IVHM Framework for Intelligent Integration for Vehicle Health Management

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Abstract: Integrated Vehicle Health Management (IVHM) systems for aerospace vehicles, is the process of assessing, preserving, and restoring system functionality across flight and ground systems. The framework presented in this paper integrates advanced computational techniques with sensor and communication technologies for spacecraft that can generate responses through detection, diagnosis, reasoning, and adapt to system faults in support of Integrated Intelligent Vehicle Management (IIVM). These real-time responses allow the IIVM to modify the affected vehicle subsystem(s) prior to a catastrophic event. Furthermore, this framework integrates technologies which can provide a continuous, intelligent, and adaptive health state of a vehicle and use this information to improve safety and reduce costs of operations. Recent investments in avionics, health management, and controls have been directed towards IIVM. As this concept has matured, it has become clear that IIVM requires the same sensors and processing capabilities as the real-time avionics functions to support diagnosis of subsystem problems. New sensors have been proposed, in addition to augment the avionics sensors to support better system monitoring and diagnostics. As the designs have been considered, a synergy has been realized where the real-time avionics can utilize sensors proposed for diagnostics and prognostics to make better real-time decisions in response to detected failures. IIVM provides for a single

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system allowing modularity of functions and hardware across the vehicle. The framework that supports IIVM consists of 11 major on-board functions necessary to fully manage a space vehicle maintaining crew safety and mission objectives. These systems include the following: Guidance and Navigation; Communications and Tracking; Vehicle Monitoring; Information Transport and Integration; Vehicle Diagnostics; Vehicle Prognostics; Vehicle Mission Planning; Automated Repair and Replacement; Vehicle Control; Human Computer Interface; and Onboard Verification and Validation. Furthermore, the presented framework provides complete vehicle management which not only allows for increased crew safety and mission success through new intelligence capabilities, but also yields a mechanism for more efficient vehicle operations.

CE Database keywords: aerospace engineering, aeronautics, integrated systems, intelligent transportation systems.

Introduction

Integrated vehicle health monitoring (IVHM) is a rapidly growing field. IVHM offer the potential for significant improvement to safety and reliability, maintenance and operations for spacecraft. Although health monitoring is not a new concept, recent advancements in sensors and sensing technologies (along with the drive to decrease maintenance costs, increase life, and vehicle safety) have brought about a renewed interest in the field of IVHM. Several technologies have been developed for IVHM. A fiber optic-based integrated vehicle health management (IVHM) system was developed for the NASA Space Shuttle and the Lockheed Martin X-33 reusable launch vehicle demonstrator; system requirements, test and verification have been developed as well as strain, temperature and hydrogen sensors systems making up the IVHM system (Sirkis et al. 1999).

IVHM is the collection and analysis of data concerning operating parameters and damage information of vehicles in real-time. In the past, global monitoring strategies of vehicle systems were implemented; where the real-time operating parameters were recorded and compared to both test and field data to assess potential damage and required maintenance of vehicle components. However, a more efficient approach is continuous operational monitoring or condition-based maintenance (CBM) which manages the frequency and extent of maintenance procedures for various components within a vehicle.

NASA's Integrated Vehicle Health Management program lays the groundwork for the next generation of space vehicles. This is achieved by integrating artificial intelligence with advanced sensor and communication technologies; spacecraft can be built that can reason, diagnose problems, and recommend solutions, giving human crews more time for the important work of exploring space. IVHM has the potential to reduce or even eliminate many of the costly inspections and operations activities required by future space transportation systems. For instance, Kristler Aerospace Corporation is developing the world's first commercial, fully reusable aerospace vehicle. Kristler Corporation has developed an avionics design and has implemented a vehicle health management system where the vehicle's on-board systems are continually monitored for performance and this performance data is used for both in-flight and maintenance turn-around actions. The in-flight decisions are made, without a person-in-the-loop, to maximize the mission success. More importantly, the operations crew on the ground obtains early visibility on the performance during the flight so they are prepared to perform the necessary actions to prepare the next flight (Bailey and McSharry 2000).

