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Meeting the Challenges of Exploration Systems: Health Management Technologies for Aerospace Systems With Emphasis on Propulsion

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October 2005

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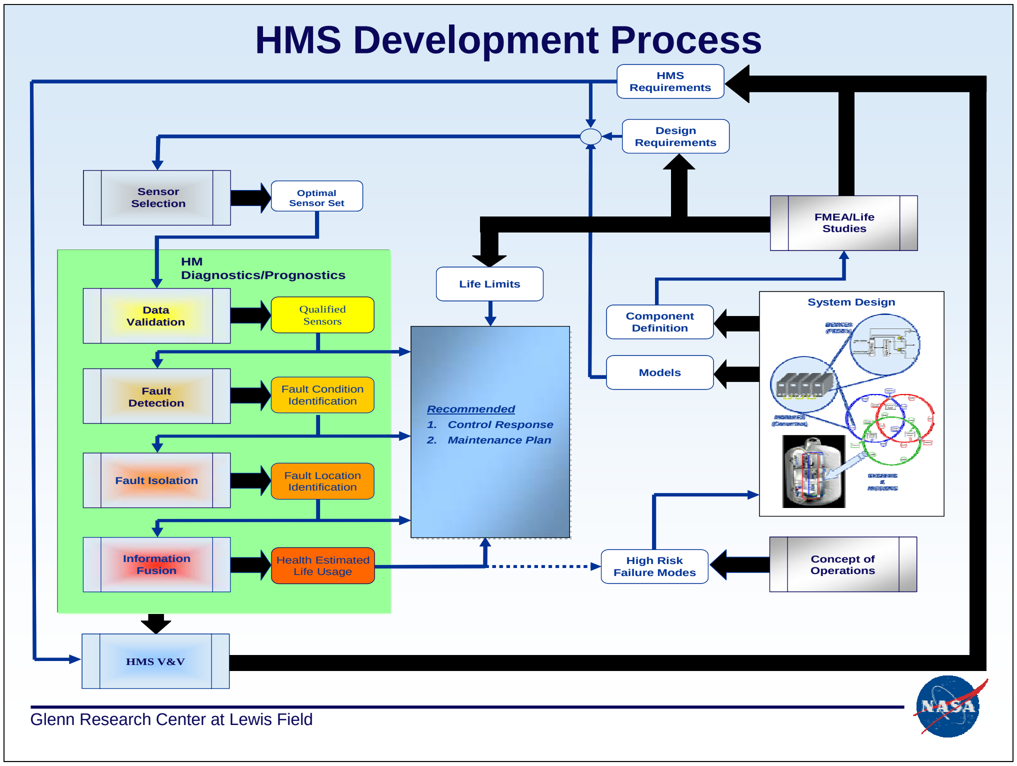
Abstract

The constraints of future Exploration Missions will require unique Integrated System Health Management (ISHM) capabilities throughout the mission. An ambitious launch schedule, human-rating requirements, long quiescent periods, limited human access for repair or replacement, and long communication delays, all require an ISHM system that can span distinct, yet interdependent vehicle subsystems, anticipate failure states, provide autonomous remediation and support the Exploration Mission from beginning to end. NASA Glenn Research Center has developed and applied health management system technologies to aerospace propulsion systems for almost two decades. Lessons learned from past activities help define the approach to proper ISHM development:

- Sensor Selection – identifies sensor sets required for accurate health assessment;
- Data Qualification & Validation – ensures the integrity of measurement data from sensor to data system;
- Fault Detection and Isolation – uses measurements in a component/subsystem context to detect faults and identify their point of origin;
- Information Fusion and Diagnostic Decision Criteria – aligns data from similar and disparate sources in time and use that data to perform higher-level system diagnosis;
- Verification &Validation – uses data, real or simulated, to provide variable exposure to the diagnostic system for faults that may only manifest themselves in actual implementation, as well as, faults that are detectable via hardware testing.

This presentation describes a framework for developing health management systems and highlights the health management research activities performed by the Controls and Dynamics Branch at the NASA Glenn Research Center. It illustrates how those activities contribute to the development of solutions for Integrated System Health Management.



