Simulation-Based Assessment of Hazardous States in a Deep Space Habitat

Luca Vaccino[1], Kenneth A. Pritchard[2], Mohsen Azimi[3], and Shirley J. Dyke[4]
Purdue University, West Lafayette, Indiana, 47906

and

Alana K. Lund[5]
University of Waterloo, Waterloo, ON N2l 3G1, Canada

The progression of the Artemis missions is bringing us nearer to extraterrestrial surface habitation and the realization of a sustainable living environment in deep space. This requires that we improve our capability in the design and evaluation of a variety of protocols to mitigate and manage a variety of hazards. Given the near impossibility of in situ testing, computer simulation is a suitable tool for this task. The Resilient Extra-Terrestrial Habitats institute (RETHi) has developed a Modular Coupled Virtual Testbed (MCVT) to simulate measures to enhance resilience in an extraterrestrial smart habitat (SmartHab). MCVT is composed of several subsystems with damageable/repairable components, and is capable of modeling different disruption scenarios. Micrometeorite impact, fire, moonquakes, and nuclear leakage are included along with typical environmental disturbances such as dust accumulation and solar flux. For each of these disruption scenarios, the location, onset time, and intensity can be specified by the user. The order and the rate of the repair are also user-defined. Consequently, the effect of the damage propagates through different components and subsystems, potentially rendering the habitat unlivable. The goal of this paper is to investigate the use of the MCVT for studying a resilient SmartHab. By altering the initial conditions, certain input parameters, and repair prioritizations across several simulations for different disruption scenarios we demonstrate some scenarios in which simulation is an effective tool to support design. In the end, the lessons learned and the conditions that contribute to placing the SmartHab in an unsafe or unrecoverable state are identified, alongside with the best-practice emergency responses. These results form a framework for future studies into resilient SmartHab design via similar methods.

I. Introduction

THE near-future advent of long-term extraterrestrial surface habitats calls for a depth of research into safe and reliable system designs beyond what humanity has achieved to date. Designing habitats able to rapidly detect changes from the nominal state and recover from hazards is fundamental to preserve crew and resources in remote locations. The unique environments of the Moon and Mars subject potential habitats to numerous external disruptions that can quickly propagate to different subsystems and compromise mission success. Micrometeorite impacts, inhospitable pressures and temperatures, seismic vibrations, radiation, and dust are all among the many hazards which constantly threaten habitat and crew safety, alongside internal hazards such as fires and equipment.[1] Given the lack of practical experience in assembling and operating extraterrestrial habitats, and the infeasibility of in-situ testing to

[1] Graduate Research Assistant, School of Mechanical Engineering, 585 Purdue Mall, West Lafayette, IN USA 47906
[2] Graduate Research Assistant, School of Aeronautics and Astronautics, 701 W Stadium Ave, West Lafayette, IN USA 47907
[3] Postdoctoral Research Associate, School of Mechanical Engineering, 585 Purdue Mall, West Lafayette, IN USA 4906
[4] Professor, School of Mechanical Engineering, 585 Purdue Mall, West Lafayette, IN USA 47906
[5] Assistant Professor,University of Waterloo, Civil and Environmental Engineering Department, 200 University Ave W, Waterloo, ON N2L 3G1, Canada

assess design choices, a different approach is needed to gather the necessary knowledge. The ISS provides a testbed and educational example for many of the components surface habitats will incorporate, but testing in space is resource intensive, and in some cases will not be a suitable analog for planetary environments.[2] Space analog missions such as those conducted by NASA Extreme Environment Mission Operations (NEEMO) are a more accessible alternative to study the practices and challenges involved with new kinds of space.[3] The lessons learned from such analog habitats are an important piece of the puzzle, but still a faster and cheaper testbed is needed.

The Resilient ExtraTerrestrial Habitats Institute (RETHi) has done work toward developing further solutions to study resilient design in such environments. The basis of this paper is RETHi's modular coupled virtual testbed (MCVT), a virtual simulation environment containing a model of an intelligent extraterrestrial surface habitat (SmartHab) and a variety of possible disruption scenarios.[1] The MCVT can be used to study how choices in both physical habitat design and operational emergency response decisions can affect the propagation of disruptions. In this paper, we demonstrate the capabilities of the MCVT as a tool for simulation based SmartHab design via analysis of several disruption scenarios as case studies.

This paper is organized as follows: Section II provides details on the relationships between simulation-based design, the MCVT, and decision-making for SmartHabs. Section III explains the selected scenarios and discusses the results of simulation. Section IV concludes and outlines future work.

II. Background

In this section, the MCVT is introduced as a tool for the simulation of smart space habitats. Additionally, the importance of smart decision-making in space habitats is highlighted.

A. MCVT and Simulation-Based Design

The MCVT is a computational simulation environment composed of several subsystems, which capture the actual key subsystems of a space habitat. This system of systems model is meant to represent the complex interactions between those subsystems and potentially capture emergent behaviors due to the failure of some components in one subsystem.[1] Modeled subsystems include the structure (ST), structural protective layer (SPL), interior environment (IE), environmental control and life support system (ECLSS), power system (PW), and agent (AG). which acts on the orders of an automated health management system (HMS). The user can select from a suite of disruptive events inspired by those which might occur on the Moon or Mars, including micrometeorite impacts, moonquakes, fires, and coolant leakage. These disruptions are propagated through the relevant subsystems according to the parameters determined by the user, such as the intensity level (IL) of the disruption, the initial conditions, starting time of the event, and certain habitat design choices. The damaged components are detected via synthetic fault detection and diagnosis (FDD) and repaired according to the AG pre-defined priorities. In this work, the AG priorities are selected by the user so that it will be possible to investigate the impact of different choices. Ideally, a command and control (C2) would be responsible to making such decisions, potentially in cooperation with human operators in the habitat or on the ground. The agent itself and its capabilities are completely user-defined – it can be modified to account for a variety of assumptions. The amount of time it takes to repair damaged components, travel between locations, and its behavior are determined in the input variables. It is often used to represent a robot, but may be altered to simulate a human crewmember.

