is required to achieve safe deep-space exploration, and supplement existing design standards and handbooks.

- **O5.1 – Coordinate with HOME demos that align with this work and/or establish conceptual scenarios involving nominal operations**

The HOME community provided support and context for this entire dissertation. The capstone demonstrations created as part of HOME's Year 5 deliverables provided relevant

conceptual scenarios for aligning the results of this work. The results from SA1-3 are related to the NASA HOME STRI Capstone 2, which was presented in June 2024 at the University of Colorado at Boulder and documented in a conference paper (Sherman et al., 2024). The 24 design attributes compiled from SA4-5 were included as guiding assumptions for the scenario investigated in Capstone 3, which was presented in July 2024 at the University of California, Davis as part of the final annual review for HOME. This scenario investigated a human-autonomy teaming maintenance task, and used the attributes derived in SA4-5 as assumptions for the simulated deep-space habitat.

The publications and presentations resulting from this work are summarized below in Tables 14 and 15 and mapped to the outputs of each research objective and specific aim.

Specific Aim	**Research Objectives**	**Resultant Publications and Application Demos**
SA1	O1.1	Klaus, D., Zaccarine, S., Pischulti, P., and Rollock, A. (2020) Establishing assessment criteria for intelligent infusion of smart systems into a space habitat, ICES-2020-419
SA1	O1.1	Klaus, D., Pischulti, P., Rollock, A. and Zaccarine, S. (2022) Functionally Aligning Emergent Technologies for Deep Space Smart Habitats, ICES-2022-120
SA1 SA2 SA3	O1.2 O1.3 O1.4 O2.1 O2.2 O3.1	Zaccarine, S. and Klaus, D. (2024). Monitoring, Maintenance and Fault Management Considerations for Self-Sufficient Deep-Space Habitat Operations, *In review.*
SA4 SA5	O4.1 O4.2 O5.2 O5.3	Zaccarine, S., Almand, A. and Klaus, D. (2024). Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats. *In work.*
SA4 SA5	O4.1 O4.2 O5.2 O5.3	Zaccarine, S., and Klaus, D. (2024). Survey Designed to Rank Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats. *In work.*

SA1 SA3	O1.5 O3.2	Zaccarine, S. and Klaus, D. (2025). Characterizing Habitability for Deep-Space Habitat Operations. *In work.*
SA4	O2.2 O3.3 O4.2	Klaus, D., Pischulti, P., Zaccarine, S., Rollock, A., Zero, M. (2025) RT1 Publication (planned 2025)
SA5	O5.1	HOME Capstone 3 Demonstration

Table 14: Specific Aims and Research Objectives mapped to paper publications.

Specific Aim	**Research Objectives**	**Presentation / Seminar Venues**
SA1	O1.1	Zaccarine, S. (2020). Intelligent Infusion of Smart Technologies into a Space Habitat. Bioastronautics Seminar Series. CU Boulder
SA1	O1.1	Zaccarine, S. (2020). Intelligent Infusion of Smart Technologies into a Space Habitat. Smead Aerospace Researchpalooza. *Awarded Honorable Mention.* CU Boulder
SA1 SA3	O1.5 O3.2	Zaccarine, S. and Klaus, D. (2021) Autonomous Systems for Enhancing Human Performance and Vehicle Operations in Deep Space Habitats, AIAA Rocky Mountain Annual Technical Symposium (ATS). CU Boulder
SA1 SA2 SA3	O1.2 O1.4 O2.1 O3.2	Zaccarine, S. (2021). Identifying Smart System Capabilities and Attributes for Nominal Operations in a Deep Space Habitat. HOME Seminar Series. Virtual
SA1 SA3	O1.4 O3.2	Zaccarine, S. and Klaus, D. (2022) Autonomous System Capabilities and Attributes for Nominal Operation Task Allocation of a 'Smart' Deep Space Habitat. International Conference on Environmental Systems (ICES), St. Paul, MN, July 2022. Poster.
SA1 SA2 SA3 SA4	O1.4 O1.5 O2.1 O2.2 O3.2 O4.1	Zaccarine, S. and Klaus, D. (2023) Characterizing the Trade Space for Incorporating Emerging Technologies into Deep-Space 'Smart' Habitats: Needs and Opportunities. International Conference on Environmental Systems (ICES), Calgary, Canada, July 2023. Poster.
SA1 SA3 SA4	O1.4 O3.1 O4.1	Zaccarine, S. (2023) Collecting, Surveying, and Assessing Criteria for Self-Sufficiency in Deep-Space Habitat Operations. HOME Seminar Series. Virtual

SA1 SA3 SA5	O1.4 O1.5 O3.2 O5.1	Zaccarine, S. and Klaus, D. (2024) Attributes of Habitability for Self-Sufficient Deep-Space Habitat Operations. NASA HRP Investigator Workshop, Galveston, TX, Feb. 2024. Poster.

Table 15: Specific Aims and Research Objectives mapped to presentations and seminars.

8.2 Key Research Outcomes / Novel Contributions to the Field

In summary, this dissertation presents a systematic process for conducting a gap analysis to identify and assess the needs associated with self-sufficient deep-space habitats, a roadmap for determining opportunities to improve habitability, and a demonstration for how to integrate top-down and bottom-up analyses using triangulation and a combination of qualitative and quantitative data collection and analysis. Combining these methods and generating the results herein represents a novel approach to documenting design decision-making for human spaceflight engineers.

The general functions and their constituent breakouts represent what needs to be included on a deep-space habitat beyond what is currently achievable by SoA technologies. A self-sufficient deep-space habitat must be able to perform monitoring, maintenance, and fault management autonomously with little to no ground control in order to keep the crew alive, health and happy and enable the completion of mission goals.

Based on assessment of historic mission operations and future needs for creating systems to perform operations that have not previously been conducted, it is recognized that anomalies, faults and failures will occur, and systems will not perform flawlessly in pathfinding crewed deep-space missions. When these failures manifest, critical systems must be easily maintainable by the onboard crew with limited support from ground control. To create such a system that can be maintained by onboard crew with limited help from

ground control, the design attributes summarized in Table 13 should be considered and implemented. This enables the general function of 'maintenance' required for self-sufficient operations, and the methods implemented to derive these attributes comprise a process that can be followed to derive the accompanying attributes for monitoring, fault management, and habitability.

Emerging technologies offer the potential to enable self-sufficiency by providing the required onboard capabilities as described above. Though specific emerging technologies were not designed or developed in this work, the process of defining functional needs and derived design attributes detailed in this dissertation provide guidance for identifying capability gaps that merit continued research and may benefit from emerging technologies. Their potential to address specific gaps should be considered while taking the following considerations into account:

1. The use of these technologies is mapped to identified functional needs and/or gaps
2. The technologies meet or exceed SoA solutions in enabling autonomous deep-space operations
3. The technologies provide a demonstrated benefit to the design
4. The technologies demonstrate reliability, maintainability, robustness and other normally required design attributes of space habitat systems
5. The technologies do not introduce additional undue risks

In summary, identifying the enabling functions required for monitoring, maintenance and fault management lays the foundation for defining the needs of self-sufficient deep-space habitat operations, and establishes a framework for conducting trade studies and gap analyses to assess existing and emerging technologies capable of meeting these needs.

8.3 Overall Outcomes

8.3.1 Publications and Presentations

The combined list of publications and presentations resulting and forthcoming from this dissertation is summarized below.

Publications

1. Klaus, D., Pischulti, P., Zaccarine, S., Rollock, A., Zero, M. (2025) RT1 Publication [planned]
2. Zaccarine, S. and Klaus, D. (2025). Characterizing Habitability for Deep-Space Habitat Operations. [in work]
3. Zaccarine, S., Almand, A. and Klaus, D. (2024). Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats. [in work]
4. Zaccarine, S., and Klaus, D. (2024). Survey Designed to Rank Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats. [in work]
5. Zaccarine, S. and Klaus, D. (2024). Monitoring, Maintenance and Fault Management Considerations for Self-Sufficient Deep-Space Habitat Operations, [n review]
6. Klaus, D., Pischulti, P., Rollock, A. and Zaccarine, S. (2022) Functionally Aligning Emergent Technologies for Deep Space Smart Habitats, ICES-2022-120
7. Klaus, D., Zaccarine, S., Pischulti, P., and Rollock, A. (2020) Establishing assessment criteria for intelligent infusion of smart systems into a space habitat, ICES-2020-419

Presentations

1. Zaccarine, S. and Klaus, D. (2024) Attributes of Habitability for Self-Sufficient Deep-Space Habitat Operations. NASA HRP Investigator Workshop, Galveston, TX, Feb. 2024. Poster.
2. Zaccarine, S. and Klaus, D. (2023) Characterizing the Trade Space for Incorporating Emerging Technologies into Deep-Space 'Smart' Habitats: Needs and Opportunities. International Conference on Environmental Systems (ICES), Calgary, Canada, July 2023. Poster.
3. Zaccarine, S. (2023) Collecting, Surveying, and Assessing Criteria for Self-Sufficiency in Deep-Space Habitat Operations. HOME Seminar Series. Virtual
4. Zaccarine, S. and Klaus, D. (2022) Autonomous System Capabilities and Attributes for Nominal Operation Task Allocation of a 'Smart' Deep Space Habitat. International Conference on Environmental Systems (ICES), St. Paul, MN, July 2022. Poster.
5. Zaccarine, S. (2021). Identifying Smart System Capabilities and Attributes for Nominal Operations in a Deep Space Habitat. HOME Seminar Series. Virtual
6. Zaccarine, S. and Klaus, D. (2021) Autonomous Systems for Enhancing Human Performance and Vehicle Operations in Deep Space Habitats, AIAA Rocky Mountain Annual Technical Symposium (ATS). CU Boulder
7. Zaccarine, S. (2020). Intelligent Infusion of Smart Technologies into a Space Habitat. Smead Aerospace Researchpalooza. Awarded Honorable Mention. CU Boulder
8. Zaccarine, S. (2020). Intelligent Infusion of Smart Technologies into a Space Habitat. Bioastronautics Seminar Series. CU Boulder

8.4 Summary of Academic Milestones

August 2019 – Began Doctoral research and coursework

Fall 2019 – Teaching Assistant for ASEN 3112 – Structures

Fulfilled PhD Teaching Practicum requirement

August 2020 – Passed Preliminary Exam

May 2022 – Completed required coursework and obtained two Master's Degrees

MS, Aerospace Engineering Sciences (Bioastronautics focus)

ME, Engineering Management

December 2022 – Passed Comprehensive Exam

May 2024 – Passed PhD Oral Defense

8.5 Limitations, Future Work, and Additional Thoughts

The limitations in this research include the low number of participants for both the qualitative interviews and survey. In total, 7 SMEs were interviewed and 9 complete survey responses were received. Although saturation was reached for this dataset, increasing this participant pool may yield additional results and attributes to consider. Also, the interview design may have biased participant responses, and a differently worded interview guide might yield additional attributes as well. The volume of data captured in the handbooks and standards that were referenced for their alignment with these interview and survey results are a testament to the complexity and multi-faceted nature of providing design guidance for human spaceflight, and continued effort to distill and communicate this amount of data seems worthwhile to retain the valuable knowledge captured.

Using human-subject testing to analyze the degrees of utilize and attributes of accommodate could be a potential method for assessing their accuracy. The degrees of

utilize in particular could be assessed with workload and situation awareness human-subject testing to monitor for 'flow state' and potentially map individual preference for a sample of autonomous teammates.

Using the methods applied in Chapters 6 and 7, the process used for assessing the general function of 'maintenance' can be applied to the remaining general functions of 'monitoring' and 'fault management'. An interesting follow on study could be to do a thorough review of existing design handbooks, standards, and best practice, present these to participants, and ask them to focus on summarizing their opinions regarding each source. The most interesting results derived from Chapters 6 and 7 were not indentifying new design attributes, as the attributes themselves are not novel, rather what came from collecting the opinions from participants regarding 'Repairability' as a design philosophy, which appeared inconsistent with some of the referenced guidance.

