Strategies for the design and operation of resilient extraterrestrial habitats

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ABSTRACT

An Earth-independent permanent extraterrestrial habitat system must function as intended under continuous disruptive conditions, and with significantly limited Earth support and extended uncrewed periods. Designing for the demands that extreme environments such as wild temperature fluctuations, galactic cosmic rays, destructive dust, meteoroid impacts (direct or indirect), vibrations, and solar particle events, will place on long-term deep space habitats represents one of the greatest challenges in this endeavor. This context necessitates that we establish the know-how and technologies to build habitat systems that are resilient. Resilience is not simply robustness or redundancy: it is a system property that accounts for both anticipated and unanticipated disruptions via the design choices and maintenance processes, and adapts to them in operation. We currently lack the frameworks and technologies needed to achieve a high level of resilience in a habitat system. The Resilient ExtraTerrestrial Habitats Institute (RETH*i*) has the mission of leveraging existing novel technologies to provide situational awareness and autonomy to enable the design of habitats that are able to adapt, absorb and rapidly recover from expected and unexpected disruptions. We are establishing both fully virtual and coupled physical-virtual simulation capabilities that will enable us to explore a wide range of potential deep space SmartHab configurations and operating modes.

Keywords: Space habitats, resilience, autonomy, robotics, decision-making, complex systems

1. INTRODUCTION

The creation of safe and comfortable habitations is one of humankind's oldest activities. Millennia of experimentation on Earth have brought the design and maintenance of our habitats to a high degree of sophistication. However, as we consider moving beyond the Earth's relatively benign surface and out into Space, new obstacles related to these harsh and unknown environments will impede safety and progress.

Beyond the protection of Earth's atmosphere, explorers and colonists will face a new range of challenges. The Moon and Mars, two of the more attractive alternatives for near-term exploration and habitation, not only lack breathable atmospheres and 'normal' gravitational fields, but also experience wild temperature fluctuations and other hazards such as meteoroid impacts and intense radiation. Countering these challenges to provide livable conditions on the surface of those bodies will require the highest application of engineering and technology.

In light of these challenges, the *vision* of the Resilient Extraterrestrial Habitats Institute (RETH*i*) is to establish the know-how to design and develop resilient and autonomous *SmartHabs*. We define SmartHabs as habitats that have the ability to autonomously sense, anticipate, respond to, and learn from disruptions. Resilience requires that we begin with the question of the system architecture and features that should be embedded in a space habitat system. However, system architecture alone is not sufficient to provide resilience, so we are exploring techniques and algorithms needed to extract the necessary amount of actionable information for repair and recovery through monitoring and embedded

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intelligence. When action must be taken, it will be necessary to select the adaptations that must be initiated and the actions that should be taken by autonomous repair and maintenance robots. Thus, SmartHabs will have appropriate defenses that are able to respond to the hazards, deterioration, and common faults that may occur. We view SmartHabs as complex systems, characterized by a high degree of technical complexity, social intricacy, and elaborate processes. Our *mission* is to propel space exploration forward by developing new knowledge, technologies and techniques and collaborating with other NASA centers and industry to establish the know-how to create smart and resilient extraterrestrial habitats.

Early in the project, we established our strategic plan to guide our efforts to advance our mission. Our four strategic goals are: (SG1) create an effective, agile and responsible organization; (SG2) produce and demonstrate new technologies and techniques; (SG3) generate new knowledge; and (SG4) foster the space systems workforce of the future. Our research activities are tightly linked to SG2 and SG3, and they focus on the knowledge and technologies that are fundamental to establishing SmartHabs. As such, we are not designing a habitat, but rather are conducting the research needed to develop the tools and techniques that will support resilience in these systems. SG1 serves to guide our governance and decisions to ensure we are responsible stewards of the resources and build suitable partnerships to extend our reach and add value to our activities. Education and outreach to the next generation of engineers, scientists and technologists is also a significant objective and is embedded in SG4. Our aim is to establish RETH*i* as a focal point for partnerships between private industry, public institutions, other Space Technology Research Institutes, and NASA.

The purpose of this paper is to share the goals and activities of the RETH Institute, and to describe our approach to developing tools that will inform the design and operation of smart and resilient space habitats. In Section 2 we will discuss the environment and range of hazards that must be managed, and the mitigative, preventive and interventive capabilities that need to be developed to provide resilience. In Section 3 we will share the approach we are taking to create and examine these capabilities, including the simulation environments where we will virtually examine the performance, and the reconfigurable cyber-physical testbed we are establishing.