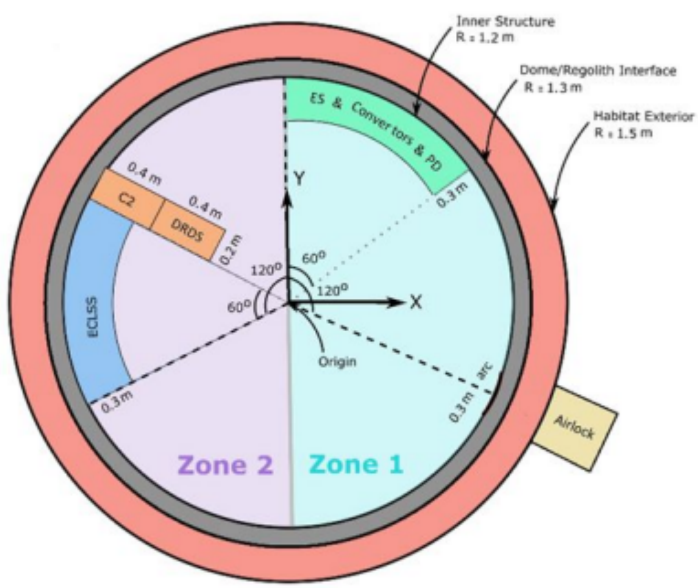

Figure 1. Dimensions of the scaled NRH.

Figure 1 shows the dimensions of the scaled notional real habitat (NRH) layout used for the MCVT. Free from the limitations of physical testbeds, the MCVT can be used to address a wide range of research questions and scenarios while taking into account some of the complexities of a SmartHab. Users have the ability to study the SmartHab at both subsystem and system levels. Potential applications of MCVT include demonstrations of new technologies and assessments of design resilience, which are the main goals of RETHi. In the future, tools like the MCVT may help researchers verify the design of SmartHabs under the intense demands and strict constraints of planetary surface environments.

Other efforts have made contributions to the field of space habitat design with simulation tools. As mentioned in the introduction and illustrated in Ref. 3, even practical, crew-in-the-loop testbeds such as analog habitats benefit from computational simulation tools. The study described in this paper involves the use of physics-based simulations for ECLSS and thermal control which can be easily manipulated and computationally controlled. Virtual reality (VR) based simulations, such as those developed in Ref. 4, strike a compromise between the human involvement of physical analogs and the accessibility of virtual testbeds. They allow users to study design choices in 3D pseudo-physical environments. The tool developed in Ref. 5 tackles the evaluation of habitat interior layout evaluation, a task one might also approach with VR. By quantifying various aspects of interior layout and accounting for mission constraints, the evaluation tool can cover a large quantity of layouts of without the need for manual CAD processing or human evaluators. As another example, Ref. 6 introduces a similar tool to be used for the design of habitats and other structures in extreme environments. This capability, applied to mission characteristics beyond the interior layout and structure of the habitat, enables engineers to make early design eliminations, rapidly adapt to changing conditions, make decisions with objective reasoning, and ultimately save on time and cost.

Simulation-based design (SBD) is clearly not a new idea to space habitat design or systems engineering in general, and it does not come without limitations. Ref. 7 identifies some of the challenges involved with and advantages of SBD for fault-injected, repairable models, including concerns with generalizability and accuracy. Ref. 8 further identifies limitations applicable to life support system models as well as some of the benefits of constructing a model for a specific research goal. The process itself of developing a system model is an effective tool in familiarizing new investigators with the intricacies and research needs of the systems they model. On the other hand, models and SBD are generally not universally applicable -- a model developed with a certain goal in mind may lack too much detail in certain areas to be informative outside of a specific domain. Computational models are at risk of software errors leading to unreliable results. To uniquely address these limitations, RETHi employs other testbeds that complement the MCVT: the control-oriented dynamic computational modeling (CDCM) framework for rapid simulations and data driven models, and the cyber-physical testbed (CPT), a real-time hybrid simulation environment being constructed to validate research methods.[1] The scaling of the MCVT dimensions is chosen to more or less match the size of the CPT. The work discussed herein focuses only on the MCVT, but future studies will exploit the complementary nature of these tools.

B. Space Habitat Decision-Making

The propagation of disruption scenarios in a SmartHab and ultimately the success or failure of a mission depend on the decisions made by the humans and/or autonomous systems responsible for maintaining critical systems. The decision-making involved in maintenance or repair courses of action is critical enough to heavily influence subsystem design. As identified in Ref. 1, proactive designing a resilient system architecture is one central approach to mitigating the long term impacts of disruptions, alongside effective situational awareness and robotic intervention capabilities. While the ISS and other missions have provided years of experience in in-flight repair, longer missions beyond Earth's orbit will stray farther from the helping hand of mission control, requiring more independence in maintenance capabilities.[9] This direction will necessitate new standards, procedures, and design considerations to keep systems working as intended. Modular systems with common subcomponents that lend themselves to repairability are one approach, but may increase the risk of common cause failures, exacerbated by the high 'infant mortality' failure rates of new component designs.[10] It is clear that few assumptions about system reliability can be carried from past missions into the realm of long-term planetary SmartHabs.

By utilizing simulation-based design (SBD), designers and modelers can address difficulties related to modeling faults and repairs. SBD addresses a range of challenges, including reducing simulation time, managing complex models, exploring various system architectures, and modeling a wide range of components. Additionally, the ability to inject various faults enables researchers to analyze how systems respond to failures.