Many ongoing advancements in human spaceflight are being developed in commercial industry and thus are proprietary. Aligning the results from this work with best practices in the industry could enhance their value, though it is understood why this is a challenge.

Additionally, an appreciation for qualitative research was gained through this process. As engineers and scientists, the desire to generate and analyze parametric data is, at times, a driving motivation. However, as described in Chapter 6, many of the research problems that concern people are not easily described using solely quantitative methods. The method of qualitative interviews, used to capture the thoughts and opinions gained from years of applied knowledge from SMEs, is a powerful tool for capturing depth and nuance within the dataset, although this method is labor intensive and time consuming. Though the nature of thematic analysis is inherently subjective, capturing these results

using this method represents a unique type of data that is not easily replicated with other approaches.

How humans make decisions, in this context for engineering design, is a fascinating and highly complex problem. Originally, it was thought that this dissertation could more fully quantify the decision-making process used by engineers when designing human space habitats for deep-space. While it did accomplish this to some degree, it is unclear whether quantifying the entire process is fully possible. Humans make decisions based on emotions, intuition, outside influence, and often display inconsistency (Summerfield & Tsetsos, 2015). Attempting to replicate decisions that would be made with SME knowledge gained through years of practical experience in a comprehensive quantifiable model may not be reasonable, though portions of this process can be captured and documented.

Finally, though effort over years was applied to being thorough in the review and rationale for this dissertation research, it is possible there are areas of the literature and existing knowledge that were not reviewed for the relevant topics in this dissertation through honest oversight.

"The most effective way to do it, is to do it".

– Amelia Earhart (Earhart, Amelia, n.d.)

"There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known."

– Carl Sagan, Pale Blue Dot: A Vision of the Human Future in Space (Sagan, 1994)

References

Albert, J., Alyea, D., Cooper, L., Johnson, S., & Uhrich, D. (1995). *Vehicle Health Management (VHM) Architecture Process Development*. 951385. https://doi.org/10.4271/951385

Almand, A., Ko, S. Y., Anderson, A., Keller, R. J., Zero, M., Anderson, A. P., Laws, J. M., Lehnhardt, K., & Easter, B. D. (2023). A Qualitative Investigation of Space Exploration Medical Evacuation Risks. *Aerospace Medicine and Human Performance*, *94*(12), 875–886. https://doi.org/10.3357/AMHP.6262.2023

Anderson, E., Fannin, T., & Nelson, B. (2018). Levels of Aviation Autonomy. *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC)*, 1–8. https://doi.org/10.1109/DASC.2018.8569280

Andreano, J. M., & Cahill, L. (2006). Glucocorticoid Release and Memory Consolidation in Men and Women. *Psychological Science*, *17*(6), 466–470. https://doi.org/10.1111/j.1467-9280.2006.01729.x

Attride-Stirling, J. (2001). Thematic networks: An analytic tool for qualitative research. *Qualitative Research*, *1*(3), 385–405. https://doi.org/10.1177/146879410100100307

Badger, J., Higbee, D., Kennedy, T., Vitalpur, S., Sargusingh, M., Shull, S., Othon, B., Davies, F.J., Hurlbert, E., Townsend, N., Mauldin, J., Nelson, E., Nagy, K., Hurlbert, K., Frank, J., & Love, S. (2018). *Spacecraft Dormancy Autonomy Analysis for a Crewed Martian Mission* (NASA Technical Memorandum NASA-TM-2018-219965). https://ntrs.nasa.gov/api/citations/20180005514/downloads/20180005514.pdf

Baggerman, S., Duvall, L., & Rando, C. (2004, September 28). Habitability and Human Factors: Lessons Learned in Long Duration Spaceflight. *Space 2004 Conference and*

Exhibit. Space 2004 Conference and Exhibit, San Diego, California. https://doi.org/10.2514/6.2004-6021

Barroga, E., & Matanguihan, G. J. (2022). A Practical Guide to Writing Quantitative and Qualitative Research Questions and Hypotheses in Scholarly Articles. *Journal of Korean Medical Science*, *37*(16), e121. https://doi.org/10.3346/jkms.2022.37.e121

Blaber, A. P., Zuj, K. A., & Goswami, N. (2013). Cerebrovascular autoregulation: Lessons learned from spaceflight research. *European Journal of Applied Physiology*, *113*(8), 1909–1917. https://doi.org/10.1007/s00421-012-2539-x

Bogorad, A., Bowman, C., Dennis, A., Beck, J., Lang, D., Herschitz, R., Buehler, M., Blaes, B., & Martin, D. (1995). Integrated environmental monitoring system for spacecraft. *IEEE Transactions on Nuclear Science*, *42*(6), 2051–2057. https://doi.org/10.1109/23.489252

Bradshaw, J. M., Hoffman, R. R., Johnson, M., & Woods, D. D. (2013). The Seven Deadly Myths of "Autonomous Systems." *IEEE Intelligent Systems*, *28*(3), 54–61. https://doi.org/10.1109/MIS.2013.70

Braun, V., Clarke, V., & Paul Weate. (2016). Using Thematic Analysis in Sport and Exercise Research. In *Routledge Handbook of Qualitative Research in Sport and Exercise* (1st ed., pp. 191–205). Routledge. https://www.taylorfrancis.com/books/edit/10.4324/9781315762012/routledge-handbook-qualitative-research-sport-exercise-brett-smith-andrew-sparkes

Buckey, J. C. (2006). *Space physiology*. Oxford University Press.

Butler, Wm. M. (2015). A Study of Aerospace Engineering Student Professional Persistence. *2015 ASEE Annual Conference and Exposition Proceedings*, 26.114.1-26.114.16. https://doi.org/10.18260/p.23455

Carlton, A., Morgan, R., Lohmeyer, W., & Cahoy, K. (2018). Telemetry Fault-Detection Algorithms: Applications for Spacecraft Monitoring and Space Environment Sensing. *Journal of Aerospace Information Systems*, *15*(5), 239–252. https://doi.org/10.2514/1.I010587

Casner, S. M., & Gore, B. F. (2010). *Measuring and Evaluating Workload: A Primer* (NASA/TM—2010-216395). National Aeronautics and Space Administration. https://matb-files.larc.nasa.gov/Workload_Primer_TM_Final.pdf

Celentano, J., Amorelli, D., & Freeman, G. (1963, May 2). ESTABLISHING A HABITABILITY INDEX FOR SPACE STATIONS AND PLANETARY BASES. *Manned Space Laboratory Conference*. Manned Space Laboratory Conference, Los Angeles,CA,U.S.A. https://doi.org/10.2514/6.1963-139

Cermack, M. (2006). Monitoring and telemedicine support in remote environments and in human space flight. *British Journal of Anaesthesia*, *97*(1), 107–114. https://doi.org/10.1093/bja/ael132

Clawson, J., Barta, D., Schneider, W., Howard, D., & Cox, M. (2023). NextSTEP Appendix A Modular ECLSS Effort Lessons Learned. *52nd International Conference on Environmental Systems52nd International Conference on Environmental Systems*, *52*.

Cockell, C. S., Bush, T., Bryce, C., Direito, S., Fox-Powell, M., Harrison, J. P., Lammer, H., Landenmark, H., Martin-Torres, J., Nicholson, N., Noack, L., O'Malley-James, J., Payler, S. J., Rushby, A., Samuels, T., Schwendner, P., Wadsworth, J., & Zorzano, M. P. (2016). Habitability: A Review. *Astrobiology*, *16*(1), 89–117. https://doi.org/10.1089/ast.2015.1295

Cohen, M. M. (2008). Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume. *SAE International Journal of Aerospace*, *1*(1), 107–142. https://doi.org/10.4271/2008-01-2027

Crawley, E, Boas, R, Cameron, B, Hofstetter, W, Rhodes, R, & Wicht, A. (2010). *A Commonality Toolkit Focused On Nasa Applications*. MIT Space Systems Architecture Group. http://systemarchitect.mit.edu/docs/NASACommonalityToolkitv4.pdf

Crone, D. J., Sanderson, P. M., & Naikar, N. (2003). Using Cognitive Work Analysis to Develop a Capability for the Evaluation of Future Systems. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *47*(17), 1938–1942. https://doi.org/10.1177/154193120304701708

Curley, S., Stambaugh, I., Swickrath, M., Anderson, M., & Rotter, H. (2012, July 15). Deep Space Habitat ECLSS Design Concept. *42nd International Conference on Environmental Systems*. 42nd International Conference on Environmental Systems, San Diego, California. https://doi.org/10.2514/6.2012-3417

David, S. (2009). *Space Rescue: Ensuring the Safety of Manned Spacecraft*. Springer Science & Business Media. https://books.google.com/books?id=wEHL8MIhRa8C&pg=PA10#v=onepage&q&f=false

Day, J. C. & Johnson, Stephen B. (2014). Fault Management Design Strategies. *SpaceOps 2014*, *13*. https://dataverse.jpl.nasa.gov/dataset.xhtml?persistentId=hdl:2014/45536

Day, J., & Ingham, M. (n.d.). *Fault Management at JPL: Past, Present and Future*.

de Winter, J. F. C., & Dodou, D. (n.d.). *Five-Point Likert Items: T test versus Mann-Whitney-Wilcoxon (Addendum added October 2012)*. https://doi.org/10.7275/BJ1P-TS64

Deal, S. V., & Hoffman, R. (2010a). The Practitioner's Cycles, Part 3: Implementation Opportunities. *IEEE Intelligent Systems*, *25*(5), 77–81. https://doi.org/10.1109/MIS.2010.129

Deal, S. V., & Hoffman, R. R. (2010b). The Practitioner's Cycles, Part 1: Actual World Problems. *IEEE Intelligent Systems*, *25*(2), 4–9. https://doi.org/10.1109/MIS.2010.54

Dinatolo, M. F., & Cohen, L. Y. (2022). Monitoring the Impact of Spaceflight on the Human Brain. *Life*, *12*(7), 1060. https://doi.org/10.3390/life12071060

Drake, B. G. (2009). *Human Exploration of Mars Design Reference Architecture 5.0* (Mars Architecture Steering Group - NASA Headquarters NASA/SP–2009–566; pp. 1–24). National Aeronautics and Space Administration. https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf

Earhart, Amelia. (n.d.). Amelia Earhart Quotes. *Amelia Earhart*. https://www.ameliaearhart.com/quotes/

Easter, B. (2023). *Content Diagram 00_Level of Care IV Medical System Foundation—Medical System Foundation for Level of Care IV: Short-Duration Lunar Orbit* [NASA HTML Report]. NASA. https://www3.nasa.gov/specials/hrp/exmc/medical-system-foundation-model/index.html

Elwany, A. H., & Gebraeel, N. Z. (2008). Sensor-driven prognostic models for equipment replacement and spare parts inventory. *IIE Transactions*, *40*(7), 629–639. https://doi.org/10.1080/07408170701730818

Endsley, M. (2011). *Technology Horizons: A Vision for Air Force Technology and Science 2010-2030.: Vol. AF/ST-TR-10-01-PR* (Washington DC.). Office of the US Air Force Chief Scientist. https://www.airuniversity.af.edu/Portals/10/AUPress/Books/B_0126_TECHNOLOGY HORIZONS.pdf

Endsley, M. (2015). *Autonomous Horizons—System Autonomy in the Air Force—A Path to the Future* (AF/ST TR 15-01; Volume I: Human-Autonomy Teaming, p. 33). United States Air Force Office of the Chief Scientist.

Endsley, M. R., Cooke, N., McNeese, N., Bisantz, A., Militello, L., & Roth, E. (2022). Special Issue on Human-AI Teaming and Special Issue on AI in Healthcare. *Journal of Cognitive Engineering and Decision Making*, 155534342211332. https://doi.org/10.1177/15553434221133288

Escobar, C. M., Nabity, J. A., & Klaus, D. (2017). Defining ECLSS Robustness for Deep Space Exploration. *International Conference on Environmental Systems (ICES), 280*.

