A Presentation of an Intelligent Integrated Vehicle Health Management Concept for Spacecraft Systems

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Abstract – *Traditional vehicle management, monitoring, and control functions have been done on an independent subsystem basis. This paper presents a framework for Intelligent Vehicle Health Management (IIVM), which provides for 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 IIVM concept. IIVM is a conceptual approach that allows the integration of advanced computational techniques with sensor and communication technologies for space vehicles. Furthermore, IIVM enables spacecraft to generate responses through detection, diagnosis, reasoning, and adaptation to system faults. The framework is necessary to achieve the autonomous operation capabilities required to assure crew safety and mission success, and it offers additional improvement to spacecraft safety, reliability, maintenance and operations.*

Keywords: IVHM, ISHM, Integrated Vehicle Health Management, Integrated System Health Management, Autonomous Flight Manager.

1 Introduction

The success of NASA's Exploration activities hinges on the ability to make space systems safer, more affordable and more self-sufficient. As these missions expand to ever increasing distances from Earth, the systems that support the missions will be required to become more self-sufficient. Time delays in communication, the inabilities to perform unscheduled re-supply, and the mass penalty of carrying large spare parts inventories will be driving factors for future mission designs.

NASA's Integrated Vehicle Health Management (IVHM) 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.

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). 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.

Traditional vehicle management, monitoring and control functions have been done on an independent subsystem basis for each major vehicle function. However, managing the interaction of these subsystems is as important as managing the system itself. Failures or anomalies in one system can significantly impact the performance or health of other systems. These interactions must be managed to mitigate failure propagation in a spacecraft. This requires an Intelligent Integrated Vehicle Management (IIVM) system. IIVM provides for the complete integration and management of all in-space vehicle functions and subsystems. Subsystem management functions are critical to the reliability and safety of a vehicle. This paper describes the integration of spacecraft functions within the IIVM architecture and illustrates the interaction of vehicle level and subsystem management functions.

2 Justification for IIVM

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 concept. Autonomous operations are broad-valued, fundamental capabilities that directly affect not only crew and vehicle size, but also crew safety and mission success. Autonomous operation 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 and safely endure the environment and provide the level of on-board autonomy required to enable missions.

Traditionally, space vehicles have had limited onboard management functions at the subsystem level. 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. Overall vehicle management has been performed on the ground (i.e., in Earth-based mission/flight control facilities) 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) and a 60-minute communications blockage while orbiting the moon are key considerations when considering 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.

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. The next Section presents the IIVM architecture and the vehicle management system that will be necessary to allow the interaction between vehicle level functions and subsystem management level functions.

3 Presentation of IIVM Architecture

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 Autonomous Mission Management (AMM)/ Autonomous Flight Management (AFM). Each of these concepts focuses on only a portion of the total vehicle functional capabilities. Avionics focuses on operational control of active systems (propulsion, thermal management, Environmental Control and Life Support, flight controls, etc.), but does not focus on the sensing capabilities needed for early detection of failures or failure of sensing components. IVHM (now ISHM) focuses 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.

