Intelligent Elements for the ISHM Testbed and Prototypes (ITP) Project

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Abstract

Deep-space manned missions will require advanced automated health assessment capabilities. Requirements such as in-space assembly, long dormant periods and limited accessibility during flight, present significant challenges that should be addressed through Integrated System Health Management (ISHM). The ISHM approach will provide safety and reliability coverage for a complete system over its entire life cycle by determining and integrating health status and performance information from the subsystem and component levels. This paper will focus on the potential advanced diagnostic elements that will provide intelligent assessment of the subsystem health and the planned implementation of these elements in the ISHM Testbed and Prototypes (ITP) Project under the NASA Exploration Systems Research and Technology program.

I. Introduction

Long-duration space exploration missions can only be accomplished with "systems-of-systems" that are robust, autonomous, and prepared to work in harsh and unforgiving environments. In-space assembly, long dormant periods and limited accessibility during flight are system requirements and constraints that pose risks to mission success. These risks present significant challenges and give rise to fundamental questions. What information is required for safe and sustainable operation, and how can it be determined? What information must be transferred to external facilities, possibly on-ground, for further analysis, and what situations require immediate autonomous response? How will systems be certified for operations in space after assembly? What tests must be conducted and what parameters must be monitored prior to system operation and throughout any dormant periods? Health Management (HM) technologies create the necessary foundation for success in such missions by providing answers to these questions.

In order to provide this foundation, an Integrated System Health Management (ISHM) system must be implemented. The ISHM system will provide safety and reliability coverage for a complete system over its entire life cycle, integrating health status and performance information from the subsystem and component levels to arrive at a system-level conclusion. The ISHM system will involve a collection of processing algorithms and intelligent elements at the

subsystem and system levels that will analyze the available data and report on the current status.

This paper will outline such a future ISHM approach by surveying the potential advanced diagnostic elements that will provide intelligent assessment of the system health and the planned implementation of these elements in the ISHM Testbed and Prototypes (ITP) Project under the NASA Exploration Systems Research and Technology program. First this paper will briefly describe the basic diagnostic approaches, highlighting their capabilities, requirements and limitations. The paper will then provide detailed examples of recent implementations in space-based systems and the basic HM implementation issues that must be addressed.

II. Potential ISHM Intelligent Elements

While the ISHM system will involve new technologies in hardware as well as software, we will focus our attention on the intelligent elements only. Hardware advances in areas, such as sensors, communications, and processing, will impact development in software and vice versa. From a perspective of intelligence or autonomy, the ISHM system shall provide the following functions:

- System Monitoring
- Data Qualification
- Feature/Information Extraction
- Classification/Isolation/Diagnosis
- Mission Projection/Prognosis
- Communication/Information Transfer
- System Recovery/Response

Many, if not all, of these functions will require intelligent software elements in order to satisfy the anticipated system-level requirements of safety, reliability and sustainability that the NASA Exploration Systems Mission Directorate will impose. This paper will focus on potential elements required for the first five functions: system monitoring, data qualification, information extraction, diagnosis, and prognosis.

A. Diagnostic Approaches

Many diagnostics techniques have been developed and applied to space systems over the last twenty years. For the sake of discussion here, these approaches will be categorized as either Model-Based or Empirical in nature (ref. 1), keeping in mind that certain hybrid techniques will blur this distinction. The following definitions will be applied:

Model-Based—First principle relationships are used to define the response of a system. Model-Based Diagnostic systems utilize a simulation of the monitored systems that can be either qualitative or

quantitative, meaning the relationships in the model can reflect symbolic or numerical relationships. The diagnostic solution is an analysis relating the actual system to the simulation. Some examples of Model-Based Diagnostic systems are listed in table 1.

Empirical—Empirically-derived features or relationship information are used as indications of system response and state. This information can be derived from expert knowledge acquisition information or via statistical data analysis. An Empirical Diagnostic system utilizes this information to justify the diagnostic solution. Several prominent classes of Empirical-Based Diagnostic systems are shown in table 1.