Deciding how to respond after a disruption that puts a SmartHab into a hazardous state is no simpler than designing for resilience proactively. There are tradeoffs to any course of action, and a certain course may not always be identifiable as strictly better or safer than another. The MCVT contains its own user-defined priorities for how to address failures if multiple occur at the same time. Ref. 11 describes and discusses the importance of prioritizing for maintenance, repair, or expansion of an advanced life support system. To minimize risk to the habitat and any people inside it, system downtime must be held to the absolute shortest time possible. If multiple types of damage occur simultaneously, the order of repair must be selected appropriately to maximize safety. Even after decisions are made, the repair of complex, damaged subsystems is not an exact science. Important aspects of the damage may go unidentified, repairs may fail, and new types of damage may develop during the course of the response.[12] This complexity calls for an approach that is flexible and conscious of vulnerability throughout the repair process. Choosing one subsystem over another may allow some health metric to persist in an unsafe range for a greater amount of time. In extreme cases, there must be a choice made between the survivability of the habitat and the risk of death or injury to the crew.[13] Catastrophic disruptions are far from being outside the range of possibility, and changing mission

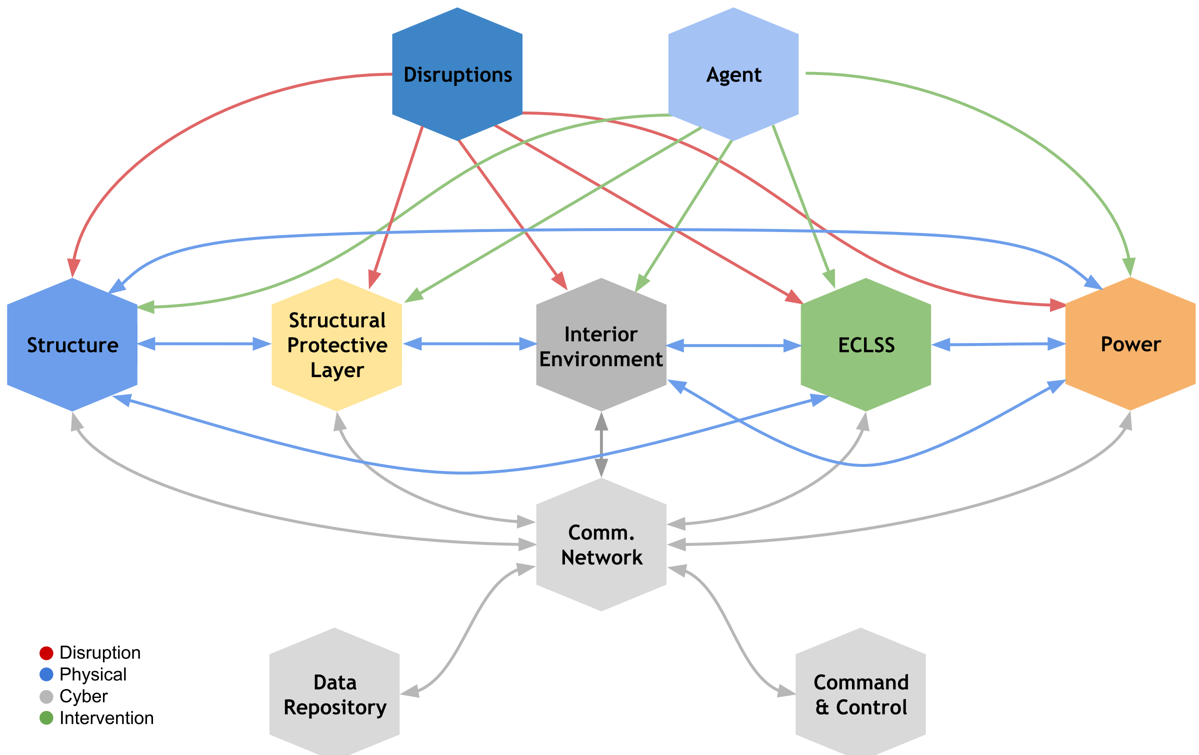

Figure 2. MCVT subsystem architecture.

objectives is an important part of the equation. Figure 2 represents graphically the interconnected relationships among the subsystems in the MCVT. The complex nature of these interconnections and the propagation of disruptions call for an accordingly well-devised response plan. This paper demonstrates how the MCVT and tools like it can be used in the study of SmartHab repair.

III. Simulations

This section demonstrates the capabilities of the MCVT modelling tool by investigating disruption scenarios in three simulation sets. In each, we identify system-critical behaviors, such as ambient temperature or pressure entering unsafe ranges, to assess the performance of the habitat. The first set focuses on the consequences of selecting various repair prioritization strategies after a micrometeorite impacts on the habitat. By choosing to repair certain components before others, the effects of the micrometeorite impact propagate differently through the system. In the second set, the initial disruption is also a meteorite impact, but it affects the nuclear and solar power generation system. In particular, in this set of simulations, we will focus on repairing the rate of dust accumulation on solar panels. As the agent is only capable of repairing a fixed amount of dust at a time, an increased rate of accumulation will cause the dust to become a more critical issue, hampering the ability of the solar power system to provide energy to the critical loads. In the third simulation set, we investigate the benefits of redundant temperature sensors during a period of faulty readings. The sensor readings are interpreted by either averaging the values or through a rudimentary voting algorithm, and the consequences of each strategy are assessed. In all the simulations the time has been scaled. One second in the proposed simulation plots corresponds to one minute in real life.

In the first and second sets of simulations, the agent actions are represented at the bottom of each plot. Each color corresponds to a different subsystem, as in figure 2. The unsafe region for crewed operations is highlighted in red.

