Impact of Integrated Vehicle Health Management (IVHM) Technologies on Ground Operations for Reusable Launch Vehicles (RLVs) and Spacecraft

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Abstract—Incorporation of Integrated Vehicle Health Management (IVHM) technologies into launch vehicle and spacecraft designs offers the potential for significant savings in operations costs. IVHM has three basic objectives. First is more autonomous operation in flight and on the ground, which directly translates to reduced workload on the ground controller team through reduction of raw vehicle data into "health summary information." Next is reduced ground processing of reusable vehicles due to more performance of system health checks in flight rather than back on the ground as well as more automated ground servicing and checkout. Lastly is enhanced vehicle safety and reliability due to increased capability to monitor system health using modern sensing systems inside even the harsh environment of an engine combustion chamber as well as through prediction of pending failures.

The "integrated" piece of IVHM is the total integration of flight and ground IVHM elements. The three elements of flight IVHM are advanced light weight/low power sensors, extensive real-time data processing and analysis and distributed data acquisition architecture with high-density mass storage. The two elements of ground IVHM are evolved control room architectures with advanced applications and automated ground processing systems. The traditional model of a vehicle's instrumentation system consists of a distribution of sensors, signal conditioning devices and multiplexing devices, a complex and cumbersome network of wiring and a centralized processor/recorder. Characteristics of a modern, distributed IVHM instrumentation system include modern sensors such as ultrasonic flow, photonic and Micro Electromechanical Systems based sensors leading to strategically placed "Health Nodes" with extensive data processing by system health diagnostic algorithms which in turn interface via fiber optic communication with a "master" processor-recorder. These diagnostic algorithms rely on models of system structure and definitions of nominal behavior, in comparison with actual system behavior, to identify and isolate current and predicted future faults. The flight system then interfaces with automated ground support equipment for system servicing and trend analysis.

A status of current flight experiments on Space Shuttle, Deep Space-1, X-33, X-34 and X-37 will be presented.

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1. INTRODUCTION

The impact of IVHM on launch vehicle and spacecraft operations is in terms of improvements in safety & reliability, maintenance and operations. Safety is enhanced for the public, astronauts & pilots, employees and high-value equipment & property on several fronts. IVHM provides the flight crew and ground with tools for faster identification of failures and predicted failures of high criticality systems and hazards as well as the uncompromising pre-programmed responses having fail-safe features derived through formal risk management practices. Probabilities of human errors are reduced. Also, reliability and robustness are improved through full vehicle and ground systems IVHM coverage and increased redundancies. Aircraft-like maintenance will be possible through automated in situ vehicle checkout during operation and robust on-board fault isolation and prediction. Ground maintenance will be performed on an exception-only basis and will be pre-planned and automatically adjusted prior to vehicle return. Operations in flight and on the ground will be enhanced through more autonomous operation allowing faster responses with fewer personnel. Also, lighter weight vehicles will provide increased capabilities and margins. Key metrics of IVHM effectiveness will be a significant reduction in turnaround time, decrease in catastrophic unreliability, increase in number of flights per year, reduction in the variable cost per flight, reduction in ground and flight support personnel and increased hardware mission life. To reach its full potential, IVHM must be designed in from the start of a program rather than being an add-on later.

National IVHM Team

A national team is developing NASA's IVHM blueprint for the Advanced Space Transportation Program (ASTP). The team is striving for representation from the entire NASA and Department of Defense (DoD) IVHM community for technology leveraging across the NASA enterprises of Aeronautics & Space Transportation, Earth Science, Human Exploration and Development of Space (HEDS) and Space Science as well as DoD programs. Many more collaborative projects beyond those described in this paper including pathfinder class, trailblazer class and a magnetic levitation launch assist vehicle are planned. IVHM is clearly an enabling technology for NASA's bold missions in space exploration and aeronautics. IVHM will transform the critical application areas of autonomous spacecraft & rovers, science data understanding, space & aviation operations, maintenance and human exploration of space. *(Ref. 1)*

2. DEFINITIONS

The "integrated" aspect of IVHM is the total integration of flight and ground IVHM elements. "Monitoring" is sometimes used instead of "Management" and describes the degree of autonomy in a particular application. There is a spectrum for the degree of autonomy. At one end, an autonomous "Management" system takes action while at the other end, a "Monitoring" system recommends action. The traditional model of a vehicle's instrumentation system consists of a distribution of sensors, signal conditioning devices and multiplexing devices, a complex and cumbersome network of wiring and a centralized processor/recorder. Benefits of a modern, distributed IVHM instrumentation system include greatly reduced volume of wiring, reduced power requirements, reduced vehicle weight, reduced avionics cooling requirements, simplified incorporation of additional sensors and extensive data processing.

