Role of Cyber-Physical Testing in Developing Resilient Extraterrestrial Habitats

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ABSTRACT

Extraterrestrial long-term habitat systems (henceforth referred to as habitat systems) require groundbreaking technological advances to overcome the extreme demands introduced by isolation and challenging environments. A habitat system must operate as intended under continuous disruptive conditions. Designing for the demands that challenging environments will place on habitat systems (e.g., wild temperature fluctuations, galactic cosmic rays, destructive dust, meteoroid impacts, vibrations, and solar particle events) represents one of the greatest challenges in this endeavor. This engineering problem necessitates that we design and manage habitat systems to be resilient. System resilience requires a comprehensive approach that accounts for disruptions through the design process and adapts to them in operation. As the habitat system evolves—growing in physical size, complexity, population, and connectivity—and diversifies in operations, it must continue to be safe and resilient. In this endeavor, we should take advantage of lessons learned in developing civil infrastructure responsive to catastrophic natural hazards, autonomous robotics platforms, smart buildings, cyber-physical testing, complex systems, and diagnostics and prognostics for intelligent health management. This study highlights the importance of system resilience and cyber-physical testing to address the grand challenge of developing habitat systems.

INTRODUCTION

The quest to send humans to the moon—this time to stay—and Mars has engaged the world's space community. This modern-day space race will eventually lead to a long-term settlement. In 2015, NASA released its plan for establishing long-term settlements on Mars stating, "We seek the capacity for people to work, learn, operate, and sustainably live beyond Earth for extended periods of time" NASA (2015). Humankind faces new challenges as we begin to move beyond the Earth's relatively benign surface and out into space. But are we ready for establishing a permanent human settlement outside Earth?

Extraterrestrial habitat systems require groundbreaking technological advances to overcome the unprecedented demands introduced by isolation and extreme environments. A long-term habitat system (henceforth referred to as *habitat system*) must function as intended under continuous disruptive conditions and with limited resources. Designing for the demands that extreme environments will place on habitat systems, such as wild temperature fluctuations, galactic cosmic rays, destructive dust, meteoroid impacts (direct or indirect), vibrations, and solar particle events, presents one of the greatest challenges in this endeavor Garcia (2018), Malla (2015), Crusan (2018), and Brown (2015). Exacerbating this scenario, habitat systems represent a class of complex systems with unpredictable interactions and interdependencies, Liu (2011), Dorogovtsev (2008), and Zanudo (2017).

Ensuring the long-term safety and *resilience* of a habitat system is extremely complicated by the interconnectedness, uncertainty, dynamic performance, and resource requirements of their different subsystems and of the environments in which they will function. Despite many accomplishments in resilience analysis of engineered and non-engineered systems, Massaro (2018), Gao (2016), Sommer (2017), Meyer (2018), and Sheffi (2007), resilience-oriented design of complex engineered systems—space systems in particular—remains almost untouched, Youn (2011). Researchers have tried to make sense of resilience by connecting it to three conceptual capacities a complex system can exhibit: absorptive, restorative and adaptive, Muresan (2015) and Vugrin (2011). Others have identified principles of resilience as a sort of roadmap used to establish this abstract quality in an indirect way Muresan (2015). *Yet, we lack a well-established design framework and technologies needed for habitat systems, to successfully achieve and maintain the desired level of system performance over an extended period of time.* Innovative approaches are needed to develop and incorporate principles of resilience to reduce, capture, model, and control emergent behaviors that habitat systems will exhibit.

Cyber-physical testing offers immediate and significant advances in the development and demonstration of techniques needed to enable transformative smart autonomous habitat systems and related technologies that will adapt, absorb and rapidly recover from expected and unexpected disruptions to deep space habitat systems without fundamental changes in function or sacrifices in safety. Cyber-physical testing integrates physical testing and computational modeling which will enable researchers to refine their understanding of *a safe boundary of system performance* subject to extreme dynamic conditions, usually with a significant reduction in time and cost.