Escobar, C., Nabity, J., & Escobar, A. (2019). *Quantifying ECLSS Robustness for Deep Space Exploration*. https://ttu-ir.tdl.org/handle/2346/84455

Evans, W. A., de Weck, Olivier, Laufer, Deanna, & Shull, Sarah. (2006). *Logistics Lessons Learned in NASA Space Flight* (NASA Technical Memorandum NASA/TP-2006-214203). National Aeronautics and Space Administration.

Fillery, N. P., & Stanton, D. (2011). Telemetry, Command, Data Handling and Processing. In P. Fortescue, G. Swinerd, & J. Stark (Eds.), *Spacecraft Systems Engineering* (1st ed., pp. 439–466). Wiley. https://doi.org/10.1002/9781119971009.ch13

Fong, T. (2018, August 24). *Autonomous Systems NASA Capability Overview*. Space Technology Mission Directorate, NASA. https://www.nasa.gov/sites/default/files/atoms/files/nac_tie_aug2018_tfong_tagged.pdf

Garcia, F. (2018). *GUIDE TO INDIGENOUS LAND AND TERRITORIAL ACKNOWLEDGEMENTS FOR CULTURAL INSTITUTIONS*. New York University.

Garetto, M., Gribaudo, M., Chiasserini, C.-F., & Leonardi, E. (2007). A Distributed Sensor Relocatlon Scheme for Environmental Control. *2007 IEEE Internatonal Conference on Mobile Adhoc and Sensor Systems*, 1–10. https://doi.org/10.1109/MOBHOC.2007.4428663

Gebraeel, N. Z., Lawley, M. A., Li, R., & Ryan, J. K. (2005). Residual-life distributions from component degradation signals: A Bayesian approach. *IIE Transactions*, *37*(6), 543–557. https://doi.org/10.1080/07408170590929018

Gratius, N., Wang, Z., Hwang, M. Y., Hou, Y., Rollock, A., George, C., Bergés, M., & Akinci, B. (2024). Digital Twin Technologies for Autonomous Environmental Control and Life Support Systems. *Journal of Aerospace Information Systems*, *21*(4), 332–347. https://doi.org/10.2514/1.I011320

Groen, F. J., Evans, J. W., & Hall, A. J. (2015). A vision for spaceflight reliability: NASA's objectives based strategy. *2015 Annual Reliability and Maintainability Symposium (RAMS)*, 1–6. https://doi.org/10.1109/RAMS.2015.7105106

Hamilton, I.A. (2021, September 27). The toilet fan on SpaceX's Inspiration4 mission malfunctioned, setting off an alarm, and the all-civilian crew had to be coached on how to fix it. *Business Insider*, *TECH*. https://www.businessinsider.com/spacex-inspiration4-mission-toilet-fan-malfunctioned-elon-musk-crew-dragon-2021-9

Harris, D. W., Kessler, P. D., Nickens, T. M., Choate, A. J., Horvath, B. L., Simon, M. A., & Stromgren, C. (2022). *Moon to Mars (M2M) Habitation Considerations: A Snap Shot As of January 2022*. https://ntrs.nasa.gov/api/citations/20220000524/downloads/M2M%20Habitation%20Considerations%20TM%20-%20Final.pdf

Hebb, D. O. (1955a). Drives and the C. N. S. (conceptual nervous system). *Psychological Review*, *62*(4), 243–254. https://doi.org/10.1037/h0041823

Hebb, D. O. (1955b). THE MAMMAL AND HIS ENVIRONMENT. *American Journal of Psychiatry*, *111*(11), 826–831. https://doi.org/10.1176/ajp.111.11.826

Hennink, M. M., Kaiser, B. N., & Marconi, V. C. (2017). Code Saturation Versus Meaning Saturation: How Many Interviews Are Enough? *Qualitative Health Research*, *27*(4), 591–608. https://doi.org/10.1177/1049732316665344

HFES. (2021). *Human Readiness Level Scale in the System Development Process* (ANSI/HFES 400-2021; p. 106). Human Factors and Ergonomics Society. https://www.hfes.org/Portals/0/Documents/DRAFT%20HFES%20ANSI%20HRL%20Standard%201_2_2021.pdf?ver=2021-01-06-142004-860&timestamp=1609964482681

Hobbs, K. L., Lyons, J. B., Feather, M. S., Bycroft, B. P., Phillips, S., Simon, M., Harter, M., Costello, K., Gawdiak, Y., & Paine, S. (2022). *Space Trusted Autonomy Readiness Levels*. https://doi.org/10.48550/ARXIV.2210.09059

Hoffman, R. R., Deal, S. V., Potter, S., & Roth, E. M. (2010). The Practitioner's Cycles, Part 2: Solving Envisioned World Problems. *IEEE Intelligent Systems*, *25*(3), 6–11. https://doi.org/10.1109/MIS.2010.89

Hutchison, Nicole. (2023). *Guide_to_the_Systems_Engineering_Body_of_Knowledge_v2.9.pdf*. https://sebokwiki.org/w/images/sebokwiki-farm!w/8/83/Guide_to_the_Systems_Engineering_Body_of_Knowledge_v2.9.pdf

Hutt, J. T. (2012). *Evolution of Training in NASA's Mission Operations Directorate*. National Aeronautics and Space Administration.

Jaifer, R., Beauregard, Y., & Bhuiyan, N. (2021). New Framework for Effort and Time Drivers in Aerospace Product Development Projects. *Engineering Management Journal*, *33*(2), 76–95. https://doi.org/10.1080/10429247.2020.1772950

Jakobsson, U., & Westergren, A. (2005). Statistical methods for assessing agreement for ordinal data. *Scandinavian Journal of Caring Sciences*, *19*(4), 427–431. https://doi.org/10.1111/j.1471-6712.2005.00368.x

Jebb, A. T., Ng, V., & Tay, L. (2021). A Review of Key Likert Scale Development Advances: 1995–2019. *Frontiers in Psychology*, *12*, 637547. https://doi.org/10.3389/fpsyg.2021.637547

Johnson, D. M. (1996). A review of fault management techniques used in safety-critical avionic systems. *Progress in Aerospace Sciences*, *32*(5), 415–431. https://doi.org/10.1016/0376-0421(96)82785-0

Johnson, S., & Day, J. (2010, April 20). Conceptual Framework for a Fault Management Design Methodology. *AIAA Infotech@Aerospace 2010*. AIAA Infotech@Aerospace 2010, Atlanta, Georgia. https://doi.org/10.2514/6.2010-3431

Johnson, S., Ghoshal, S., Haste, D., & Moore, C. E. (2017, January 9). Fault Management Metrics. *AIAA Information Systems-AIAA Infotech @ Aerospace*. AIAA Information Systems-AIAA Infotech @ Aerospace, Grapevine, Texas. https://doi.org/10.2514/6.2017-1295

Johnson, S., Gormley, T. J., Kessler, Seth S., Mott, Charles D., Patterson-Hine, Ann, Reichard, Karl M., & Scandura, Philip A. Jr. (Eds.). (2011). *System health management: With aerospace applications* (1. ed, Vol. 1). Wiley. https://books.google.com/books?hl=en&lr=&id=80O0c66pdngC&oi=fnd&pg=PA1941&dq=system+health+management+with+aerospace+applications+pdf&ots=kuAszNp4s0&sig=Vz_YLf3u2JZ1ofybEC4WB6FGx2o#v=onepage&q=system%20health%20management%20with%20aerospace%20applications%20pdf&f=false

Kamire, R., Yates, S. F., Skomurski, S., Zaki, R., Henson, P., Bonk, T., & Loeffelholz, D. (2021). Carbon Dioxide Removal by Ionic Liquid System (CDRILS): Continuous

Operation and Full Scale Brassboard Testing. *50th International Conference on Environmental Systems*, *209*. https://hdl.handle.net/2346/87156

Keeter, Bill. (2021a, July 29). *ISS Daily Summary Report—7/29/2021*. NASA ISS On-Orbit Status Report - July 2021. https://blogs.nasa.gov/stationreport/2021/07/

Keeter, Bill. (2021b, September 30). *ISS Daily Summary Report—9/30/2021*. NASA ISS On-Orbit Status Report - September 2021. https://blogs.nasa.gov/stationreport/2021/09/

Keeter, Bill. (2021c, November 30). *ISS Daily Summary Report—11/30/2021*. NASA ISS On-Orbit Status Report - November 2021. https://blogs.nasa.gov/stationreport/2021/11/

Keeter, Bill. (2021d, December 6). *ISS Daily Summary Report—12/06/2021*. NASA ISS On-Orbit Status Report - December 2021. https://blogs.nasa.gov/stationreport/2021/12/06/iss-daily-summary-report-12-06-2021/

Khazaei, S., Amin, Md. R., & Faghih, R. T. (2021). Decoding a Neurofeedback-Modulated Cognitive Arousal State to Investigate Performance Regulation by the Yerkes-Dodson Law. *2021 43rd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, 6551–6557. https://doi.org/10.1109/EMBC46164.2021.9629764

Kintz, N. M., & Palinkas, L. A. (2016). Communication Delays Impact Behavior and Performance Aboard the International Space Station. *Aerospace Medicine and Human Performance*, *87*(11), 940–946. https://doi.org/10.3357/AMHP.4626.2016

Klaus, D. (2017). Functional Integration of Humans and Spacecraft through Physics, Physiology, Safety and Operability. *2017 IEEE Aerospace Conference*, 1–7. https://doi.org/10.1109/AERO.2017.7943710

Klaus, D., Ocampo, R., & Fanchiang, C. (2014). Spacecraft Human-Rating: Historical Overview and Implementation Considerations. *2014 IEEE Aerospace Conference*, 1–7. https://doi.org/10.1109/AERO.2014.6836308

Klaus, D., Pischulti, P., Rollock, A., & Zaccarine, S. (2020). Establishing Assessment Criteria for Intelligent Infusion of "Smart Systems" into a Space Habitat. *International Conference on Environmental Systems*. International Conference on Environmental Systems.

Klaus, D., Zaccarine, S. A., Pischulti, P., & Rollock, A. (2022). Functionally Aligning Emergent Technologies for Self-Sufficient Deep Space Smart Habitats. *51st International Conference on Environmental Systems*, *51*. https://ttu-ir.tdl.org/handle/2346/89689

Kolcio, K., & Fesq, L. (2016). Model-based off-nominal state isolation and detection system for autonomous fault management. *2016 IEEE Aerospace Conference*, 1–13. https://doi.org/10.1109/AERO.2016.7500793

Kothamasu, R., Huang, S. H., & VerDuin, W. H. (2006). System health monitoring and prognostics—A review of current paradigms and practices. *The International Journal of Advanced Manufacturing Technology*, *28*(9–10), 1012–1024. https://doi.org/10.1007/s00170-004-2131-6

La Duc, M. T., Kern, R., & Venkateswaran, K. (2004). Microbial Monitoring of Spacecraft and Associated Environments. *Microbial Ecology*, *47*(2), 150–158. https://doi.org/10.1007/s00248-003-1012-0

Larson, W. J., & Pranke, L. K. (Eds.). (2000). *Human Spaceflight: Mission Analysis and Design*. McGraw-Hill.

Laws, J. M., Bruce-Martin, C., Caplan, N., Meroni, R., & Winnard, A. (2022). Exercise countermeasure preferences of three male astronauts, a preliminary qualitative

study. *Acta Astronautica*, *201*, 224–229. https://doi.org/10.1016/j.actaastro.2022.09.012

Laws, J.M., Bruce-Martin, C., & Winnard, A. (2020). *AMSRG Basic NVivo user guide for systematic reviews.* Northumbria University.

Lee, J. D., & See, K. A. (2004). Trust in Automation: Designing for Appropriate Reliance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *46*(1), 50–80. https://doi.org/10.1518/hfes.46.1.50_30392

Lewis, R. (2021, May 19). Habitability Design—NASA [NASA Article]. *NASA Human Health and Performance*. https://www.nasa.gov/feature/habitability-design

Limero, T. F., & Wallace, W. T. (2017). What Air and Water Quality Monitoring Is Needed to Protect Crew Health on Spacecraft? *New Space*, *5*(2), 67–78. https://doi.org/10.1089/space.2017.0004

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Sage Publications.