TABLE 1.—CLASSIFICATION OF SYSTEMS

	Model-based	Empirical
Diagnostic Technology	**Constraint-based** • Livingstone, MEXEC, State Diagnosis, MARPLE, TEAMS **Rule-based** • SHINE, Mycin **Bayesian** • Hidden Markov Models	**Statistical** • BEAM, SPRT, PCA **Bayesian** • Kalman Filters • Neural Networks **Particle Filters**

One important class of empirically-based approaches, which can be used for feature extraction, fault detection, and diagnosis, is those based on data mining. Data mining seeks to discover previously unknown regularities or anomalies in large data sets. There are a number of commonly used techniques in data mining, including:

- Basic Statistics: Statistical techniques are used to summarize, consolidate and generalize the information in large sets of data.
- Artificial neural networks: Non-linear predictive models that learn through training and resemble biological neural networks in structure (ref. 2).
- Decision trees: Tree-shaped structures that represent sets of decisions. These decisions generate rules for the classification of a dataset. (Examples: Classification and Regression Trees (CART) (ref. 3) and C4.5 (ref. 4)).
- Genetic algorithms: Optimization techniques that use processes such as genetic combination, mutation, and natural selection in a design based on the concepts of evolution.
- Nearest neighbor method: A technique that classifies each record in a dataset based on the classes of its

nearest neighbors in the feature space. (Example: Orca (ref. 5)).

- Rule induction: The extraction of useful if-then rules from data based on statistical significance (Example: C4.5 rules (ref. 4)).

Data mining applies these techniques to large data sets, and often combines them with relational database and on-line analytic processing (OLAP) technologies.

In realistic applications, a simulation or model often relies upon prior process history in order to establish the relationships. General relationships may be generic for a component, but the actual simulation is often anchored by test data. For this reason a working distinction between the two categories in table 1 would be that a Model-Based approach uses physics in an attempt to add structure to the diagnostic system and in this way ensure completeness and attempt to provide coverage to unanticipated failures. On the other hand, Empirical techniques provide diagnostic coverage for systems where the explicit relationships are not known or the information from the system is sparse and not well distributed for diagnostic purposes.

The requirements of the diagnostic system will influence the selection of the diagnostic technique. The diagnostic system may be a hybrid system containing elements from both categories. In addition, it may be a system that evolves from one category to another. For example, due to the sparse availability of data, the initial diagnostic system may be a simple collection of heuristic rules, and may evolve into a model of relationships as more information is gathered.

Recent applications/developments.—State-of-the-art studies in the area of diagnostics and prognostics have been conducted several times recently (refs. 6 to 8). Using these studies as a guide, specific technology developments have been applied in the space-based vehicle arena and will be initial candidates in the ITP project. The lessons learned in the following sections that highlight four recent implementation areas will be used in the development of the ITP health management system.

BEAM/SHINE: The NASA-developed Beacon-based Exceptions Analysis for Multimissions (BEAM) is an example of a hybrid technique with a strong empirical component. BEAM is a comprehensive self-analysis tool suitable as a monitor in many systems. BEAM seeks to mimic the logic of a human operator, and draws its training from many of the same sources. The fault detection, isolation, and prognostic conclusions are based upon physical models of arbitrary fidelity, symbolic models, example nominal data, real-time data, and architectural information such as connectivity and causal diagrams. BEAM detects anomalies by computing dynamical invariants (i.e., coefficients of an auto-regressive model) and comparing them to expected values as extracted from previous data. BEAM is particularly sensitive to anomalies caused by faulty sensors, subtle and sudden performance shifts, and unexpected transients, and can discriminate between these different event types. The algorithms have also been scaled to operate reliably on current-generation flight processors.

BEAM has been applied to many different domains, including propulsion system fault detection, deep space radio antenna automation, hydraulic system condition-based maintenance, and spacecraft attitude and articulation control subsystem anomaly detection. It has been demonstrated on numerous military/civilian space and aircraft systems (refs. 9 and 10).