2. CAPABILITIES NEEDED TO ESTABLISH SMARTHABS

On Earth, our habitats are periodically affected by natural hazards such as hurricanes, earthquakes, typhoons, drought, tsunamis, tropical storms, and snowstorms. Moreover, in certain regions of the planet, quite extreme regular weather conditions prevail, for instance, the heat of a desert or the cold conditions at the North and South Poles. Through necessary trial and error, humankind has learned a great deal about how to engineer our habitats here on Earth to withstand these severe conditions. And although those lessons took millennia to learn, these are still relatively mild conditions compared to the extreme conditions beyond the Earth's protective environment. Notwithstanding the challenges of its natural hazards, the Earth is abundant in the critical resources required to sustain life, such as oxygen, water, food, building materials, and fuels. This luxury is unique to the Earth – and is either lacking on other known potential worlds, or at least requires new knowledge to access. *Thus, the need for resilient and sustainable space habitats is essentially a matter of how to select, manage and use the limited resources available.*

SmartHabs will have to be designed with features and technologies that increase the chance of survival and continued operation for the habitat. SmartHabs will have a range of sensors and fault detection capabilities to provide situational awareness, combined with decision-making capabilities to assess potential actions and decide among those actions. SmartHabs will also need robots to take action in the case of a disruption, and to maintain the habitat subsystems, especially when the habitat is uncrewed.

2.1 Extreme environments and other hazards

Clearly the Moon's environmental conditions are orders of magnitude more extreme and more hazardous than on Earth[1-10]. Some of the primary factors that must be quantified and considered for the resilient design and construction of human habitats are:

- **Pressure Differentials**: The presence of hard vacuum and a lack of atmosphere on the Moon requires sufficient internal pressurization for human habitation[1,2,5]. This requirement provides not only a structural challenge, but also a challenge in the detailed design and construction of reliable containment of breathable air.
- **Micrometeoroids:** The lack of atmosphere also allows small particles to strike the Moon's surface with speeds as high as 20 km/sec[3].
- **Temperature Extremes**: The length of a lunar diurnal cycle is 29.53 earth days, consisting of almost 15 days of sunlight and 15 days of darkness. The lunar surface temperature changes drastically from high noon to predawn, presenting thermal expansion and thermal cycling problems for lunar structures. Temperature differentials between +111°C and -171°C were measured by Apollo 17[1,3,6].
- **Radiation**: High-energy galactic cosmic rays (GCR) and solar flares (SPEs) are the two major sources of deep space radiation. Because of the Moon's very small magnetic field and nearly absent atmosphere, space radiation bombards lunar-based structures directly[1,2,3].
- **Lunar Regolith/Substrate**: Lunar regolith (soil) is more cohesive than most terrestrial soils and has an angle of internal friction of about 30-50 degrees[1]. The long-term vibrational settling of regolith caused by meteoroid impacts also results in extremely high relative densities. The bulk density of lunar regolith ranges from 0.9 to 1.1g/cm^3 near the surface, and reaches a maximum of 1.9 g/cm^{3}at about 20 cm depth[2,4]. This means that excavation will be difficult, but once disturbed, no amount of in-situ compaction can restore the natural relative density. Conversely, it is expected that undisturbed subsurface layers of material may provide excellent foundation substrate.
- **Lunar Gravity:** Lunar gravitational acceleration is approximately 1/6 that of Earth. This means that lighter structural members can be used to span longer distances than on Earth, making structures more flexible and their dynamic behavior more critical to their integrity.
- **Moonquakes**: The moon's core is assumed to be rather cool due to its small size, making geological activities low relative to that of the Earth. Moonquake data were collected from 1969 to 1977 with relatively low sampling rates and in a small region of the surface area[2,4]. Measured moonquakes have been weak, but appear to be quite high frequency and long-duration compared to Earthquakes. We know little about their potential impacts on a habitat system, including the structure itself, the contents, and its inhabitants.
- **Dust**: Particles finer than 70 micrometers form approximately 50% of lunar regolith[2,3]. These particles are extremely jagged and stick electrostatically to objects they touch. These properties can be attributed to the anhydrous vacuum environment. Thus, dust from the lunar regolith is abrasive and clumps together, which can be an operational nuisance.
- **Biological and Bio-film hazards**: Bacterial biofilms pose a particular challenge in the isolated environments of space habitats. Their formation, growth, prevention and management are a topic of great interest to current researchers[9,10].