Health Management System Development Process

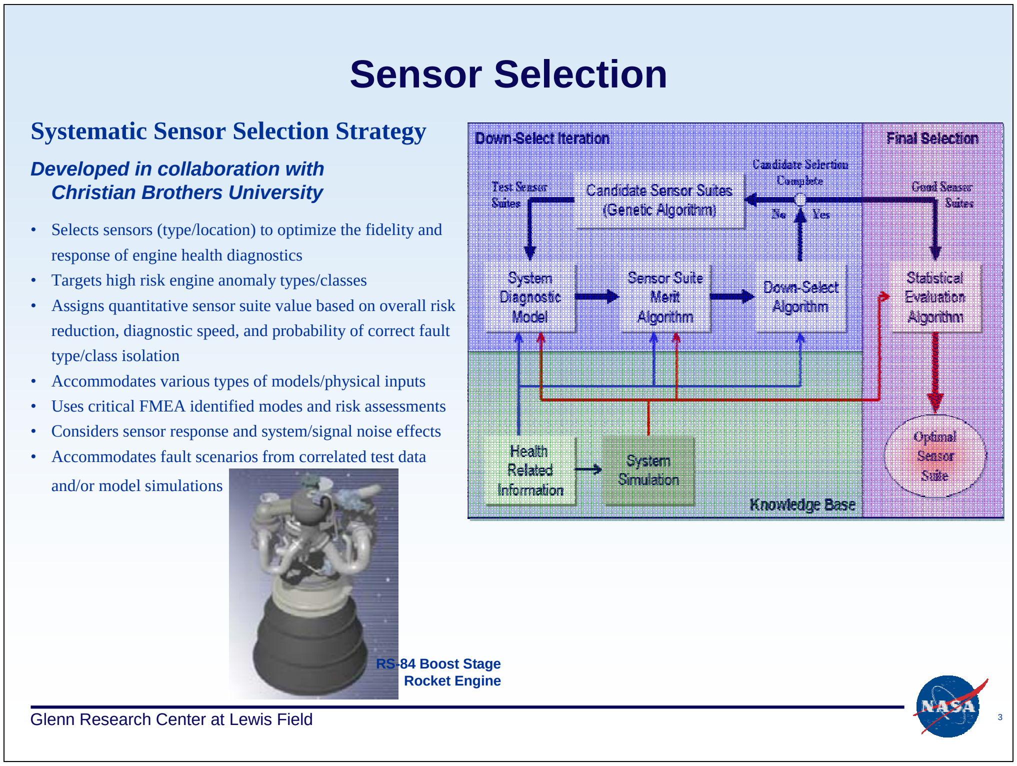
Optimum performance and effectiveness of a health management system (HMS) is achieved when its development coincides with the development of the system whose health it is being tasked to manage. It is much less effective and efficient when it is implemented after the fact.

The chart shown above was developed by the NASA Glenn Controls and Dynamics Branch to describe its process for developing HMSs. In general, the HMS development process requires a thorough understanding of the system being managed. Knowledge acquisition from domain experts is essential in establishing the scope of a HMS. A clear set of system requirements and concept of operations are some of the first essential elements. A Failure Modes and Effects Analysis must be performed to identify the critical faults and document how those faults manifest themselves in the system. Also, when development of a health management is incorporated early in the system design, little, if any, test data is available and a models of the system are essential. These system models must be developed with sufficient detail and complexity so that they provide a sound basis for developing and testing the required health management system.

Focusing on the design requirements for the monitored system, as well as, for the HMS itself, elements of the development process may be identified as follows :

- Sensor Selection
- Data Validation
- Fault Detection
- Fault Isolation
- Information Fusion

Note that clear boundaries between these elements do not necessarily exist. There is some overlap and distinctions between the elements are not always clear. However, it is useful to address technology capabilities and gaps in each of these elements separately. Therefore, in an attempt to discuss the advances required for future exploration missions, the charts that follow describe in more detail each of the HMS elements identified above.



Systematic Sensor Selection Strategy

S4 is a model-based procedure for systematically selecting an optimal sensor suite for overall health assessment of a given host system. S4 was developed in collaborative effort by the Controls and Dynamics Branch at NASA GRC and Christian Brothers University. Initial efforts to apply the technology focused on the Rocketdyne RS-83 and RS-84 boost stage liquid rocket engines. This systematic sensor selection strategy identified a minimum suite of 22 sensors (from a candidate set of 59 sensors) that maximize risk reduction potential for the RS-84 engine.

