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## X-33 / RLV

## SYSTEM HEALTH MANAGEMENT / VEHICLE HEALTH MANAGEMENT

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134091**ABSTRACT**

To reduce operations cost, the RLV must include the following elements: highly reliable, robust subsystems designed for simple repair access with a simplified servicing infrastructure and incorporating expedited decision making about faults and anomalies. A key component for the Single Stage to Orbit (SSTO) RLV System used to meet these objectives is System Health Management (SHM). SHM deals with the vehicle component—Vehicle Health Management (VHM), the ground processing associated with the vehicle fleet (GVHM) and the Ground Infrastructure Health Management (GIHM). The objective is to provide an automated collection and paperless health decision, maintenance and logistics system. Many critical technologies are necessary to make the SHM (and more specifically VHM) practical, reliable and cost effective. Sanders is leading the design, development and integration of the SHM system for RLV and for X-33 (a sub-scale, sub-orbit Advanced Technology Demonstrator). This paper will present the X-33 SHM design which forms the baseline for the RLV SHM. This paper will also discuss other applications of these technologies.

**BACKGROUND**

The X-33, shown in Figure 1, is a sub-scale, sub-orbit Advanced Technology Demonstrator (ATD). experimental flight test vehicle that is a cooperative development between Lockheed Martin and NASA.

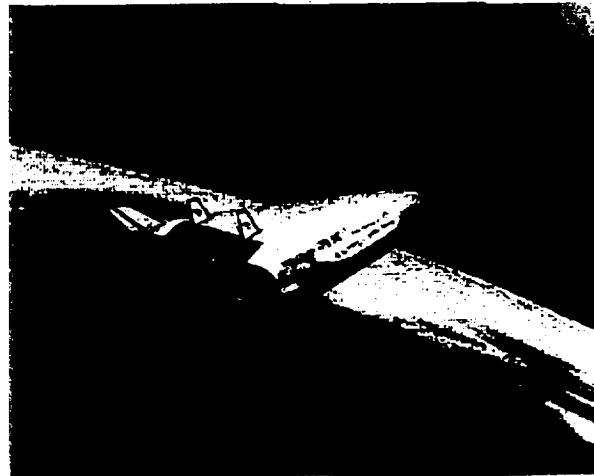


Figure 1. X-33 Concept

The X-33 follow-on Single Stage To Orbit (SSTO) Reusable Launch Vehicle (RLV) fleet will provide a low cost access to space. The RLV is being designed to provide sufficiently lower cost per pound payloads to

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space than existing launch methods. An entire new RLV infrastructure is being developed to meet these objectives. Reliable, low cost maintainability of the entire infrastructure is critical to success. During the X-33 technology demonstrator program many of the technologies necessary and traceable to make RLV successful will be developed and demonstrated. The entire System Health Management (SHM) must be engineered in an integrated approach to reduce cost, risk and meet the program objective. The Lockheed Martin Team approach to the program is to strike a balance between on-vehicle health management and associated prognostics with the entire ground infrastructure and operational cost goals.

The goal of RLV is launch on time with near maintenance free operations. To do this all the subsystems themselves must be reliable and easily maintainable, and the SHM system must be able to detect and predict faults far enough in advance to enable low cost, automatic maintenance scheduling using paperless procedures. The SHM is applied to the entire vehicle, including the structural and mechanical subsystems. Sanders, working with the Lockheed Martin IPT Teams, has developed a smart distributed

Health Management System for both the vehicle and the ground systems and an automated, computerized, paperless ground environment. The team is demonstrating much of this technology during the X-33 program and is using the latest COTS workstation, software and Internet tools to support the ground environments. This paper will primarily focus on the on-board VHM architecture and implementation, and some of the unique concepts that are being implemented to utilize COTS in this harsh environment.

**X-33 / RLV VHM ARCHITECTURE**

The X-33 VHM System monitors and records all data on the X-33 including all the flight busses, all Vehicle Health Data (structural, mechanical and system BIT status), and all the Flight Test Instrumentation (FTI) sensor data. The VHM system is the downlink telemetry source, providing the data to the RF downlink for transmission.

The VHM System, shown in Figure 2, collects data using three subsystems.

