A Method for Self-Healing System Integration within Human Habitation Systems

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Abstract

This document serves as a summary of the creation of a method that supports and enables the development, integration, evaluation, and selection of self-healing systems within deep space habitats. We begin with developing the inherent motivation and desire for the inclusion of self-healing systems within space habitats: the problem with traditional methods of fault recovery and how they fail in a space habitat context. The intrinsic links between the concept of the self-healing system, Prognostics and Health Management, and affiliated areas of research are then shown to prove the relevance of this thesis' work to the PHM Society. The research plan is then laid out fully, beginning with the initial architecting of the baseline system of interest, generation of promising self-healing architectures, development of an analytical model to investigate faults, failures, and promising self-healing architectures, approaches to trade said self-healing architectures, and finally, showcasing how a selection process could be handled for a user-defined optimal architecture to be integrated within a habitat of choice. Preliminary results will be presented here. Finally, the novelty of the problem and approach is showcased specifically, along with contributions to the field of PHM, but also self-healing system development, and resilience engineering as a whole.

1. Introduction and Motivation

Recently, there has been an increasing interest in revitalizing cis-lunar and deep space exploration by a variety of entities, such as SpaceX, NASA, and other industry leaders (Goodliff et al., 2023) (SpaceX, n.d.) (Yarlagadda, 2022) (Drake, Hoffman, & Beaty, 2010). These plans are explicitly investigating the human exploration of space to develop a cis-lunar economy; as such, there is a particular focus on technology development for human habitation systems. These habitats will be highly removed from traditional supply lines that habitation systems on earth rely on, while also dealing with hostile environments above and beyond what terrestrial buildings are designed for (Burke, Rucker, Chai, & Chappell, 2024) (Dede, 2022). Faults, failures, and degradations will occur inevitably within such a habitat. These habitats should be capable of autonomous diagnostics, prognostics, recovery, and learning of system performance without human influence throughout the duration of a mission (Harris et al., 2022).

A system with self-healing capabilities would meet the needs of such an autonomous habitat. For this dissertation, a self-healing system is defined as a system that has the intrinsic capability to autonomously detect, diagnose, predict future performance, recover, and learn from faults as they occur (Psaier & Dustdar, 2011) (Ali Naqvi, Astekin, Malik, & Moonen, 2021). This thesis looks at the architecting and tradespace exploration of the self-healing system, focused on sensing, diagnostics, early prognostics capabilities within a space habitat context. Extensibility of this research into other fields and use-cases is also of interest.

Now, there is a wealth of various approaches that can potentially satisfy these core desires within a habitat. Sensing, Diagnostics, Prognostics, Recovery Methods, and System Verification and Validation are all booming areas of research (Hwang, Kim, Kim, & Seah, 2010) (Li, Verhagen, & Curran, 2020) (AlKuwaiti, El-Sayed, Farag, Al-Durra, & El-Saadany, 2024) (Trothe, Shaker, Jradi, & Arendt, 2019) (Hua, Lazarova-Molnar, & Francis, 2022). As such, with the ever evolving landscape, there is a desire to develop an agnostic framework to investigate promising self-healing architectures among the myriad of potential acceptable architectures. This thesis develops such a method, and implements the method onto a deep space habitat to show the value of Self-Healing capability being integrated within this context.

2. PROPOSED RESEARCH PLAN AND PRELIMINARY FINDINGS

To develop this method, there are two major areas of research that are of primary interest to this dissertation:

1. The capability to repeatedly and rapidly quantify performance improvement due to self-healing integration within a habitat system
2. The capability to leverage this quantifiable improvement to evaluate and trade potentially satisfactory architectures, across a variety of architectures and fault scenarios

These two research areas are preliminarily investigated using a smaller scale "toy problem", which will be a traditional office building. Once the two research areas are thoroughly investigated, the knowledge gained will inform and develop the overarching methodology to be established. This methodology will then be implemented on a Mars Surface Base, to show how the method is agnostic to the specific use-case, and how it can be extended to any system that requires self-healing capability.