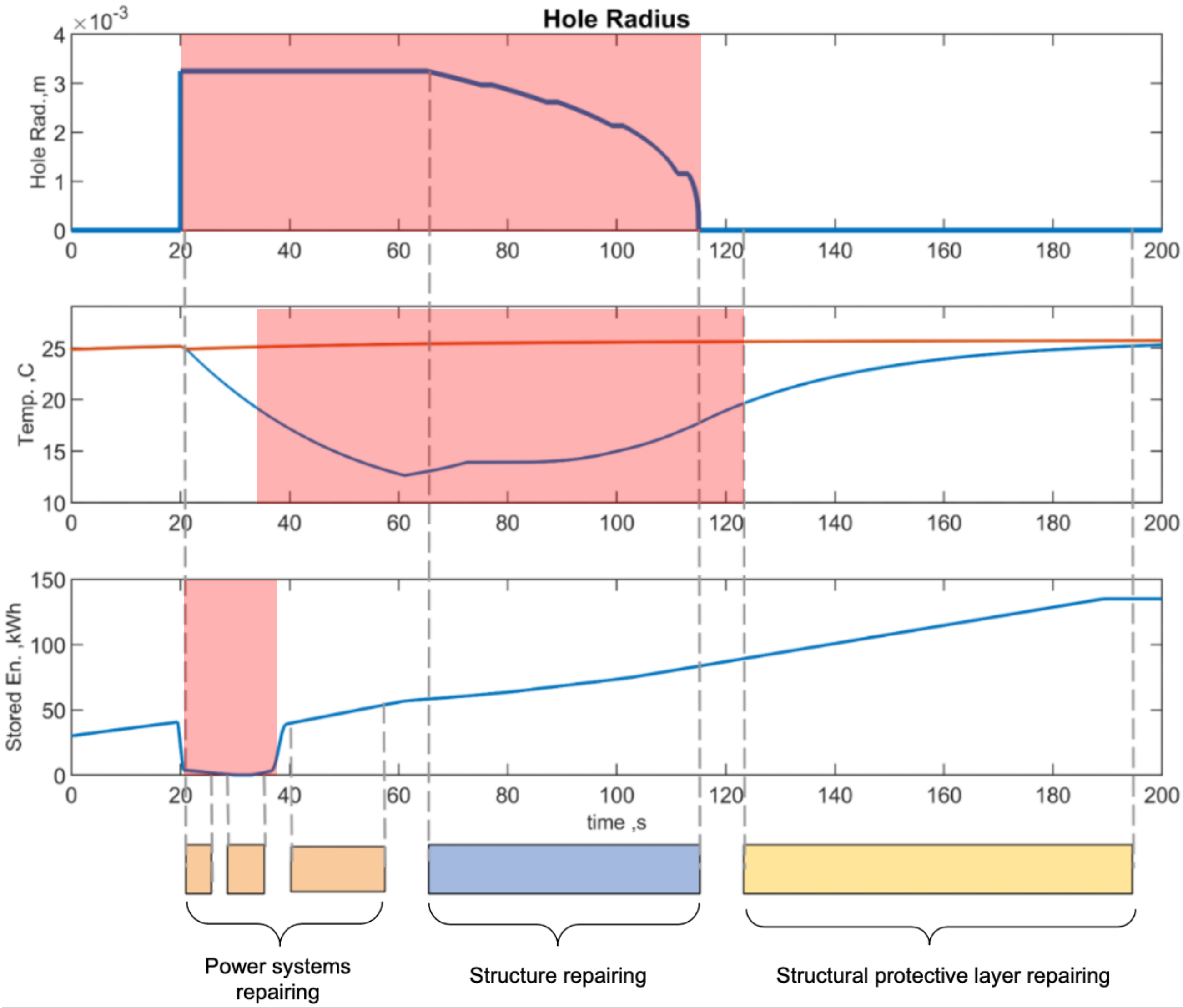

Figure 3. Simulation results for the first scenario and first repairing strategy.

A. Simulation Set #1

The first proposed scenario starts with the habitat in nominal operating conditions. The meteorite impact event happens very early at the beginning of the Lunar day. Considering that a Lunar day lasts 29 Earth days[14] , it is reasonable assume that the solar power energy is not available. Because of that, the available energy is provided only by nuclear power generator and energy storage system. After 20 seconds have elapsed from the start of the simulation, a micrometeorite with maximum damage effect strikes the habitat, penetrates the SPL and the ST, and the resulting debris damage converters number one and four and the energy storage system in PW. Converter one is used to deliver nuclear power to the systems and converter four controls the heating, cooling and critical loads of the ECLSS.

The micrometeorite impact causes an immediate pressure and temperature drop inside the habitat, which can be seen in Figure 3. The repair algorithm, in this case, prioritizes the repair of the nuclear power converter, which begins 27 seconds after the start of the simulation. While the agent is repairing the converter, pressure and temperature keep dropping without any ECLSS compensation. After power converter two is repaired, the agent is scheduled to next repair the power storage system (batteries), and this begins 35 seconds after the start of the simulation. Because the repair is performed, the stored energy is available again, but the critical loads required for ECLSS is not provided yet because the power converter four is damaged.

When batteries are repaired, the agent start repairing converter four, at a time 50 seconds after the start of the simulation. At this point the ECLSS temperature controller start to heat the habitat, to restore the temperature to the safe range. The pressure controller is supplying the same air volume that is flowing out of the habitat because of the hole. At this point, the temperature, reaches an equilibrium state, in which temperature is neither decreasing nor increasing. However, this temperature is still in the unsafe range, as can be seen in Table 1*.

Table 1. Safe temperature and pressure ranges for crewed and uncrewed operations.

Crewed operations		Uncrewed operations	
Temperature, C	18.3-26.6	Temperature, C	1.6-36.6
Pressure, Pa	$7 \cdot 10^4 - 1.01 \cdot 10^5$	Pressure, Pa	$6.5 \cdot 10^4 - 1.01 \cdot 10^5$

At time equal to 60 seconds, the agent starts repairing the hole in the ST. This operation requires iteration, due to the limited capability of the agent to carry materials needed for the repair. After five iterations, the hole repair is completed. In the meanwhile, since the leak area is decreasing, the temperature is gradually converging to the setpoint.