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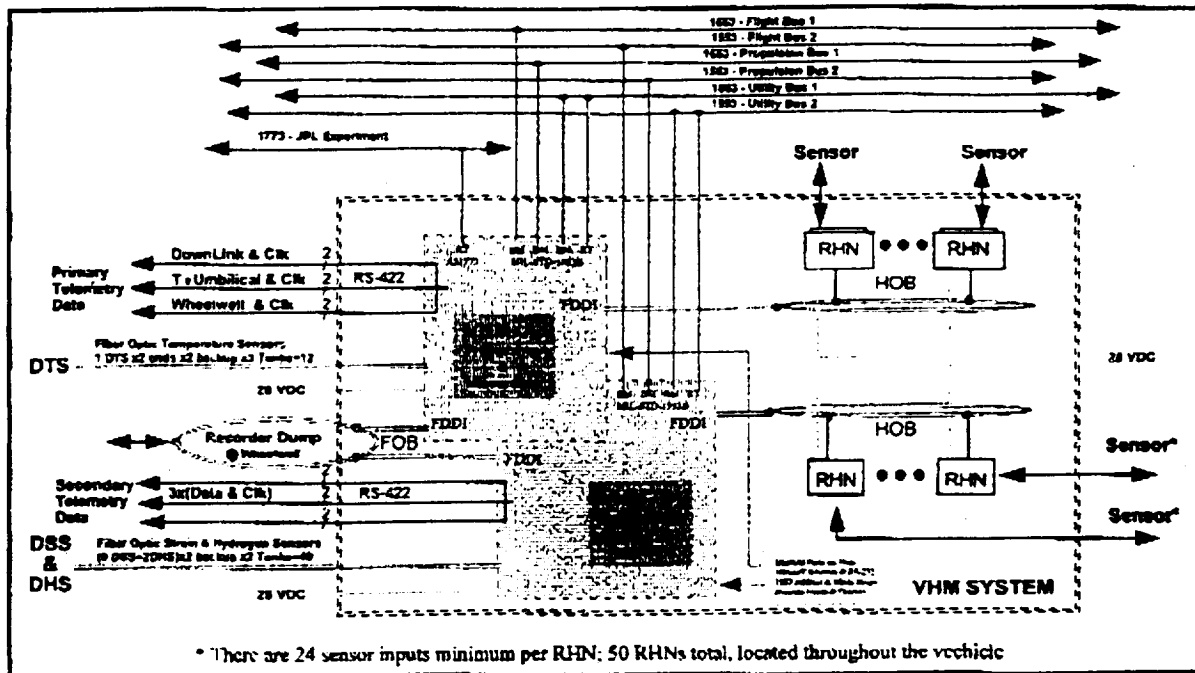


Figure 2. Vehicle Health Management (VHM) System Diagram

The first subsystem uses a smart distributed sensing architecture to collect data from conventional sensors. The data is concentrated using 50 Remote Health Nodes (RHN) accessing local sensors throughout the vehicle. The primary sensor information is structural and mechanical data. Each RHN can access 40 sensors and communicates with the VHM Computer over a fiber optic Health Optical Bus (HOB). The second subsystem located within the VHM central units, monitors and records all MIL-STD-1553 bus traffic on the six (6) MIL-STD-1553 busses. The third subsystem monitors the reusable cryogenic tanks using state-of-the-art Fiber Optic Distributed Temperature, Hydrogen and Strain sensors. The optical sensors are mounted directly on the tanks and the optics and processing are housed in the central VHM units. The Fiber Optic Sensors are a key technology to RLV and future systems requiring large amounts of data to monitor system health because they offer high reliability and low weight over the conventional sensors.

The VHM-A and VHM-B, shown in Figure 3, are open architecture COTS/MOTS based VME chassis consisting of mostly NDI modules.

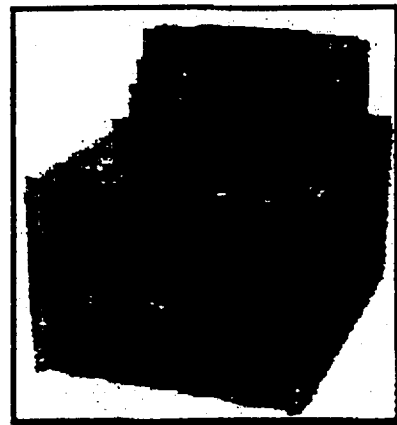


Figure 3. VHM-A / B

The X-33 Vehicle Health Manager-A (VHM-A) is one of two nearly identical VME-based line replaceable units (LRU's) that monitors and records the data. The VHM-A contains a COTS/MOTS standard MIPS-based Processor interfaced to a 4.5 GB PC-based hard disk drive storage module and various I/O modules. The VHM-A connects to 25 RHN's via the fiber optic HOB implementing a FDDI network. Three primary and three back-up Distributed Fiber Optic Temperature