Sensor data are the basis for performance and health assessment of most complex systems. Therefore, careful selection and implementation of sensors is critical to enable high fidelity system health assessment. S4 is designed with these considerations in mind.

S4 can be logically partitioned into three major subdivisions: the knowledge base, the down-select iteration, and the final selection analysis. The knowledge base consists of system design information and heritage experience together with a focus on components with health implications. The sensor suite down-selection identifies a group of sensors that provide good fault detection and isolation for targeted fault scenarios. This process is composed of three basic components: a system health diagnostic model, a merit algorithm, and a selection algorithm. In the final selection analysis, a statistical evaluation algorithm provides the final robustness test for each down-selected sensor suite.

Though this systematic sensor selection process was developed to enhance design phase planning and preparation for in-space propulsion health management, the S4 process can also be applied to a broad range of non-propulsion health management systems (e.g., power, communications) that are part of the Exploration Systems architecture.

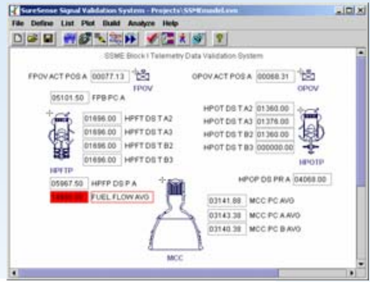
Ref: Santi, L.M., Sowers, T.S., Aguilar, R.B., "Optimal Sensor Selection for Health Monitoring Systems", 41st Joint Propulsion Conference and Exhibit, AIAA 2005-4485, July 2005.

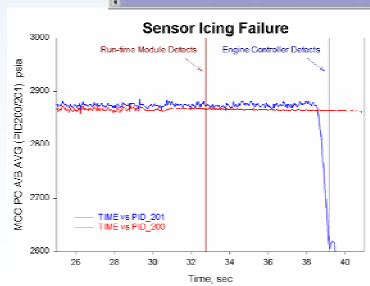
Sensor Data Validation

Data Qualification Validation Studio (DQVS ™)

Developed in collaboration with Expert Microsystems, Inc.

- Real-time detection of sensor failures and other data anomalies
- Rapid model prototyping enabled by development studio
- Uses analytical redundancy models, statistical limit filters and Bayesian fault decisions
- Provides operating mode partitioning and generalized data interfaces





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Sensor Data Qualification and Validation

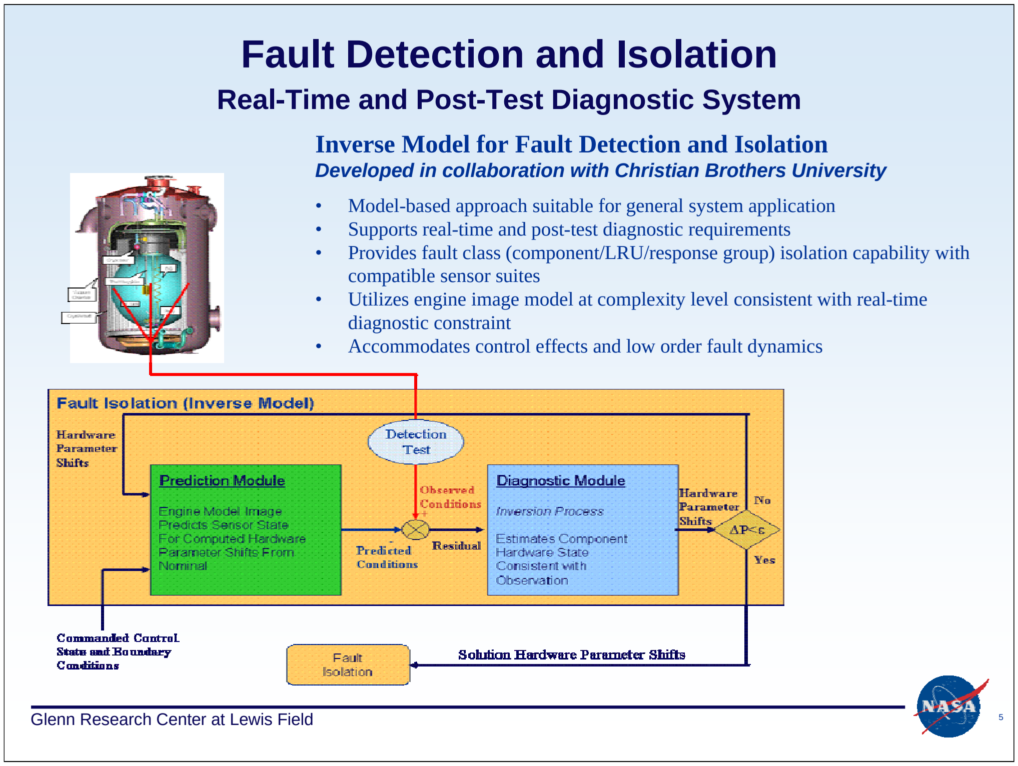
Sensor data qualification and validation is the process of analyzing sensor data to insure that it accurately represents the system state being measured. NASA Glenn has developed and implemented a number of sensor qualification and validation technologies, e.g. Neural Networks, Model-Based Analytical Redundancy, Kalman Filters and Wavelets. These methods are used not only to identify hard sensor failures, but also soft sensor failures, such as drift and noise.

