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Integrated System Health Management (ISHM) for Test Stand and J-2X Engine: Core Implementation

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ISHM capability enables a system to detect anomalies, determine causes and effects, and predict future anomalies. It provides advice to improve operations based on health status, and includes user interfaces for integrated awareness of the health of the system. NASA Stennis Space Center (SSC), NASA Ames Research Center (ARC), and Pratt & Whitney Rocketdyne (PWR) are currently implementing a core ISHM capability that encompasses the A1 Test Stand and the J-2X Engine. The implementation incorporates all aspects of ISHM; from anomaly detection (e.g. leaks) to root-cause-analysis based on failure modes and effects analysis (FMEA), to a user interface for an integrated visualization of the health of the system (Test Stand and Engine). The implementation provides a low functional capability level (FCL) in that it is populated with few algorithms and approaches for anomaly detection, and root-cause trees from a limited FMEA effort. However, it is a demonstration of a credible ISHM capability, and it is inherently designed for continuous and systematic augmentation of the capability. The paper describes all aspects of the current implementation, and on-going activity leading to a pilot capability that could potentially support the J-2X test program.

Nomenclature

DIaK	=	Data, Information, and Knowledge
DTM	=	Detailed Transient Model
DRTM	=	Detailed Real-Time Model
EDS	=	Earth Departure Stage
FCL	=	Functional Capability Level
ISHM	=	Integrated System Health Management
SSC	=	Stennis Space Center
PWR	=	Pratt & Whitney Rocketdyne

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ARC = Ames Research Center
IP = Intelligent Process.
ISHM = Integrated System Health Management.

I. Introduction

INTEGRATED System Health Management (ISHM) is a capability that often has multiple interpretations or definitions. We will adhere to the following definitions taken from a prior publication[1], and also addressed by two other references[2, 3].

"ISHM is a capability that is achieved by integrating data, information, and knowledge (DIaK) that might be distributed throughout the system elements (which inherently implies capability to manage DIaK associated with distributed sub-systems). DIaK must be available to any element of a system at the right time and in accordance with a meaningful context. ISHM Functional Capability Level (FCL) is measured by how well a system performs the following functions: (1) detect anomalies, (2) diagnose causes, (3) predict future anomalies/failures, and (4) provide the user with an integrated awareness about the condition of every element in the system and guide user decisions.

The primary technologies that enable achievement of ISHM capability include:

- Algorithms/approaches/methodologies for anomaly detection.
- Approaches and methodologies for root-cause analysis to diagnose causes of anomalies.
- Approaches and methodologies for prediction of future anomalies.
- Architectures/Taxonomies/Ontologies (management of DIaK – where management implies distributed storage, sharing, processing, maintenance, configuration, and evolution).
- Software environments that integrate contributing technologies in a modular plug&play fashion, adhering to a defined architecture/taxonomy/ontology.
- User interfaces to provide the user with integrated system awareness.
- Intelligent elements (e.g. sensors, valves, pumps, etc.).

The ISHM philosophy is predicated on:

- Lives and missions depend on vigilant systems.
- Data is valuable: No data should be left uninterpreted.
- Information is hidden: Intelligence is required to extract information.
- Interpretation, reasoning, and decision making require knowledge of how elements interact as part of an integrated system."

This paper describes results and on-going activities leading to implementation of ISHM capability for the A1 Test Stand at NASA Stennis, and the J-2X Engine that will be tested using A1. In a prior publication[4], the authors provided details of the planned activities, approaches, and tools to be employed in this endeavor. The implementation encompasses the following major activities: (1) development of infrastructure to flow real-time data through an ISHM model, (2) development and fine-tuning of ISHM models for the test stand and the engine, (3) basic failure modes and effects trees for the test stand and engine, (3) simulation results of the real-time transient model of the engine, including insertion of simulated anomalies, and (4) approach for an operational ISHM capability implementation.

II. ISHM Model of the Test Stand and Engine

ISHM models encompass management of data, information, and knowledge (DIaK) focused on determination of the health of all elements in a system. DIaK management implies storing, using, updating, and evolving DIaK, and making DIaK available to any element of the system when needed, filtered to address a proper context. Detailed descriptions of the paradigm, architecture, standards, and tools to build ISHM models are provided in references 1-3.