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Sensors (DTS) interface directly to the VHM-A. In addition to direct sensor information, VHM-A also monitors and records data and traffic on three (3) of the MIL-STD-1553 busses. A fourth MIL-STD-1553 interface provides Remote Terminal (RT) functionality, for VHM command and control information. VHM-B is nearly identical to VHM-A. The differences are that this LRU contains the Distributed Fiber Optic Strain and Hydrogen Sensors (DSS & DHS). Collected data is selected and organized for transmission to the telemetry downlink subsystem and two hardwired umbilicals using RS-422 drivers providing data and clock for each link. Another fiber optic bus is connected between VHM-A, VHM-B, and the Wheelwell Umbilical. Debug interfaces include an 10BaseT Ethernet and a RS-232 serial port for the processor.

### Remote Health Nodes (RHN)

#### Architecture

The RHN's are a part Vehicle Health Management (VHM) system. The RHN performs as a data concentrator for structural, mechanical and environmental information. The RHN block diagram is shown in Figure 4.

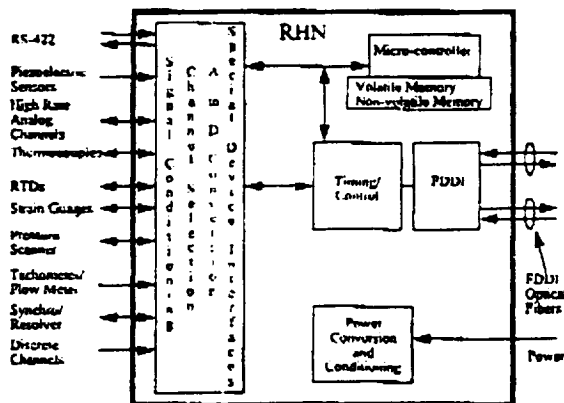


Figure 4. Functional Block Diagram of the Remote Health Nodes (RHN)

There are 50 RHN's strategically located throughout the vehicle, as shown in Figure 5.

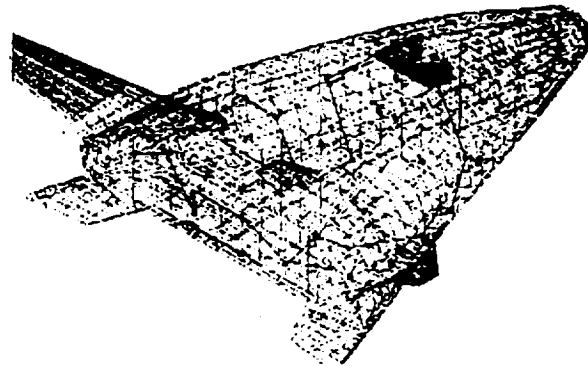


Figure 5. RHN Locations in X-33

Of these, 25 are interface to VHM-A and 25 to VHM-B over two (2) independent HOB's. The only power required for the RHN is +28 VDC. The FDDI uses the full duplex, dual counter-rotating token ring topology to provide reliable communications in the event of a failure. The RHN's collect the data from sensors located in the immediate vicinity of the RHN mounting location to reduce sensor wire weight and the chance of lost data due to EMI and other outside phenomena. The sensors types that the RHN's can interface to include accelerometers, strain gages, thermocouples, Resistive Temperature Devices (RTD), pressure (individual and 64 channel pressure scanner), rate (RPM and flow meters), synchro-resolver (angle), voltage, current, angular rate, and linear position. With the cooperative effort between the end users of the system and Sanders the X-33 Master Measurement List (MML) has been defined. All the RHN's have the same hardware configuration and are adapted to their sensor suite through software.

The sensor data is conditioned as required, digitized, and sent to the associated VHM-A or VHM-B to be recorded on a mass storage device, and the data is timed tagged and logged for each individual sensor. The data is downloaded via an optical connection to the VHM-A/B computers after the vehicle lands, and is analyzed to determine the vehicle health and to provide critical flight data that can not be predicted using pre-flight computer modeling: temperature-time profiles at locations throughout the vehicle, acoustic emissions and sound levels during powered flight and re-entry, vibration environments during powered flight and re-entry, pressure-time profiles, and strain/loading of the vehicle structure.