2.1. Research Area 1

To answer research area one, a baseline architecture of interest must be defined. Nominal operational modes and scenarios are defined and captured, along with fundamental requirements of the HVAC system within a traditional office building. Faults of interest are defined, and an analytical model is leveraged to simulate nominal and faulty performance. Looking at literature, a promising self-healing architecture for integration within the baseline system can be generated. This architecture will be integrated within the baseline system for comparison to faulty operation. Key metrics, such as time of recovery, resource waste mitigation, maximum degradation point, etc, will be extracted from all simulations to show a general improvement of performance due to self-healing capability integration. This experimental research area was captured within an MBSE environment, supporting the flexibility and extensibility of the method. Showcasing this improvement via simulation methods supports our research area one as complete: we can quantifiably and rapidly demonstrate improved performance within a habitation system by introducing self-healing capabilities.

2.2. Research Area 2

With a rapid way to quantify performance of a self-healing system during early stages of design, various potentially satisfactory architectures can be implemented across a variety of fault scenarios for final evaluation and trade. With multiple, potentially contradicting, performance metrics of interest, we suspect that a Pareto optimal set of architectures will appear, and that some final end designer will be able to select the ideal architectural alternative for their use-case. Completing this area provides the final insight required to fully develop this methodology, and apply it to a hypothetical Mars surface habitat.

2.3. Application of the Method

Finally, with the method defined and substantiated by the completed research areas, it can be implemented to investigate and select an optimal self-healing architecture for a Mars surface habitat. The procedure for this application is represented in Figure 1.

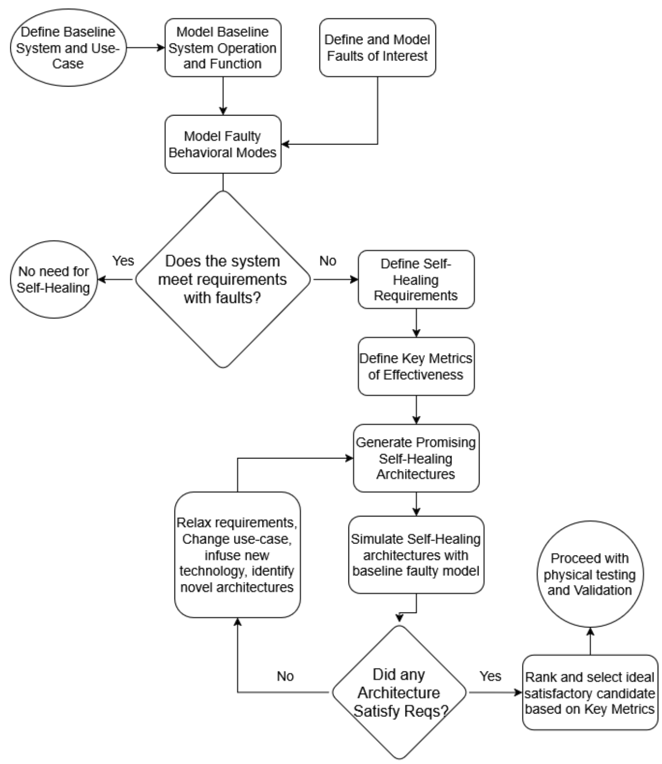

Figure 1. Proposed Self-Healing Integration Methodology

2.4. Preliminary Results

As of this writing, research areas one and two have been investigated, and results have been found. For brevity's sake, we will summarize the findings here, but more in-depth discussions on our findings are being written up for publication in the near future. The systems have been architected, with requirements, fault scenarios, and analytical models defined within SysML and Modelica. Simulations have been completed through baseline, faulty, and self-healing enabled scenarios, leveraging promising self-healing architectures found within a wealth of literature.

To begin, the baseline system of interest is a traditional office building, with a pre-validated analytical model coming from the Modelica Buildings Library (Wetter, 2009) (Frank, Kim, Cai, & Braun, 2018).Operational parameters are manipulated to simulate operational faults within the model. Promising self-healing architectures are then integrated within the faulty model to extract performance metrics, such as energy consumption and occupant comfort parameters, like room temperature. Various architectures are then analyzed to show variation in these parameters, and allow trading of architectures.

Self-healing architectures of interest were broken down into five major areas for this dissertation: Sensing, Diagnostics and Prognostics, Recovery Mechanisms, Verification of Recovery, and Online Learning, informed by (Ali Naqvi et al., 2021). The focus of this thesis was on sensing, diagnostic, and prognostic methods. Two different sensing configurations, and three different diagnostic and prognostic methods were investigated, resulting in six different architectures being evaluated within the traditional office building.