Lintern, G. (2013). *Cognitive Work Analysis.*

Liu, Y.-Y., Slotine, J.-J., & Barabási, A.-L. (2013). Observability of complex systems. *Proceedings of the National Academy of Sciences*, *110*(7), 2460–2465. https://doi.org/10.1073/pnas.1215508110

Lorenz, B., Di Nocera, F., Röttger, S., & Parasuraman, R. (2001). The Effects of Level of Automation on the Out-of-the-Loop Unfamiliarity in a Complex Dynamic Fault-Management Task during Simulated Spaceflight Operations. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *45*(2), 44–48. https://doi.org/10.1177/154193120104500209

Lorenz, B., Di Nocera, F., Röttger, S., & Parasuraman, R. (2002). Automated fault-management in a simulated spaceflight micro-world. *Aviation, Space, and Environmental Medicine*, *73*(9), 886–897.

Malterud, K. (2001a). Qualitative research: Standards, challenges, and guidelines. *The Lancet*, *358*(9280), 483–488. https://doi.org/10.1016/S0140-6736(01)05627-6

Malterud, K. (2001b). The art and science of clinical knowledge: Evidence beyond measures and numbers. *The Lancet*, *358*(9279), 397–400. https://doi.org/10.1016/S0140-6736(01)05548-9

Manu, Samidha. (2023). *Autonomous Systems and Operations for the Lunar Orbital Platform-Gateway* (Small Business Innovation Research (SBIR) & Small Business Technology Transfer (STTR) Program Artificial Intelligence for the Gateway Lunar Orbital Platform; Artificial Intelligence for the Gateway Lunar Orbital Platform). National Aeronautics and Space Administration. https://sbir.nasa.gov/content/autonomous-systems-and-operations-lunar-orbital-platform-gateway-0

Manzey, D. (2000). Monitoring of mental performance during spaceflight. *Aviation, Space, and Environmental Medicine*, *71*(9 Suppl), A69-75.

Mark Garcia. (2023, January). International Space Station Facts and Figures. *NASA Features*. https://www.nasa.gov/feature/facts-and-figures

Mays, N. (2000). Qualitative research in health care: Assessing quality in qualitative research. *BMJ*, *320*(7226), 50–52. https://doi.org/10.1136/bmj.320.7226.50

McIlroy, R. C., & Stanton, N. A. (2012). Specifying the requirements for requirements specification: The case for Work Domain and Worker Competencies Analyses. *Theoretical Issues in Ergonomics Science*, *13*(4), 450–471. https://doi.org/10.1080/1463922X.2010.539287

Miles, M. B., & Huberman, A. M. (1994). Qualitative Data Analysis: An Expanded Sourcebook. In *Qualitative data analysis: An expanded sourcebook* (2. ed., [Nachdr.], pp. 266–268). Sage. https://books.google.com/books?hl=en&lr=&id=U4lU_-

wJ5QEC&oi=fnd&pg=PR12&dq=qualitative+data+anlaysis:+an+expanded+sourceb ook&ots=kGSE1IPV1O&sig=X_6zfuJYiG1FFVu94MrQmhcPr20#v=snippet&q=trian gulation&f=false

Miller, M. J., & Feigh, K. M. (2019). Addressing the envisioned world problem: A case study in human spaceflight operations. *Design Science*, *5*, e3. https://doi.org/10.1017/dsj.2019.2

Miller, M. J., McGuire, K. M., & Feigh, K. M. (2015). Information flow model of human extravehicular activity operations. *2015 IEEE Aerospace Conference*, 1–15. https://doi.org/10.1109/AERO.2015.7118942

Miller, M. J., McGuire, K. M., & Feigh, K. M. (2017). Decision Support System Requirements Definition for Human Extravehicular Activity Based on Cognitive Work Analysis. *Journal of Cognitive Engineering and Decision Making*, *11*(2), 136–165. https://doi.org/10.1177/1555343416672112

Mindock, Jennifer. (2012). *Development and Application of Spaceflight Performance Shaping Factors for Human Reliability Analysis* [Doctoral Thesis]. University of Colorado at Boulder.

Mohanty, S., Jørgensen, J., & Nyström, M. (2006, September 19). Psychological Factors Associated with Habitat Design for Planetary Mission Simulators. *Space 2006*. Space 2006, San Jose, California. https://doi.org/10.2514/6.2006-7345

Naikar, N. (2005). A Methodology for Work Domain Analysis, the First Phase of Cognitive Work Analysis. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *49*(3), 312–316. https://doi.org/10.1177/154193120504900321

Naikar, N. (2017). Cognitive work analysis: An influential legacy extending beyond human factors and engineering. *Applied Ergonomics*, *59*, 528–540. https://doi.org/10.1016/j.apergo.2016.06.001

Naikar, N., Pearce, B., Drumm, D., & Sanderson, P. M. (2003). Designing Teams for First-of-a-Kind, Complex Systems Using the Initial Phases of Cognitive Work Analysis: Case Study. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *45*(2), 202–217. https://doi.org/10.1518/hfes.45.2.202.27236

NASA. (2007). *NASA Systems Engineering Handbook* (SP-2007-6105 Rev 1; pp. 67–68). https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook.pdf

NASA. (2012). *Fault Management Handbook* (NASA Technical Memorandum NASA-HDBK-1002; p. 203). National Aeronautics and Space Administration. https://www.nasa.gov/pdf/636372main_NASA-HDBK-1002_Draft.pdf

NASA. (2014). *HUMAN INTEGRATION DESIGN HANDBOOK (HIDH)* (NASA/SP-2010-3407/REV1; p. 233). National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/human_integration_design_handbook_revision_1.pdf

NASA. (2017). *NASA RELIABILITY AND MAINTAINABILITY (R&M) STANDARD FOR SPACEFLIGHT AND SUPPORT SYSTEMS* (NASA Technical Standard NASA-STD-8729.1A; Revision A). NASA. (Approved: 2017-06-13)

NASA. (2019). *NASA Systems Engineering Handbook* (NASA Handbook NASA SP-2016-6105 Rev2; Revision 2). NASA. http://www.nasa.gov/seh/index.html

NASA. (2020a). *2020 NASA Technology Taxonomy* (p. 239) [NASA Technology Taxonomy]. National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/2020_nasa_technology_taxonomy_lowres.pdf

NASA. (2020b, October 23). The 20 Most Frequently Asked Questions about the International Space Station. *Kennedy Space Center Visitor Complex Blog*.

https://www.kennedyspacecenter.com/blog/the-20-most-frequently-asked-questions-about-the-international-space-station

NASA. (2022). *NASA SPACE FLIGHT HUMAN-SYSTEM STANDARD VOLUME 2: HUMAN FACTORS, HABITABILITY, AND ENVIRONMENTAL HEALTH* (NASA Technical Standard NASA-STD-3001, VOLUME 2, REVISION C; Revision C). National Aeronautics and Space Administration. https://standards.nasa.gov/sites/default/files/standards/NASA/C/2022-04-08-NASA-STD-3001-Vol-2-Rev-C-Final_0.pdf (Approved)

NASA. (2023). *Moon-to-Mars Architecture Definition Document (ESDMD-001)* (NASA STI Program Report Series NASA/TP-20230002706; Exploration Systems Development Mission Directorate). National Aeronautics and Space Administration. https://ntrs.nasa.gov/api/citations/20230002706/downloads/M2MADD_ESDMD-001(TP-20230002706).pdf

Nowell, L. S., Norris, J. M., White, D. E., & Moules, N. J. (2017). Thematic Analysis: Striving to Meet the Trustworthiness Criteria. *International Journal of Qualitative Methods*, *16*(1), 160940691773384. https://doi.org/10.1177/1609406917733847

O'hagan, B., & Crocker, A. (2011). Fault Management Techniques in Human Spaceflight Operations. In S. B. Johnson, T. J. Gormley, S. S. Kessler, C. D. Mott, A. Patterson-Hine, K. M. Reichard, & P. A. Scandura (Eds.), *System Health Management* (1st ed., pp. 351–367). Wiley. https://doi.org/10.1002/9781119994053.ch22

Parasuraman, R., & Riley, V. (1997). Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *39*(2), 230–253. https://doi.org/10.1518/001872097778543886

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *30*(3), 286–297. https://doi.org/10.1109/3468.844354

Peifer, C. (2012). Psychophysiological Correlates of Flow-Experience. In S. Engeser (Ed.), *Advances in Flow Research* (pp. 139–164). Springer New York. https://doi.org/10.1007/978-1-4614-2359-1_8

Petrick, D., Geist, A., Albaijes, D., Davis, M., Sparacino, P., Crum, G., Ripley, R., Boblitt, J., & Flatley, T. (2014). SpaceCube v2.0 space flight hybrid reconfigurable data processing system. *2014 IEEE Aerospace Conference*, 1–20. https://doi.org/10.1109/AERO.2014.6836226

Pischulti, P. K., Duke, T. L., Smith, A. L., Klaus, D., & Amick, R. Z. (2024). Surveying and assessing 'smart' technologies to identify potential applications for deep space human exploration missions. *Acta Astronautica*, *222*, 534–549. https://doi.org/10.1016/j.actaastro.2024.02.036

Read, G. J. M., Salmon, P. M., & Lenné, M. G. (2015). Cognitive work analysis and design: Current practice and future practitioner requirements. *Theoretical Issues in Ergonomics Science*, *16*(2), 154–173. https://doi.org/10.1080/1463922X.2014.930935

Richards, M. G., Hastings, D. E., Rhodes, D. H., & Weigel, A. L. (2007). *Defining Survivability for Engineering Systems*. Conference on Systems Engineering Research, Hoboken, NJ, USA.

Robbins, Naomi B., J. & Heiberger, Richard M. (2011). Plotting Likert and Other Rating Scales. *Survey Research Methods*, 1058–1066. https://www.montana.edu/msse/Old_Data_analysis/Likert%20Survey%20Graphs.pdf

Robert Zemeckis (Director). (1997). *Contact* [Video recording]. Warner Bros.

Rollock, A. E., & Klaus, D. (2022). Defining and characterizing self-awareness and self-sufficiency for deep space habitats. *Acta Astronautica*, *198*, 366–375. https://doi.org/10.1016/j.actaastro.2022.06.002

Roth, E. M., & Bisantz, A. M. (2013). *Cognitive Work Analysis*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199757183.013.0015

Rotolo, D., Hicks, D., & Martin, B. R. (2015). What is an emerging technology? *Research Policy*, *44*(10), 1827–1843. https://doi.org/10.1016/j.respol.2015.06.006

Russell, J. F., & Klaus, D. (2007). Maintenance, reliability and policies for orbital space station life support systems. *Reliability Engineering & System Safety*, *92*(6), 808–820. https://doi.org/10.1016/j.ress.2006.04.020

Russell, J. F., Klaus, D., & Mosher, T. J. (2006). Applying Analysis of International Space Station Crew-Time Utilization to Mission Design. *Journal of Spacecraft and Rockets*, *43*(1), 130–136. https://doi.org/10.2514/1.16135

SAE International. (2018, June). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*. Society of Automation (SAE) Engineers International. https://www.sae.org/standards/content/j3016_201806/

Sagan, C. (1985). *Contact*. Simon and Schuster.

Sagan, C. (1994). *Pale Blue Dot: A Vision of the Human Future in Space* (1st ed). Random House.