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The RHN will provide the excitation to the sensor, if any is required. For example, for the RTD, the RHN must provide a constant current source which allows the resistance of the device to be read (and the temperature inferred). Similarly, for the pressure gages (external bridges), the RHN must provide power to the bridge to allow the measurement to be made. Also, the RHN must provide the excitation to the synchro-resolver armature thus producing the voltages on the readout stator which allow the angle to be computed. Similarly, the RHN must provide excitation to the linear position sensor which allows the position to be read out.

#### Packaging

The requirements that drove the design and packaging of the RHN, as shown in Figure 6, included the cost, schedule and the unique environment that the X-33/RLV would provide to the RHN. The cost and schedule drove the use of COTS to minimize lead times and costs. The environment lead to some unique solutions.



Figure 6. Remote Health Node Chassis (RHN)

The X-33/RLV environment ranges from low to high temperature extremes, high vibro-acoustic levels and explosive atmospheres. The temperature in some areas of the vehicle range from -150°F to +350°F. The cold extreme are addressed by proper placement of the RHN's in the integration of the vehicle since the driver of this temperature is the cryogenic tanks. The high temperature is experienced after the vehicle has gone through its maximum aero induced heating. Since X-33/RLV have a metallic Thermal Protection System (TPS), there is a thermal soak back into the vehicle

after the thermal driver is removed. It is this thermal soak back into the vehicle which causes a transient high temperature. To address this, the RHN has a Phase Change (PC) core designed into it. The PC will transition from solid to liquid and return to solid when the thermal load is removed. This feature allows the RHN to operate in remote areas without the aid of external cooling. The RHN electronics wrap around this PC core. This is accomplished using a rigid-flex circuit board configuration as shown in Figure 7.

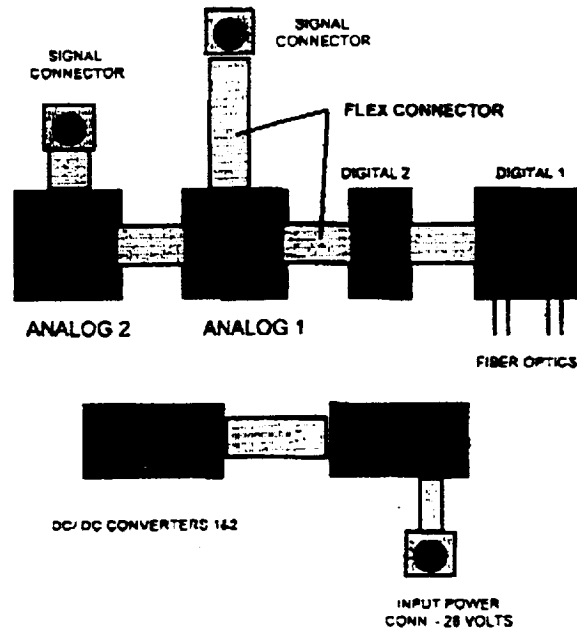


Figure 7. RHN Rigid-Flex Circuit Board Configuration

The high vibro-acoustic levels are addressed through the high density packaging and the use of isolating grommets.

Perhaps the most challenging area to address was the explosive atmosphere. The X-33/RLV utilize hydrogen and oxygen for its main propellant. Since hydrogen is very explosive and difficult to contain, there will be a small quantity of hydrogen in the vehicle cavity at all times. The vehicle addresses this issue through purging and venting, but since the RHN's are located in remote areas the purge may not be sufficient to guarantee hydrogen is not present in the areas around the RHN's. To address this, Sanders and Lockheed Martin Skunk Works applied ceramic bead and foam technology to alleviate the problem. Several

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approaches were traded, these included: sealing of the chassis, filling all voids in chassis with potting, creating a flame quenching path and the ceramic bead/foam technologies. Since weight is critical in any launch vehicle, the ceramic bead/foam technology was pursued through testing. A representative chassis was fabricated and run through explosive atmosphere testing. The chassis was filled with various ceramic beads, ranging from coarse to fine, aircraft fuel tank foam and pour in syntactic foam. The results of the testing showed that the coarse beads acted to quench the flame path so it could not reach the exterior of the chassis. The fine beads, the aircraft fuel tank foam and the pour in syntactic foam prevented an explosive atmosphere to be present in the RHN by occupying the entire volume of the chassis, thus not allowing any hydrogen to exist. These techniques developed have direct application to other electronic components that could be exposed to an explosive environment.