A recent NASA demonstration of BEAM is the Space Shuttle Main Engine (SSME) anomaly detection system developed in a joint effort between JPL and the Marshall Space Flight Center (MSFC). It was developed as a prototype of an automated tool for rapid analysis of SSME data. As such, BEAM automatically indicates specific time periods, signals, and features contributing to each anomaly. For the SSME application, a custom version of BEAM was built to analyze data gathered during ground tests. BEAM was used to detect anomalies in seven different test data sets that contained some of the most commonly encountered anomalies in SSME testing. Overall, BEAM was sensitive to all of the major anomalies in the seven anomalous data sets and detected the shift in the data characteristics (ref. 11).

Propulsion IVHM Technology Experiment (PITEX): The Propulsion IVHM (Integrated Vehicle Health Management) Technology Experiment (PITEX) was a subsystem health management demonstration performed under the Space Launch Initiative (SLI) Program. The PITEX objective was to mature and demonstrate key IVHM technologies on a relevant 2nd Generation Reusable Launch Vehicle (RLV) propulsion system. The PITEX demonstration was originally selected to fly on the X-34 RLV developed by Orbital Sciences Corporation under an earlier program. Although the X-34 program was cancelled, PITEX carried forward the previous research by building upon a prototype diagnostic system that was developed (refs. 12 to 14).

PITEX was a complete health assessment package, containing both the data processing algorithms and an intelligent element, Livingstone (fig. 1). The Livingstone module is a model-based diagnostic engine that processes qualitative constraints of the monitored system and compares the anticipated output with the actual sensor information. If a discrepancy is found, the Livingstone engine attempts to determine conditions within the various components that would align to the current system state. The processing algorithms of PITEX, the Monitors and the Real-Time Interface, are tasked with providing system information in a timely and reliable fashion.

Lack of experimental data and the need to demonstrate robustness to system variations required the extensive use of simulations to characterize nominal and failure conditions. The PITEX demonstration used flight-like data (noise, sensor resolution, and hardware uncertainties) and realistic nominal and failure modes, supported real-time operation, and addressed computer resource management issues.
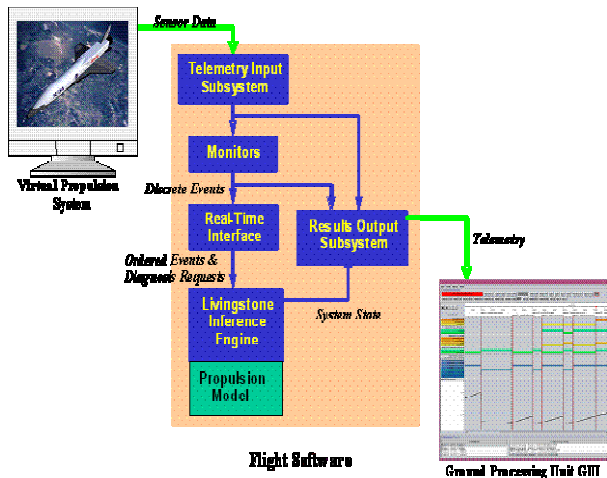
Figure 1.—PITEX demonstration architecture.

PITEX demonstrated the potential of Livingstone's qualitative model-based diagnostic engine in propulsion system health assessment. Lessons learned in the development of the PITEX demonstration software, as well as the demonstration itself (simulation development, test metrics and testing suites) are a valuable resource to the ITP project.

X-37 IVHM Experiment: The X-37 IVHM Experiment was a complementary effort to PITEX in several ways. The goals were similar: to integrate and mature IVHM technology and demonstrate in flight. The experiment integrated Livingstone 2 with the X-37's flight software, which involved developing monitors and a real-time interface. The X-37 IVHM Experiment modelled the X-37's electrical power system and electro-mechanical actuators instead of the propulsion system, and while PITEX was planned to have its own computer onboard the X-34, the X-37 IVHM Experiment was designed to run on the same flight computer as the X-37's critical flight software. Both of these differences provided important opportunities to mature the HM technologies, expanding into different critical spacecraft systems and flight-qualified computing resources. The decision to run it on the flight computer resulted in safety requirements to ensure that the IVHM software could not interfere with critical flight software. It also resulted in very tight CPU and memory resource usage requirements. Although this experiment did not reach flight testing phase, it was a valuable demonstration of IVHM capabilities meeting these stringent requirements (ref. 15).

