Wireless Power and Data System for Integrated System Health Management of Systems Operating in the Harsh Environment of Deep Space

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ABSTRACT

Large and complex deep space platforms such as the Deep Space Habitat (DSH) being developed by NASA will require a robust, on-platform, Integrated System Health Management (ISHM) function. Currently the DSH is contemplated to be stationed at the L2 Lagrangian point outbound from the lunar orbit. This will provide a vantage point of the back side of the moon as well as to serve as a jumping off platform for manned trips to Mars, the Moon, or near Earth asteroids. The ISHM function includes the monitoring, diagnostics, prognostics, and failure mitigation strategies and capabilities for any viable failure modes of the DSH. To evaluate a prototype of this approach, NASA has assembled a full scale, ISS derived, DSH prototype at the Marshall Space Flight Center (MSFC), involving a wired ISHM sensor network of over 80 sensors located at various points where early system failure mechanisms may be detected and analyzed. However, it is anticipated that a wired, distributed architecture could involve many pounds of complex cable harnesses and connectors, along with the commonly encountered problems of accessibility, flexibility and maintainability. In the high likelihood that modifications or upgrades are needed, these complexities result in higher design and build cost along with increased operational costs as in-flight anomalies occur that could require the addition of different sensors or different sensor locations. To address these issues, the ISHM team at MSFC is studying a wireless, distributed architecture with on-platform, advanced prognostic and diagnostic capabilities. The approach being considered is based on the X-33 ISHM system which consisted of hardware identical remote health nodes (RHN) and a central vehicle health management computer. Each RHN was very flexible and reprogrammable to enable it to interface directly with all the health monitoring sensors. For application on the DSH, modifications to the RHN are being considered. These changes and resulting upgraded capabilities are described in this paper. As ISHM sensor technology gets smaller, more robust, and includes wireless interfaces for communication and power, the approach will be to connect these wireless sensors by adding state-of-the-art wireless technology to the X-33 developed RHN. This wireless approach eliminates connectors and cables, thus reducing development, installation and life cycle costs while improving reliability and flexibility of the ISHM systems.

1. DESCRIPTION OF ISHM ON THE DSH

As we move into deep space and establish long life systems for human occupancy, the attributes of ISHM systems become more valuable and border on being an enabling capability. In the case of the DSH prototype being considered for long life at the L2 Lagrangian point, parked in Cis-Lunar space, a large amount of sensing, diagnosing, and prognostication will be required. The state of health data and the algorithms that drive ISHM functions will be crucial to the survivability of the crew and the assurance of mission success at the lowest life cycle cost. These ISHM algorithms will involve structural health monitoring including the effects of micrometeoroid and orbital debris (MMOD) hits, monitoring of accumulated radiation dosage, and air quality monitoring along with other human protective systems such as the Environmental Conditioning and Life Support Systems (ECLSS). To feed these algorithms with system states of health (SOH) information will require numerous types of sensing, analyzing, and prognosticating elements. Because of the large physical size of the facility, these elements will be separated at significant distances in a network that must be extremely reliable as well as flexible and maintainable. This paper discusses the types of data needed to detect the onset of the several failure mechanisms, along with the diagnostic and prognostic algorithms that will assure the maintenance of a safe and functionally healthy system. The backbone of the ISHM system will be the sensors, along with several RHN boxes that enable end to end availability of all pertinent data needed to assess and control the overall state of health of the DSH facility. The specific design of the first DSH is still to be determined but will likely be based on heritage from the International Space Station (ISS) because much thought and investment has gone into that asset already and program re-use will be highly desirable. Figure 1 shows the concept that NASA is considering that uses the ISS laboratory and the multipurpose logistics module (MPLM) connected by a tunnel to serve as living quarters with all the essential elements for habitation, including a capability to grow green leafy plants for salad-type food. On the other hand, Figure 2 shows a futuristic structure that looks like the Star Trek science fiction version of a DSH. In either instance one thing is very clear; they both have a need for integrated system health management which will be critical for the long term support of human presence in deep space.