These conditions represent a significant, although incomplete, subset of the anticipated hazards that space habitats will inevitably be exposed to during their lifecycle. In addition, there will be a range of unanticipated disruptions. Furthermore, to achieve sustainable living conditions for longer-term habitation, beyond scientific and exploratory activities, space habitats will potentially expand considerably. As an extraterrestrial habitat evolves—growing in physical size, complexity, population, and connectivity—and diversifies in operations, it must continue to be resilient. In this context, we need to leverage the thousands of years of engineering experience gained by building habitats on Earth, while integrating new technologies and techniques available, such as robotics and autonomy, with a systems engineering perspective.[11-13]

2.2 Three ways to achieve resilience

Traditional approaches for design focus on reliability, robustness and redundancy, and are aimed at avoiding or minimizing the occurrence of anticipated failures and faults. While these efforts have made operations such as the International Space Station (ISS) feasible, the philosophy behind these advances is inadequate in the context of a deep space habitat system for three main reasons: (i) high reliability is inefficient and costly; (ii) in a long-term habitat, disruptions are inevitable, yet difficult to predict; and, (iii) humans will not always be present.[14] Current approaches do not adequately account for the range of anticipated and unanticipated hazards that can affect the habitat, the unforeseen emergent behaviors of such complex systems, or the potential for degradation in hardware over time. Below we discuss the existing gaps in current capabilities, and the ways in which we will approach meeting this challenge.

2.2.1 System architecture

Our approach to developing resilient system architectures is based on the concept of preventing the habitat from transitioning to hazardous or accident states, or, if the habitat does enter these states, enabling it to return to a nominal state. We use *safety controls* to maintain or return the habitat to a nominal state. This approach has been successfully used by system safety engineers in various forms on systems ranging from aircraft to oil platforms to nuclear power plants, and accordingly a range of methods and modeling approaches are available. Space habitats pose two additional and significant challenges compared to Earth-based systems: (1) we cannot foresee everything that might go wrong, and (2) whatever does go wrong will have to be addressed with the safety controls that are available on the habitat—it will not be possible to ship in parts or supplies, at least not without extensive forewarning or delays. Therefore, it is essential that we select an appropriate set of safety controls up front, such that a habitat can respond to both foreseen and unforeseen events over its design lifetime.

Current approaches to identifying potential disruptions and hazards, and from there appropriate safety controls, are largely based on experience. Engineers in different fields have built up bodies of knowledge on what may go wrong, and how to adequately control hazards. For example, in the chemical process industry, HAZOP is essentially a sophisticated checklist based on decades of experience. Note that none of these methods guarantee that engineers will have identified all the hazards—there is no way to guarantee completeness. Where we do not have such experience, engineers must resort to techniques like storytelling to try to identify how, for example, a new technology might interact with existing technology to create hazards. In such contexts, there will inevitably be gaps in the risk identification, incorrect assessments of the nature and extent of risks, and as a result, inadequate safety controls. Further, while there is a large body of work on reliability optimization (e.g., how to maximize reliability given a cost constraint, or vice versa), safety control identification and selection tends to be done on a hazard-by-hazard basis. "Optimization" typically entails ranking hazards by significance and then identifying safety controls that bring each hazard down to an acceptable level. Less consideration has been given to how the complete set of safety controls works together to reduce the total system risk while, for example, minimizing cost or mass. Finally, there is little guidance on how to select a set of safety controls that maximize our ability to respond to either foreseeable but missed or unforeseeable hazards.

2.2.2 Situational awareness and autonomy

Situational awareness refers to knowing both the current and likely future states of the habitat. Do we have enough air filters in our inventory? Are the ambient conditions of a habitat zone safe enough for crew members? Is there any damage to the structure? If yes, what do we know about the damage location and extent? How much dust is accumulated on the photovoltaic panels? Are the robotic agents charged? What are the scheduled robotic activities for the next 10 hours? What is the remaining useful life of the air filter of the ECLSS? What will happen to the ambient conditions if power to the thermal management system temporarily shuts down? Answering such questions requires developing specialized sensors, optimizing sensor placement, collecting the data and transmitting them through a communication network to a data repository, and communicating the habitat's state to humans.

For some aspects of the state of the habitat, e.g., the temperature, humidity, and air pressure of the interior, common off-the-shelf sensors can be employed with some minor modifications. However, many standard sensing devices, e.g., cameras, quickly lose their functionality in harsh radiation environments. Therefore, one of the critical challenges for awareness is developing sensor technologies robust to extraterrestrial disturbances. Even with robust sensors, certain aspects of the state of the habitat are only indirectly observable. Take, for example, the case of a clogged air filter in the thermal management subsystem. If a visual inspection is not possible, a drop in the system's thermal efficiency is a clear indication that something is off (*detection*), and an abnormal pressure drop sensed before and after the filter indicates that the filter is clogged (*diagnosis*). Thus, such *anticipated faults* may not be directly observable, but can be inferred from the sensor data combined with a physical understanding of the system. This process is often called *fault detection and diagnostics* (FDD). To build and validate the FDD component for a system of interest, we need physics-based system models that explicitly account for anticipated faults' effects on measurable quantities.