BEAM-Livingstone Integration: BEAM-Livingstone Integration was an effort to create a prototype hybrid reasoning system utilizing the strengths of Jet Propulsion Laboratory's (JPL) BEAM and Ames Research Center's (ARC) Livingstone technologies under NASA's Strategic Launch Initiative (SLI) program. The effort demonstrated the feasibility of integrating BEAM, a continuous domain feature-based detector, and Livingstone, a discrete domain model-based reasoner, to create a hybrid diagnostic system. The hybrid diagnostic system was validated on one scenario from the PITEX simulation of the X-34 main propulsion feed system. In the scenario, Livingstone could not distinguish between a double regulator failure and a pressure sensor failure. By integrating BEAM as a virtual sensor into Livingstone, it provided an independent source of evidence, and the hybrid system was able to correctly diagnose the proper failure without an ambiguity. The results of the hybrid reasoner demonstrated the synergistic benefits of integrating BEAM and Livingstone (ref. 16).

III. Implementation Issues

There are several implementation issues that need to be defined and addressed. Each issue will impact not only the type of diagnostic technique applied, but also the effectiveness of the HM application. Figure 2 provides a graphical view of the issues involved in HM system design. Each issue group will be discussed in greater detail.

A. Monitored System Design

First, the system or subsystem to be monitored must be defined. Issues, like what measurements are available and what failures can be detected, need to be identified. The next step would be the characterization of the "healthy" system, as well as these identified failures. This may be done through historical assessment of the system using expert domain knowledge, system modelling and data mining technologies. Diagnostic techniques depend critically on the behaviors and modes of the system being managed and require in-depth knowledge of nominal operations and failure modes. To support both development and verification and validation, the system behaviors and modes must be modeled in a simulation of sufficient fidelity to properly reflect system responses to events.
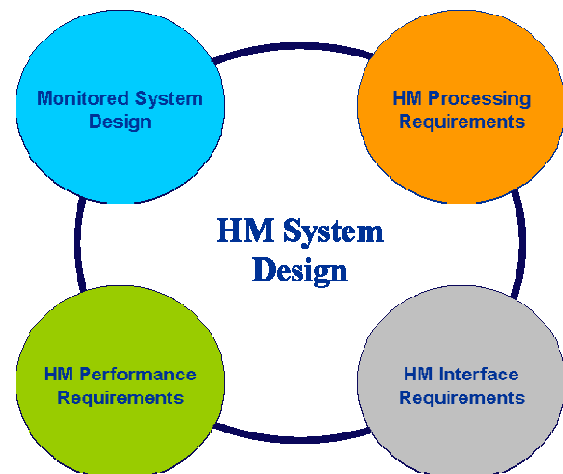

Figure 2.—HM System design issues.

Along with the ability to detect the fault condition, the ability to isolate failures needs to be evaluated. At a minimum, failures only require isolation when the remediation strategy differs between the faults. It should be noted that the remediation strategy for the same failure may vary greatly depending on the mission objectives, mission phase and current system configuration. Once the feature processing and diagnostic requirements are established, the proper health management techniques can be selected and developed.

The success of any diagnostic system is dependent on the diagnostic algorithms' awareness of the system behaviors and modes. The definition of sensor types and placement can be derived directly from the behavior and mode models developed in knowledge capture. Sensor selection and type will also need to be commensurate with the application environment of the space based system. Therefore, sensor selection will be based on the diagnostic benefit provided, weighed against the cost. For future system designs, each component, including sensors and software, will need to "buy" its way on-board.

B. HM Processing Requirements

The processing constraints for the intelligent elements must also be determined. In order to provide the signal-processing and diagnostic analysis, each element will require system resources in the form of CPU and memory. There is also communication bandwidth and information storage to consider. The required response time for each monitored failure must be considered. Failure manifestation can be on the order of milliseconds to days. How quickly the diagnostic system is required to detect and resolve the failure will drive the applicable technique and the system resource load required by that technique. Finally, every HM element will require resources for development and validation. These resources will generally take the form of historical information; the amount of information required and how the information will be utilized will depend on the selected technique.