Sandelowski, M. (1995). Sample size in qualitative research. *Research in Nursing & Health*, *18*(2), 179–183. https://doi.org/10.1002/nur.4770180211

Sandelowski, M. (1997). "To be of use": Enhancing the utility of qualitative research. *Nursing Outlook*, *45*(3), 125–132. https://doi.org/10.1016/S0029-6554(97)90043-9

Sandelowski, M. (2004). Using Qualitative Research. *Qualitative Health Research*, *14*(10), 1366–1386. https://doi.org/10.1177/1049732304269672

Sanderson, P. M. & Carroll, John M. (2003). Cognitive Work Analysis. In *HCI Models, Theories, and Frameworks* (pp. 225–264). Elsevier. https://doi.org/10.1016/B978-155860808-5/50009-5

Scheuring, R. A., Jones, J. A., Novak, J. D., Polk, J. D., Gillis, D. B., Schmid, J., Duncan, J. M., & Davis, J. R. (2007). *The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations* (NASA/TM–2007–214755; pp. 980–987). National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/medical_distributed_planning_systems_lessons_learned.pdf

Schlosberg, H. (1954). Three dimensions of emotion. *Psychological Review*, *61*(2), 81–88. https://doi.org/10.1037/h0054570

Shelhamer, M., & Gersh, John. R. (2023, March). *A Mission Architecture to Integrate Human and Spacecraft Functional Performance*. IEEE Aerospace Conference, Big Sky, MT, USA.

Sheridan, T. B., & Verplank, W. L. (1978). *Human and Computer Control of Undersea Teleoperators* (p. 186). https://apps.dtic.mil/sti/citations/ADA057655

Sherman, S. O., Pischulti, P. K., Hwang, Min Young, Bergés, Mario, Mohanty, Ayush, Gebraeel, Nagi, Ivey, Daniela B., Robinson, Stephen K., Klaus, David, & Anderson, Allison P. (2024). A Development Framework for a Comprehensive Capstone which Demonstrates Human Interaction with Autonomous Habitat Technology. *53rd International Conference on Environmental Systems*, *53*.

Sherwood, B., & Capps, S. (1990). *Long Duration Habitat Trade Study: Space Transfer Concepts and Analyses for Exploration Missions*. (NASA Study Contract NAS8-37857). Boeing Aerospace and Electronics.

Sibonga, J. D., Spector, E. R., Johnston, S. L., & Tarver, W. J. (2015). Evaluating Bone Loss in ISS Astronauts. *Aerospace Medicine and Human Performance*, *86*(12), 38–44. https://doi.org/10.3357/AMHP.EC06.2015

Smith, J., Hamm Jr, K., Imtiaz, K., & Raju, I. S. (2020, January 6). Lesson Learned from Recent Space Flight Assessments. *AIAA Scitech 2020 Forum*. AIAA Scitech 2020 Forum, Orlando, FL. https://doi.org/10.2514/6.2020-0246

Stanton, A. & Unkrich, L. (Directors). (2003). *Finding Nemo* [Video recording]. Disney Pixar.

Stuster, J. (2010). *Behavioral Issues Associated with Long- Duration Space Expeditions: Review and Analysis of Astronaut Journals. Experiment 01-E104 (Journals): Final Report* (01-E104 (Journals)). National Aeronautics and Space Administration. https://ntrs.nasa.gov/api/citations/20100026549/downloads/20100026549.pdf

Suedfeld, P., Brcic, J., Johnson, P. J., & Gushin, V. (2015). Coping strategies during and after spaceflight: Data from retired cosmonauts. *Acta Astronautica*, *110*, 43–49. https://doi.org/10.1016/j.actaastro.2014.12.011

Sullivan, G. M., & Artino, A. R. (2013). Analyzing and interpreting data from likert-type scales. *Journal of Graduate Medical Education*, *5*(4), 541–542. https://doi.org/10.4300/JGME-5-4-18

Summerfield, C., & Tsetsos, K. (2015). Do humans make good decisions? *Trends in Cognitive Sciences*, *19*(1), 27–34. https://doi.org/10.1016/j.tics.2014.11.005

Tipaldi, M., & Bruenjes, B. (2014). Spacecraft health monitoring and management systems. *2014 IEEE Metrology for Aerospace (MetroAeroSpace)*, 68–72. https://doi.org/10.1109/MetroAeroSpace.2014.6865896

Tokadlı, G., & Dorneich, M. C. (2018). Development of Design Requirements for a Cognitive Assistant in Space Missions Beyond Low Earth Orbit. *Journal of Cognitive*

Engineering and Decision Making, *12*(2), 131–152. https://doi.org/10.1177/1555343417733159

Tuckett, A. G. (2005). Applying thematic analysis theory to practice: A researcher's experience. *Contemporary Nurse*, *19*(1–2), 75–87. https://doi.org/10.5172/conu.19.1-2.75

Ulusoy, U., & Reisman, G. (2022). Human Autonomy Teaming for Task Execution Support in Next Generation Deep Space Habitats. *73rd International Astronautical Congress (IAC)*, *73*, 13. https://www.researchgate.net/profile/Ulubilge-Ulusoy/publication/365187028_Human_Autonomy_Teaming_for_Task_Execution_Support_in_Next_Generation_Deep_Space_Habitats/links/63698809431b1f53007b7ca5/Human-Autonomy-Teaming-for-Task-Execution-Support-in-Next-Generation-Deep-Space-Habitats.pdf

University of Colorado at Boulder. (n.d.). *Land Acknowledgment*. University of Colorado at Boulder - Land Acknowledgment. https://www.colorado.edu/land-acknowledgment#:~:text=CU%20Boulder%2C%20founded%20the%20same,many%20other%20Native%20American%20nations.

Uri, J. (2020, November 16). *The Real Story of the Skylab 4 "Strike" in Space* [NASA History]. NASA. http://www.nasa.gov/feature/the-real-story-of-the-skylab-4-strike-in-space

Vagia, M., Transeth, A. A., & Fjerdingen, S. A. (2016). A literature review on the levels of automation during the years. What are the different taxonomies that have been proposed? *Applied Ergonomics*, *53*, 190–202. https://doi.org/10.1016/j.apergo.2015.09.013

Vicente, K. J. (1999). *Cognitive work analysis: Toward safe, productive, and healthy computer-based work*. CRC Press, Taylor & Francis Group.

https://web.s.ebscohost.com/ehost/ebookviewer/ebook/bmxlYmtfXzI0MjQ4X19BTg2?sid=4b976393-5c23-4732-b80b-354f89f53679@redis&vid=0&format=EB&rid=1

Vidulich, M. A., Wickens, C. D., Tsang, P. S., & Flach, J. M. (2010). Information Processing in Aviation. In *Human Factors in Aviation* (pp. 175–215). Elsevier. https://doi.org/10.1016/B978-0-12-374518-7.00007-9

Wallace, W. T., Limero, Thomas F, Thomas, F., Loh, L. J., Mudgett, P. D., & Gazda, D. B. (2017, July 16). Monitoring of the Atmosphere on the International Space Station with the Air Quality Monitor. *NASA Center for AeroSpace Information (CASI)*. https://ntrs.nasa.gov/search.jsp?R=20170002579

Wang, E., & Caldwell, B. (2003). Human Information Flow and Communication Pattern in NASA Mission Control System. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *47*(1), 11–15. https://doi.org/10.1177/154193120304700103

Wasson, C. S. (2005). *System Analysis, Design, and Development: Concepts, Principles, and Practices* (1st ed.). Wiley. https://doi.org/10.1002/0471728241

Weigel, A. L. (2010, January). *Survey of Aerospace Student Attitudes: Request for Assistance, 2009 Results Highlights*. https://web.mit.edu/caspar/adcajan2010.pdf

Wickens, C. D., & Carswell, C. M. (2021). Information Processing. In G. Salvendy & W. Karwowski (Eds.), *HANDBOOK OF HUMAN FACTORS AND ERGONOMICS* (5th ed., pp. 114–158). Wiley. https://doi.org/10.1002/9781119636113.ch5

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed). Prentice Hall.

Wiener, E. L. (1988). Cockpit Automation. In *Human Factors in Aviation* (pp. 433–461). Elsevier. https://doi.org/10.1016/B978-0-08-057090-7.50019-9

Willms, D. G., Best, J. A., Taylor, D. W., Gilbert, J. R., Wilson, D. M. C., Lindsay, E. A., & Singer, J. (1990). A Systematic Approach for Using Qualitative Methods in Primary

Prevention Research. *Medical Anthropology Quarterly*, *4*(4), 391–409. https://doi.org/10.1525/maq.1990.4.4.02a00020

Woods, D., & Dekker, S. (2000). Anticipating the effects of technological change: A new era of dynamics for human factors. *Theoretical Issues in Ergonomics Science*, *1*(3), 272–282. https://doi.org/10.1080/14639220110037452

Wu, S., Gebraeel, N., Lawley, M. A., & Yih, Y. (2007). A Neural Network Integrated Decision Support System for Condition-Based Optimal Predictive Maintenance Policy. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, *37*(2), 226–236. https://doi.org/10.1109/TSMCA.2006.886368

Wu, S & Vera, A.H. (2019). *Supporting Crew Autonomy in Deep Space Exploration: Preliminary Onboard Capability Requirements and Proposed Research Questions. Technical Report of the Autonomous Crew Operations Technical Interchange Meeting* (NASA Technical Memorandum NASA-TM—2019–220345). National Aeronautics and Space Administration. https://ntrs.nasa.gov/api/citations/20190032086/downloads/20190032086.pdf

Xu, Z., Guo, Y., & Saleh, J. H. (2022). Accurate Remaining Useful Life Prediction With Uncertainty Quantification: A Deep Learning and Nonstationary Gaussian Process Approach. *IEEE Transactions on Reliability*, *71*(1), 443–456. https://doi.org/10.1109/TR.2021.3124944

Xu, Z., & Saleh, J. H. (2021). Machine learning for reliability engineering and safety applications: Review of current status and future opportunities. *Reliability Engineering & System Safety*, *211*, 107530. https://doi.org/10.1016/j.ress.2021.107530

Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology*, *18*(5), 459–482. https://doi.org/10.1002/cne.920180503

Yerkes, R. M., & Morgulis, S. (1909). The method of Pawlow in animal psychology. *Psychological Bulletin*, *6*(8), 257–273. https://doi.org/10.1037/h0070886

Appendix A: IRB #23-0669 Qualitative Interviews Materials

Pre-Screening Questionnaire

Title of research study: ***Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats***

Investigator: ***Dr. David M. Klaus***

You do not have to answer any question that you would not like to answer, but without answers to these questions, you will not be eligible to participate in the study.

Name: ____ _____

Can you read and speak English fluently?

☐ Yes

☐ No

Years of ECLSS-related experience:

☐ Less than 4

☐ 4+

Years of spaceflight-related experience:

☐ Less than 4

☐ 4+

Which type of experience describes your ECLSS-related experience? Select all that apply:

☐ Academic Research and Development

☐ Engineering Design

☐ Ground Operations (launch or mission control center)

☐ In-flight Operations (Astronaut)

Pre-interview Project Background

Title of research study: ***Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats***

Investigator: ***Dr. David M. Klaus***

What should you know about this research study?

Given your expertise in this area, we invite you to take part in our research study investigating attributes of maintainable, self-sufficient ECLSS that drive decision-making when designing a human space habitat for a deep-space mission. The following sections provide some context and our descriptions of *deep-space mission*, *operational autonomy*, *ECLSS robustness*, *self-sufficiency,* and *emerging technologies*.

- ECLSS is a critical subsystem for human spaceflight because it provides the necessary functionality to keep the crew alive and healthy. *ECLSS robustness* is defined as the "ability to maintain habitable conditions for crew survival and productivity over the mission lifetime under a wide range of conditions" [1]. On ISS and Skylab, crews have spent significant time maintaining these systems to ensure their critical functionality [2]. Many of the associated operations with this maintenance currently rely on real-time support with ground control.
- This research study targets *deep-space missions* at or between the Moon to Mars. As we send astronauts to deep-space, the onboard crew must become increasingly *operationally autonomous*, able to complete time-critical operations with reduced ground support. These operations include maintaining a critical subsystem to restore nominal functionality in the event of an anomaly (e.g., carbon dioxide removal for atmospheric revitalization failed) that cannot afford the time delay needed to communicate with ground operators or that cannot wait for logistical resupply to replace parts.
- We define *self-sufficiency* as the ability to act independently from outside support [3].
- Incorporating various low-TRL *emerging technologies* may assist in increasing self-sufficiency, but might also introduce additional risk compared to heritage equipment.