The objectives of this study are to highlight the importance of (1) resilience as a comprehensive approach that accounts for habitat system disruptions through the design process and adapts to them in operation, and (2) cyber-physical testing to address the grand challenge of developing a resilient habitat system. The organization of this paper is as follows: **Section 2** provides a brief review of the extreme environmental conditions on the moon and Mars; **Section 3** reviews lessons learned—in civil engineering—from past natural disasters and the importance of resilience as a key to avoiding catastrophic engineered system failures; and **Section 4** provides an overview of the enabling role of cyber-physical testing in developing a resilient habitats system.

A BRIEF REVIEW OF ENVIRONMENTAL CONDITIONS

Extraterrestrial environmental conditions are different from those on Earth for many reasons. Some differences between Earth, the moon and Mars are obvious in comparisons of their physical characteristics in **Table 1**.

Beyond the protection of Earth's atmosphere and magnetic field, elements of the habitat system will be subjected to extreme conditions as well as anticipated and unanticipated hazards. Designing for the demands that extreme environments will place on long-term deep space habitat systems, such as wild temperature fluctuations, galactic cosmic rays, destructive dust, meteoroid impacts (direct or indirect), vibrations, and solar particle events, presents some of the greatest challenges in this mission. An effective design philosophy requires a comprehensive assessment of the risk (i.e. likelihood and consequences) associated with the design of habitat systems. Here, we briefly review some of these environmental conditions.

Table 1. Physical comparison of Earth, the moon, and Mars.

Property	*Earth*	*Moon*	*Mars*
Mass (kg)	5.97×10^{24}	7.35×10^{22}	6.42×10^{23}
Spherical radius (km)	6378	1738	3393
Equatorial gravity (m/sec)	9.80	1.62	3.71
Temperature extremes (°C)	-89 to 58	-233 to 123	-153 to 20
Atmospheric pressure (kPa)	101	3×10^{-12}	0.4 to 0.87
Surface magnetic field (G)	0.31	$\leq 2 \times 10^{-3}$	$\leq 5 \times 10^{-4}$
Sidereal rotation (day)	0.997	27.322	1.03

The lack of (or existence of an insignificant) atmospheric pressure and magnetic field on the moon (or Mars) creates hazardous environmental conditions (e.g., radiation and extreme temperature fluctuations) and raise challenges for the design of the habitat system. On the surface, there are high-energy galactic cosmic rays (GCR) composed of heavy nuclei, protons and alpha particles, and the products of solar particle events (SPE), which are a flow of high-energy protons due to solar eruptions. The former is relatively constant or changes on time scales of days to years (e.g., the 11-year solar cycle), however the latter is highly variable, on the scale of minutes to a few days, in response to events on the Sun. Radiation-related hazards impose some critical design requirements for habitats due to their severe impacts on the survivability of humans and plants, Arena (2014), as well as the functionality of mechanical/electronic components and materials, Benaroya (2018).

In addition, on the moon and Mars, temperatures can range from the extremely cold, hundreds of degrees below freezing to hundreds of degrees above freezing. For instance, at the Apollo landing site, the temperature range was from 111 °C to -171 °C resulting in major thermal expansion and contraction Hickson (1970). For habitat systems, extreme thermal fluctuations will lead to material fatigue, especially where the frequency of the diurnal cycle is relatively short. On the moon, the temperature transition from daylight to nighttime is almost 5 °C/hr.

On the moon and Mars, dust-related hazards will adversely impact any human settlements. Thus, for habitat systems, the development of an effective mitigation strategy for dust-related hazards is considered critical. Adverse impacts of dust-related hazards include the malfunction of mechanical and electronic devices, total/partial loss of power generated by solar panels, inhalation hazards, and the obscuration of optical windows and lenses Mazumder (2010). Astronaut Eugene Cernan, Apollo 17 commander, stated that "… one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be …" Stubbs (2005). Dust related hazards have been investigated by many researchers Gaier (2005), Greeley (1991), Toon (1977), Landis (1996), and Landis (2000).