* Based on discussion with Sargusingh, M. (*NASA Johnson Space Center, Houston, TX 77058)* in September 2021.

The simulation ends at 200 seconds, when the temperature inside the two habitat zones reaches the setpoint.

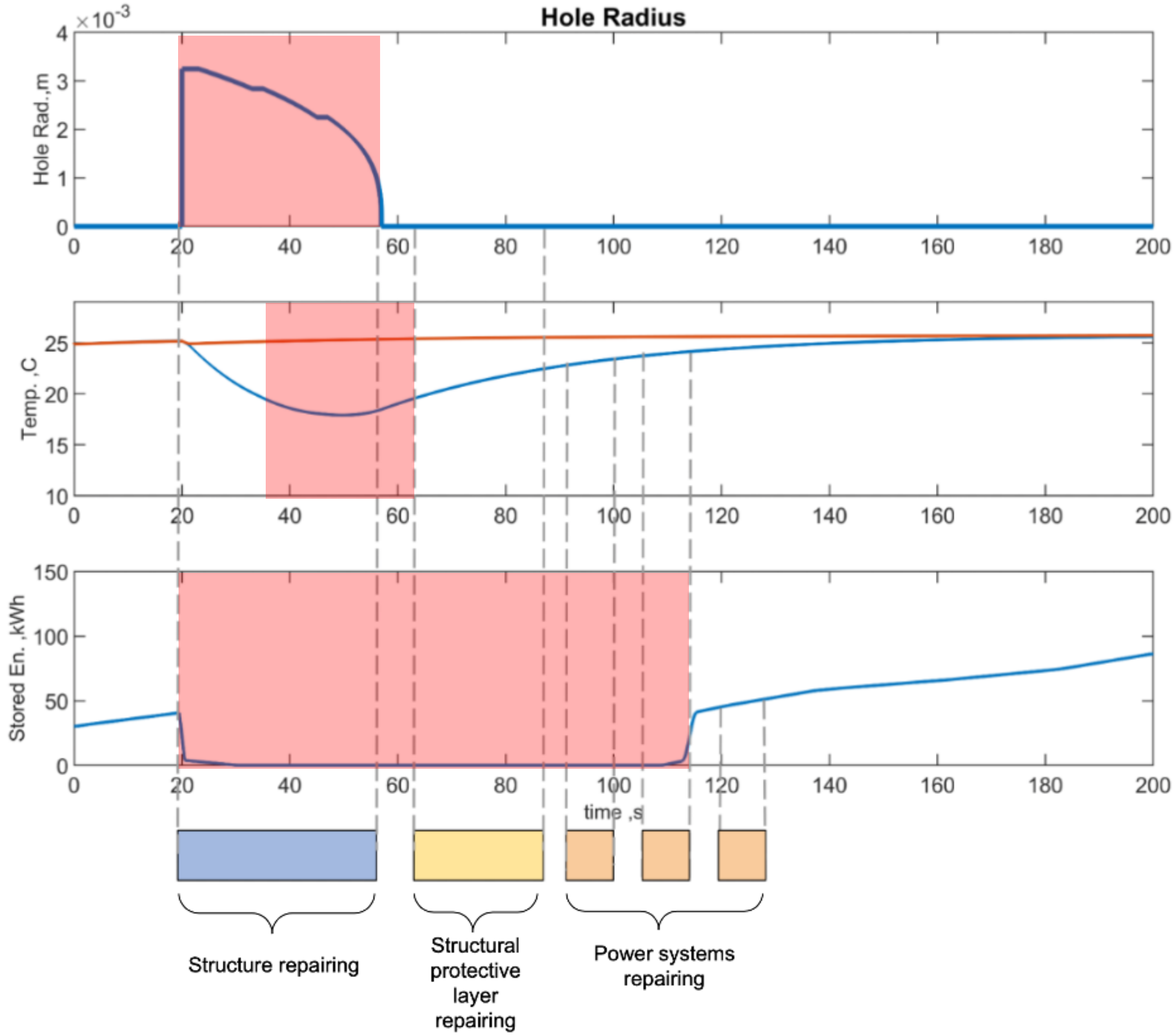

Figure 4. Simulation results for the first scenario and second repairing strategy.

In the second scenario, showed in figure 4, the initial disruption is the same as the previous scenario and only the order of the repair tasks changes. The first event of this simulation is a meteorite strike on the habitat after 20 seconds after the start of the simulation. As before, power converters two and four are damaged, as well as the batteries, ST and SPL.

As soon as the impact happens penetrating the ST and SPL, the ambient temperature and pressure start dropping. In this case, the repair strategy prioritizes the hole patching before repairing the power elements. After 70 seconds from the start of the simulation, the hole is successfully patched, and after 120 seconds the habitat structural system is fully restored, but the power is still not available, since the converters are not repaired. 140 seconds after the disruption occurs the power converter one is repaired, at which point the batteries are restored, and at 150 seconds the power storage is available again.

At 160 seconds the ECLSS power converter is repaired. The simulation ends at 200 seconds, when the temperature and pressure have returned to safe ranges for crewed operations.

This first set of simulations demonstrates that changing the order of repairs can improve mission success and crew safety. Note that in the second simulation the temperature exceeds the safe range for less than 40 seconds, while in in the first simulation an unsafe condition persists for around 100 seconds.This shows how an appropriate decision makng system can keep the crew and equipment safe for a longer time, using the same available resources.

B. Simulation Set #2

A second set of simulations further demonstrates the value of different strategies to deal with hazards. The first strategy is based on the assumption that a robot agent may have a limited carrying capability. In this case, the mission cost is reduced in the preliminary phase, because less payload needs to be transported to the space habitat location.