Flight IVHM

The three elements of flight IVHM are advanced light weight/low power sensors, distributed data acquisition architecture with advanced storage and extensive real-time distributed data processing. Examples of advanced sensors include highly redundant micro/nano sensors such as a grid of hundreds of pressure sensors; photonic sensors such as Fiber Bragg-Grating (FBG) sensors for strain, temperature and hazardous gas detection; wireless sensors such as temperature sensors inside an engine turbine and radio frequency powered devices; smart sensors that directly communicate digitally on a data bus, are regenerative, auto-calibrate and data cross-check for improved accuracy and data validation and non-intrusive sensors such as clamp-on Hall Effect current detection and ultrasonic fluid flow detection.

Distributed data acquisition architecture with advanced storage involves a strategically placed network of processors known as "health nodes" utilizing lightweight and low power microelectronics with advanced high density solid state memory. These devices may communicate with each other using a fiber optic data bus protocol such as Fiber Data Distributed Interface (FDDI).

Extensive real-time distributed data processing involves software modules resident on the health nodes processing in parallel. This includes health diagnostic algorithms for fault isolation, health prognostic algorithms for detecting trends and fault prediction, adaptive mission planning and scheduling which takes into account vehicle systems health status and mission objectives and autonomous control of a vehicle. Within these modules are sensor data validation for improved reliability, model based reasoning which rely on models of system structure and definitions of nominal behavior in comparison with actual system behavior and neural networks for data pattern recognition and learning.

Ground IVHM

The two elements of ground IVHM are evolved control room architectures with advanced applications and automated ground processing systems. Today's control room architectures have unique system-dedicated consoles with hardwired panel switches. Evolved control rooms have a core of identical and reconfigurable consoles for flexibility and ease of maintenance. The advanced software applications resident on these consoles include intelligent maintenance scheduling and logistics coordination, diagnostic and prognostic algorithms for analysis of flight and ground systems, paperless work documents and reference materials and expert systems as tools for flight and ground control personnel for rapid identification of problems and corrective actions. Utilization of automated ground support equipment enables extensive parallel operations including vehicle towing, jacking and positioning; umbilical mate and demate; thermal protection system, window, radiator panel and structural inspections; rapid vehicle systems checkout; payload removal, installation and checkout; rapid servicing of propellants and other commodities; expedited range clearance and launch sequencing.

3. HARDWARE TECHNOLOGIES

There are several key characteristics of Space Shuttle era data acquisition hardware technologies. Avionics boxes are best described as large, heavy, high powered and require active cooling. Interfaces with these boxes are not standard. Connectors of various sizes and shapes are distributed throughout a vehicle providing power and communication between different types of sensors, signal conditioning devices, multiplexing devices and recorders. All sensors are "point sensors" meaning one sensor for one measurement with all the associated wiring. Avionics architectures are custom or heavy and large ruggedized commercial versions such as Versa Module Eurocard (VME) bus. Also, there are extensive heavy runs of copper wiring for communication and power distribution. Data rates are relatively low as compared to commercial applications. Similarly, data storage is relatively low and often uses tape media.

The above technologies are evolving into a more modern, distributed IVHM instrumentation system. Included are lightweight and low power avionics boxes, which require greatly reduced or no active cooling. Interfaces are becoming more standardized which allows for a reduced parts count and more interchangeability. There are modular and distributed data acquisition architectures using strategically placed "Health Nodes" with localized data processing. Multiple sensors and multiple parametric sensors are packaged together simplifying installations and providing built-in redundancies through self-healing and self-calibration. Modern sensor types include ultrasonic flow, photonic strain/temperature/hydrogen-oxygen detection, smart sensors with analog-to-digital conversion at the source, magnetic sensors for non-intrusive current detection, Silicon Carbide sensors for high temperature applications using thin film and sputtered parent metal techniques, acoustic emission and microelectronic versions of common sensors. Fiber optic communication such as Fiber Data Distributed Interface (FDDI) or MIL-STD 1773 as well as wireless communication reduces copper wiring requirements. With this comes greatly increased bandwidth communication. Additionally, smart telemetry systems further increase effective bandwidth by only transmitting parameter changes. High-density solid state recording in the Gigabit range allows for increased numbers of sensors and more extensive post-flight data analysis as a contingency operation.