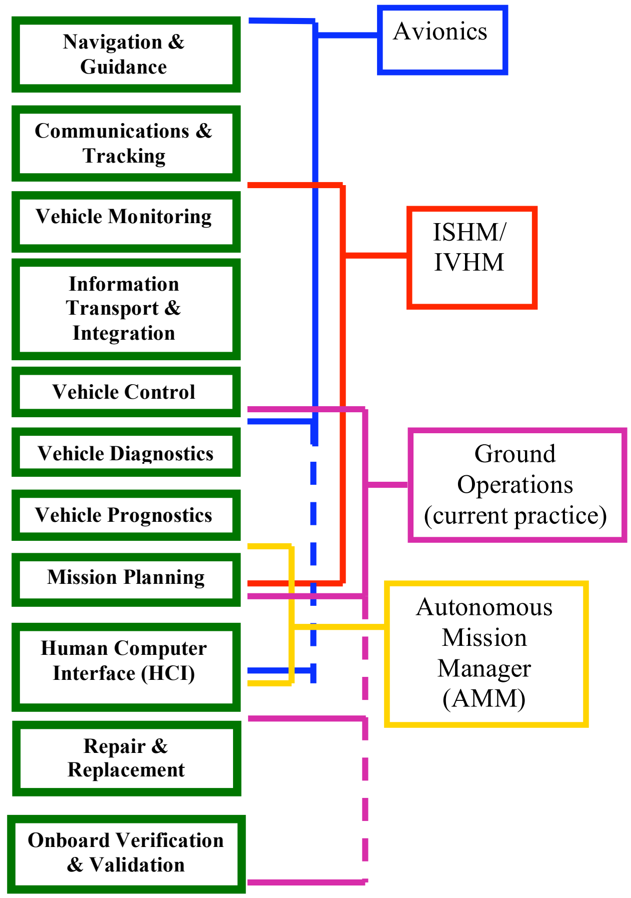

Figure 1. IIVM Framework.

Current vehicles still rely on ground based manual procedures to diagnose problems and modify mission plans in response to these problems; and problems are often detected after system failure in most cases. AMM (also called AFM) is a concept that provides 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, is 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.

As shown in Figure 1, IIVM is a complex system encompassing all vehicle functions. 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. For long duration missions (e.g., long duration lunar exploration operations) 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 that 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 vehicle 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 Space Shuttle Orbiter; 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.

Figure 2 shows interactions between vehicle systems and management functions. As indicated in the model, all functions and systems interact with the AMM. The AMM not only interacts with other systems, but it also manages resource consumption. For example, the AMM will determine if there is enough liquid oxygen (LOX) and fuel. The AMM also mitigates subsystem failures at the vehicle level and it looks at integration failure modes. For instance, if a failure has been detected in the electrical power system, the autonomous mission manager will determine if there is a problem solely with the power supplies, or if the problem resulted from an overheated radiator. The radiator is a part of the thermal management system.

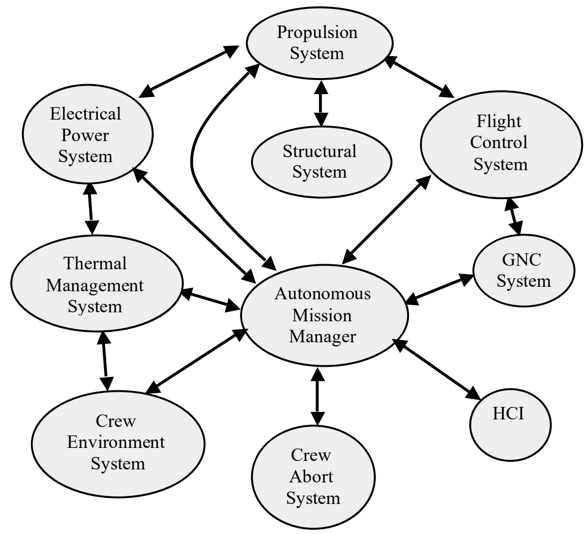

Figure 2. Vehicle systems and autonomous mission management interactions.

The vehicle systems and functions are described as follows:

1) Propulsion System – consists of the engine, tanks, and the Main Propulsion System (MPS).
2) Flight Control System – consists of thrust vector actuators, and provides steering to the vehicle.
3) Guidance, Navigation, and Control (GNC) System – responsible for the direction, altitude, and angle in which the vehicle travels.
4) Human Computer Interface (HCI) – this is the user interface used for data display and data entry; this is used by flight crew and ground operators.
5) Thermal Management System – includes radiators and provides active cooling for electronics and crew cabin.
6) Structural System – mounting structure that connects engine to vehicle and supports tanks.
7) Crew Abort System – receives information from the autonomous mission manager on failures and determines if an abort system should be activated.
8) Electrical Power System – provides power for valves, actuators, sensors, and processors. This system is responsible for power distribution, power generation, and power storage.
9) Crew Environment System – includes the ambient temperature to maintain appropriate ventilation and oxygen levels for the flight crew.