Data validation is an important element in the health assessment process. The goals of a sensor validation system are to prevent safety system false alarms, unnecessary shutdowns, or improper system responses by ensuring that automated health management systems “reason” with valid data. Proper fault detection and isolation can only be performed when information provided by the sensors is valid. Therefore, an initial analysis of sensor data to filter beyond simple off-scale data is crucial to any HM system performance.

For one such project, NASA Glenn partnered with Aerojet and Expert Microsystems to develop an advanced sensor validation technology that utilized a Bayesian Belief network to provide real-time solutions for RS-83 and RS-84 propulsion systems. This technology incorporated the analytical redundancy relationships between all the sensors in the engine to establish a belief network that would identify faulty sensors and a level of confidence of this identification. The result of this effort is contained within a commercially available software suite, The Data Quality Validation Studio™ produced by Expert Microsystems, Inc. NASA Glenn’s Controls and Dynamics Branch supported the development and gained expertise in the use of the software by providing space shuttle main engine domain expertise, models for sensor relationships, and by conducting validation testing of the new sensor failure detection algorithms.

Data validation is vital for any system that relies solely on sensor information to evaluate system performance and to assess system health. For Exploration Systems Missions where automation and remediation are based exclusively on sensor data and limited human input, advancement of these technologies to ensure optimum implementation, development and certification is required.

Ref: Bickford, R. L., et al., “Real-Time Flight Data Validation for Rocket Engines”, 32rd Joint Propulsion Conference, AIAA/ASME/SAE/ASEE, 96-2827, July 1996..



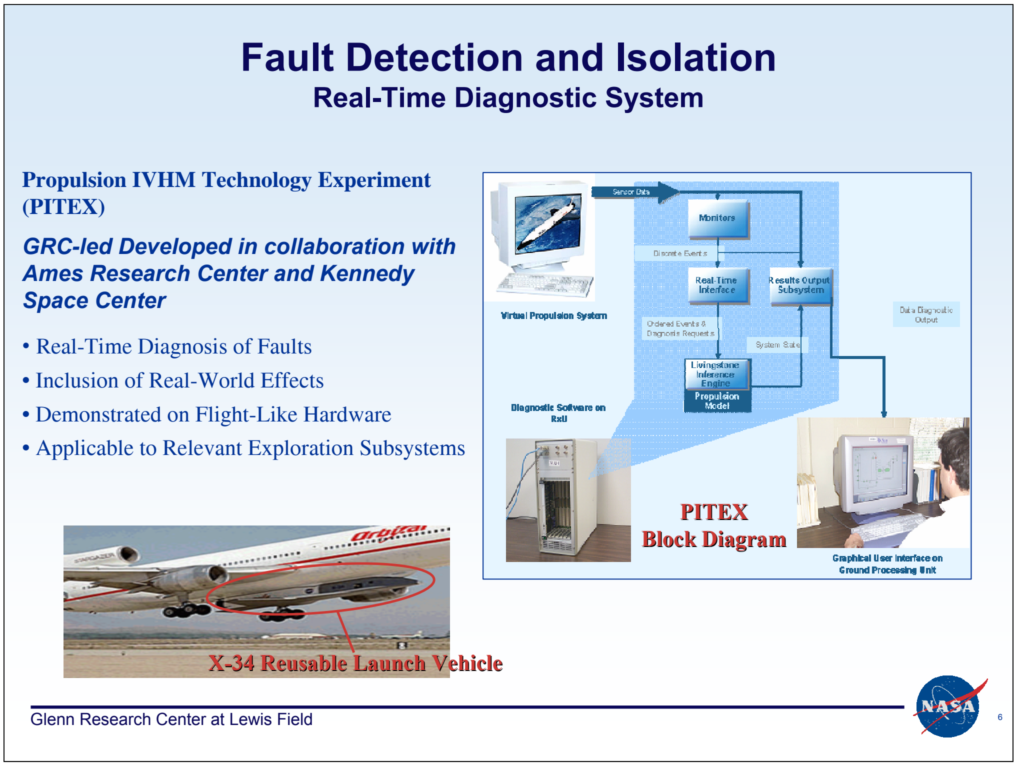
Model Inversion for Fault Detection and Isolation