Further evolutions of these technologies will continue to reduce size, weight, power and active cooling requirements. This includes wireless power, wireless sensor networks, micro/nano electronics/computers, optical power and electronics, further advanced semi conductor materials, avionics embedded into structures eliminating boxes and cabling and overall continued miniaturization of sensors. *(Ref 2)*

4. SOFTWARE TECHNOLOGIES

Health Monitoring vs. Health Management

One of the three elements of flight IVHM mentioned above is extensive onboard data processing. This includes the assessment of vehicle state, tracking of time-related conditions such as component degradation and drift, and recovery and/or safing reactions to failures.

In space environments near Earth, it has been possible to manage spacecraft in the past without having onboard IVHM by adding to design margins and through extensive ground-based monitoring and control of a given spacecraft. Apart from large operations costs, this largely manual approach becomes increasingly infeasible for deep-space missions where lightspeed transmission time lags become significant compared to the time for failures to manifest themselves.

Given the relatively low performance of past space-qualified computers and the lack of formal verification methods for complex IVHM codes, initial onboard experimental IVHM systems, such as those described in this paper for X-33 and Space Shuttle, focused on health monitoring – that is, acquiring and filtering data, sometimes performing sensor limit checks, then transmitting the data to the ground as telemetry or storing it onboard for later downloading. In contrast, onboard health management systems also analyze, diagnose problems, and generate reactive plans onboard in real-time.

Integrated software architectures-Given multiple heterogeneous sensors, data types, and update rates, these onboard health management systems need to be able to combine and compare various health data sources, in real-time, in order to correctly assess current vehicle state.

Sensor drift and component degradation often exhibit symptoms, which can only be detected over time. These time dependencies add further complexity to onboard IVHM software. Further, physical process propagation lags during vehicle mode changes may cause apparent transient inconsistencies between the (expected) model vehicle state and the (actual) transitioning state. This can in turn lead to false-positive diagnoses of failures without some representation of and reasoning about time-varying processes and events.

Traditional command-driven software waits patiently for command strings – onboard IVHM software is automated and must be able to react to changing data values signifying vehicle events.

Onboard IVHM Software Functions

Sensor validation, data filtering and fusion-In a data-driven IVHM system, once sensor data is acquired it will be examined by both a sensor validation program (to look for sensor failures) and a feature detection program (to flag "high", "low" and drifting values).

Event detection-Not all detected abnormal features reflect failures – some may reflect transients due to physical time lags during nominal state changes. One weakness of conventional fault table or rule-based feature detection is their "brittleness" or inability to automatically compensate for transients. Consistency-based model-based reasoning approaches such as those of DeKleer *(Ref 3)* or the Livingstone inference engine *(Ref 4)* can propagate physical parameters (such as fluid flow or temperature changes) which allows transient states to be followed as nominal rather than off-nominal events.

Failure mode identification and recovery-If failures are diagnosed, a health status message may be sent by downlink to a ground-based system. Optionally, if cost, schedule and software confidence permit, recovery or reconfiguration commands may be generated based on the nature of the failure.

Task planning and scheduling-Ordinary state-changes as well as failure recoveries require some kind of plan or command sequence. These plans may be pre-stored for simple or commonplace actions, or generated dynamically during flight by planning and scheduling software.

Execution of commands and tasks-Once a task plan has been created or activated, some kind of executive process must carry out the plan. Executives can be simple, looping or single-threaded types or more complex multi-threaded types capable of executing multiple simultaneous plans.

Integration with ground operations software-Onboard diagnosed failures and generated plans in turn may be integrated with ground-based depot-level maintenance programs, as well as with mission operations. This integration facilitates subsequent ground processing and vehicle turnaround times by virtue of optimizing the pre-positioning of spares, personnel, materiel and ground test equipment, prior to vehicle return. Figure 1 shows a notional IVHM onboard architecture which is integrated with a ground-based planning and scheduling system.