4 Artificial Intelligence for VHM

Several research efforts on VHM have been performed especially with regards to Artificial Intelligence (AI) techniques like expert systems, artificial neural networks, and fuzzy logic systems [1-7]. For fuzzy logic systems, linguistic variables, simple rules and memberships functions are defined for building a knowledge base to support fuzzy logic inference [4, 5] (e.g., to infer fault conditions or spacecraft health from sensor data). The variables, rules, and membership functions are used to represent and reason about approximate or imprecise data and information. Artificial neural network models are constructed in some cases [6]. They are typically used for data pattern recognition or learning of associations between sensor data and system faults and/or failure conditions. In other cases, "If-Then" rules are formed on the bases of historical data for expert systems [2, 7]. The rules represent embedded expertise about spacecraft system health that can be used for onboard fault diagnosis or prognosis. The appropriate use of such advanced computational techniques to enable intelligent space vehicle responses depends on the application.

5 Applications

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.

IIVM can be employed on any space vehicle from launch vehicles to interplanetary vehicles. The application will determine the amount of onboard intelligence required. 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 also be required to successfully complete the mission.

6 Challenges and Conclusions

In-space propulsion technologies will play an integral role in the next few years in developing plans for space exploration activities that involve missions to destinations beyond low Earth orbit. Intelligent IVHM will play an important role in making sure that the integration of in-space propulsion technologies is safe, affordable, and self-sufficient. While traditional vehicle management, monitoring, and control functions have been done on independent bases, IIVM frameworks for spacecraft will enable integration of advanced computational techniques [1-3] with sensor and communication technologies. IIVM is a necessary framework for achieving the autonomous operation capabilities required to assure crew safety and mission success.

The design of an IIVM system for in-space technologies 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. Some of these challenges include:

- Real-time decision executives: the ability to detect failures and make flight decisions real-time;
- Unambiguous diagnostics: the ability to be able to correctly detect faults at the subsystem and vehicle level;
- Prognostics: the ability to successfully predict when a component is going to fail;
- Crew abort determination: the ability to determine when the mission should abort at a high confidence level;
- Integration of multiple intelligence algorithms – ability to employ several algorithms that have the capability to detect, diagnosis, and correct system faults.

The IIVM framework presented in this paper enables NASA Space Exploration efforts and offers additional improvement to safety, reliability, maintenance and operations for spacecraft.

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References

[1] W.G. Fenton, L.P. Maguire and T.M. McGinnity, "Fault diagnosis of electronic systems using intelligent techniques: A review," *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, Vol. 31, No. 3, pp. 269-281, Aug. 2001.

[2] N. Dev and B. Anderson, "Pimtool: An expert system to troubleshoot computer hardware failures," Proc. 9th Conference on Innovative Applications of Artificial Intelligence, Providence, RI, July 1997.

[3] O. Duffaut and C. Castel, "A method to aid test-tree generation for hardware fault isolation in automotive electronic control systems," Proc. International Conference on Fault Diagnosis (Tooldiag'93), Toulouse, France, pp. 230–237, Apr. 1993.

[4] J. Cecil, M. Erraguntla and R. Mayer, "A fuzzy inferential approach for the diagnosis of defects in electronics assembly," Proc. 16th IEEE/CMPT International Electronics Manufacturing Technology Symposium, Vol. 1, pp. 70-74, La Jolla, CA, Sept. 1994.

[5] A. Siddique, G.S. Yadava and B. Singh, "Applications of artificial intelligence techniques for induction machine stator fault diagnostics: Review," Proc. 4th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives, Altlanta, GA, pp. 29- 34, Aug. 2003.

[6] A.A. AL-Jumah and T. Arslan, "Artificial neural network based multiple fault diagnosis in digital circuits," Proc. IEEE International Symposium on Circuits and Systems, Vol. 2, Monterey, CA, pp. 304–307, 1998.

[7] S. Katipamula and M.R. Brambley, "Methods for fault detection, diagnostics, and prognostics for building systems – A review, Part I," *HVAC&R Research*, Vol. 11, No. 1, pp. 3-25, Jan. 2005.