C. HM Performance Requirements

Another set of issues to consider is the performance requirements for the HM elements and the verification and validation process. HM elements should demonstrate the ability to scale and evolve as the monitored system matures in its development. These elements should also demonstrate robustness to common sources of system uncertainty, such as sensor signal noise, build-to-build variation and environmental condition changes. The ability to handle system uncertainty should not require the HM element to become insensitive to failure detection. This is a common trade-off between competing HM requirements (false alarms versus missed detections) that needs to be addressed.

D. HM Interface Requirements

Finally, the interface requirements for each element must be defined. Each element will need to determine the health assessment information that will be transferred externally. The element may also require input from other elements, such as an understanding of current system state/operation. How the element will behave if this external information is not available or corrupted, must be considered. These are important ISHM design issues that could severely impact the performance of the HM system

The ISHM system design process should be conducted in tandem with the overall vehicle design and development. The ISHM requirements in addressing these issues could push back on the overall vehicle or system design and development.

III. Verification and Validation Techniques

Verification and validation (V&V) of diagnostic algorithms is a challenging and critical phase of ISHM development. The V&V of these algorithms requires not only operational systems, but the ability to test systems to failure to demonstrate the ability of the diagnostic algorithms to identify nominal conditions and failure conditions. This can be accomplished through an integrated series of software simulations, hardware-in-the-loop simulations, and hardware testing. Each phase provides differing abilities to exercise failure modes and demonstrate diagnostic performance.

A. Simulation Definition and Development

System simulation can be developed directly from the system behaviors and modes incorporating defined sensor responses. These simulations should provide an accurate, physics-based model of the system. These simulations incorporate nominal operating conditions as well as failure modes to exercise diagnostics. Execution of simulated systems will need to account for realistic system conditions, multi-processing requirements, communications and data buses (data processing and throughput), latencies, environment effects, real-time sensor and data fusion, system hardware characteristics and interfaces, supplied system behavior models and interfaces, computing and storage resources, and fault insertion scenarios. Furthermore, the simulation facility shall require the following features: software performance monitoring, sensor health monitoring, data integrity, fault detection and quick assertion and analysis, and identification of false positive conditions. By incorporating the diagnostic algorithms into the software simulations, a complete investigation of the algorithms can be conducted.

B. Simulation Execution (S/W)

Software simulations of the system being monitored and the diagnostic system provide a rich environment in which to evaluate, verify, and validate diagnostic performance. Failure modes, which may not be feasibly executed in hardware, can be exercised in the software simulation. In addition, the software system can be run faster than real time, allowing many more cases to be verified and validated than when using a hardware system. This does not replace hardware testing, but allows a level of investigation into scenarios and state spaces not otherwise available.

C. Hardware-In-The-Loop Simulation

Hardware-in-the-loop simulation would further define and qualify the underlying hardware and software diagnostic technologies. In this case, flight or prototype hardware executes the diagnosis software interactively with the software simulation of the system being monitored. System hardware can be added in this case to test interaction of the diagnostic systems with hardware components. With this capability integrated system performance testing, integrated procedure testing, operations and maintenance requirements development as well as operator training and familiarization could be performed. The capability to perform real-time, hardware-in-the-loop simulation of space vehicles and their subsystems will better provide for realistic system fault scenarios and performance assessment. Extensive resources for data processing, data archival, and hosting special configuration requirements will be required. This testing could not be performed faster than real-time due to the implementation of the diagnostic system hardware. However, failure modes not feasible in a hardware test, such as faults that are difficult or hazardous to induce or that require extended state space testing not practical with hardware systems due to limited life of components, testing time frames and costs, can be evaluated. In addition, performance of the diagnostic system can be validated by incorporating the diagnostic hardware into the simulation. Results of this testing can be fed back to the software simulation of the diagnostic system to improve the diagnostic system behavior modeling. Hardware-in-the-loop testing can also be used to identify scenarios which need full hardware testing, thus defining the hardware test program.