Examples of IVHM Software Architectures

Over the past decade, NASA has developed and tested several generations of experimental IVHM software which have implemented many or all of the IVHM software functions above.

For example, in 1990 the Thermal Expert System (TEXSYS) demonstrated a model-based (De Kleer approach) diagnosis capability together with data fusion, sensor validation and a separate executive for failure identification and recovery of the Space Station thermal subsystem. *(Ref 6)* TEXSYS was successfully tested in direct, real-time control of a full-scale Space Station prototype. Its chief drawback was its implementation in Lisp (and hence need to occasionally perform software garbage collection).

Another example of IVHM software functions integrated with ground operations is the GPSS *(Ref 7)* maintenance planning and scheduling system, which advanced to active operational use at NASA's Kennedy Space Center in the mid-1990s and has subsequently saved tens of millions of dollars in Shuttle refurbishment costs.

This year, a new agent-based IVHM architecture was flown and successfully flight-tested on the Deep Space-1 (DS-1) probe. As shown in Figure 2, the Remote Agent experiment (RAX) incorporates the Livingstone model-based diagnostic engine *(Ref 4)*, a separate task onboard planning and scheduling system, data validation, and a multithreaded executive.

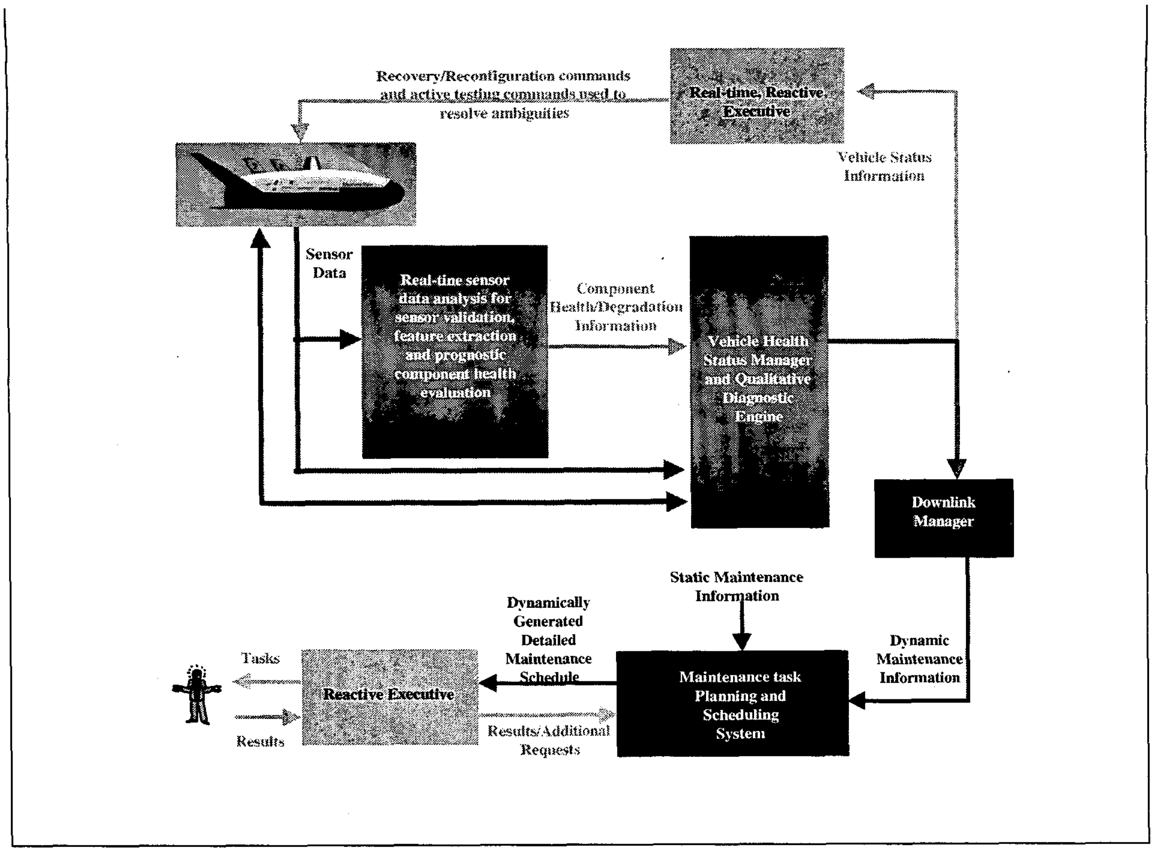


Figure 1. A proposed onboard IVHM software architecture for reusable launch vehicles (Ref. D)