IVHM offer the potential for significant improvement to safety and reliability, maintenance and operations for spacecraft. Recognizing these benefits, a national IVHM has been formed to develop aerospace technologies for the future (Fox and Glass 2000). As part of the overall goal of developing IVHM systems for aerospace vehicles, NASA has focused considerable resources on the development of technologies for Vehicle Health Management (VHM). Traditionally, NASA space vehicles are developed and managed by subsystems with predefined response databases; however, there is limited communication across these systems that limit the vehicle response to events. A shift is needed within NASA to move away from the notion that subsystems are separate entities and must be controlled via elaborate Interface Control Documents. Vehicle intelligence must be integrated across all vehicle functions so that the vehicle can make an appropriate response to events. Thus, NASA must embark on the development of intelligence functions that are integrated across the vehicle.

Integration of intelligence functions involves new issues to consider. When two different intelligence algorithms respond to the same event, they must respond constructively, not destructively. Similarly, verification and validation techniques for non-deterministic algorithms also require new techniques to generate a confidence in the algorithm operation. Thus, traditional integration, verification, and validation techniques will not support IIVM functions. New techniques must be developed early in the program so that they will be available as the design phase is completed. The motivations for these efforts are to increase the safety and reliability of aerospace structural systems, while at the same time decreasing operating and maintenance costs.

IVHM BACKGROUND INFORMATION

Over the past several years, NASA has made considerable investment in the area of health management for re-useable launch vehicles (RLV). This investment was motivated from the view of operations cost reductions. For the Shuttle program, these costs have been shown to be driven by the large efforts required to service the vehicle between missions. As a consequence, health management technologies have been directed towards a system separate from real-time avionics functions. These two systems were envisioned to share some sensor data but maintain separate processing functions. The health management system became known as the Integrated Vehicle Health Management system. Within this concept, IVHM would be responsible for diagnostics, prognostics, and risk mitigation of all vehicle systems to support replacement of failed or near failure components. These functions reduce the amount of vehicle inspections required between missions and greatly reduce ground maintenance costs. The real-time avionics systems would then continue in the role of controlling the vehicle flight and sustaining crew and systems to carry out the mission objectives.

As the IVHM concept has matured, it has become clear that IVHM requires the same sensors as the real-time avionics monitoring functions to support diagnosis of subsystem problems. New sensors have been proposed to augment the avionics sensors to support diagnostics and prognostics. As the designs have been considered, a symbiosis has been realized where the real-time avionics can make use of sensors proposed for diagnostics and prognostics to make better real-time decisions in response to detected failures. This symbiosis not only reduces ground maintenance but also increases vehicle safety by supplying new information to the vehicle real-time avionics to allow responses to vehicle subsystem failures and performance degradation. These real-time responses allow the avionics system to modify the vehicle subsystem prior to a catastrophic event. A good example of this is the vibration systems proposed for the Space Shuttle Main Engine (SSME) turbo-pumps. These sensors were conceived as a health management capability as part of the Advanced Health Management System (AHMS) to detect turbine blade failures through changes in vibration modes. However, by supplying this information to the SSME Controller, an engine could be throttled back or shut off in response to a turbine blade failure, preventing a catastrophic explosion of the combustion chamber.

In considering the symbiosis of real-time avionics and IVHM, it is apparent that these are not separate systems, but a single system. This single integrated system encompasses the real-time control and crew & system sustaining functions with new diagnostic and prognostic capabilities to provide a safer, more reliable, lower maintenance vehicle. Producing a single system opens the door to new vehicle level intelligence functions which allow real-time control of the vehicle as a whole, and not just through scripted actions controlling only individual subsystems. This vehicle level intelligence can respond in real-time failures in one subsystem and compensate with adjustments in another. For example, a failure in a flight control system could be compensated by engine adjustments (independent thrust vector adjustments). These compensations would be made within the bounds of sustaining the crew first and the mission second. This philosophy opens a whole new arena of possibilities for crew safety and mission success.

JUSTIFICATION FOR IVHM

Traditionally, monitoring and control functions have been done on an independent subsystem basis. However, this approach does not provide for intelligence, but is based on relatively simple control laws. Also, this approach does not support vehicle level intelligence integrated across the entire vehicle. IIVM addresses this void and provides for the complete integration and management of all vehicle functions and subsystems.