This research study will use qualitative interviews with ECLSS subject matter experts (SMEs) following a set of semi-structured questions to augment our understanding of relevant trade attributes. Our research objective is to *determine design attributes to consider for improving ECLSS maintainability in deep-space missions.*

[1] Escobar, C. M., Nabity, J. A., & Klaus, D. M. (2017). Defining ECLSS Robustness for Deep Space Exploration, ICES 2017-280

[2] Russell, J.F. and Klaus, D.M. (2007) Maintenance, Reliability and Policies for Spacecraft Life Support Systems on Orbital Space Stations. *Reliability, Engineering and Systems Safety* 92(6): 808-820

[3] Rollock, A. E., & Klaus, D. M. (2022). Defining and characterizing self-awareness and self-sufficiency for deep space habitats. Acta Astronautica, 198, 366–375. https://doi.org/10.1016/j.actaastro.2022.06.002

How will the interviews be conducted?

Introduction

- We will review this Project Background and answer any questions you have on its content.
- We will go over the interview process and ensure that you consent to participation.
- You may stop participating at any time. Your answers will not be associated with your name.

Part 1: Event Description

- We would like to hear about your experience involving aspects of ECLSS maintenance.
- We will ask questions about your experience as a researcher, developer, or during operations.
- We will ask which ECLSS subsystems you have worked with.

Part 2: Interpretation

- We will ask questions related to what you learned based on your experiences from Part 1 and how you think systems can be improved.
- Specifically, we are interested in soliciting specific attributes of ECLSS maintenance that are important to consider for deep-space missions.

Part 3: Experience-specific questions

- We will ask additional questions related to your experience in academic research and development, engineering design, ground operations, and/or flight-operations.
- These questions are meant to elaborate on your unique insight and how that informs your interpretation from Part 2.

Wrap-Up and Additional Topics

- We will give you the opportunity to share any remaining thoughts and to bring up any additional topics we didn't cover.

Consent Document

Title of research study: *Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats*

IRB Protocol Number: 23-0669

Investigator: David Klaus

Sponsor: NASA HOME STRI

Key Information

This study aims to understand attributes of maintainable, self-sufficient ECLSS that drive decision-making when designing a human space habitat for a deep-space mission. We will be conducting interviews with individuals who are SMEs of human spaceflight and ECLSS. We expect that you will be in this research study for approximately 45 minutes during a single interview, and at a maximum this will not exceed 1.5 hours. Only one interview will be conducted and recorded.

There is no direct benefit to the participant. There are no serious risks associated with this study.

Although this study is funded by the NASA HOME STRI, only the researchers at CU Boulder approved to work on this study will have access to any identifiable information during the data collection phase.

Purpose of the Study

The purpose of the study is to identify opinions on what designers should consider when creating maintainable ECLSS. Sending humans to deep-space requires us to reimagine how we can support increasingly autonomous operations as the time delay in deep-space disallows instantaneous communication with ground support. Performing maintenance on ECLSS has been standard part of human spaceflight operations in low Earth orbit, and we anticipate this will be true in deep-space as well. This motivates our study to understand more about the decisions that are made when ground teams create ECLSS to be maintainable by astronauts onboard a space habitat. This research will improve the body of knowledge about how we can enable deep-space human missions. We expect about 15 people will be in this research study.

Explanation of Procedures

This research will be performed remotely over Zoom. The bulk of this research consists of a interview that will take about forty-five minutes. We will ask you questions about your previous experiences with ECLSS. Audio from the interview will be recorded for data analysis. Audio will be recorded using your own microphone. Video will not be recorded. These interviews will take place from December 2023 to January 2024 during single interviews with all participants.

Voluntary Participation and Withdrawal

Whether or not you take part in this research is your choice. You can leave the research at any time and it will not be held against you. Refusal to participate will not involve penalty or loss of benefits to which you are otherwise entitled. If you leave early, you can request that the recorded interview be deleted and we will immediately remove any store audio files from our equipment. Otherwise, we will attempt to use the recorded audio from the partial interview.

The person in charge of the research study can remove you from the research study without your approval. Possible reasons for removal include not following the instructions or being dishonest in your responses.

Confidentiality

Information obtained about you for this study will be kept confidential to the extent allowed by law. Research information that identifies you may be shared with the University of Colorado Boulder Institutional Review Board (IRB) and others who are responsible for ensuring compliance with laws and regulations related to research, including people on behalf of the Office for Human Research Protections. The information from this research may be published for scientific purposes; however, your identity will not be given out.

After the study is completed, we will deidentify the data by removing the identifiers that link it to you. The deidentified data may be used for future research purposes by the Principal Investigator of this study.

Payment for Participation

You will not be paid to be in this study.

Questions

If you have questions, concerns, or complaints, or think the research has hurt you, talk to the research team at sophia.zaccarine@colorado.edu or contact the principal investigator at klaus@colorado.edu.

This research has been reviewed and approved by an IRB. You may talk to them at (303) 735-3702 or irbadmin@colorado.edu if:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You have questions about your rights as a research subject.
- You want to get information or provide input about this research.

Interview Guide

Title of research study: *Qualitative Interviews to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats*

IRB Protocol Number: 23-0669

Investigator: David Klaus

Sponsor: NASA HOME STRI

General Guidelines

- Facilitate conversation through open-ended questions and requests for details/elaboration
- Aim for 45 minute -1 hour total interview time, maximum of 1.5 hours

Pre-Interview

- Review interviewee's background and experience with ECLSS
- Send interviewee consent and project background prior to interview
- Ensure communication and recording methods (audio only) are clear and functioning

Introduction

- Introduce interviewer (self) and project
- Clarify the following:
  - You can stop at any time
  - Your answers will be anonymous by default (give respondent number)
  - Project and interview have been approved by CU IRB (#IRB **23-0669**)
    - *If clarification is needed*: The Institutional Review Board (IRB) is an administrative body established to protect the rights and welfare of human research subjects recruited to participate in research activities

- Verbally obtain consent to begin with the interview
- Start the recording and announce that the interview is now being recorded.
- Offer a chance for them to ask any questions about the process.

Review Project Background

- ECLSS is a critical subsystem for human spaceflight because it provides the necessary functionality to keep the crew alive and healthy. *ECLSS robustness* is defined as the "ability to maintain habitable conditions for crew survival and productivity over the mission lifetime under a wide range of conditions" [1]. On ISS and Skylab, crews have spent significant time maintaining these systems to ensure their critical functionality [2]. Many of the associated operations with this maintenance currently rely on real-time support with ground control.
- This research study targets *deep-space missions* at or between the Moon to Mars. As we send astronauts to deep-space, the onboard crew must become increasingly *operationally autonomous*, able to complete time-critical operations with reduced ground support. These operations include maintaining a critical subsystem to restore nominal functionality in the event of an anomaly (e.g., carbon dioxide removal for atmospheric revitalization failed) that cannot afford the time delay needed to communicate with ground operators or that cannot wait for logistical resupply to replace parts.
- We define *self-sufficiency* as the ability to act independently from outside support [3].
- Incorporating various low-TRL *emerging technologies* may assist in increasing self-sufficiency, but might also introduce additional risk compared to heritage equipment.

Interview Objectives

To provide context for this interview, we want to hear about your experiences and thoughts regarding the design of maintainable ECLSS. We're hoping to understand what attributes of ECLSS maintainability you consider important in the design phase, specifically to understand which of these attributes support operational autonomy in deep-space operations.

- This will help us assess how existing or emerging technologies might be incorporated into these designs to meet the needs of deep-space
- We are not addressing mass and volume considerations in this interview, rather the focus is on operational ECLSS robustness in terms of maintainability
- *(Ensure they understand these terms. Use the background information sheet. Do not assume they read it)*
- Are you ready to begin the interview or do you have any questions?

Interview questions

(1) Event Description

- Please specify which ECLSS subsystems you have worked with, air revitalization (atmospheric and thermal), water management, and/or waste management?

- We want to hear about your experience involving aspects of ECLSS maintenance, either research and development or operational. This can be one or more examples. As context, maintenance describes the actions needed to ensure nominal functioning of a subsystem or component. This includes both preventative maintenance and reactive maintenance.
    - For example, preventative maintenance would include replacing a filter on a predetermined frequency or defining the need for preventative maintenance.
    - Reactive maintenance could include response to an anomaly with ECLSS that needed immediate action such as replacing a failed fan.

(2) Interpretation of attributes of ECLSS Maintenance

- We have a select set of attributes of maintainability currently in work, such as fault tolerance and accessibility, and we're soliciting open-ended inputs to augment our ideas.
- In your opinion, which attributes of the ECLSS design contribute to maintainability of the system? This can include your thoughts for the subsystem-level, including sensors and overall complexity of the ECLSS, and also can include your thoughts at the component level.
- From a LEO baseline, what needs to be improved or enabled for Lunar ECLSS?
- Beyond this, what needs to be improved or enabled for Mars ECLSS?
- What attributes of current ECLSS capabilities and maintainability do you think ARE suitable for deep-space operations?

Experience-specific

(3) If Academic Research and Development experience:

- In your academic research and development experience, what are some of the recurring challenges that you have seen with designing maintainable ECLSS?
- If you were to picture designing an ECLSS to be maintainable by crew with less reliance on ground support, what attributes would you consider?

(4) If Engineering Design experience:

- In your engineering design experience, what were your primary challenges when designing ECLSS for operations?
    - Do these challenges contribute to the maintainability of ECLSS?
- Describe some of the trade-offs you had to consider when designing ECLSS.
    - *(If the interviewee needs more prompting, could provide examples such as)*
    - Designing ECLSS to be more regenerative because we are mass or volume-limited
- In your engineering design experience, did you intentionally design the ECLSS to be accessible and maintainable by the crew?

- If you were to picture designing an ECLSS to be maintainable by crew with less reliance on ground support, what attributes would you consider?

(5) If Ground Operations experience:

- In your ground operations experience, did you ever support astronauts performing maintenance on ECLSS in-flight?
  - What were the primary issues you experienced with supporting maintenance?
  - Were there design strengths of the ECLSS that made supporting maintenance easier or less tedious?
- In your ground operations experience, did you ever support maintenance for ECLSS refurbishment?
  - What were the primary issues you experienced with supporting maintenance?
  - Were there design strengths of the ECLSS that made supporting maintenance easier or less tedious?
- In your opinion, which types of activity during maintenance operations needed the most support from ground control?

(6) If Flight Operations experience:

- Did you ever perform maintenance on ECLSS while in-flight?
- Did you ever observe ECLSS maintenance being performed in-flight?
  If no to both, what is your in-flight maintenance experience?

- What were the primary issues or challenges you experienced with performing ECLSS or any maintenance?
  - Were there design features of the ECLSS that made maintenance easier or less tedious?
- In your opinion, which steps of ECLSS or other maintenance operations needed the most support from ground control?

- (*If time permits*) Were there aspects of the ECLSS hardware or software that were enjoyable to maintain?

(7) Additional Topics

- Are there any additional thoughts you have about ECLSS maintainability, or topics we didn't address that you think are important to mention?

Interview Closeout

- Ensure my contact information given
- Thank them for their participation!

Appendix B: IRB #23-0669 Amendment: Survey Materials

Consent Form and Recruitment Email

Hello,

We are reaching out to ask if you would be interested in participating in a study to rank attributes of maintainable ECLSS that affect the design of a deep-space human habitat. This study is being performed by the Bioastronautics Lab at the University of Colorado Boulder (CU) as part of our NASA Space Technology Research Institute Habitats Optimized for Missions of Exploration (HOME) project.

For this study, you will complete a Qualtrics survey to rank the attributes of maintainable ECLSS that were derived in Phase 1 of this study through qualitative interviews with subject matter experts (SMEs). We anticipate that the survey will take around 20-25 minutes to complete. Please note that we cannot ensure privacy if you choose to complete the survey at your place of work or a public location.

No payment is provided for this activity.

If you are interested in participating, please review the consent information below and enter the survey using the link. No response to this email is necessary to participate.

We would appreciate your survey responses by April 5, 2024, if possible.