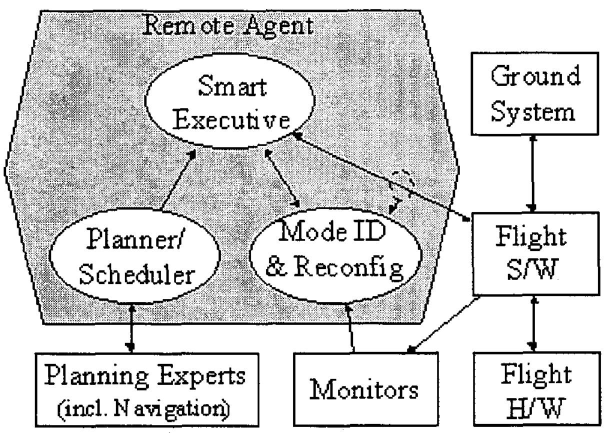


Figure 2. Remote Agent Experiment (RAX) architecture.

May 1999 RAX experiment-A recent paper by Nayak et al. *(Ref. 8)* describes the 1999 RAX testing and validation in detail. Due to delays with unrelated spacecraft anomalies, the 3-week planned RAX test period was curtailed to two weeks. Asteroid encounter preparation subsequently cost RAX another week, leaving only one week for tests.

Beginning on May 17, 1999, RAX ran a 2-day series of tests while resident on the DS-1 spacecraft. These tests were curtailed at about the 70% completion level when a recovery command failed to be executed as expected from a simulated spacecraft switch failure. Quick ground-based analysis of the software's performance led to the discovery of a rare task execution deadlock bug which had eluded all previous ground-based software verification and validation.

This bug was deemed to be sufficiently rare in practice that DS-1 mission managers preferred to leave it alone rather than risk inducing new, unknown bugs from an uploaded software patch. RAX tests then were allowed to resume on May 21 and ran to completion, accomplishing all experiment validation objectives.

6. Summary of Flight Experiments

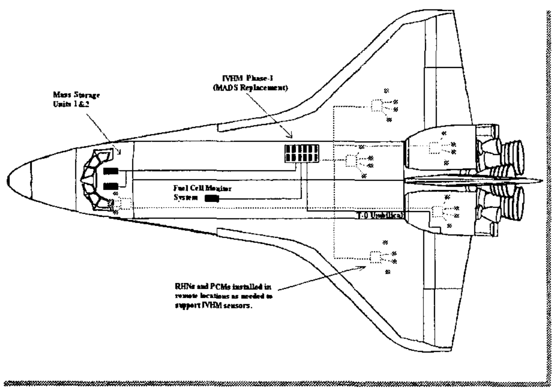


Figure 3.Proposed Space Shuttle IVHM Architecture

IVHM HTD's

The purpose of the Integrated Vehicle Health Management Human Exploration and Development of Space (HEDS) Technology Demonstration-2 (IVHM HTD-2) was to advance the development of selected IVHM technologies in a flight environment and demonstrate the potential for reusable vehicle ground processing savings. The focus of the experiment was real-time system health determination of selected Orbiter Main Propulsion System (MPS), Space Shuttle Main Engine (SSME) and Power Reactants Storage and Distribution (PRSD) functions. The technologies developed included: advanced sensors such as fiber bragg-grating (FBG) photonic sensors for hydrogen, strain and temperature sensing and smart sensors for hydrogen, oxygen and pressure sensing; distributed data acquisition using X-33 Remote Health Nodes (RHNs) with Fiber Data Distributed Interface (FDDI) communication and a lightweight/low power microelectronic hardware platform; real-time information processing of SSME pump vibration and FBG sensors; solid state storage and ground based advanced control room equipment and applications. The experiments consisted of an air transport rack (ATR) for data acquisition and processing, two X-33 RHNs, interconnect cabling, cabling for power & IRIG timing and cabling to 120 sensors installed through the Orbiter aft compartment and payload bay. Within this hardware platform resides the operating system and information processing software. The experiment interfaced with a ground computer through the Orbiter's T-0 umbilical for command and control. Follow-on IVHM HTDs are in the planning stages to develop and flight test the following technologies: SSME health determination through spectroscopy, wireless sensors, neural networks, nano/micro electronics, integrated electronic chemical species sensors and miniature mass spectrometry. *(Ref. 11)*