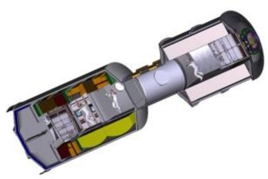

Figure 1. ISS Derived

Figure 2. Fiction Version

The possibility of abort, or mission abandonment, from the L2 Lagrangian orbit in Cis-Lunar space is not a trivial matter, making time to criticality (TTC) of utmost importance. Therefore, accurate monitoring of individual, as well as integrated systems states of health, along with diagnostics and prognostics related thereto is paramount to the viability of such an endeavor. Assuring that the life support environment is monitored and maintained constitutes only part of the equation. The ability to prognosticate and deal with future changes in that environment is equally necessary. The ISS-derived prototype being evaluated by NASA is populated with sensors dealing with determining states of health (SOH) and state of health trends that drive preemptive fault mitigation strategies and algorithms. This is necessary to assure the total monitoring and SOH understanding of the afore mentioned structural, communication, thermal, air quality, space radiation attributes, and the complete environmental conditioning and life support hardware and software over its full, functional, cradle to grave life. This not only drives the overall safety and reliability of the DSH but is the primary factor determining its life cycle cost.

To sense all the parameters that feed into the failure detection algorithms, the DSH prototype at MSFC presently consists of 84 various sensors that are highly distributed throughout the facility. These ISHM sensors are sampled by the data system on a two second sampling interval and data are analyzed according to the algorithm shown in Figure 3.

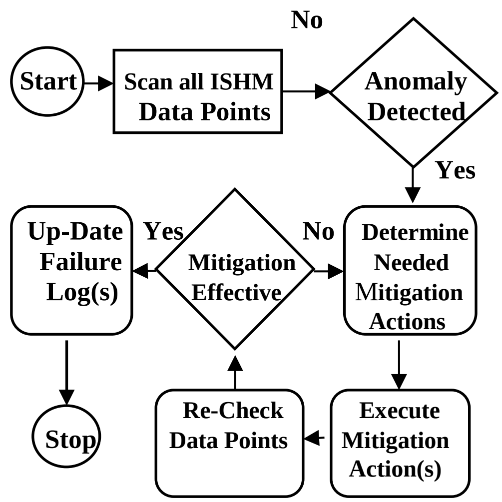

Figure 3. Failure Detection and Analysis Algorithm

The sub-tier algorithms noted in the diagnostic and prognostic boxes are specifically designed to accommodate the myriad of failure types and failure mechanisms that may arise. They are based on the failure modes and effects analyses (FMEAs) developed by the subsystem design engineers along with the fault management (FM) criteria established for the program. One basic assumption is that these algorithms are exhaustive and that all possible failures will be detected and mitigated in some fashion, including the possibility of mission abort and abandonment of the DSH if necessary. A data log of all triggers of the fault detection and analysis algorithm will be maintained. The major life critical subsystems of the DSH are shown below.

Critical elements of failure mechanisms are:

- Pressure vessel temperature and heat distribution
- Pressure vessel micrometeoroid and orbital debris hits
- Attitude determination and/or control
- Ability to communicate with Earth
- Air quality including O2 and/or hazardous gases
- Cabin temperature and rates of change
- Cabin air pressure and rates of change
- Aggregate of space radiation levels

An obvious engineering concern, and a major motive for the writing of this paper, is the consideration for the complexity of the sensor networks and associated cable harness. One very valuable lesson learned on previous programs, including the X-33, is that complex sensor cable networks are unreliable, heavy, intrusive, and expensive to modify. The application of a wireless system based on the X-33 developed RHN and the more recently upgraded REU should significantly improve the system reliability and cost by eliminating unnecessary sensor cable harnesses and reduce complexity. The result will be a very flexible design that lends itself to easy changes made necessary through growth in system complexity, parts obsolescence, or subsystem failures. Even after the DSH is placed in service at a deep space location such as the L2 Lagrangian point, the ISHM system based on a wireless sensor network will easily accommodate architectural changes as needed.