Model inversion is the process whereby system states are identified from measurement values rather than the converse which is typical of the modeling process. An inverse model for fault detection and isolation in rocket engines was developed collaboratively by NASA Glenn's Controls and Dynamics Branch and Christian Brothers University as part of a health management system for NASA's Next Generation Launch Technology program. The inverse model framework is a component of the Systematic Sensor Selection Strategy (S4) mentioned previously.

The algorithms that effect inversion are referred to as inverse models (IM). The core of any inverse model is a parameter optimization algorithm whose function is to determine component performance that best reconcile system model prediction and observation. Diagnosis of system condition and conclusions related to health status are inferred from the magnitude and/or variance of health parameter excursions from the accepted norm. Most common model-based techniques that assign health status to parameter state estimates can be classified within the inverse model framework. This would include the broad class of influence methods as well as state space techniques and various hybrid model-based strategies.

An inverse model may be constructed to accommodate system nonlinearity, system dynamic response, and external control inputs at nearly any level of detail required. For each specific application, the appropriate inverse model form is suggested by the trading of diagnostic response time and state discrimination level. It is important to note that the design, maintenance, control, and health monitoring functions can all be supported by inverse models. Therefore the development of a robust inverse model for a given Exploration Systems application will likely support all diagnostic functions at some level.

The reader should note that references on this effort are currently unavailable as reporting of this work is in progress.