Human missions to Mars require a paradigm shift in the development of autonomous operations capabilities for space vehicles that are embodied in the Intelligent Integrated Vehicle Management (IIVM) concept. Autonomy and operations are broad-valued, fundamental capabilities that directly affect not only crew and vehicle size, but also crew safety and mission success. Autonomy and operations capabilities can be defined by vehicle intelligence functions that allow a small crew to safely operate a complex vehicle in a hostile and remote environment. These capabilities must provide robustness to reliably and safely endure the environment and the level of on-board autonomy required to enable the affordability of missions. Traditionally, space vehicles have had limited onboard management functions at the subsystem level. Overall vehicle management has been performed on the ground in a mixture of manual and limited automated operations functions. These functions must be integrated, automated, and placed onboard to maintain crew safety and mission assurance in remote space environments. Communications latency to Mars (15 minutes one way) is a key consideration in the level of autonomy necessary to maintain crew safety. The vehicle and crew must be able to respond to unexpected events to maintain vehicle integrity and crew safety before communications signals can travel to the earth and return.

This is especially challenging with complex systems and small crew sizes (4-6). Vehicle size is directly related to crew size through habitation volume, consumable storage, and life support systems. Autonomy of the many complex systems on a space transfer vehicle supports smaller crew sizes and therefore smaller vehicle sizes. Autonomy, required to maintain crew safety in remote space environments, also greatly reduces the ground staffing necessary for the mission. To address these considerations, vehicle intelligence functions that integrate all vehicle systems and capabilities are necessary to maintain crew safety and mission assurance, support small crew and vehicle size, and minimize mission operations costs. This paper describes the IIVM framework that will be necessary to achieve the autonomous operation capabilities necessary to assure crew safety and mission success.

IIVM FRAMEWORK

IIVM encompasses all vehicle functions and systems as illustrated in Figure 1. IIVM is a super set of what has traditionally been defined as Avionics, Integrated Vehicle Health Management (IVHM)/Integrated System Health Management (ISHM), functions performed on the ground, and some new concepts known as Autonomous Mission Management (AMM)/Autonomous Flight Management (AFM). Each of these concepts focused on only a portion of the total vehicle functional capabilities. Avionics focused on operational control of active systems (propulsion, thermal management, Environmental Control and Life Support, flight controls, etc.), but did not focus on the sensing capabilities needed for early detection of failures or failure of sensing components. IVHM (now ISHM) focused on early detection of failures and failures in passive components such as structures. IVHM incorporates concepts currently done on the ground including diagnostics and some prognostics. However, IVHM information was not utilized by the vehicle flight computer to effect changes in the vehicle control commands. Current vehicle still rely on ground based manual procedures to diagnose problems and modify mission plans in response to these problems. Problems are often detected after the failure of the system in most cases. AMM (also called AFM) is a new concept that considers the intelligence to incorporate IVHM data and adapt vehicle control decisions to the detected conditions. These concepts are also focused on crew display of information to ease crew flight operations. Each of these concepts alone performs necessary, but incomplete and sometimes duplicative tasks. IIVM is the combination of these functions into a single system which is fully aware of the complete vehicle state, able to make decisions based on crew safety, mission objectives, and vehicle status, and can effect changes in the vehicle based on these decisions. IIVM seeks to optimize the vehicle autonomy design, eliminating overlap, and expanding some functions into previously uncovered areas including autonomous repair and replacement of parts onboard and verification and validation of intelligence adaptations to unexpected vehicle states.

The operational complexity of IIVM requires advances in every level of intelligence and computer technology. The framework that supports IIVM consists of 11 major on-board functions necessary to fully manage a space vehicle maintaining crew safety and mission objectives: Guidance and Navigation; Communications and Tracking; Vehicle Monitoring; Information Transport and Integration; Vehicle Diagnostics; Vehicle Prognostics; Vehicle mission Planning; Automated Repair and Replacement; Vehicle Control; Human Computer Interface; and Onboard Verification and Validation. Furthermore, the presented framework provides complete vehicle management which not only allows for increased crew safety and mission success through new intelligence capabilities, but also yields a mechanism for more efficient vehicle operations.