Deep Space-1

The Deep Space-1 (DS-1) spacecraft, had a successful flyby of asteroid Braile in July 1999 and is well on its way to a flyby in January 2001 of the dormant comet Wilson-Harrington to be followed by a flyby of an active comet, Borrelly. DS-1 is validating 12 new technologies for scientific space missions of the next century including a xenon ion engine and first use of autonomous navigation-mission operations using AutoNav remote agent IVHM technologies.

X-33

It is planned to fly an LH2 tank IVHM experiment on the X-33 precursor vehicle to the Lockheed Martin Skunkworks-led Venturestar RLV. This experiment will attempt to verify the structural and functional integrity of the LH2 tank and provide information to support rapid post-flight ground maintenance. Sensor locations were selected based on critical areas as determined by analysis. These areas include: joints, attachment points, skins and stiffeners. Sensor types include: strain (standard, thin film, fiber optic), temperature (thermocouple, fiber optic, thermal imaging), hydrogen detection, smoke detection, vibroacoustic (microphone, accelerometer) and pressure. Additionally, ground based informed maintenance development is being performed by Lockheed Martin Skunkworks. *(Ref. 12)*

X-34

The NASA IVHM Technology Experiment for X-vehicles (NITEX) has been selected to fly on the X-34 reusable launch vehicle being developed by Orbital Sciences Corporation. NITEX is led by Kennedy Space Center with additional team membership from Glenn Research Center and Ames Research Center. The goal of the X-34 IVHM flight experiment is to advance the technology readiness levels of selected IVHM technologies within a flight environment and to begin the transition for these technologies from experiment status into accepted RLV baseline designs. Multiple flights of the experiment are planned beginning in April 2001.

The experiment will monitor the X-34 vehicle throughout all mission phases using detailed diagnostic algorithms to detect degraded component performance as well as a system-level health monitoring system that integrates information from multiple components to perform real-time fault detection, isolation and recovery. In addition, the experiment will demonstrate the use of an advanced, user friendly ground station that combines information provided by the on-board IVHM software with information obtained while the vehicle was on the ground to provide high-level status information on the health of the vehicle along with the ability to access more detailed information when required. The ground station will also provide justification for the inferences made by the IVHM system and alternative recovery recommendations following a failure while in flight. It is planned to fly NITEX multiple times. The focus of the experiment will be on the X-34's Main Propulsion Subsystem (MPS) including the Fastrac Engine and the Reaction Control System (RCS). into the current state of the vehicle by displaying high-level health status information and providing access to the raw sensor data along with a justification for the inferences that are made by the diagnostic algorithms. *(Ref. 13)*

X-37

An IVHM experiment focussing on the electromechanical actuator and power systems will be embedded and firewalled into the avionics system of the Boeing Advanced Technology Vehicle (ATV), or X-37. This experiment is led by Glenn Research Center with additional team membership from Ames Research Center and Kennedy Space Center. The X-37 is slated to begin five months of Approach and Landing Tests (ALTs) beginning in early 2002. In late 2002 the ATV will then be a space deployed vehicle from the Space Shuttle or expendable launch vehicle (ELV), maintaining itself on-orbit until it re-enters, returns and lands automatically. Later versions of the initial X-37 may be upgraded with additional on-orbit electrical power-generating capability, allowing it to loiter on-orbit for weeks or months. IVHM during these longer-duration, self-contained flight periods is similar in many respects to IVHM issues for long-duration deep space operations. Given an on-orbit loitering capability, constellations of X-37-derived vehicles are conceivable. These would be a large operations burden given traditional ground-based mission operations, but would be much more affordable if the vehicles were largely self-contained with onboard IVHM capability.