For habitat systems and their critical infrastructure subsystems, ground vibrations represent a serious design consideration. In May 2018, NASA's InSight was launched to Mars carrying three instruments designed to peer through Mars's shell and investigate its interior, including a seismometer that will detect seismic activities, Voosen (2018). An important question that NASA hopes to answer is whether Mars is still a dynamic planet with quaking rumblings like our own earthquakes? On the moon between 1969 and 1972, Apollo astronauts placed seismometers at their landing sites, known as the Apollo Passive Seismic Experiments (APSE). On the lunar surface, researchers identified four different types of ground vibrations: (1) deep moonquakes, (2) thermal quakes, (3) vibrations due to the impact of meteorites, and (4) shallow moonquakes Bell (2006), shallow moonquakes (a.k.a. high-frequency teleseismic or HFT events) are an important hazard for a lunar habitat because they last a remarkably long time. For comparison purposes, earthquakes usually end within minutes. Conversely, moonquakes can continue for hours Lammlein (1977). Furthermore, hypervelocity meteorite impacts present serious threats to habitat systems due to their speed, concurrent with the lack of (or very thin) atmospheric shielding. In addition to the seismic vibrations resulting from the impact itself and their effects on the habitat system, a meteorite penetrating a habitat module (a direct hit) has the potential to cause a catastrophic failure of the entire habitat system.

RESILIENCE IS KEY TO AVOIDING CATASTROPHIC SYSTEM FAILURES

The safety profile of a habitat system and its critical infrastructure is markedly different from that of its terrestrial counterparts and critical infrastructure systems. While scientists and engineers have learned much about extraterrestrial environments, it should be expected that these environments pose many unanticipated hazards. Complexity and tight-coupling are likely to prevail in many aspects of the habitat system and these two features both make identifying and preparing for hazards even more challenging and more important*: when failures do occur they may rapidly cascade through the habitat system*.

Lessons Learned from Past Critical Infrastructure Disasters

In Japan, the Fukushima nuclear disaster was initially caused by a magnitude nine underwater earthquake. Although only about 100 people were killed as a direct result of this event, almost 19,000 died by the ensuing tsunami, Pescaroli (2015). The tsunami damaged Fukushima Daiichi Nuclear Power Plant and caused a radiation hazard in the entire Fukushima Prefecture. After the power plant's core leaked radiation into the sea and the surrounding area, almost 200,000 people were evacuated from the area. In addition, dams, utilities, and coastal defensive units were destroyed, which significantly complicated the recovery plan, Pescaroli (2015). Three major impacts of this disaster, related to public health, global economy, and global energy strategy, were: (1) chronic physical diseases Maeda (2017) and severe psychological distress among the residents from evacuation areas Hasegawa (2016); (2) more than US$500 billion direct and indirect costs to the global economy, Green (2015); and (3) significant decrease in international investments in nuclear energy, Froggatt (2011) and Kim (2013). An important lesson learned from this catastrophe and other similar natural disasters (e.g. Hurricane Katrina in 2005 and more recently Hurricane Maria in 2017) is, *if resilience is not a major consideration for development and management of interconnected complex systems, the devastating and costly consequences of natural disasters can become matters of local, national, or even global security.*

System Resilience is Necessary for a Long-term Human Settlement

The environmental conditions are extreme and it is inevitable that things will go wrong, often with little or no warning, whether it is a component failing, an operator or robot taking the wrong action (or not taking the correct one), or a dysfunctional interaction between correctly functioning components that results in undesirable behavior. *Ultimately, a habitat system must be designed to be resilient*. Habitat systems will involve complex—and in many cases tightly-coupled—combinations of hardware, software, and humans. Yet, resilience is not simply robustness or redundancy, Gao (2016), Maghareh (2018), Uday (2015). Instead, it requires a comprehensive approach that accounts for disruptions through the design process and adapts to them in operation. *As the habitat system evolves—growing in physical size, complexity, population, and connectivity—and diversifies in operations, it must continue to be safe and resilient.*

Currently, most conceptual habitat designs are grounded on reliability-based design philosophy (passive capacity) and therefore, may become unsafe subjected to unanticipated disruptive events. Reliability is interpreted as the probability that a system performance meets its marginal value subjected to anticipated variability. These techniques are driven by avoiding or minimizing the occurrence of anticipated failures and faults in the system. While these efforts have made significant operations such as the International Space Station (ISS) possible, the philosophy behind these approaches is not suitable for habitat systems. Two important differences exist, including: (i) high reliability is inefficient and costly; and (ii) disruptions are inevitable, yet difficult to predict. Reliability-based design is, therefore, focused on maintaining a particular pre-determined level of system-level performance, even when subjected to extreme disruptive events, and providing system redundancy is often the answer. Moreover, these approaches do not adequately account for the range of anticipated and unanticipated disruptive events that can impact the habitat system throughout its *lifecycle*. Nor do they allow for consideration of unforeseen emergent behaviors of such complex systems, or the potential for degradation over time, Maghareh (2019).