FDD components reveal the current health state of a system. It is often possible to use this information to predict the likelihood of developing specific faults after a particular time, a process called *prognosis*. These models are useful because they allow one to evaluate mitigating actions to prevent the occurrence of a fault. In our working example, one could predict that the filter will likely require replacement in about a week and schedule an action to send robotic agents to replace it. To build prognostic capabilities, one needs to endow the physical system models with the faults' stochastic dynamics, e.g., modeling the rate of accumulation of particles on the filter surface under any operating conditions.

FDD and prognosis of anticipated faults are essential for resilience since without such capabilities an extraterrestrial habitat would be very brittle unless it was overdesigned. However, in the unfamiliar environment of a space habitat, resilience also requires detecting and diagnosing *unanticipated faults*. Detection of an unanticipated fault seems to require either extensive sensor coverage of the habitat or the ability to redeploy sensors. Diagnosing unanticipated faults is an extremely challenging process. Humans can undoubtedly diagnose unanticipated faults when they have the right expertise and enough resources (tools, sensors, computers). However, human experts may not be available on-site in an extraterrestrial environment, and the delays in transferring data to Earth may prove devastating in critical, unanticipated situations. Artificial intelligence (AI) may help, but unfortunately, it is not possible to automate this process with existing or near-future AI capabilities.

Situational awareness is essential for making decisions to achieve mission goals. If one knows where they are and can predict where they are likely to be if they take specific actions, they can make the right decisions. Some decisions involve sending cyber-commands to the habitat system, and fall in the regime of control of cyber-physical systems. Classical monolithic approaches (one central authority controls every detail) are not scalable to complex systems because the number of possible action combinations scales exponentially with increasing system complex. Hierarchical approaches (e.g., the system decision-maker controls the settings of subsystem controllers) are better equipped to deal with this curse of dimensionality.

Furthermore, one also needs to plan the actions of human and robotic agents. The major challenge here is executing each action requires resources – power, inventory, and human or robotic agent time – to be achieved. Given the restricted environment in an extraterrestrial habitat, one has to systematically address resource allocation. Therefore, there is a need to build models that capture the effect of agent actions on the habitat, including the resources consumed, the time elapsed, the likelihood of completing a task successfully, and the value in doing so.

The situation is much more complicated for unanticipated faults. Humans have proven that they can make decisions and perform actions that can mitigate unanticipated faults with limited resources. However, solving such open-ended planning problems autonomously is a grand challenge beyond existing capabilities.

2.2.3 Robotic intervention and maintenance

As mentioned already, a critical capability for SmartHabs is the ability to make repairs and apply other needed interventions.[14] In general, there will be a need for these actions to be achievable by autonomous robots: during uncrewed periods, no human alternative will be available; during crewed periods, the crew members' time should be protected for other needs to the greatest extent possible; and communication delays for remote habitats make extensive support from Earth not an option in either case.

To keep a SmartHab functional and safe for long periods, needed interventions will range from relatively simple tasks of regular maintenance (e.g., cleaning dust off solar panels), to more complex but still essentially structured and predictable operations (e.g., removing a burnt-out circuit board and installing a replacement from a supply), to unanticipated and fundamentally unpredictable needs (e.g., patching a tear in the habitat shell).

Enabling robots to carry out the necessary functions, reliably and autonomously, presents a variety of challenges. Different maintenance and repair tasks will require a variety of different tools, some involving complex manipulation. Visual perception will pose additional problems in high-radiation environments, where digital cameras can degrade rapidly. Many tasks will not be achievable by a single agent (robot or astronaut) acting alone; coordinating the efforts of multiple independent agents will be necessary to achieve desired collective outcomes. Operation outside the habitat, and potentially inside it during emergency situations, will take place in unstructured, unpredictably variable environments. During crewed periods, robots inside the habitat will need to operate in a dynamic environment, and to do so safely around humans; and humans will need to be able to work with robots effectively and intuitively.

Our efforts to meet the above challenges can be divided into two complementary categories. The first is to improve the capabilities of the robots: to make the robots more competent at carrying out challenging tasks in demanding circumstances, and to narrow the gap between the abilities of robots and those of humans. The second is to modify the environment to suit the robots: to develop design principles and tools for creating SmartHabs that make it easier for robots with today's level of capability to reliably carry out the functions that need to be performed.