Also, intelligent X-37 ground IVHM will be developed by Boeing and Kennedy Space Center which will leverage Boeing Phantomworks Informed Maintenance efforts. This system will focus on the health summary information provided by the flight experiment as well as additional information already available in the vehicle's telemetry stream. It will be included into an overall rapid vehicle turnaround demonstration planned utilizing a wireless work documentation system and a wireless communication system for maintenance personnel.

7. CONCLUSIONS

IVHM technologies offer the potential for significant improvement to safety & reliability, maintenance and operations for reusable launch vehicles and spacecraft. However, IVHM technology development is not mature and will require effort, time and money to realize its full potential. A national IVHM has formed to develop these technologies through an IVHM blueprint for the future.

8. REFERENCES

[1] Gormley, T., "3rd Generation Blueprint for IVHM", presented at 3rd Generation/Spaceliner 100 Conference at Kennedy Space Center, May 1999.

[2] Baroth, Edmund, "Advanced Sensor System Workshop", JPL Publication 99-9, June 1999.

[3] de Kleer, J. and B. C. Williams, "Diagnosis with behavioral modes," *Eleventh International Joint Conference on Artificial Intelligence*, Detroit, MI, 1989, pp. 1324-1330.

[4] Williams, B. C. and P.P. Nayak, "A model-based approach to reactive, self-configuring systems", *Proceedings of the Thirteenth National Conference on Artificial Intelligence (AAAI-96).*

[5] Merope Experiment Project Plan, draft, Computational Sciences Division, NASA-Ames Research Center, Moffett Field, CA, January 1999.

[6] Glass, B.J., Erickson, W.K., and K.J. Swanson, "TEXSYS: a large-scale demonstration of model-based real-time control of a space station subsystem," *7th IEEE Conference on Artificial Intelligence Applications*, Miami, Florida, February, 1991.

[7] Deale, M., et. al., "The space shuttle ground processing system". In *Intelligent Scheduling*, Zweben, M. and Fox, M. (eds). Morgan Kaufmann, 1994.

[8] Nayak, P.P., et. al., "Validating the DS-1 Remote Agent Experiment," to be presented at the Fifth International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS-99), October, 1999.

[9] Fox, J., "Impact of IVHM Technologies on RLV Ground Processing", presented at RLV Payload Processing and Launch Operations Workshop, Cocoa Beach, Florida, June 1998.

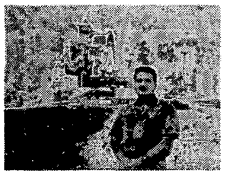
[10] Fox, J., "Integrated Vehicle Health Management (IVHM) Concepts for Space Shuttle", presented at Space Shuttle Development Conference, July 1999.

[11] NASA Fact Sheet, IVHM HTDs, Kennedy Space Center, Florida, May 1999.

[12] Franklin, W., et. al., "RLV LH2 Tank VHM Meeting Minutes", November, 1998.

[13] Clancy, D., Zakrajsek, J., Kruhm, D., "NASA IVHM Technology Experiment for X-vehicles (NITEX) Project Plan", May, 1999.

9. BIOGRAPHIES



Jack Fox *is manager of Integrated Vehicle Health Management technology development for Advanced Development and Shuttle Upgrades at the Kennedy Space Center. He is responsible for the development of IVHM technologies for possible application on the Space Shuttle, future launch vehicles and spacecraft. He was project manager for two Orbiter Integrated Vehicle Health Management Human Exploration and Development of Space (HEDS) Technology Demonstration (IVHM HTD) flight experiments. Launches of the IVHM HTDs were on the Orbiter Discovery on STS-95 in October 1998 and STS-96 in May 1999. After receiving a B. S. from Ohio State University in Aeronautical and Astronautical Engineering in 1983, Jack began his career with NASA at Kennedy Space Center. Jack has held a variety of technical positions in systems engineering, project engineering and advanced development for Space Shuttle and Payloads. He received an Astronaut Office "Silver Snoopy" award in 1987 for contributions to returning the Shuttle Program to flight status in the post-Challenger era. Jack completed a M. S. degree in Engineering Management from University of Central Florida in 1995. Jack was awarded a NASA Exceptional Service Medal in 1999 for Space Shuttle IVHM development.*

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