A Control-theoretic Approach to a Resilient Habitat System Design

In a control-theoretic approach to a resilient habitat system design, the resilience of a habitat system translates to maintaining the system performance using passive controls (preventive capability) and adaptive controls (interventive and mitigative capabilities) within *a dynamic safe boundary of system performance*, see **Figure 1**. During operation, the dynamic safe boundary of system performance, the current state, and the trajectory of the habitat system performance are determined/estimated by a *health management system*. The health management system will make preventive, interventive and mitigative decisions while also learning and predicting future behaviors, needs, and responses.

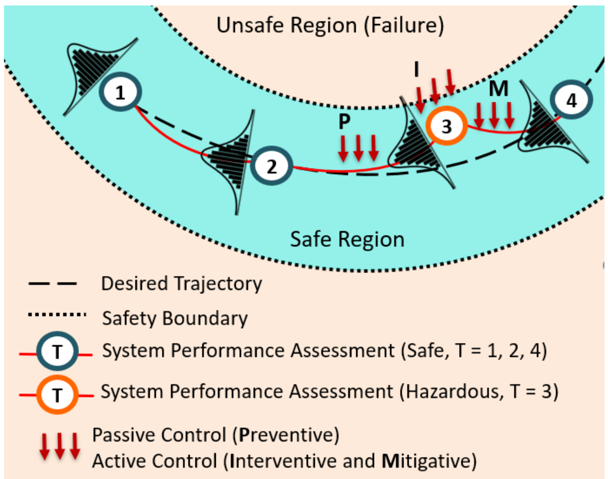

Figure 1. A control-theoretic view of a resilient habitat system.

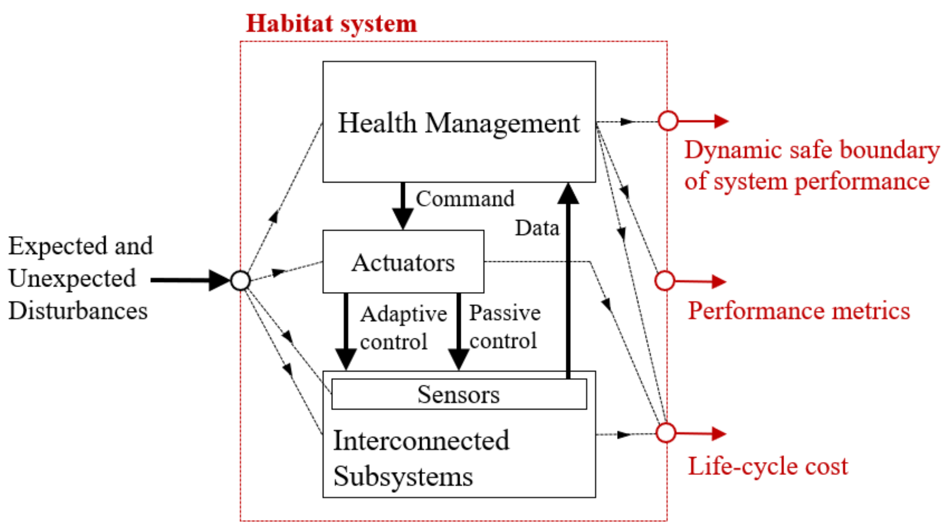

Figure 2. System architecture of the control-theoretic approach to a resilient habitat system design.