	Energy Consumed	Room Temp.
Simulation Based	Architecture 1	Architecture 2
Rules Based	Architecture 3	Architecture 4
Support Vector Machine	Architecture 5	Architecture 6

Table 1. Architectural Combinatorial

These six architectures represent Quantitative, Qualitative, and Process History Based diagnostic methods, leveraging two different data streams for diagnostics and prognostics approaches. These architectures were implemented within the analytical model, where the self-healing architecture was allowed to modify operational parameters of the system as necessary to affect a recovery of the system from a degraded state. Performance metrics were extracted from this analytical model for final evaluation and trade.

The results of integrating these six promising architectures are found below. Architectures 2, 3, 4, and 5, fundamentally failed to recover the system from its fault modes within the acceptable amount of time, as such, they were removed from these results. Architectures 1 and 6 were deemed fundamentally acceptable. Each architecture was investigated over two faults, both operational in nature. These faults (F1 and F2) represent an incorrect HVAC on/off schedule, and an inappropriate thermal setpoint respectively.

No architecture here is presented as the optimal selection, that decision would be left to the system designer, as both acceptable architectures has their merits. However, with this data,

	Arch 1		Arch 3		Arch 6	
	F1	F2	F1	F2	F1	F2
Energy Waste Mitigated (kWh)	2266	2037	1273	1534	1875	1769
Max. Degradation Improvement (kWh)	91	67	91	67	91	67
Time of Recovery (Days)	6	11	8	9	12	11

Table 2. Results for Research Areas 1 and 2

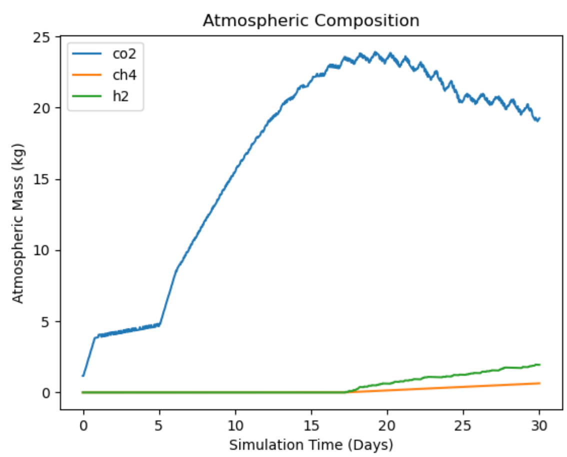

Figure 2. CO2 Scrubbing Fault with Self-Healing Redundancy

we can see that the capability for intelligent trade of self-healing architectures is possible utilizing this method. Thus, the methodology can be implemented onto the Mars surface habitat to show the rigor and flexibility of the method.

We are in the process of implementing this methodology onto a Mars surface habitat. SIMOC, a Scalable, Interactive Model of an Off-World Community (Team, 2023) (Greythorne & and Staats, 2024) is being leveraged as an analytical testbed for methodology implementation. This is a pre-validated, agent based model that leverages a resource-exchange approach to simulate ECLSS performance. SIMOC serves as the analytical testbed for this demonstration. Architecting of this system has been completed within an MBSE environment, capturing fundamental requirements, performance metrics, and fault scenarios of interest. Shown in Figure 2 are the results of including an oxygen generation failure within the system with a simple rule-based, diagnostic module affecting a redundant system as a self-healing architecture. Various self-healing architectures have been defined, and evaluated across various fault scenarios for final trade.

3. NOVELTY AND EXPECTED CONTRIBUTIONS

This dissertation proposes a novel methodology for the development, integration, evaluation, and selection of a self-healing habitat, comprised of sensing, diagnostics, prognostics, recovery, verification, and learning components. This method is agnostic to the potential satisfactory methods proposed, as well as the underlying system of interest. As such, it is highly flexible, extensible, and improves as each of the constituent technologies improve. This methodology is formulated on a traditional office building, showing value on more mundane and terrestrials systems. This methodology is then extended to a deep space habitat to show its flexibility, robustness, and extensibility. Further applications, such as implementation of such a method on energy grids, cyber-security systems, maritime systems, and automotive systems are also of concern in this dissertation. Another point of novelty for this dissertation is the direct comparison made between novel diagnostic and prognostic approaches. Rules Based, Simulation based and AI/ML based diagnostic and prognostic methods are compared head-to-head despite their inherent differences.

4. ACKNOWLEDGMENT

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