Thank you,

Sophia Zaccarine (PhD Candidate, CU Boulder)
Dr. David Klaus (Professor, CU Boulder)

CONSENT FORM *(not required since this research was classified as 'Exempt' by the CU IRB, but was included as part of the email)*

Title of research study: Qualitative Interviews and Survey to Determine Attributes of Maintainable Environmental Control and Life Support Systems (ECLSS) for Deep-Space Habitats
IRB Protocol Number: 23-0669
Investigator: David Klaus, PhD

Purpose of the Study: The purpose of this research survey is to determine relative importance of design and operational attributes for improving ECLSS maintainability in deep-space missions.

We expect this survey will take approximately 20-25 minutes to complete and that a total of 50 people will participate in the study. Whether or not you take part in this research is your choice. You can choose not to open the survey link and you can leave the survey at any time and it will not be held against you.

Explanation of Procedures: This research study uses a qualitative survey of individuals with ECLSS experience. Your contribution will consist of completing the 20-25 minute web-based Qualtrics survey on a laptop, phone or tablet. You will be asked to read brief project background material, review the proposed attributes of maintainable ECLSS derived from subject matter expert

(SME) interviews during Phase 1 of this protocol, and then rank the attributes as:

0 – Not Important
1 – Somewhat Important
2 – Important
3 – Very Important
Unsure

The interview responses will be recorded, and you may select 'Unsure' for any rankings you do not have experience with, knowledge of, or do not want to rank. If you want to leave the survey for any reason, you can exit the survey at any point and your responses will not be recorded. There is no compensation for taking place in this study.

Confidentiality: We will not collect any personal information about you during the survey. All survey data will be stored securely and only accessed by the research team.

You will be directed to the start of the survey after you have read this consent information and click the survey link. Please note that this survey uses a 'click to consent' option. Opening the survey link indicates you have read and understand this consent information and you consent to take place in this study.

Questions

If you have questions about the survey, you can contact the research team at sophia.zaccarine@colorado.edu or contact the Principal Investigator at klaus@colorado.edu.

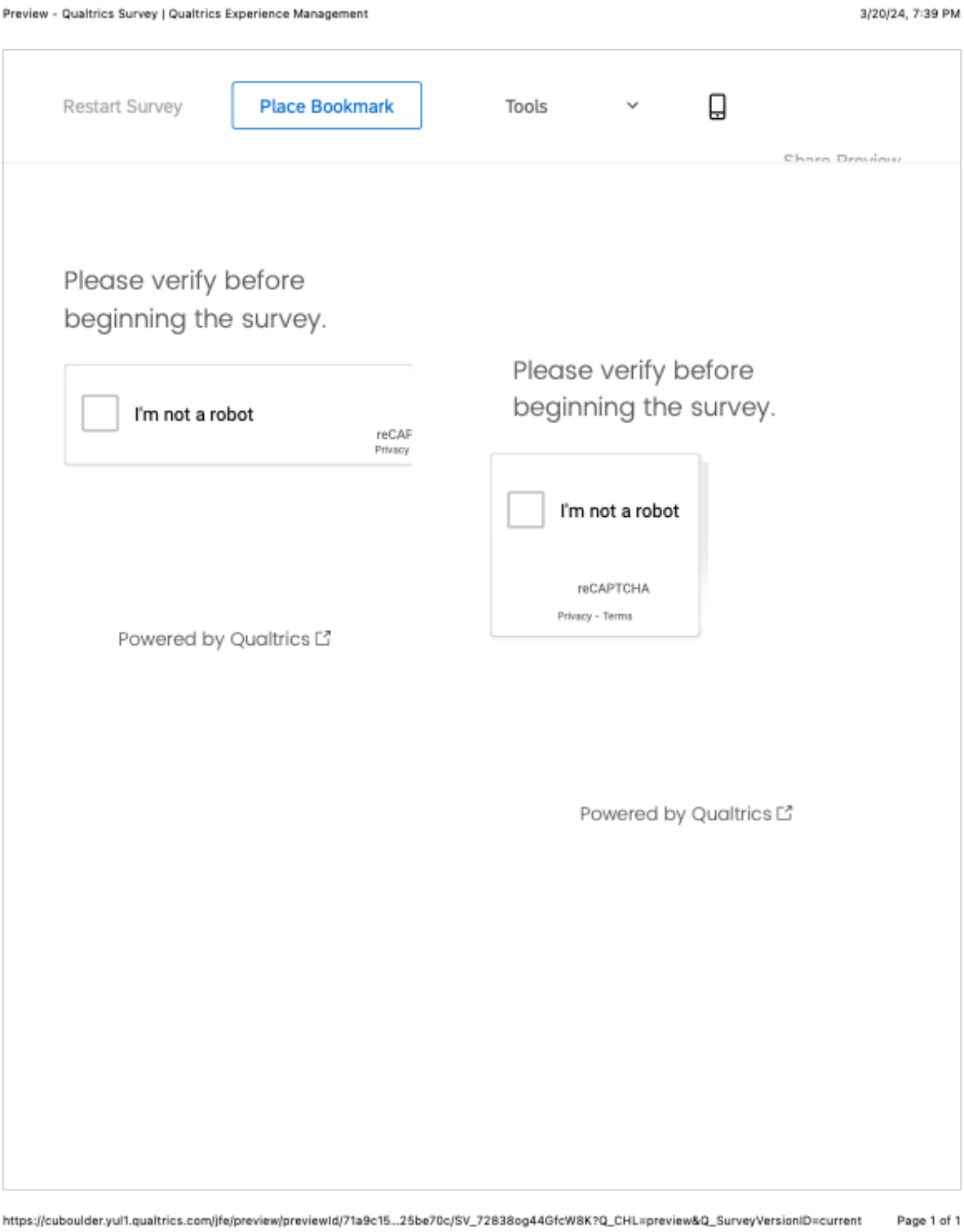
If you have concerns or complaints about the research you can contact the CU Boulder IRB at (303) 735-3702 or irbadmin@colorado.edu if:

- Your questions, concerns, or complaints are not being answered by the research team.
- You cannot reach the research team.
- You want to talk to someone besides the research team.
- You have questions about your rights as a research subject.
- You want to get information or provide input about this research.

ANONYMOUS SURVEY LINK:

[anonymous survey link was provided here]

Survey Design



Thank you for choosing to participate in the attributes of maintainable ECLSS survey! This survey was approved under CU Boulder IRB Protocol #23-0669. This survey should take about 15 minutes to complete.

Project Background

- ECLSS is a critical subsystem for human spaceflight because it provides the necessary functionality to keep the crew alive and healthy. On ISS and Skylab, crews have spent significant time maintaining these systems to ensure their critical functionality [1]. Many of the associated operations with this maintenance currently rely on real-time support with ground control.
- This research study targets *deep-space missions* at or between the Moon to Mars. As we send astronauts to deep-space, the onboard crew must become increasingly *operationally autonomous*, able to complete time-critical operations that cannot afford the time delay needed to communicate with ground operators or that cannot wait for logistical resupply to replace parts.

Our research objective is to *determine relative importance of design and operational attributes for improving ECLSS maintainability in deep-space missions*.

This research study uses a qualitative survey of individuals with ECLSS experience. This survey will request you to rank attributes of maintainable ECLSS, derived from interviews with

ECLSS subject matter experts (SMEs), as:

0 - Not Important

1 - Somewhat Important

2 - Important

3 - Very Important

Unsure

Where 'Unsure' allows you to not rank any attribute you do not have experience with, knowledge of, or do not want to rank. These attributes are separated into the categories of *Design Considerations* and *Operational Considerations*. These attributes are generated with a goal of enabling ECLSS robustness, defined as the "ability to maintain habitable conditions for crew survival and productivity over the mission lifetime under a wide range of conditions" [2].

At the end of the survey you will be asked to contribute additional attributes if you feel they are missing from the survey.

The complete list of attributes are summarized in the following table. Each set of relevant considerations, *Design* or *Operational*, will be displayed on the following pages along with definitions and representative statements from the SMEs interviewed. Note that we will not ask you to rank the attributes in the first column, *Overarching Mission Drivers for Deep-Space*, as these are not unique to creating maintainable ECLSS.

Overarching Mission Drivers for Deep-Space	Maintainable ECLSS Drivers	
	Design Considerations	Operational Considerations
Functional Needs	Reliability	Accessibility
Mission Duration	Resiliency	Explainability
Mass, power, volume	Adaptability	Ease of maintenance
Cost	Observability	Integrated systems
Project Schedule	Commonality	Complexity
Vendor Availability	Redundancy	Maintenance time
	Regenerability	Repairability
	Fault Management	Capability
	Risk Management	Operator Safety
	Material Properties	Onboard Control Authority
	Consumable Margin	
	Spare Parts Provision	
	Survivability	

Table 1: List of maintainable ECLSS attributes derived from Phase 1 of experimental protocol CU IRB #23-0669 designed by Zaccarine and Klaus, 2024.

[1] Russell, J.F. and Klaus, D.M. (2007) Maintenance, Reliability and Policies for Spacecraft Life Support Systems on Orbital Space Stations. Reliability, Engineering and Systems Safety 92(6): 808-820

[2] Escobar, C. M., Nabity, J. A., & Klaus, D. M. (2017). Defining ECLSS Robustness for Deep Space Exploration,

ICES 2017-280

The following table displays Design Considerations of ECLSS maintainability collected from interviews with SMEs. Please reference this table to inform your rankings below.

Design Considerations		
Theme	**Definition**	**Representative Statements**
Reliability	“The probability of a system or system element performing its intended function under stated conditions without failure for a given period of time.” [3] Often relies on ground or in-flight testing.	"I don't know what the number is of hours tested on the ground versus hours in space - but it's a pretty big number. And so their whole philosophy is, if it's gonna die, let's let it die while we can just change it out with a tech rather than in orbit."
Resiliency	The elastic or flexible ability to withstand unexpected failures and recover functionality after failure. Includes the concept of graceful failure modes (paraphrased from [2])	"So even if it's saturated or goes into a regime where it can no longer perform… ultimately, it's recoverable. And it will self-recover once the scenario is corrected."

Adaptability	How easily a system can be redesigned to achieve updated functionality if mission objectives change.	"Being able to introduce sensors or new components that might ultimately be required without a massive redesign of the entire system."
Observability	The ability to fully reconstruct the internal state of a system from system output variables [4]	"For a rapid depress, for example. We have access to…all the cabin pressure sensors. And we can see that data on the plot, so it's easy to visualize." "Wherever feasible, as long as it doesn't alter...it significantly, I want sensors."
Commonality	The reuse of identical design elements, including systems and components, in multiple places throughout an architecture [5] Includes commonality of tools	"Having common parts such that … you don't have unique parts for every different piece of hardware. Therefore you could… have a limited sort of spares logistics."
Redundancy	Whether a habitat has a secondary, duplicate ability to achieve a given function	"You need backups for those systems if they're the kind that are gonna keep you alive to give you time to fix the first system."

Regenerability	The ability of a system to recapture or recycle byproducts and make use of them.	"Do you use very simple lithium hydroxide canisters that are that are almost fail-safe … or a very complicated carbon dioxide removal system, you know, like a CDRA?"
Fault Management	The proactive design strategies used to 'preserve or maximize [a] system's ability to achieve its goals in the face of current or prospective failure' [6]	"Fault tolerance. Just having 2 systems talking to each other doesn't help you because you don't know which one's right." "There was a requirement that you can't have cascading failures. You can't have failure of one component fail a downstream component."
Risk Management	Likelihood of risk coupled with the severity of the consequence should it occur (paraphrased from [7])	"Concentration on, in terms of development, on parts that maybe are more prone to failure is something that's necessary."
Material Properties	Unique physical or chemical properties of components in a design that can assist in maintenance or pose a	"If you drag any into the vehicle with you by accident because you were outside and you got sprayed with ammonia, you can kill everybody in the vehicle." "For wires and hoses...if something needs

	hazard to the crew	to be routed in a particular way, having...shape memory helps crew members put things back together."
Consumable Margin	How much volume of a consumable material is accessible for onboard operations	"Everything leaks. It's just how much… you can stand and how much you plan for on a logistic resupply."
Spare Parts Provision	Number and type of spare parts that are provided or manufacturable onboard	"For...any piece of equipment…do you have enough components to fully replace…it? If you don't, what are you gonna prioritize for those components that you could replace?"
Survivability	"The ability of a system to minimize the impact of a finite disturbance on value delivery" [8]	"There is some concern right now for periods of either spacecraft quiescence, or when the crew is not present...systems...wouldn't have been operating. Now you're gonna operate it."