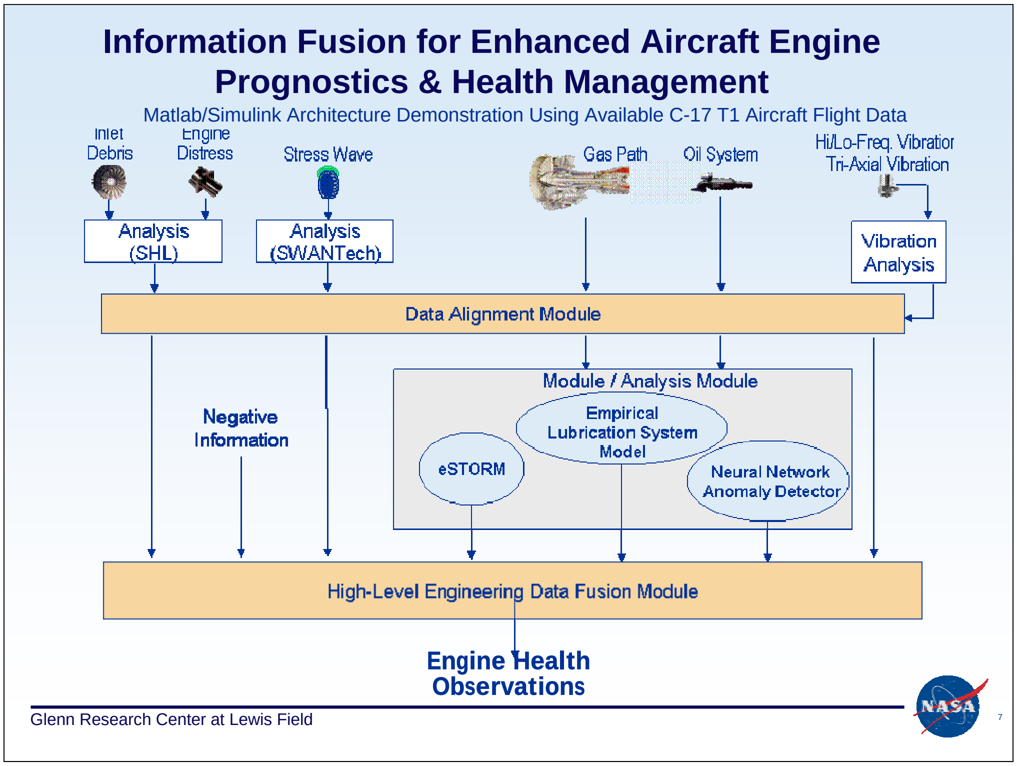
Propulsion IVHM Technology Experiment

The Propulsion IVHM Technology Experiment (PITEX) is a real-time model-based diagnostic system for the main propulsion system of the X-34 reusable launch vehicle, a space-launch technology demonstrator. PITEX was developed by a multi-center team led by NASA Glenn. During development, the Controls and Dynamics Branch was responsible for acquiring knowledge of the system, for developing signal processing algorithms and feed system simulations, for providing failure scenario data, and for conducting extensive testing and evaluation.

PITEX was demonstrated in a simulation-based environment that used detailed models of the propulsion subsystem to generate nominal and failure scenarios during captive carry – the most safety-critical portion of the X-34 flight. Since no system-level testing of the X-34 Main Propulsion System (MPS) was performed, these simulated data were used to verify and validate the software system. Advanced diagnostic and signal processing algorithms were developed and tested in real-time on flight-like hardware. In an attempt to expose potential performance problems, these PITEX algorithms were subject to numerous real-world effects in the simulated data including noise, sensor resolution, command/valve talkback information, and nominal build variations. The current research has demonstrated the potential benefits of model-based diagnostics, defined the performance metrics required to evaluate the diagnostic system, and studied the impact of real-world challenges encountered when monitoring propulsion subsystems.

PITEX has applicability to a wide variety of long duration systems, especially propulsion systems, that are likely to be part of NASA's Exploration Systems Program.

Ref: Maul, W. A., et al, "Addressing the Real-World Challenges in the Development of Propulsion IVHM Technology Experiment (PITEX)", First Intelligent Systems Technical Conference, AIAA, September 2004.