3. APPROACH TO STUDY SMARTHABS

To realize SmartHabs, RETH*i* comprises three interconnected research thrusts. The Resilience Thrust examines key systems contained in the habitat (e.g., structure, life-support, environmental controls), considering their interactions and spatial distribution to establish a framework for identifying resilient architectures. The Awareness Thrust develops the techniques and algorithms needed to extract the greatest amount of actionable information for repair and recovery through intelligent monitoring. Both inform the Robotics Thrust by anticipating in advance, and then selecting during deployment, the combinations of actions to be taken by autonomous robotic repair and maintenance crews.

3.1 System architecture

Our *control-theoretic approach* to resilient design considers systems as being in one of three types of states: nominal, hazardous, or accident. A state describes a segment of time wherein a system exhibits a particular behavior. A system can be in one and only one state at any given point in time. A *nominal state* is when the system is within the boundaries of safe behavior. A *hazardous state* is when the system is in a state that, if left uncontrolled, will result in an accident or loss of life. The system transitions from one state to another via triggers. *Disruptions* are a type of trigger that initiates the transition from a nominal state to a hazardous state. We use safety controls to maintain the system in a nominal state, or, if the system does transition into a hazardous or accident state, to return it to a nominal state. A *safety control* is any part of the system design or operation that maintains the system in a nominal state, prevents the system from propagating to a hazardous state, or restores the system from a hazardous or accident state to a nominal state.

To help designers identify sets of safety controls that, for example, maximize risk reduction for a given system mass, and that have the potential to address hazards that were not identified during the design process, we are developing two safety control metrics. *Safety control effectiveness* measures how effectively a safety control addresses the specific disruption, hazardous state, or accident state it was designed for. Control effectiveness takes into account aspects such as how likely a safety control is to be implemented as designed, and, if it is correctly implemented, how likely it is to prevent a disruption, prevent transition to a hazardous state, etc. A set of safety controls that maximizes total control effectiveness should result in a habitat that is more resilient than one with a lower total control effectiveness. In our current work, we are using our simulation environment to evaluate this hypothesis. Control effectiveness only addresses how well the habitat responds to known and addressed hazards. Our second metric, *resilience power*, will estimate how effective a safety control may be at addressing hazards other than its specific targets. A set of safety controls that maximizes total resilience power should result in a habitat that is more resilient than one with a lower total resilience power.

We will use control effectiveness and resilience power in two ways: during design, to select the appropriate set of safety controls to embed in the habitat design so as to maximize resilience, and, during operations, to help select the appropriate safety control to apply in a specific context.

3.2 Situational awareness and autonomy

The development of our situational awareness is mostly affected by the restrictions of current and near-future technologies, and by the nature of the research questions that we would like to address. Here, we present a conceptual design of the health management system (HM) suitable for a SmartHab. The HM consists of a command and control system (C2), a data repository, and a distributed network of sensors and fault detection and diagnosis (FDD) components. One sensor and FDD component are encapsulated within each SmartHab subsystem. For example, the structural subsystem may include sensor components measuring the mechanical, thermal, and electromechanical properties of the structure, and an FDD component tasked with analyzing the sensor data to infer the health state of the structure. These data are sent to the data repository to make them accessible to C2 which, in turn, uses them to make decisions to ensure that mission goals are met. C2 can access current and past information regarding the state of all systems as well as the external environment, and it can select safety controls to be implemented.

Non-human (robotic) and human actors that can carry out activities as directed by the C2. Each agent type is associated with a set of actions. The various classes of activities can be thought of as algorithms, potentially including conditionals and loops, made out of action statements. The set of actions that can be performed by human agents is not the same as the set of actions that can be performed by robotic agents. For instance, actions that require advanced cognitive skills can only be performed by humans, whereas actions that require hauling heavy objects can only be carried out by robots. During the uncrewed mode only robotic activities can be performed. Some activities may require robot and human agents to collaborate.

Ultimately, achieving resilience requires that appropriate decisions are made to choose the proper safety controls. Decision-making may be manual (all safety-critical decisions made by humans), human-supervised (there is some automation, but safety-critical decisions are either made or approved by humans), or fully automated (all decisions made by algorithms). However, as we discussed in Section 2.2.2, "full automation" is beyond the capabilities of current technology, although it is our target. These limitations have affected our research goals regarding the HM.