For instance, the control-theoretic approach to a resilient habitat system design can be further simplified to a multi-objective optimization problem, in which the three objectives are to (1) maximize *system plasticity*, (2) maximize *system rapidity*, and (3) minimize *lifecycle cost*, Maghareh (2019). Here, system plasticity quantifies the ability of the habitat system to prevent performance loss, diagnose malfunctions and damages, assess system-level performance, and intervene during a *hazardous state* to restore its performance. A hazardous state is a system state that, if not corrected, will lead to performance loss. Rapidity quantifies the ability of the habitat system to restore performance in a timely manner. Lifecycle cost is attributed to the sum of all costs associated with the development and implementation of passive and adaptive controls.

Indeed, a platform—whether computational, physical, or cyber-physical—is required to validate and refine different design approaches, such as the control-theoretic approach shown in ***Figure 2****, and evaluate the dynamic performance of a habitat system design subject to expected and unexpected disturbances.*

CYBER-PHYSICAL TESTING OF HABITAT SYSTEMS

In the civil and mechanical engineering community, novel and cost-effective cyber-physical testing approaches are emerging as a powerful and cost-effective technique for realistic examination and validation of physical components and techniques. In the community, cyber-physical testing goes by many names, such as hybrid simulation, dynamic sub-structuring, dynamic virtualization, pseudo-dynamic testing. However, the underlying features common to all of these approaches include: 1) leveraging of established knowledge and understanding about the physical world, to gain insight into the behavior of physical systems for which we have limited prior knowledge; and 2) coupling of physical and computational models in a way to realistically include their dynamic interactions. Cyber-physical testing of civil infrastructure systems played an important role in enabling new engineering concepts to be developed and validated under more realistic conditions, contributing to advance the practice of earthquake and multi-hazard engineering around the world, expanding the types of experimental testing that is possible to improve resilience and reduce risk in the built environment, Gomez (2015).

In hybrid simulation of a structural system, the system is partitioned into primarily two types of domains: computational domains containing reliable and accurate models of the majority of the structural system (i.e. *computational subsystem*), and physical domains comprising physical specimens of those parts of the system that are novel or difficult to model computationally (i.e. *physical subsystem*). These subsystems interact with each other, through sensors and actuators at their interfaces. A *transfer system* enforces the necessary boundary conditions between the subsystems. This approach allows larger and more complex experiments to be conducted than would be feasible otherwise, Gomez (2015).

The complexity profile of a habitat system and its critical infrastructure is different from that of its terrestrial counterparts and critical infrastructure systems. Habitat systems are noticeably more complex and interconnected, and achieving breakthroughs in these systems requires development of innovative techniques and technologies, and validation of the methods. *We currently lack an innovative design framework and technologies needed for deep space habitat systems to successfully achieve a suitable level of resilience and function autonomously under—and transition between—a variety of unmanned and manned operating modes*. *It is due to the fact that a realistic* *examination of a large-scale habitat system subject to different combinations of the hazardous conditions provided in* ***Section 2*** *would either be impossible or cost hundreds of millions of dollars to run a single experiment.*

Establishing a high-fidelity cyber-physical testing platform is essential for examining emergent behaviors in a habitat system, as a complex interconnected system. Cyber-physical testing offers immediate and significant advances in the development and demonstration of techniques needed to enable transformative smart habitat systems and related technologies that will adapt, absorb and rapidly recover from expected and unexpected disruptions without fundamental changes in function or sacrifices in safety. Similar to hybrid simulation, cyber-physical testing of habitat systems integrates physical testing and computational modeling which will enable researchers to evaluate different design approaches, *usually with a significant reduction in time and cost.*

In the case of the control-theoretic approach to resilience, for instance, a cyber-physical testing platform enables researchers to refine their understanding of the safe boundary of system performance subject to the extreme environmental and hazardous conditions, see **Figure 3**. More specifically, the platform will enable researchers to (1) model dynamic reconfiguration of the habitat system during different scenarios (e.g., disruption or growth); (2) represent different combinations of expected/unexpected disturbances (e.g., radiation exposure, or loss of atmosphere); (3) develop and validate effective health management frameworks; (4) incorporate and evaluate new passive and adaptive capabilities over time; and (5) inform trade-studies (e.g., design concepts).