2. DESCRIPTION OF THE RHN

2.1. X-33 Generation 1 RHN Description

In the 1990s, NASA began development of a reusable launch vehicle (RLV) called the X-33 space plane. The integrated vehicle health management (IVHM) system for the X-33 consisted of a pair of host processors and 50 Generation 1 (Gen 1) Remote Health Nodes (RHN) distributed around the periphery of the X-33 to collect data from a variety of sensor types, (Garbos, Childers, & Jambor, 1997, and Garbos, & Mouyos, 1998). The RHN's interface to the health sensors and amplify, filter, and sample sensor signals before converting the data to digital format. Next, they analyze and perform some local prognostics decisions and store the data. The data is then packed with other information and tagged (e.g., ID and time sample) and transmitted to the vehicle health management (VHM) central processor.

The DSH will require a considerable amount of sensing, diagnosing, and on-platform prognostication to predict and ensure facility availability and safety. Because of the DSH size and possibility of on-facility maintenance and upgrading, a distributed ISHM architecture is proposed using wireless remote electronic units (REU's) derived from the RHN and shown in Figure 4 installed around the platform and interfacing to the state-of-health sensors. As discussed elsewhere in this paper, the wireless REU's were developed by NASA under the Extreme Temperature SiGe ETDP program, (Cressler, 2008, and Berger, Garbos, & Cressler, 2008, and Garbos, 2011) and are therefore much more robust and reliable for deep space use than the original RHN units, shown in Figure 5, developed for the X-33 program.

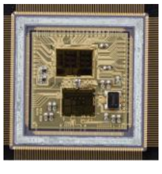

Figure 4. REU

Figure 5. RHN

The Generation 1 RHN was an 11 kilogram box that dissipated 17 watts of power. The mixed-signal data acquisition unit was assembled from a combination of commercial integrated circuits and custom hybrids for the analog front-end arranged on three cards interconnected by ribbon cables. On one end of the box, a pair of large multi-pin connectors provided the sensor interface. On the other end, a pair of optical connections provided a redundant interface to the host computers. The RHN communicated with the hosts via a token-ring network topology, and power was provided through a +28 VDC bus.

The original RHN design sought modularity by combining multiple types of sensor interfaces into a single hardware implementation that was usable throughout a spacecraft or exploration vehicle to provide mission critical environmental and health data to engineers in an efficient, reliable manner. A key feature of the Gen 1 RHNs is the flexibility and re-programmability that enables one hardware design to interface with a wide variety of health sensors (e.g., temperature, strain, pressure, acceleration, vibration, acoustic, heat flux, position, rate and flow). Samples rates, gains, resolution, differential/single, full, half bridge inputs were all selectable for each sensor. In addition a programmable supply current was available.

On X-33, these sensors serviced all the vehicle health management requirements of the different vehicle subsystems (Propulsion, Thermal Protection, Cryo Tanks, Structures and Landing Systems, etc.). For the X-33 IVHM system 50 hardware identical Gen 1 RHNs interfaced to over 1200 health sensors were developed, tested, qualified and delivered to the program. The DSH wireless REU will incorporate the same basic flexibility as the previous designs but add wireless interfaces to eliminate cables and connectors where appropriate. This will lower the life cycle cost, increase reliability, and add flexibility for maintenance and possible upgrades over the life of the facility.

While the X-33 space plane program was terminated prior to flight, RHN box operation was demonstrated on an F/A-18 aircraft. Over 50 missions were flown during 1999 and 2000 with over 25 Gigabytes of information gathered which demonstrated the functionality and reliability of the box.