The goal of these simulations is to show how space shuttle cargo transport cost[15] can affect space habitats preliminary design decisions In the first simulation we will show what the limitation of this choice are on the mission safety.In the second simulation we will show the effects of using a robot agent with increased repairing speed and carrying capability. In this simulation set we will assume the same repair order, and we have the same distance between the habitat and resource storage.

Both scenarios start when the sun is at the intermediate position between the sunrise position and highest sun position during the Lunar day. Here we assume that the habitat has an ambient temperature of 40°C, due to a previous fire event during uncrewed operations. At this point, the thermal management system starts cooling the habitat, to make it ready for crew ingress. After 2 seconds have elapsed from the start of the simulation, however, a meteorite impacts the nuclear panels located outside of the habitat. This disruption affects the nuclear power availability, and the dust generated decreases the solar PV arrays efficiency. Under these circumstances, we simulate the consequences of two different recover strategies, which differ based on the agent size and reflect its ability to carry different loads and tool sizes. In the first scenario we simulate the repair action of a small agent, which requires that it perform several steps to restore the solar PV arrays. The second case considers a recovery strategy of a larger agent, which will complete the repair only in one step. The consequences of both recovery strategy are simulated and compared.

The results of the first repairing strategy, based on lighter and smaller robots, are shown in Figure 5. The dust removal process on solar panels takes 120 seconds. During this period, the habitat temperature exceeds the limit for crewed operations shown in Table 1.

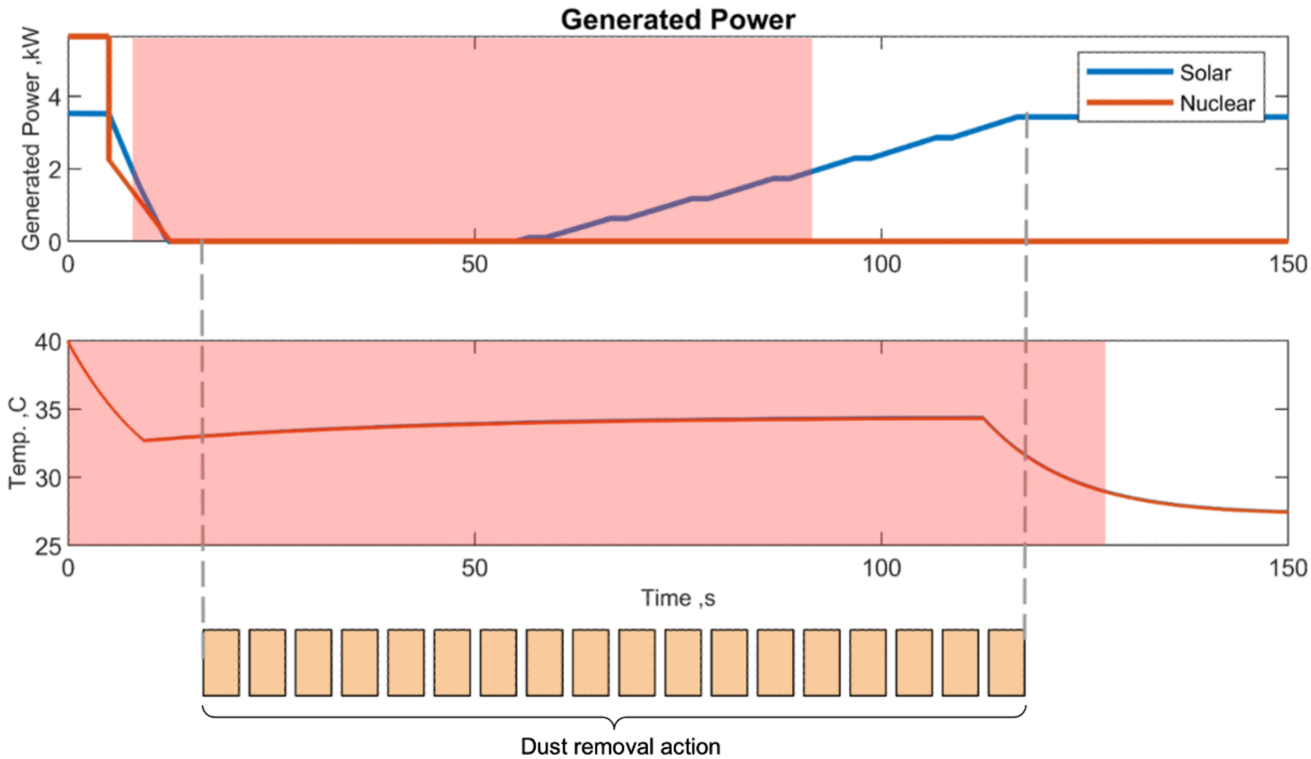

Figure 5. Simulation results for the second scenario and first repairing strategy.