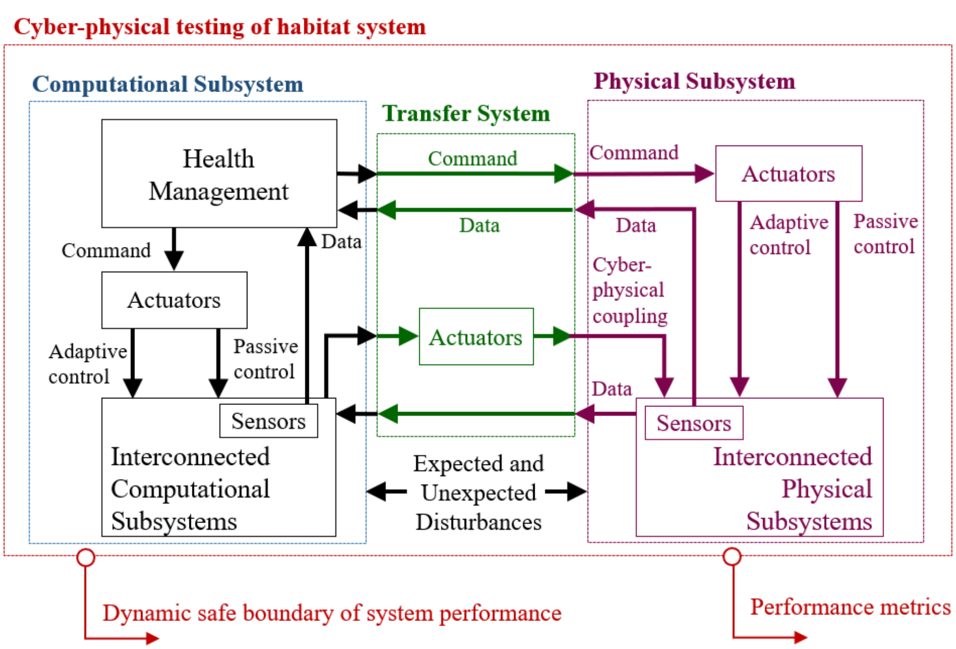

Figure 3. A cyber-physical architecture to validate and refine the control-theoretic approach to a resilient habitat system design.

Resilient ExtraTerrestrial Habitats research institute

The Resilient ExtraTerrestrial Habitats research institute (RETHi) has been established to develop the technologies needed for resilient extraterrestrial habitat systems. In RETHi, we are currently in the process of designing a novel cyber-physical testing platform on which (1) to validate and refine the control-theoretic approach to a resilient habitat system design, (2) to develop and apply methods evaluating the performance of integrated health management models, algorithms and architectures, and eventually (3) to design a resilient habitat system. Such a cyber-physical testing platform will be reconfigured based on the purpose of a particular study to include different subsystems, sensors or models. It will also enable an analysis of manned and unmanned conditions and changes to the habitat system size and functionality as it evolves over time. Automated decision making techniques will be studied by either imposing or simulating various disruptions representing realistic situations.

Our cyber-physical testing platform is essential for examining emergent behaviors in habitat systems and the interactions among the computational and physical subsystems. The physical subsystem of our habitat system will include key subsystems and sensors for fault detection. The computational subsystem will be control-oriented and coupled with the physical subsystem. The cyber-physical testing platform will enable us to model dynamic reconfiguration of the habitat system during different distributive scenarios, incorporate and validate new features, functions, passive and adaptive controls over time and simulate the (accelerated) passage of time.

CONCLUSION

For habitat systems, resilience is a key contributor to success. These systems will involve a complex and tightly-coupled combination of hardware, software, and humans, embedded in extremely challenging environments. Countering these challenges and achieving breakthroughs in the design process of resilient habitat systems require innovative techniques, such as cyber-physical testing of interconnected habitat systems. This study highlighted the importance of (1) resilience as a comprehensive approach that accounts for habitat system disruptions through the design process and adapts to them in operation, and (2) cyber-physical testing to address the grand challenge of developing a resilient habitat system.

ACKNOWLEDGEMENTS

This work was supported by a Space Technology Research Institutes grant (number 80NSSC19K1076) from NASA's Space Technology Research Grants Program and the Resilient Extraterrestrial Habitats project, funded by the Purdue University Office of the Provost, New Horizons program.

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