This single intelligent system provides IIVM for all vehicle functions. This system not only provides increased crew safety and mission success through new intelligence capabilities, but also provides the framework for more efficient vehicle operations. For long duration missions (e.g. Lunar bases, Mars) efficient vehicle operations is essential to maintain small crew sizes and therefore small vehicle sizes. Vehicles with nuclear systems must contain all the operations systems necessary to complete the mission, in spite of communication outages. This requires onboard intelligence and automation to allow a small crew to operate the vehicle safely, a critical capability for any interplanetary mission. This also reduces dependence on interplanetary communications systems, reducing infrastructure costs. Previously, some artificial intelligence tools were used on the ground to support mission diagnostics and mission planning. These capabilities will need to be transferred from the ground operations centers to the vehicle's flight systems. IIVM is the framework which easily accommodates these diagnostic and mission planning functions. The vehicle then has the capability to respond to unexpected events, such as radiation effects from solar flares, by reconfiguring systems and orientations. The impact of such changes can then be prognosticated to determine changes in time of arrival, consumables depletion, etc. By incorporating all vehicle management functions onboard, response times to critical events for the ground crew reduce from hours to minutes; reduce from minutes to seconds by the shuttle; and reduce from seconds to milliseconds by the Intelligent Integrated Vehicle Management System. These quick responses to unexpected events greatly enhance crew safety and mission success.

IIVM Technological Advances

Commercial and military systems represent the most advanced performing systems available from which to start IIVM technology development. Notably, both The Boeing Company and Air Bus have integrated considerable intelligence and automated health management capabilities into their newest commercial jet liners. Likewise, the Department of Defense Joint Strike Fighter Program has incorporated a considerable level of intelligence and autonomy to improve survivability in combat. Technology starting points also exist with U.S. Navy Nuclear and Attack Submarines. Nuclear submarines must operate communication-free for long-duration underwater missions to prevent enemy detection. Both nuclear and attack submarines offer state-of-the-art self-contained nuclear systems, but have crew sizes of 155 and 134 respectively. The level of autonomy represented in submarine systems (even excluding weapons systems crew members) must be greatly increased to achieve a crew size of only 4-6 for a 3 year mission.

Recent NASA attempts in the X-33 program proved costly in applying standard (commercial of the shelf) COTS hardware to a space vehicle. An example is the LN 100 navigation system selected to fly on the X-33 flight demonstrator system. This system required an 18-month development effort to make the COTS system function properly in space. Similar experience was also gained in the unsuccessful attempts to flight-qualify the Honeywell Space Integrated Global Positioning System (GPS)/Inertial Navigation System (INS) (SIGI) and the Miniaturized Airborne GPS Receiver/Shuttle (MAGR/S) over a 10-year period.

Within the commercial world there are currently no radiation hardened computer processors, although the PowerPC 750 is available as a radiation "tolerant" part. This lack of radiation hardened hardware creates a large technology gap in the development IIVM hardware technologies. Thus, while military and commercial systems offer starting points in terms of basic performance, the level of intelligence achieved and the space qualification of these systems require significant advancement by NASA. This integration of intelligence functions to a single cognizance of the vehicle state strongly drives the IIVM development, integration, verification, and validation philosophies. One approach that is being implemented at MSFC is the development of the Marshall Avionics and Marshall Avionics and Systems Testbed (MAST) lab as shown in Figure 2.

Proposed IVHM Integration and Test Facility

Intelligent System Health Management Integration and Test Facility will be developed for integrating key technologies for demonstration, benchmarking, validation, and development purposes. The test facility will address the intelligence needs for future spacecraft, autonomous systems, adaptive systems, and intuitive and highly networked engineering design environments. This test facility will also support the space transportation and space systems where advanced data networking, advanced vehicle intelligence, and their integration, verification, and validation of key technologies are paramount. Key systems that will require IVHM as follows:

(1) **Propulsion Systems:** Main, Auxiliary, and Propellant Feed Systems;

(2) **Structural Systems:** sensing, analysis interpretation, and prognostics;

(3) **Thermal Protection Systems:** avoid loss of crew, vehicle, or mission;

(4) **Power & Actuators:** Power management and distribution, power sources (i.e., batteries, fuel cells, turbine power units, flywheels);

(5) **Avionics:** single bit upsets, software and hardware anomalies, sensor and data validation, and communication systems; and

(6) **GN&C**: Fault detection, isolation, and recovery software, reconfiguration (mitigation strategies) upon loss of jets or actuators, real-time health monitoring and diagnostics of engine conditions, aerosurface failures, off-nominal vehicle dynamics, and related subsystem failures.