### **X-33 REUSABLE CRYOGENIC TANK VHM USING FODSS TECHNOLOGY**

The Fiber Optic sensing systems that will be flown on X-33 as experiments will be critical to RLV and application of Health Management to other vehicles. The backbone of the X-33 Reusable Cryogenic Tank VHM system lies in the optical network of distributed strain, temperature and hydrogen sensors that make up the FODSS. This network of fiber sensors will create a global strain, temperature and hydrogen leak map for monitoring the health of the tank structure and cryogenic insulation. Figure 8 shows such a network of sensors on the  $\text{LO}_2$  and  $\text{LH}_2$  tanks of the X-33 vehicle.

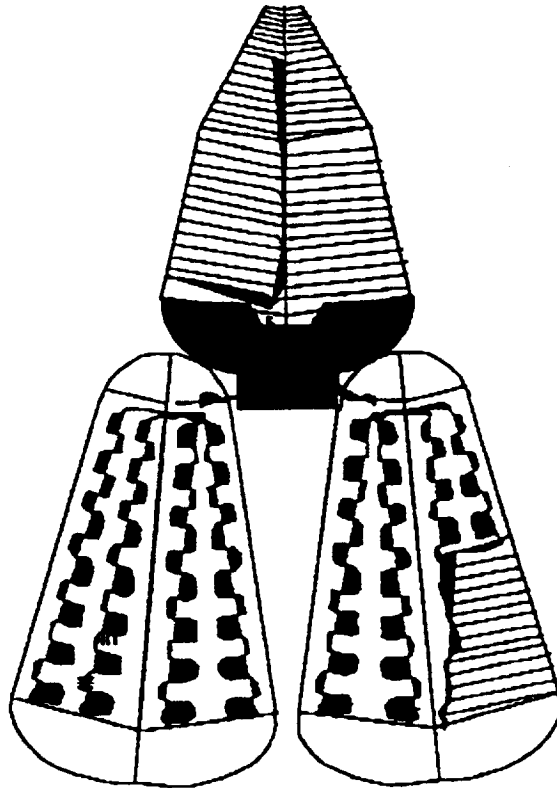


Figure 8. Fiber Optic Sensors on Cryogenic

### **Fiber Optic Sensor Components**

The Fiber Optic Sensors consists of two (2) unique sensing systems. The strain and hydrogen leak detection utilize a wavelength tunable narrow linewidth laser, a fiber optic network containing a sensing fiber with Bragg grating sensors, light detection photodiodes, signal conditioning electronics, and a digital signal processor. The sensing fiber is routed from the VME chassis in the avionics bay to the cryogenic tanks for strain and hydrogen measurement. The temperature sensor utilizes a multimode fiber with a broadband laser source. This fiber is also from the VME chassis in the avionics bay to the cryogenic tanks.

This technology is being developed utilizing COTS technology to meet the cost and schedule commitments of the X-33 program. Once the technology is implement and validated the system will be updated to meet the specific needs of the platform it will be installed on. Some of the future plans include a RHN

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like fiber optic sensor module. The goal of the fiber optic sensors are to reduce weight while providing large amounts of quality data.

### FIBER OPTIC INTERCONNECTS

To connect the VHM system a fiber optic cable plant that could survive the environment was selected. One of the cable plants to be used on X-33 is shown in Figure 9.



**Figure 9. Fiber Optic Cable Plant**

Due to the same low and high temperature environments that drove the design of the RHN, the fiber optic cable plant had some unique design features. The fiber optic cable selected was a ruggedized, high density, ribbon cable. The cable has a modular design which allowed it to be tailored to the environments that the X-33/RLV will encounter. By utilizing a high density ribbon cable, it is possible to build in growth to the system. Currently, only two (2) fibers are implemented out of a five (5) fiber cable. If there is a requirement for additional signal carrying capabilities, there is no need to rewire the vehicle. This can be done with fiber since the weight penalty is insignificant.