A. ISHM Models of the Test Stand and the Engine

ISHM models for the test stand and the engine were created using a software environment based on G2[5], hereto forth denominated ISHM Model Building Toolkit (IMBT). G2 is a commercial product specifically developed for

implementation of "intelligent" applications. NASA Stennis developed the IMBT. ISHM models are object models that include every element in the system of interest, e.g. sensors and components (valves, tanks, switches, etc.). Information about each element is encapsulated in each object, e.g. specifications. Sensor objects embed a "transducer electronic data sheet" or TEDS, which adheres to the IEEE 1451.4 standard for smart sensors. Component objects embed a "Component Electronic Data Sheet" or CEDS. Sensor and component objects embed a "Health Electronic Data Sheet" or HEDS. All embedded information and knowledge is focused on enabling ISHM functionality, and includes:

Strategies that use process models for consistency checking that lead to anomaly detection. For example, a tank object might be associated with process models such as a "tank pressurization model" that is used to make consistency checks involving pressure and temperature sensors that can lead to detection of sensor or tank anomalies. All sensors that share a power source might be evaluated against a common mode anomaly that might be associated with the power supply, etc.

Root-cause (RC) trees that implement FMEA information in graphic form in order to provide automated diagnostics and effects results from anomaly events. An example root-cause tree is shown in Figure 1. The tree enables diagnosis for leakage events, and it is associated with an embedded strategy to find leaks as described by the flow diagram in Figure 2. The system automatically determines "pressurizable subsystems" (PSS), which are sections isolated by closed valves, and as such are supposed to maintain internal pressure. It then looks for pressure sensors in each PSS, checks if the pressure is changing, and if so, it sends a leak event to the corresponding node in the tree, for a particular instance of the tree that corresponds to the PSS where the leak was found. The tree then disseminates the event to the left to diagnose causes (all members of the PSS become suspect of leak), and to the right to indicate effects of the leak (all pressure sensors changing in the same way). Root-cause trees are object oriented, and can be mostly generic (e.g. representing failure modes of classes of objects such as motor valves). RC trees in the IMBT can be powerful representations that might include relationships for applying the tree to specific sets of objects with specific behaviors and/or affiliations.

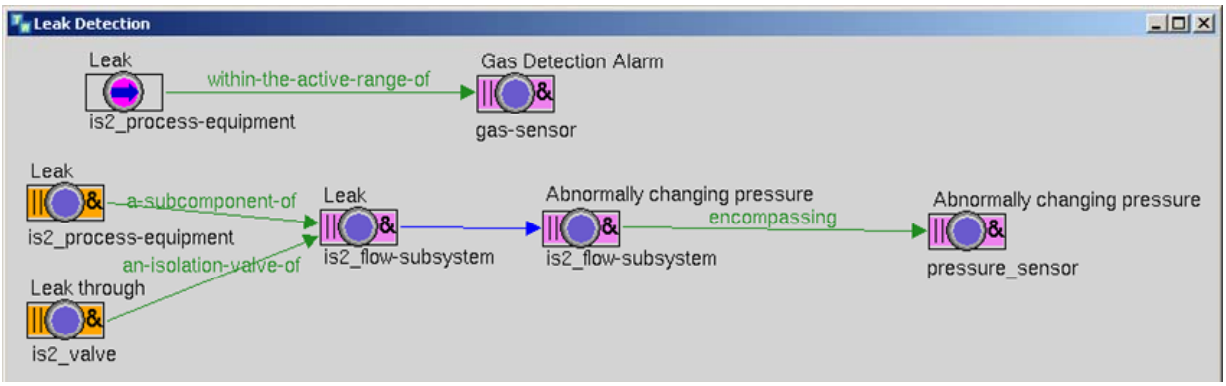

Figure 1. Example FMEA trees associated with leak anomalies

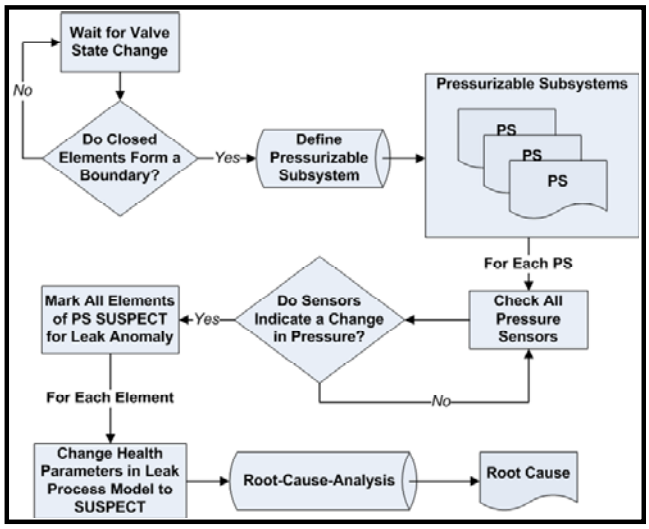

Figure 2. Stategy for detection of leaks in a pressurizable subsystem.