CONCLUSIONS

IIVM and the technologies researched by the faculty members will be implemented in the MAST lab. Technology maturation is needed to allow incorporation of subsystems and elements into an ISHM test environment which provides realistic interface characteristics minimizes interface compromises, and provides meaningful early testing results to realize the benefits from improved integrated operations confidence. This capability could allow selection or elimination of candidate architectures earlier in the development cycle to avoid unnecessary work.

Also, this will provide the ability to capture hardware and software parametric data that includes a wide variety of failure modes and data signatures early in the development cycle. The data collected can be used by the health management community, to generate prognostic algorithms capable of predicting the onset of impending failures and for other studies. The prognostic algorithms will allow the system to react and redirect system resources to avert a system shutdown or catastrophic event proactively rather than reacting to a failure after the fact. This integrated approach to testing benefits the IVHM and operations communities by establishing and developing the standard data and communication protocols and associated software that will support the hardware throughout the program life cycle which will drastically reduce the software costs for a system.

Also, an integration test environment for IVHM needs to be designed and established to perform the integration testing and provide an integrated systems testbed for system level testing. This capability would allow the ability to perform integrated system performance testing, integrated procedure testing, operations and maintenance requirements development as well as operator training and familiarization.

The MAST lab provides capabilities to perform real-time, hardware-in-the-loop simulation of propulsion vehicles and their subsystems. Furthermore, the MAST lab provides extensive resources for data processing, data archival, and hosting special configuration requirements. Advanced technology testbeds for flight vehicle systems would certainly improve the attributes of effectiveness, reliability, and safety. The effectiveness of the technology will further improve assurance and reliable trustworthiness of on-time delivery of ISHM components. In effect, safety and reliability margins would be improved. The affordability aspect of developing a state-of-the-art ISHM Integration and Test Facility would be realized in cost savings in minimizing the resolution of software-to-system and system-to-system system integration anomalies.

Intelligent Integrated Vehicle Management not only provides the framework for manageable vehicle operations and quick response to system failures and space environmental events, but the single system can make extensive use of system modularity and commonality. By having a single system, the common hardware architectures can be employed across the vehicle on the component level. This substantially reduces spares required to be carried on a long duration mission and substantially lowers software validation costs.

Intelligent Integrated Vehicle Management can be employed on any space vehicle from launch vehicles to interplanetary vehicles. The application will decide the amount of intelligence required to be employed onboard. For an expendable launch vehicle (ELV), flight times are short, and intelligence is limited to the ability of the vehicle to plot flight trajectories onboard and safely manage subsystems. In addition, interoperability with the launch site systems is important for diagnostics of interface problems. A reusable launch vehicle (RLV) would expand on the ELV intelligence functions to include more complicated diagnostics and the addition of prognostics to maintain low ground maintenance costs. Mission planning would also be required to maintain affordable flight operations costs. A lunar transfer vehicle would be similar to a re-useable launch vehicle requiring servicing interface interoperability, diagnostics, prognostics, some level of repair/replacement, and complete mission planning functions. For an interplanetary vehicle diagnostics, prognostics, mission planning, repair/replacement, and algorithm verification and validation functions will be required to successfully complete the mission.

The design of an Intelligent Integrated Vehicle Management System is achievable today, but requires a strong understanding of available technology capabilities and limits, new verification and validation techniques, and real-time flight operations functions. This understanding enables the correct decisions to be made on the level of intelligence achievable onboard with current, emerging, or obtainable technologies in the development time frame available and on the level of automatic responses versus crew authorized responses. The understanding of these areas is essential to developing an achievable

Intelligent Integrated Vehicle Management System architecture for the NASA vehicles currently planned for the next decade.

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