[2] Escobar, C. M., Nabity, J. A., & Klaus, D. M. (2017). Defining ECLSS Robustness for Deep Space Exploration. International Conference on Environmental Systems (ICES), 280.

[3] Adcock, R. D. (Ed.), "Guide to the Systems Engineering Body of Knowledge (SEBoK)," October 27, 2016, http://sebokwiki.org/.

[4] Liu, Y.-Y., Slotine, J.-J., & Barabási, A.-L. (2013). Observability of complex systems. Proceedings of the National Academy of Sciences, 110(7), 2460–2465. https://doi.org/10.1073/pnas.1215508110

[5] Crawley E., Boas, R., Cameron, B., Hofstetter, W., Rhodes, R., and Wicht, A. (2010). A COMMONALITY TOOLKIT FOCUSED ON NASA APPLICATIONS. MIT Space Systems Architecture Group. http://systemarchitect.mit.edu/docs/NASACommonalityToolkitv4.pdf

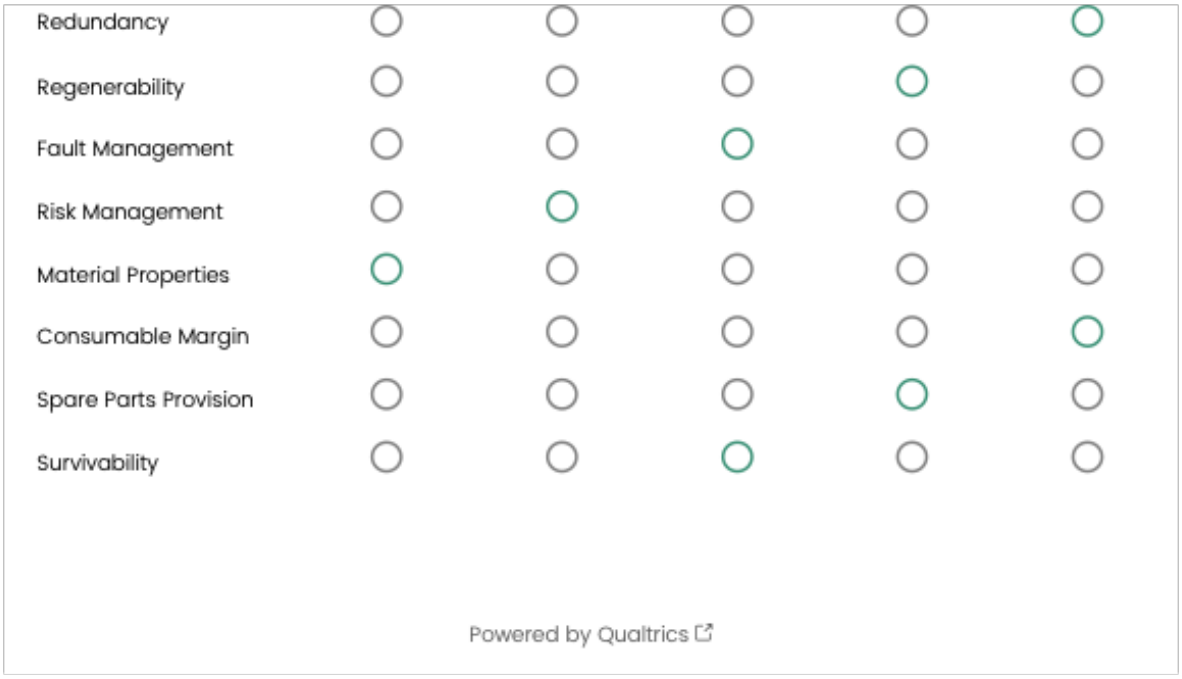
[6] Johnson, S. B., Ghoshal, S., Haste, D., & Moore, C. E. (2017, January 9). Fault Management Metrics. AIAA Information Systems-AIAA Infotech @ Aerospace. AIAA Information Systems-AIAA Infotech @ Aerospace, Grapevine, Texas. https://doi.org/10.2514/6.2017-1295

[7] Hirshorn, S. 2016. NASA SP-2016-6105 Rev2. NASA Systems Engineering Handbook. https://www.nasa.gov/wp-content/uploads/2018/09/nasa_systems_engineering_handbook_0.pdf

[8] Richards, M. G., Hastings, D. E., Rhodes, D. H., & Weigel, A. L. (2007). Defining Survivability for Engineering Systems. Conference on Systems Engineering Research, Hoboken, NJ, USA.

Please rank each of the following Design Considerations for maintainable ECLSS in deep-space.

	0 - Not Important	1 - Somewhat Important	2- Important	3 - Very Important	Unsure
Reliability	○	○	○	○	●
Resiliency	○	○	○	●	○
Adaptability	○	○	●	○	○
Observability	○	●	○	○	○
Commonality	●	○	○	○	○


Redundancy
Regenerability
Fault Management
Risk Management
Material Properties
Consumable Margin
Spare Parts Provision
Survivability
Powered by Qualtrics

The following table displays Operational Considerations of ECLSS maintainability collected from interviews with SMEs.

Operational Considerations		
Theme	**Definition**	**Representative Statements**
Ease of Access	How easily a crew member can physical maneuver to reach a component or system to perform a maintenance task	"So you would occasionally have to remove some items to get to another item, and that caused more work and risk and, and things like that. But in general it would be great if everything you needed to get access to was directly accessible by a crew member." "Access to things is critically important… even if you don't ever expect to have to access particular parts or pieces of a piece of equipment."
Explainability	How easily the data presented to the crew can be understood. Includes easily interpretable procedures and	"The adage of a picture is worth a thousand words is so so true…don't send up a gazillion words, just sent up a picture with arrows pointing to things… it made it way easier for anybody to execute." "And so I can see us moving to a direction where

	human factors design.	we have basically a YouTube channel of just 'how to fix it' type videos."
Ease of Maintenance Action	The relative simplicity of the required maintenance action. E.g. replacing a filter versus soldering a replacement PCB	"Don't make any system that you design in the vehicle…so complex that a person can't, with a … reasonable amount of tools, dig into it and fix it." "We have color-coded hoses. And that helps out the crew…the simple things really do pay dividends."
Integrated Systems	Number of interfaces – functional, physical, logical, or otherwise - between components	"Unfortunately, that system is all encapsulated in this one, basically one piece of equipment. And so we had a failure…and it essentially brought down the entire unit."
Complexity	Number of components within a system	"They're complicated systems. You know, they have lots, a lot of parts, lot of functions, some things you can jury-rig, some things you can't."
Maintenance Time	How long it takes to perform a given maintenance task	"Any routine maintenance you should think about packaging and those sorts of things to make sure that that, it's not an unnecessary time required to do things."
	A system designed	"And what that underscored to me was, when you go outside of low Earth orbit, you can't possibly use

Repairability	to allow for component-level or ‘intermediate-level’ maintenance. The counter of this is the ORU-model.	the ORU model…maintenance in deep space has to be I-level maintenance concept from the start." "The parts that are the component parts have to be accessible, which means…having the build-up such that maybe parts are more separated, so you can get wrenches or other things in there."
Capability	Current ability of the unique operator based on their training and available equipment (Based on [9])	"So that's very complex. How those interact and how the crew has to interact with those computers required an immense amount of training, just an immense."
Operator Safety	Systems designed to mitigate unnecessary hazards from affecting the crew.	"The only way to know for sure which one was right, you had to follow the tubes that went from the valve to the different port locations. So it was a truly hazardous operation, just because of the lack of labeling."
Onboard Control	Whether there is the ability to make time-	"If you design it simple, then someone on their own, maybe even without a whole lot of documentation, can do something about it."

Authority	critical decisions onboard the habitat.	"I think in a lot of ways we we … kind of cut the legs off under our crew in terms of autonomy because we make them so reliant on [ground control]."

[9] Easter, B. (2023) Medical System Foundation for Level of Care IV: Short-Duration Lunar Orbit. NASA Short Duration Lunar Orbit (SDLO) Model - https://www.nasa.gov/hrp/exmc/short-duration-lunar-orbit-model/

Please rank each of the following Operational Considerations for maintainable ECLSS in deep-space.

	0 - Not Important	1 - Somewhat Important	2 - Important	3 - Very Important	Unsure
Ease of Access	○	○	○	○	○
Explainability	○	○	○	○	○
Ease of Maintenance Action	○	○	○	○	○
Integrated Systems	○	○	○	○	○
Complexity	○	○	○	○	○
Maintenance Time	○	○	○	○	○
Repairability	○	○	○	○	○
Capability	○	○	○	○	○
Operator Safety	○	○	○	○	○

Onboard Control Authority	○	○	○	○	○

Powered by Qualtrics

Are there any attributes of maintainable ECLSS for deep-space that you want to contribute to this analysis, for either Design or Operational Considerations? Please share your thoughts and details for your rationale, or skip this question if not applicable. The survey will end after you submit this question.

n/a

We thank you for your time spent taking this survey.
Your response has been recorded.

Powered by Qualtrics

Appendix C: Raw Data from Survey

This deidentified, anonymized dataset can also be found on Open Science Framework at the following link: https://osf.io/jzaeq/?view_only=a5e01c4b27af4b2dbd85187718f16472

Duration (s)	Q2_1	Q2_2	Q2_3	Q2_4	Q2_5	Q2_6	Q2_7	Q2_8	Q2_9	Q2_10	Q2_11	Q2_12	Q2_13	Q2_1	Q2_2	Q2_3	Q2_4	Q2_5	Q2_6	Q2_7	Q2_8	Q2_9	Q2_10
Duration (s) seconds)	Reliability	Resiliency	Adaptability	Observability	Commonality	Redundancy	Regenerability	Fault Management	Risk Management	Material Properties	Consumable Margin	Spare Parts Provision	Survivability	Ease of Access	Explainability	Ease of Maintenance	Integrated Systems	Complexity	Maintenance Time	Repairability	Capability	Operator Safety	Onboard Control
468	3	3	1	1	1	2	1	3	3	2	3	2	2	2	2	3	2	3	2	2	2	2	3
870	3	1	1	2	2	3	2	3	2	1	2	3	3	3	2	2	0	2	1	3	2	3	3
1883	3	3	2	2	1	3	3	2	2	2	3	3	3	3	2	3	2	2	3	3	1	3	3
2014	3	3	2	2	2	3	2	3	2	1	2	3	2	3	2	3	2	2	2	3	2	3	3
2573	1	1	1	1	2	2	2	1	1	3	3	3	1	2	2	3	1	1	1	2	3	1	1

1582	3	2	1	1	3	3	2	2	3	2	1	3	1	1	1	1	4	0	0	3	3	2	2
122	2	2	2	2	3	3	2	3	3	2	3	2	2	3	1	2	2	2	3	3	3	3	2
38	4	3	2	1	0	1	3	3	3	3	3	3	3										
85																							
290	3	2	1	1	1	2	2	2	3	2	3	1	2	2	3	3	2	2	3	3	2	2	2

Example of Descriptive Statistics Function from Excel

Run by selecting the data column representing the set of participant answers for one attribute starting from row 3 in Appendix C and selecting Data → Data Analysis → Descriptive Statistics. Microsoft Excel Version 16.83 was used for this analysis.

Repairability	
Mean	2.75
Standard Error	0.163663418
Median	3
Mode	3
Standard Deviation	0.46291005
Sample Variance	0.214285714
Kurtosis	0
Skewness	-1.4401646
Range	1
Minimum	2
Maximum	3
Sum	22
Count	8
Largest(1)	3
Smallest(1)	2
Confidence Level(95.0%)	0.387002487