Our goal is to understand what the HM requirements for a resilient space habitat are. We break this goal into three objectives:

- **Objective 1: Develop the ability to simulate the operation of hypothetical HMs.** We plan to develop the ability to simulate, in the context of the modular coupled virtual testbed and the cyber-physical testbed introduced in Section 3.4, hypothetical HMs with various attributes related to FDD, decision-making automation, and relevant constraints. For example, in our simulated environment FDD performance could range from omniscient to unaware, decision-making automation may span the range from manual to full automation, and computational capabilities may vary from existing spaceflight computing architectures to hypothetical architectures. With this capability, we will be able to carry out trade studies to rank existing technologies or to assess the merits of a hypothetical technology before investing in it.
- **Objective 2: Develop benchmark problems for automation algorithms.** We plan to develop a series of well-designed benchmark problems that would allow AI researchers to improve fully automated decision-making under space habitat constraints. For example, one could use such a benchmark problem to study the effect of various existing reinforcement learning algorithms on resilience for any choice of FDD performance and available computational capabilities. As another example, consider the possibility of demonstrating explainable AI technologies using a space habitat benchmark problem. We anticipate that we can engage AI researchers beyond our team by creating an easily accessible API for running our simulation environments, e.g., one that is compatible with Open AI's gym framework.
- **Objective 3: Develop reference scenarios for experimentally investigating the effect of human-machine interfaces on resilience.** In such experiments, one would fix the degree of automation, the decision-making algorithms, the computational capabilities, and the human-machine interface, and observe the behavior of human subjects and the performance of the space habitat. In this way, one can answer research questions like "for a given set of constraints, which human-machine interfaces are more effective?"

3.3 Robotic intervention and maintenance

A review of the systems considered by the Resilience Thrust, and an enumeration of ways that those systems could depart from a nominal state, let us identify a relevant set of actions that robots may be called on to perform in order to keep a SmartHab functioning safely. These actions in turn provide the motivations for our research foci.

As a few broad examples of common features that many such actions share: Components will need to be replaced in equipment both for routine maintenance and in case of unexpected failures, involving a range of manipulations and the use of many different tools, depending on how the equipment is designed. Many elements that robots need to interact with, from cargo transfer bags to layers of the habitat shell, will be made of flexible materials. Some large-scale operations (e.g., moving large items) will require the coordinated efforts of multiple agents; during uncrewed periods, these agents will all be robots, while during crewed periods, teams may be a mixture of robots and astronauts.

Developing a degree of dexterity for robots comparable to that displayed by humans, in order to give robots a general-purpose ability to wield any tools designed for human use, is a research challenge beyond the scope of this project. Conversely, designing a habitat where all possible operations could be performed using just one or two specialized tools is infeasible. Instead, for flexibility in a fleet of limited size, we take the approach of developing an interchangeable system of *modular end-effectors*[15-16]. With such a system, a single robot will be able to select and use the appropriate implement for a given situation from a predetermined toolkit. The generic interface for that toolkit will need to provide a number of features for the connection between the robot and end-effector sides, including electrical power, two-way communications, and (as discussed further below) a pneumatic line. Further, robots will need to be able to select and exchange new end-effectors as needed, with the connection providing the mechanical stability needed to carry out the end-effector's function while also allowing the robot to replace it solo.

End-effectors will include not just manipulators for affecting the world, but also sensor packages: robots will be called on to act as mobile sensors[17], to provide additional information needed by the SmartHab to diagnose and disambiguate hazard states, when the fixed sensor array is insufficient. Sensors may include examples such as microphone arrays for sensing leaks, radiation meters, air quality monitors, and structural interrogation systems.

While a suite of modular end-effectors will give robots the ability to deal with a range of situations, no set of specialized tools determined before a mission will be able to handle all possible situations that could arise; unanticipated needs are essentially certain to occur. A general-purpose manipulator is necessary for use in such cases. Here we are taking an approach from within *soft robotics* (i.e., robots fabricated from soft rather than rigid materials)[18]. In particular, we are exploring the use of pneumatically actuated soft grippers[19,20] for general tasks (hence the need for the pneumatic line in the modular end-effector interface as mentioned above). Soft grippers have the advantage of compliance, allowing them to conform to a range of possible target objects, as well as to handle delicate objects safely. One area in which soft robots are less effectual than traditional rigid ones is in the precision of their control. In contrast to rigid hardware with its well-behaved kinematics, soft robots move less predictably due to their elastic deformability and nonlinear material characteristics; controllers are often created through ad-hoc hand-designing by experts, in the absence of a universally applicable framework. Machine learning may provide a way of addressing this need, as a framework for automatically generating controllers for novel soft robots with arbitrary geometry. We are exploring approaches for using *learning for control*[21], together with new computationally-efficient approaches for continuum manipulator path planning, to enable and improve precise use of soft grippers for operational needs that are not predictable ahead of time.