Figure 1 shows two root cause trees. The bottom tree implements a "generic" leak failure mode analysis and effects for flow subsystems. The "leak" node with pink background color receives a "leak" event in a type of flow-subsystem (PSS). The event is received in the leak node corresponding to "is2_flow-subsystem" class of objects. The arrow to the right implies that a consequence of the leak is that the subsystem is experiencing abnormally changing pressure (which has a special meaning for a PSS – pressure should not be changing). This node has yet another effect that is abnormally changing pressure on any pressure sensor of the subsystem (notice the denomination "encompassing" on the arrow). To the left of the "leak" event (node) are two possible causes: (1) leak in all elements that make up the subsystem (notice the denomination "a-subcomponent-of" on the arrow), and (2) leak on an isolation valve of the subsystem (notice the denomination "an-isolation-valve-of").

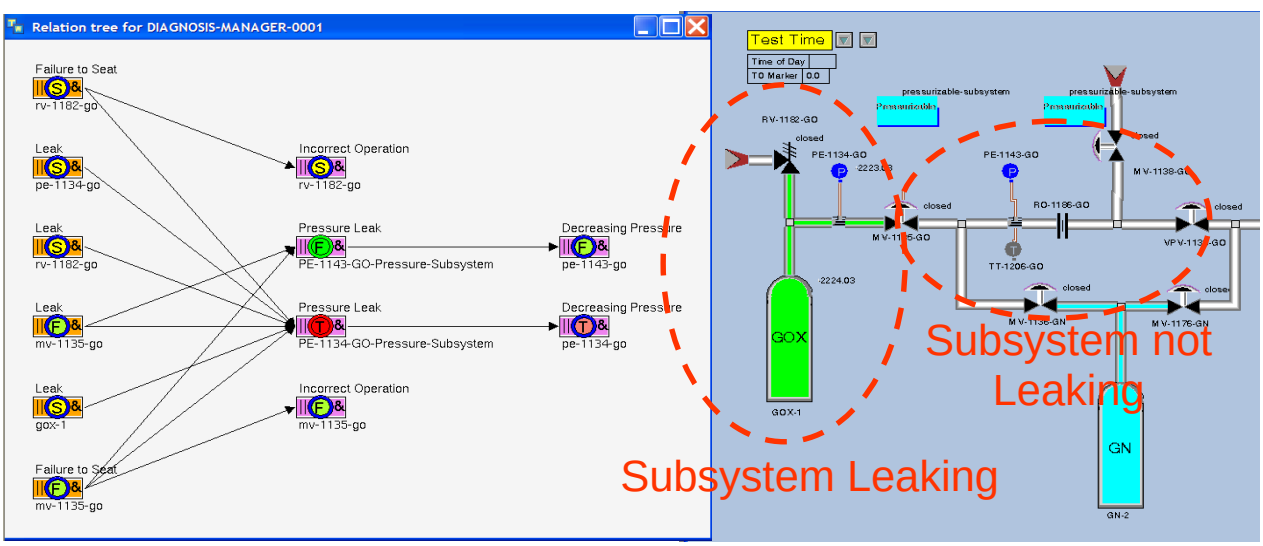

Figure 3. Specific root-cause tree when leak is detected in a subsystem.

Figure 3 shows an instantiation of the leak root-cause tree, applied to two pressurizable subsystems separated by a valve. Leak is detected on the subsystem to the left, but not on the right. All elements of the left subsystem become suspect of leak, except for the valve joining the two subsystems. The specific tree indicates precisely the state of the specific nodes (representing events) as being "suspect (S)," or "true (T)," or "False (F)." The event "leak" of the valve that is part of both subsystems is False (F), indicating that the valve is not leaking. The tree also shows, on the right, the nodes that are consequences.