2.2. SiGe Gen 2 RHN Description

Whereas the X-33 Gen 1 RHN represented a significant improvement over the state-of the-art sensor networks of the day, there were obvious improvements that could be made in the miniaturization of the box. It was estimated that miniaturization would result in roughly two orders of magnitude improvement in volume, a 10x improvement in weight, and a 5x decrease in power dissipation. Extensive miniaturization as well as enhanced toughness led to the application of the more robust Gen 2 RHN (the REU) using SiGe technology which was funded by NASA under the

Extreme Temperature Development Program (ETDP) contract NNL06AA29C using mixed signal SiGe technology, (Cressler, 2008 and Berger, et. al., 2008, and Garbos, 2011). This development was led by a multi-center NASA ETDP team with support from multiple universities and demonstrated a Gen 2 SiGe System on a Chip (SOC) RHN based on the design of the X-33 Gen 1 Remote Health Node and implementing the same functionality. Two of the 16 channel REU's using mixed signal Application Specific Integrated Circuits (ASICs), are functionally equivalent to one X-33 thirty two channel unit.

The focus of this work was on a monolithic 16-channel system with integrated data conversion. It occupied an area of 10 x 14 mm and consumed 0.5 W + 0.25 W per universal/high-speed channel. These metrics represent an approximate 10x reduction in power consumption and a 100x reduction in form factor when compared to the Gen 1 RHN described above. Individual blocks that comprise the Gen 2 RHN were also flown in space as part of a Materials International Space Station Experiment (MISSE) Project in an effort to validate total-dose hardness and wide-temperature operability. The Gen 2 RHN was also radiation tested at cryogenic temperature under the ETDP program

2.3. Wireless Gen 2 RHN Description

As technology evolves, the power requirements for both sensors and health nodes will be greatly reduced. Also, a fully wireless sensor to Gen 2 RHN connection can be developed along with a fully wireless connection between RHNs and the central ISHM computer. The result will be that the need for connectors and cables for most of the distributed ISHM system will be eliminated and the entire system will be lighter and more reliable.

Depending on the type of smart sensor and required sample rate, there are different techniques for developing the wireless sensors. Some sensors that are sampled at a very low rate can self-generate and temporarily store data by scavenging energy from the local environment (vibration, temperature, etc.) then wirelessly transmit the data to a Gen 2 RHN. Also, these very low sampled sensors could be designed to respond to an RHN "ping" much like Radio Frequency Identification (RFID) tags operate today. These sensors could be easily interfaced to a wireless Gen 2 RHN.

For sensors that require a high sample rate and therefore more power than can be self-generated, the wireless Gen 2 RHN would be required to wirelessly transmit energy to the sensor. The sensor would then convert and store the energy within the device for response to the interrogation. Once the Gen 2 RHN is modified for a wireless interface and can provide energy to the ISHM sensors it can also be designed for wireless interface to the central ISHM computer. In some cases, however, the RHN may still require a wired power interface. However, this power would be a standard power that would be available around the platform and, therefore, not add much weight to the system. Since most of the technical solutions are already state-of-the-art in other applications, this would not be considered a high technical risk. Also, the Generation 2 RHN should be able to act as a relay station for other remotely located RHN's.

One big challenge will be to ensure that both ISHM wireless communication and wireless energy transmitting must not interfere with other subsystems, including other RHNs on the same platform. As the DSH ISHM work continues to define the sensor requirements, these issues can be addressed. Once these devices become available, the existing DSH prototype can be used to validate the approach. The benefits of eliminating most ISHM connectors and cables greatly exceed the risk.

Since the Gen 2 RHNs will be distributed throughout the platform they can also serve as the host for sensors, such as those for air quality and cabin temperature, since these will also be highly distributed. These sensors can be mounted directly to the RHN hardware.