Tasks that involve simultaneous operation over a large area or manipulation of objects beyond the capacity of a single individual (e.g., repairing larger-scale damage to the habitat shell) will require multiple agents to coordinate their efforts. Particularly in the case of astronauts working together with robot assistants, this coordination will need to take place with limited direct communication; as a practical matter, a human leading a robot team should not be expected to give each individual robot detailed instructions at every step of the way. We are developing methods for *implicit coordination* through shared environmental elements of a task[22], allowing a leader to simply act and the assistants to support their inferred intent.

To perceive and interpret the world around them, robots will use vision as a key sensory modality; vision remains an ongoing challenge for machines and a large active research area, but its utility is too great to set aside. *Vision in a SmartHab context* will be met with additional challenges: high-radiation environments can cause rapid degradation of CCD cameras, and interpretation of scenes involving deformable objects and materials adds complexity to the already difficult task of reliably recognizing objects and their poses under general conditions. We are developing approaches for accurate visual registration of the geometry of soft materials, with the expectation that camera performance will degenerate and a substantial fraction of pixels may be unreliable.

In addition to the above topics related to furthering the capabilities of the robots, we are investigating ways that SmartHabs and constituent equipment can be designed to facilitate operations by autonomous robots. By analogy to the field of human factors, this study may be termed *robot factors*[23], with the goal of engineering environments and interfaces that are "robot-friendly". At the lowest level, this involves ensuring to the extent possible that operations can be performed as easily as possible—*e.g.*, one-handed, with a pinch grip or other simple grasp, requiring minimal dexterity and precision.

3.4 Frameworks and testbeds under development to build capacity

To build the capacity to investigate the above research topics, we are developing three versatile testing environments that are intended to be used in a hierarchical manner including the: i) modular coupled virtual testbed, ii) control-oriented dynamic computational modeling platform, and iii) cyber-physical testbed. Developing these testbeds involves the entire team in assessing resilience, and thus is a major mechanism for integration of the work across the team.

3.4.1 Modular coupled virtual testbed

The *modular coupled virtual testbed* (MVCT) is a "plug-and-play" simulation environment that is meant to be used for examining resilience throughout the project. This virtual testbed will allow us to consider a wide variety of SmartHab configurations in order to study complex systems and various degrees of autonomy, assess control effectiveness and resilience power, identify vulnerabilities, determine how to set priorities, perform trade-studies, and so on. While a fully physical testbed would limit us to a small number of experiments, this virtual testbed can be exploited to greatly expand the number of research questions we address and scenarios that are considered.

Before developing the MCVT, we established a standardized notation, subsystem schema, and input/output format for our simulation models, along with relevant common terminology. Additionally, we adopted a design-structure matrix to track the numerous interactions among the subsystems in the SmartHab and support automatic assembly of these highly coupled models. These steps are essential to facilitate the systematic integration of subsystem models in a single simulation environment. With this approach, we can systematically expand our SmartHab and refine the models as needed to incorporate new knowledge (SG2) and new technologies (SG3) generated within the research.

Our initial realization of the MCVT includes low- to moderate-fidelity physics-based models, each with appropriate and relevant damageable/repairable subsystem properties. This approach supports scalability (e.g., for the cyber-physical testbed, real-time execution). With this simulation environment, we can incorporate research products from our team members, our industry partners, other STRI projects, related NASA research projects, etc. We aim to not lock ourselves to a specific idea of how something is currently done, but instead to provide an environment that enables new ideas, techniques and capabilities to be encoded in this framework to support a wide range of research.

3.4.2 Cyber-physical testbed

The *cyber-physical testbed* integrates physical testing and numerical simulation to provide a modular and reconfigurable testbed that has both the necessary complexity, and the necessary flexibility, to answer a range of research questions. Based on the concept of real-time hybrid simulation in the natural hazards research community[24,25], cyber-physical testing is essential to realistically examine emergent behaviors in a habitat system and the interactions between the computational and physical components. Such a testbed can be reconfigured based on the purpose of a particular study to include different subsystems, sensors or models.[26]

To deploy the cyber-physical testbed, we need to make strategic decisions about what to model physically and what to model computationally. Physical models of smart habitat subsystems will include key subsystems such as the structural system as well as the sensors for fault detection. Computational models from the MCVT are leveraged as much as possible. These models will need to be both *control-oriented*, in the sense that they have inputs and outputs to connect to the physical models and to other computational models, and *dynamic,* to capture and predict the changing states of key subsystems, as well as their interconnectedness, level of functionality, and resource requirements. Transfer systems will be needed, with appropriate controllers, to couple the physical and computational components.