Information Fusion for Extended Gas Path Analysis Capability

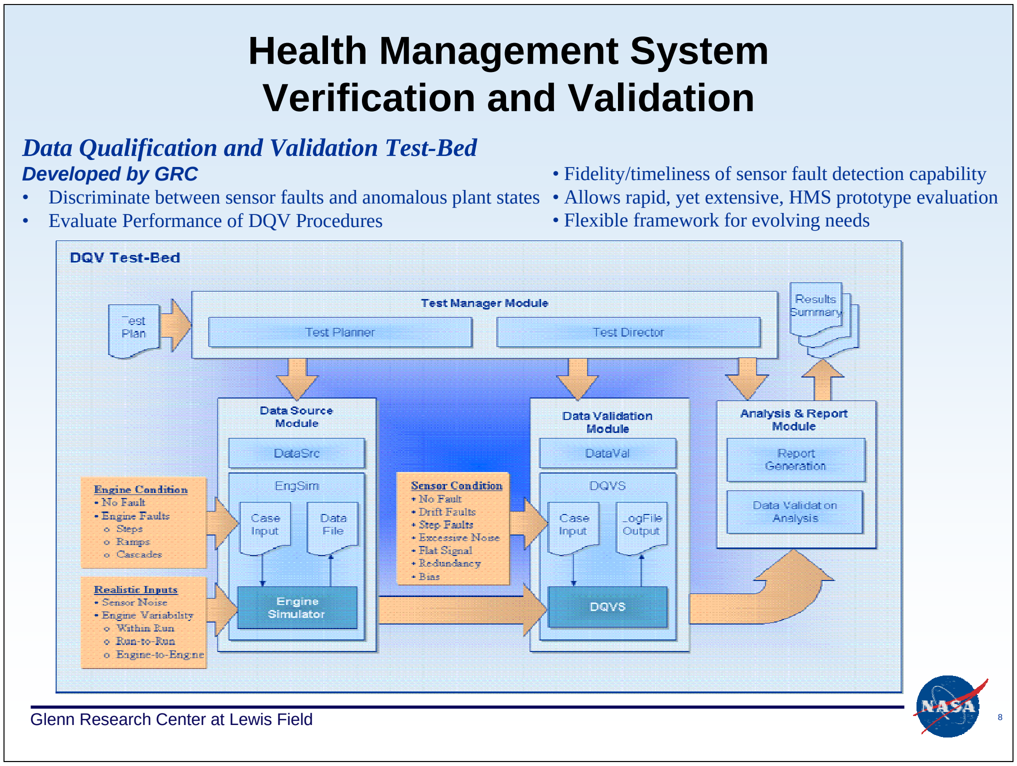
Information, or data, fusion is the ability to align data from similar and disparate sources in time and use those data to perform higher-level system diagnosis. In this area, expertise within NASA Glenn's Controls and Dynamics Branch is historically found on the aeronautics, rather than the space, side of the house. Under NASA's Aviation Safety Program, NASA and Pratt & Whitney (P&W) are collaborating to develop Information Fusion technologies.

A wealth of aircraft turbine engine data is available from a variety of sources including on-board sensor measurements, operating histories, and component models. Furthermore, additional data will become available, as advanced prognostic sensors are incorporated into next generation gas turbine engine systems. The challenge is how to maximize the meaningful information extracted from these disparate data sources to obtain enhanced diagnostic and prognostic information regarding the health and condition of the engine.

To address this challenge, NASA and Pratt & Whitney (P&W) have developed a modular hierarchical information fusion architecture. To demonstrate the efficacy of this architecture, a fusion demonstration of two gas path analysis algorithms, the Enhanced Self-Tuning Onboard Real-time Model (eSTORM) and a neural network-based Gas Path Anomaly Detector (GPAD), was performed. The architecture used to fuse these two algorithms is shown above. This fusion allows the system to detect and isolate both sensor and component faults. Furthermore, once a sensor fault is detected, it is accommodated by replacing the faulty physical measurement with a estimated value. This allows the system to continue to accurately estimate component performance even in the presence of a sensor fault.

Data Fusion is an enabling technology for long duration missions where self diagnosis of very complex systems may be the difference between mission success and failure.

Ref: Volponi, Allan J. et al, "Development of an Information Fusion System for Engine Diagnostics and Health Management," Prepared for the 39th Combustion/27th Airbreathing Propulsion/21st Propulsion Systems Hazards/3rd Modeling and Simulation Joint JANNAF Subcommittee Meeting Colorado Springs, Colorado, December 1-5, 2003