D. Hardware System Test

An integrated hardware system test environment is necessary to perform complete diagnostic system testing. Based on results of the software simulation and hardware-in-the-loop testing, full hardware tests will be conducted to V&V the diagnostic system performance in nominal operational scenarios as well as selected failure modes. These tests also provide the best medium to V&V overall system performance. Feedback from this testing can be provided to improve the software simulations used for development and hardware-in-the-loop testing.

V. ITP Intelligent Elements

For the ITP Project, there are two distinct areas where multiple intelligent elements will be applied. The first area will be the insertion of real-time health assessment capabilities within a rocket component test facility at NASA Stennis Space Center (SSC). This activity will involve the development and integration of advanced hardware and software elements within a controlled, relevant environment in order to assess the health management benefits and capabilities. The second area within the ITP Project involves using the International Space Station (ISS) as a testbed for ISHM software. It will include the use of historical ISS data, simulated ISS data, and possibly near-real-time ISS data to validate the performance of a variety of ISHM algorithms.

For the ITP project, diagnostic intelligent elements will be specifically developed for the E2 rocket component test facility at NASA SSC. Information processing will be performed on historical data from the testing facility, using conventional signal processing algoithms (legacy algorithms from earlier propulsion health assessment projects, including PITEX) and the BEAM processing and classification capabilities. The resulting detection and diagnostic elements will be incorporated within a G2 software framework of the monitored system. In Phase 1, a focused demonstration system will be developed to highlight the potential HM capabilities. In Phase 2, the detection and diagnostic elements will be expanded in fault coverage, and more sophisticated techniques and elements will be incorporated in the hybrid system.

In the ITP project, two data mining approaches will be explored to improve fault detection, diagnosis, and failure prognosis. In Phase 1, historical data from the SSC test stand will be analyzed using unsupervised anomaly detection algorithms, which only use nominal training data to generate a model of nominal sensor data. During run-time, the algorithm signals an anomaly when sensor data no longer fits the model. In Phase 2, supervised anomaly detection will be added, which learns to distinguish nominal and off-nominal patterns based on past examples of both, and can be used for diagnosis by learning to distinguish among examples of different types of faults. These algorithms will also be applied to data from the International Space Station during Phase 2. A variety of data mining algorithms that have been proven in other applications will be applied during this project, such as Orca, an unsupervised anomaly detection algorithm previously used for Earth science and aviation security applications (ref. 5), and C5.0, a supervised decision tree induction system from Rulequest Research.

In both of these activity areas, implementation and V&V issues will need to be addressed throughout Phase 1 and 2.

The architectures for both of these research projects will need to incorporate individual elements into a unified hybrid diagnostic system that allows for expansion and evolution. In addition, simulation and testing capabilities need to be established that will enable the proper evaluation of the final ISHM product.

VI. Summary

For the ITP project, we have begun to identify and define the applied system and develop the requirements for the ISHM elements. Selection of HM techniques for this project will be based on the lessons learned in recent applications of BEAM and Livingstone, as well as experience in data mining activities. We have outlined the potential design, development and testing issues that must be addressed:

- System definition and characterization
- Simulation development
- HM requirements definition
- HM element selection and development
- ISHM Evaluation Testing
  - Simulation
  - Hardware-In-The-Loop Simulation
  - Hardware System

We also discussed the specific research areas within the ITP project from the intelligent element perspective. Along with the HM requirements, implementation and development issues will be anticipated and resolved as part of the research in each element development process.

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13. ABSTRACT (Maximum 200 words)

Deep-space manned missions will require advanced automated health assessment capabilities. Requirements such as in-space assembly, long dormant periods and limited accessibility during flight, present significant challenges that should be addressed through Integrated System Health Management (ISHM). The ISHM approach will provide safety and reliability coverage for a complete system over its entire life cycle by determining and integrating health status and performance information from the subsystem and component levels. This paper will focus on the potential advanced diagnostic elements that will provide intelligent assessment of the subsystem health and the planned implementation of these elements in the ISHM Testbed and Prototypes (ITP) Project under the NASA Exploration Systems Research and Technology program.

14. SUBJECT TERMS

Fault detection; Systems health monitoring

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