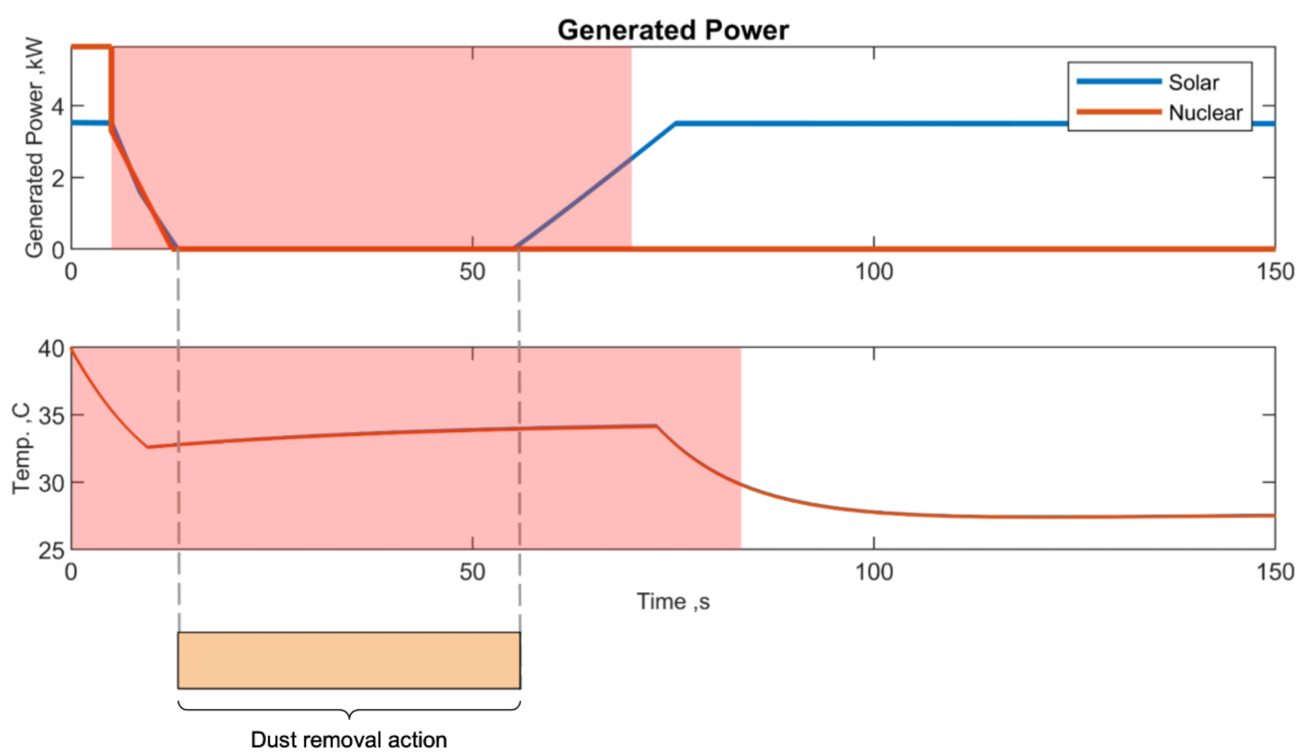

Figure 6. Simulation results for the second scenario and second repairing strategy.

The second simulation is using a reparing agent able to carry heavier tools and perform faster operations. In this case, the repair action takes 70 seconds, and the temperature is restored inside the safe ranges reported in Table 1 after 20 seconds from the repair completion.

C. Simulation Set #3

For the third simulation set, we assess two different rudimentary methods of sensor fusion. Sensor fusion is a deep field, the intricacies of which are beyond the scope of this paper. Regardless, this case study is presented as an example of how SmartHab awareness influences the effects of a disruption. The scenario here is that one zone of the habitat employs three redundant thermocouples, which were artificially introduced to the MCVT architecture for this simulation. The signals provided by these redundant sensors can be fused either by simple averaging or by a 'voting' algorithm where the readings of the two closest sensors are averaged and the third sensor is omitted. The ECLSS is instructed to maintain a temperature between 18°C and 22°C.

In the Figures 7a and 7b, one of the three thermocouples has malfunctioned and sends a constant signal of 0°C, while the other two remain operational with noisy readings about the actual ambient temperature. The *averaging* approach, shown in Figure 7a, leads the ECLSS to act as if the temperature is about two-thirds of the actual value. As a result, the temperature maintained is about 10°C higher than the target range. The *voting* approach, shown in Figure 7b, omits the reading of the faulty sensor by recognizing that a majority of the sensors have a different signal. The ECLSS is provided an accurate temperature reading and functions normally, despite the disruption.

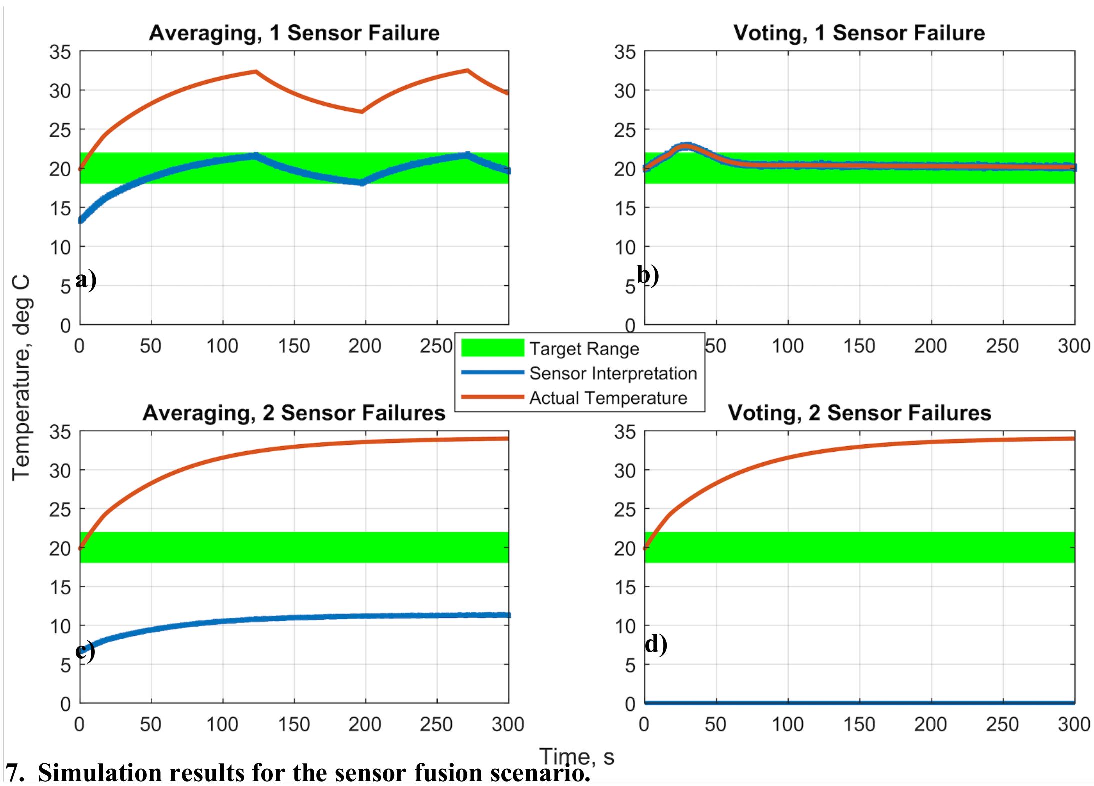

Figure 7. Simulation results for the sensor fusion scenario.