3. CONCEPT OF OPERATONS FOR THE ISHM SYSTEM

Being at least three days away from a rescue and/or a re-supply from Earth, the crew of the deep space habitat will be totally reliant on the system's on-board health management system for mitigation of any credible failure scenario. In addition to such consumables as food, water, and oxygen, the crew must have spare parts, repair procedures, and materials on hand to deal with life threatening situations, such as those discussed earlier in this paper. Each failure scenario will be accompanied with a time to criticality, and the needed failure mitigation strategies must be tailored to fit within that TTC window. This means that at the time of failure detection the crew must be alerted as to the type, location, and TTC of the particular failure mechanism and the location and mitigation procedure(s) of needed actions to prevent the failure from causing life threatening consequences. Normally the time to criticality will be sufficiently long as to allow for a more leisurely repair. This would be true of a communication failure or cabin temperature rise. However, the TTC for a more severe hazard such as an MMOD puncture of the pressure vessel would be very short and would require rapid, emergency procedures.

In either case stated above, the crew would be notified initially by a caution and warning alarm consisting of both audible and on-screen annunciation(s). These would also appear in the personal hand held device(s) of each crew member. Once the caution and warning alert is received, the responsible crew member would use the touch screen techniques to drill down into the system diagrams and schematics to pinpoint the nature and location of the fault. One step further in the drill down procedure would bring the crew member to the mitigation procedure along with the location of spares, materials, and procedures needed to fix the problem. A very severe failure such as MMOD puncture may require emergency donning of space suits to survive the declining atmospheric pressure until the proper repairs are completed and the system is re-pressurized. A warning of an oncoming solar storm that will inflict life threatening radiation levels would require the crew to gather in a radiation shielded room, such as the exercise room. The radiation shield may be a heavy metallic enclosure or perhaps a water barrier surrounding the safe haven. In either event, the ISHM system will give the "all clear" signal when the threat has passed and/or dropped to a safe level.

The final action in all failure and/or life threatening situations that the ISHM system is responsible for is to update the event log and notify mission control back on Earth as to the nature of the event, the mitigation strategies employed, and the spares and materials used to fix the problem. The mission control personnel will then prepare the next supply vessel to carry replacements for all that was consumed during the failure event.

4. CONCLUSIONS

Travel and exploration in deep space within the next decade is likely and providing a habitat for long stopover and rendezvous for trips to Mars, the Moon, or Asteroids are the most likely missions. Whatever the state of technology of materials, structures, communications, or avionics and power, one requirement is conspicuous: the need for an integrated system health management (ISHM) capability. The sensors needed to provide total health monitoring will constitute the equivalent of the human nervous system and their sensed information must be gathered in a diagnostic and prognostic location where caution and warning alerts and mitigation actions are determined. Desirable attributes of such a system will be flexibility, maintainability, and reliability, all of which point to a wireless network free of electrical harness complexities and problems experienced in systems of the past. To provide the technology base for such systems, the remote health nodes described in this paper will prove to be the backbone of the ISHM system. Marginal improvements in the RHN circuitry to add wireless capabilities and improve robustness will assure the availability of the technology needed as the deep space habitat and other deep space systems are developed.

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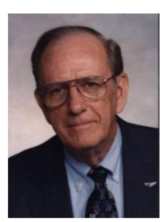
BIOGRAPHIES



Jim Miller is a NASA Manager responsible for Integrated System Health Management (ISHM) in the Spacecraft and Vehicle Systems Department of the Marshall Space Flight Center. He holds a BSEE from Tennessee Technological University, an MSEE from the University of Alabama in Huntsville, and is a 1974 Sloan Fellow from Stanford University in Palo Alto, CA. He began his NASA career with the Langley Research Center in 1959 and later relocated to the Marshall Center following a three year tour of duty as a commissioned officer in the U. S. Army. During his time on active duty he taught radar and computer to NATO field grade officers in the Officer Training Division of the U. S. Army Ordnance Guided Missile School at Redstone Arsenal, AL. His entire career has been in the domain of avionic systems and advanced avionics technologies with special emphasis on ISHM and structural health management systems. He has served in team lead, Branch Chief, Division Manager, and Assistant Department Manager positions over the past several years. He has received several awards including the NASA Exceptional Service Medal, the Engineering Directorate's Technology Achievement Award, the Director's Commendation Award from the MSFC Center Director, Dr. Petrone, and the Award of Achievement from the MSFC Center Director, Dr. Werner Von Braun. Mr. Miller has authored and/or co-authored several technical papers in the domain of advanced avionics systems and ISHM. His most recent was presented at the International Workshop on Structural Health Monitoring (IWSHM) at Stanford University in September 2011. He is currently working on the ISHM system for the ISS Derived Deep Space Habitat.