Our virtual habitat will be able to grow in complexity (more subsystems and interactions) as the models expand in sophistication (more faults and features and higher fidelity) and encode new technologies (such as new robotic capabilities). These choices are being made deliberately and systematically based on the research questions we seek to address. Each configuration leverages the range of skills across the team for generating the key physics-based models needed to simulate the various subsystems in the habitat system. Those models are then systematically developed and integrated based on their physical (and data) interactions to bring those individual models together to build a virtual habitat system. System models will also be identified when possible based on physical specimens in the cyber-physical testbed. We are currently conducting a series of prototyping and learning experiments that are leading to the design and commissioning of the cyber-physical testbed.

3.4.3 Control-oriented dynamic computational modeling framework

The final environment needed for conducting the research on resilience is our *control-oriented dynamic computational modeling* (CDCM) platform. The CDCM enables us to automatically build a coarse dynamic model of the interconnected system (or generate many system models with different configurations) with the functionalities and features we intend to investigate. We can simulate thousands of realizations of that habitat model, and the performance of each configuration can be assessed by examining the ensemble of realizations. With this environment we can rapidly compare several alternatives to perform trade studies to weigh the pros and cons of different habitat configurations to make decisions about what system architecture is the best option for a given mission.

The diagram below provides an overview of the functions of the CDCM. In step 1, disturbances are simulated, as they can potentially cause the habitat to move from a safe state to a hazardous state. In step 2, various system configurations are defined, each with combinations of features to be compared to define a trade study to be performed. In step 3, the corresponding habitat system models are automatically constructed for simulation. Step 4 uses pre-defined performance metrics to quantitatively assess the performance of the habitat by considering the ensemble of thousands of realizations. Then in step 5, this process is repeated for each of the configurations to be considered in the trade study. In step 6, several of the highest-ranking feature combinations are selected and examined in greater detail for further study and design.

The CDCM framework will serve two purposes in the project: (i) rapid simulation to automate performing the trade studies; and, (ii) rapid simulation to support decision-making within the command and control modules.

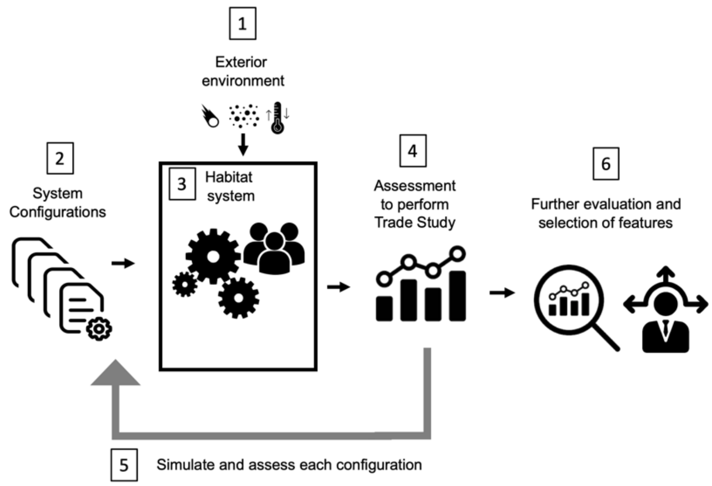

Figure 1. Diagram showing the functions and implementation of the CDCM for performing trade studies.

4. CLOSURE

Extraterrestrial habitat systems must operate safely and as intended under continuous disruptive conditions and with limited resources. The RETH research institute is tackling this scientific grand challenge by conducting research that will support the design and operation of SmartHabs, long-term habitats with built-in situational awareness and integrated decision-making and intervention capabilities, in these extreme environments. We are treating the habitat system as a complex system exhibiting unpredictable interactions and interdependencies. While our research is powered by our three simulation environments, the MCVT, CDCM and cyber-physical testbed, our research is not intended to design the best possible habitat system, but rather to learn as much as possible about maintaining desired operating conditions in these classes of complex systems. Our goal is to generate new knowledge to support resilient design, operation and management, while anticipating an evolving and growing habitat over time.

Furthermore, RETH*i* aims to contribute to NASA's mission to educate the next generation, while serving as a hub for world-class smart habitat research, project-based learning, and industrial outreach activities. We are exposing engineering students and faculty from participating institutions to a multidisciplinary culture that develops and applies state-of-the-art tools, enabling graduates to develop experience-based expertise in resilience, modeling, simulation and computational techniques.

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