In Figures 7c and 7d, two of the three thermocouples have malfunctioned. The *voting* approach (Figure 7c) now interprets the majority faulty signals as correct, causing the ECLSS to heat indefinitely. The temperature inside the habitat reaches a limit when the maximum ECLSS heating load balances out with the effect of the external temperature.The *averaging* approach (Figure 7d) now provides the more accurate reading, albeit still causing the ECLSS to heat excessively into an unsafe temperature range. As neither fusion method can be seen to be clearly better than the other, the ideal solution calls for flexibility, improved awareness of performance, and consideration of all possible failure cases. A direct, overconfident approach is insufficient. The actual algorithms that govern the fusion of IE sensors in a SmartHab would be much more sophisticated, and failures should be readily identified and repaired.

This illustrative example is intended only to demonstrate the positive or negative consequences of selecting different designs.

IV. Conclusions and Future Work

This paper demonstrates the use of the MCVT to assess decision strategies and resilience in SmartHabs. Testing different repair and recovery strategies ahead of time via SBD allows designers to reduce mission costs and increase crew safety. As demonstrated in Section III, the MCVT provides several ways to explore design choices in simulation. Simulation Set 1 demonstrates the consequences of varying repair priorities after a disruption occurs. Simulation Set 2 demonstrates how SBD can be used to assess the importance of including certain system capabilities, which is important to understand under design constraints. Lastly, Simulation Set 3 demonstrates how proactive design choices and SmartHab awareness influence the effects of a disruption. The flexible nature and accessibility of SBD make such tools valuable to the future progression of space habitat design.

Areas for future work include deeper exploration and analysis of individual disruption scenario responses, expanding the scope of the simulation set to perform a larger-scale trade study, combining the use of MCVT with RETHI's other simulation tools, and working to extract generalizable design principles via simulation.

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References

[1]Dyke, S., Marais, K., Bilionis, I., Werfel, J., and Malla, R., "Strategies for the design and operation of resilient extraterrestrial habitats," *SPIE Smart Structures + Nondestructive Evaluation Conference*, Virtual, 2021.

[2]West, W., Samplatsky, D., Gentry, G. J., and Duggan, M., "ISS as a Test Bed for Exploration ECLS Technology Development and Demonstration," *47th International Conference on Environmental Systems*, ICES-2017-027, Charleston, South Carolina, 2017.

[3]Zu Qun, L., Crues, E. Z., Bielski, P., and Moore, M., "A Simulation Based Investigation of High Latency Space Systems Operations," *AIAA Aviation Forum*, Denver, Colorado, 2017.

[4]Cecil, J., Krishnamurthy, R., Huynh H., Tapia, O., Ahmad, T., and Gupta, A., "Simulation Based Design Approaches to Study Transportation and Habitat Alternatives for Deep Space Missions," *IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, SMC.2018.00251, Miyazaki, Japan, 2018.

[5]Simon, M. A., and Wilhite, A. W., "A Tool for Automated Design and Evaluation of Habitat Interior Layouts," *AIAA SPACE 2013 Conference and Exposition*, San Diego, California, 2013.

[6]Lagarde, T., and Lipiński, M. B., "Human outpost creation using multiple data sets and computational design," *51st International Conference on Environmental Systems*, ICES-2022-181, St. Paul, Minnesota, 2022.

[7]Goswami, K. K., "Design for dependability: A simulation-based approach," Ph.D. Dissertation, Department of Computer Science, University of Illinois, Urbana-Champaign, Illinois, 1994.

[8]Jones, H. W., "How Should Life Support Be Modeled and Simulated?" *47th International Conference on Environmental Systems*, ICES-2017-88, Charleston, South Carolina, 2017.

[9]Rohrig, J. A., O'Neill, J., and Stapleton, T. J., "In-Flight Maintenance Design Philosophy for Gateway and Deep-Space Life Support Systems," *49th International Conference on Environmental Systems*, ICES-2019-305, Boston, Massachusetts, 2019.

[10]Jones, H. W., "We Can't Count on Repairing All Failures Going to Mars," *46th International Conference on Environmental Systems*, ICES-2016-113, Vienna, Austria, 2016.

[11]Nakane, M., and Miyajima, H., "Dealing Order Determination for Various Simultaneous Device Failures for Material Circulation Control in ALSS by Hierarchical Approach." *51st International Conference on Environmental Systems*, ICES-2022-176, St. Paul, Minnesota, 2022.

[12]Jones, H. W., "High Reliability Requires More Than Providing Spares," *49th International Conference on Environmental Systems*, ICES-2019-14, Boston, Massachusetts, 2019.

[13]Trujillo, A., and de Weck, O. L., "Contingency Operations for Failures in a Generalized Mars Transit Architecture," *48th International Conference on Environmental Systems*, ICES-2018-235, Albuquerque, New Mexico, 2018.

[14] NASA's Goddard Space Flight Center, "100 Lunar Days - Parts I and II", https://svs.gsfc.nasa.gov/12739

[15]Jones, H., "The Recent Large Reduction in Space Launch Cost," *48th International Conference on Environmental Systems*, ICES-2018-81, Albuquerque, New Mexico, 2018.