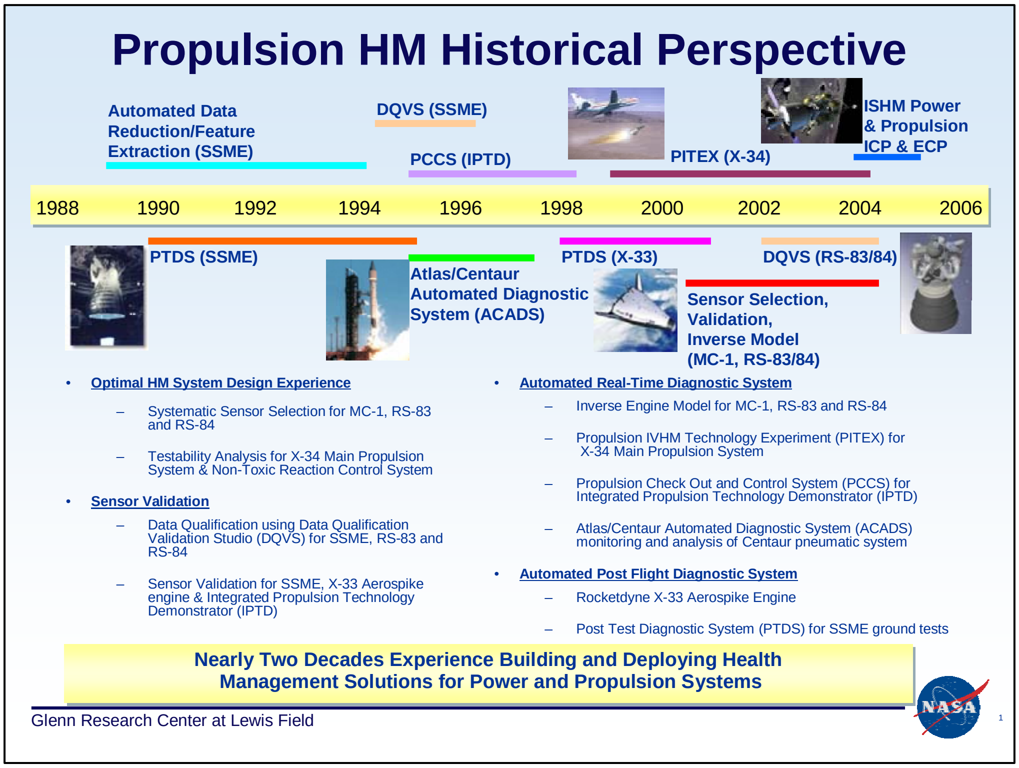
Data Qualification and Validation Test-Bed

On-line data validation, one aspect of system verification and validation, is a performance-enhancing component of modern control and health management systems. It is essential that performance of the data validation system be verified prior to its use in a flight-rated control and health management system. A new Data Qualification and Validation (DQV) Test-Bed application was developed by NASA Glenn's Controls and Dynamics Branch to provide a systematic test environment for this performance verification. The DQV Test-Bed was used to evaluate a model-based data validation package being employed as the data validation component of a rocket engine health management system.

Four major modules compose the test-bed framework. The Test Manager Module defines the test conditions and controls the overall execution of the test sequence. Test data is provided by the Data Source Module. The Data Validation Module manages the system under test (SUT). The Analysis and Reporting Module evaluates the output from the SUT using the known test conditions and generates a series of reports summarizing the results.

The DQV Test-Bed was shown to be an effective tool for reducing development time and providing comprehensive testing of a health monitoring system for the RS-84 propulsion system. It provides an efficient avenue for assessing the strengths and weaknesses of prototype data validation and fault detection systems by improving the understanding of those systems' capabilities and trade-offs. The DQV Test-Bed provides a potentially useful and important element of the necessary infrastructure to iteratively develop and flight-qualify health management systems for NASA Exploration Systems Program.

Ref: Sowers, T.S., Santi, L.M., Bickford, R.L., "Performance Evaluation of a Data Validation System", 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2005-4486, July 2005.



Conclusion

The Controls and Dynamics Branch at the NASA Glenn Research Center has been involved in the development and application of critical health management technologies for aerospace propulsion systems for almost two decades. These technologies have been applied in real-time and non-real-time analyses and have included conventional and non-conventional techniques. The Branch has recently broadened its focus to include propellant and reactant feed systems, power distribution systems, and environmental control systems. While each subsystem has its own unique constraints and issues, there also exists an underlying commonality in the development and implementation of the their health management systems. Each subsystem requires that …

- the health management system developers acquire extensive knowledge and that they develop an intimate understanding of the subsystem's operation;
- health management system development take place in parallel with development of the monitored system to achieve optimal effectiveness;
- techniques in addressing optimum sensor placement, fault detection and isolation and information fusion, be developed and implemented based upon the unique constraint implied by the monitored system itself and imposed by the application or mission;
- each health management system implemented be verified and validated to the satisfaction of the systems' designers and developers.

NASA Glenn's has a rich legacy of health management research in both aeronautics and space to draw upon when developing Integrated Health Management Systems for future exploration missions.

Ref: Garg, S., "Controls and Health Management Technologies for Intelligent Aerospace Propulsion Systems", 42nd AIAA Aerospace Sciences Meeting and Exhibit, AIAA-2004-0949, January 2004.

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13. ABSTRACT ***(Maximum 200 words)***
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