The fiber optic cable plant is a key component to making the VHM system a highly flexible and functional system. This is due to the high amounts of

data that can be transmitted, the light weight and the growth that can be built into the system.

### X-33/RLV PROGNOSTICS

The X-33 Prognostics is a demonstration of the techniques that RLV will use to reduce cost of operations and expedite maintenance to meet scheduling turnaround requirements. This demonstration is ground based and uses the data collected from the on board VHM system. The demonstration will provide an estimate of the operations efficiency that will be realized on a much larger scale on the RLV and will provide a basis for a more comprehensive system on RLV. The prognostics accesses the operations data archives to retrieve vehicle data and VHM data. The database is reconstructed and the data is fused, synchronized and coordinated to vehicle flight events.

The prognostics demonstration will include the following two major functional elements:

1. Onboard collection of system and event information/data

- Information collected by the Vehicle Health Manager (VHM-A/B) for the Fiber optic sensors and the MIL-STD-1553 Bus monitoring.
- Information collected by the VHM-A/B from the RHN's that describes current operating conditions of selected subsystem component(s).

2. Ground based analysis (processing of downloaded post-flight information/data)

- Analysis of the data from the selected subsystem components using statistical models designed to detect anomalies and trends; this analysis will assist in operations maintenance decision-making for the prognostics monitored components.
- For one pre-selected LRU, provide maintenance solution options to Operations management personnel. This may include information on predicted time to failure, interaction of constraints imposed on/by other subsystems for the maintenance action, resource availability to remove and replace the LRU, access required to change out or

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repair the LRU, required system retest following LRU anomaly resolution, most efficient time in the processing flow to replace or repair the LRU, and overall schedule impact.

Prognostics helps operations management by detecting trends in subsystems that would lead toward potential failures. Detecting trends allows operations management to replan the schedule to reduce unplanned test and maintenance requirements. The objective of prognostics is to enable a greatly reduced ground support staff with reduced skill levels to maintain the vehicle in a cost-effective manner by reducing unscheduled maintenance. The goal of the RLV prognostics system is to provide operations management personnel with early information on potential hardware deterioration so that efficient maintenance decisions can be made and bring about improvements to operations timelines and reduce costs.

### **OTHER APPLICATIONS OF SHM TECHNOLOGIES**

The entire X-33/RLV SHM architecture has a primary objective of reducing operation and maintenance costs. This objective is important to all new and existing vehicles whether these vehicles are being developed by NASA, DoD or commercial industry. Safety of vehicles carrying people can also be improved through this technology since the SHM with prognostics can provide early warning of major failures. If the event is near term then the crew can then modify flight profile to avoid failure or if it is a developing problem then the maintenance force can take the appropriate actions to alleviate an accident. The SHM infrastructure that is being developed by Sanders provides the means for creating a modular smart structure system. By utilizing the RHN as a smart data concentrator, various systems can be interconnected to the overall system creating an integrated system that will provide a common database and central processing point. Since the Sanders approach is leveraging commercial standards and tools, both the on and off vehicle elements of the SHM infrastructure can also be applied to a variety of vehicles. In addition, some of the specific technologies like the fiber optic distributed sensing technologies as well as the overall architecture can be applied to other structures such as ships, bridges and buildings at low cost. Therefore, by having a clean-sheet-of-paper

approach to SHM and having clear operational costs goals set early, our SHM team was able to not only leverage COTS technologies but architect a complete SHM concept. Much of this concept will be built and demonstrated under the X-33 program. The SHM solution itself will have a wide reaching impact for future manned space systems beyond X-33 / RLV.

### **ACRONYMS**

COTS	Commercial Off-The Shelf
DTS	Distributed Temperature Sensor
FODSS	Fiber Optic Distributed Sensing Systems
FTI	Flight Test Instrumentation
GVHM	Ground processing associated with Vehicle Fleet Health Management
GIHM	Ground Infrastructure Health Management
HOB	Health Optical Bus
IPT	Integrated Product Team
IVHM	Integrated Vehicle Health Management
LRU	Line Replaceable Unit
MOTS	Military Off-The Shelf
NDI	Non Developmental Item
PC	Phase Change
RF	Radio Frequency
RHN	Remote Health Node
RLV	Reusable Launch Vehicle
RT	Remote Terminal
SHM	System Health Management
SSTO	Single Stage to Orbit
VHM	Vehicle Health Management