Jon Patterson is a member of the Integrated Systems Health Management (ISHM) and Automation Branch, at the Marshall Space Flight Center. He holds Bachelor and Master of Science degrees in Computer Science from the College of Engineering at Louisiana Tech University in 1983 and 1984. In addition, he completed the coursework in the PhD Computer Science program in 1992 in the College of Engineering at the University of Alabama in Huntsville with an emphasis on Artificial Intelligence. Jon has worked in software development in industry with SCI, Inc. and General Electric prior to coming to NASA. He came to NASA, Marshall Space Flight Center in 1991 in the Avionics Department Simulation Division. Shortly after coming to NASA, he served as the chairperson for the MSFC Artificial Intelligence Working Group (AIWG). In 1995, he was selected as the Chief for the Design and Implementation Branch in the Software Division, where he provided technical software oversight for the Tethered Satellite System Re-Flight (TSS-R) Skip-rope Observer project and the Advanced X-Ray Astrophysics Facility (AXAF) Science Center (ASC). Jon has also served as a branch chief or team lead until he was selected to support NASA's X-33 program in Palmdale, California, in 1999 as NASA's X-33 Lead Software Engineer. Following his return to Huntsville, he continued to provide technical leadership in the areas of software and ISHM for numerous NASA programs. Throughout his 30 year career he has supported programs such as the Advanced X-Ray Astrophysics Facility for Spectroscopy (AXAF-S), the Atlas/Centaur Automated Diagnostic System (ACADS), the X-33 Health Management System, the Space Launch Initiative (SLI) Integrated Vehicle Health Management Task Area, and the Orbital Space Plane (OSP) program. Jon has most recently served as the technical lead for the Ares I Failure Detection, Notification, and Response (FDNR) system. He is currently serving as the Space Launch System (SLS) Vehicle Management (VM) lead for the development of the SLS Mission and Fault Management (M&FM) capabilities. He is deeply involved in the promotion and improvement of ISHM definition and development across the agency, including numerous collaborative efforts with other NASA centers.

Ray Garbos is an Engineering Fellow. He is responsible for the development of advanced Avionics/ISHM concepts, architectures and technologies for aerospace applications. He has over forty years of circuit and system architecture design experience. He was an Engineering Fellow for Sanders Associates (1984-85), Lockheed Martin (1986 -2000) and BAE Systems (2001-06). He was VP and Chief Engineer of Aura Instrumentation Inc. (1998-2010). He was the X-33 IVHM lead and the Reusable Launch Vehicle Avionic IPT lead for Lockheed Martin and has participated in many Advanced Space Avionics Studies supporting MSFC. He was the technical lead for the BAE Systems lead ARES I Avionics Proposal Team. Mr. Garbos was a charter member of the NASA initiated Strategic Avionics Technology Working Group (SATWG) circa 1988 that evolved into the Aerospace Technology Working Group (ATWG) where he participated until 2008. He received a BSEE/MSEM degrees from Northeastern University, Boston, MA, in 1968/1971 and a Math (MAT) degree from Rivier College, Nashua, NH, in 2001. He was an Adjunct Assistant Professor at the University of New Hampshire. He has been involved with Science Technology Engineering and Mathematics (STEM) outreach for over 20 years.