Intelligent Sensors are part of the ISHM Model, with "intelligence" enabled through a Virtual Intelligent Sensor Environment (VISE). The VISE acts like a pre-processing system whereby traditional sensors are augmented with

functionality of "intelligent" sensors[6, 7]. VISE includes TEDS information and processes that apply to streaming data, to detect indicators of anomalies. Currently VISE can detect (1) high noise, and (2) limit violations. Spike detection and flat signal detection algorithms have been validated and will be embedded in VISE for real-time operation.

The top view of the ISHM model of the test stand and engine is shown in Figure 4. Detailed object models of each subsystem are accessed by clicking on the subsystem at the operator's console. Each element, e.g. a sensor, includes an electronic data sheet with complete specifications. Each element also includes a health electronic data sheet (HEDS) that contains health related information such as "good" or "suspect" or "anomalous." In the case of sensors, HEDS also includes a measure of the quality of the data produced by the sensor. Process models for consistency checking are associated with elements or subsystems that take part in the process. For example, pressurizable subsystems are associated with the leak process; and a pressurization process is associated with a tank or a pressurizable subsystem.

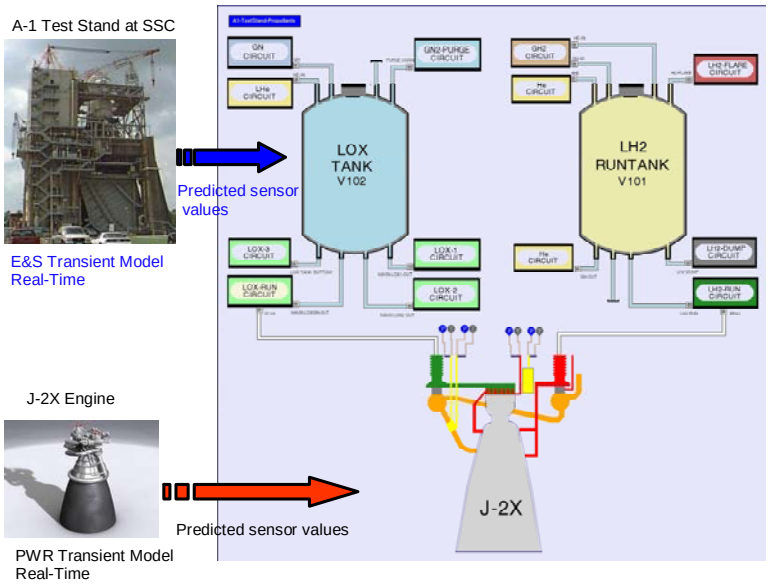

Figure 4. Top view of the ISHM Model of the A1 Test Stand and Engine. Predictive models will contribute to health assessment.

One important objective of this effort was to incorporate "***predictive models***" for obtaining predictions of values that sensors should be measuring. This information is to be used to check consistency between the model and the actual system. Any inconsistencies are to be used as indicators of anomalies. These indicators are to be used in conjunction with other indicators and models to detect anomalies. For example, if the pressure in the LOX inlet to the engine is significantly different than its prediction, a suspicion on the sensor integrity is raised. This suspicion might be further confirmed or dismissed by other information. For instance, if the sensor has a history of excessive noise, suspicion on the sensor will increase. Figure 4 shows pictorially how predicted values from the transient model of the engine will be used in the ISHM model. Although not in the scope of the current effort, predictive models of the test stand could be used in the same manner. Predictive models for the test stand are currently being developed by other parties.

Initially we will incorporate the predictive model using a three-pass approach: (1) test data is stored in a repository, (2) input parameters from the test are used to run the predictive model, and (3) test data and predicted values are run through the ISHM model. This activity is expected to take place in the June-July 2008 timeframe. The subsequent task is to incorporate predicted values from the predictive model at each time-step. This will require some modifications to the predictive model and the IMBT in order to maintain proper synchronization.

The A1 ISHM Model includes approximately 240 sensors, 250 valves, and various tanks, pumps and other elements. In addition, each pipe section and connector is modeled as an object. The engine model is considered like a black box with 4 sensors visible through the ISHM Model; and the predictive model provides expected values for these sensors, which are to be used by health assessment functions.

B. Infrastructure for Near Real-Time ISHM Capability

The infrastructure at the test stand for real-time operation has been established. Figure 5 shows the configuration. The box on the top left represents the data acquisition and control system at the A1 Test Stand. Data from this system is made available on an Ethernet bus. The ISHM system includes two elements that could be housed in one computer. To simplify the description we will assume to have two computers. The VISE computer includes verification and validation processes based on local sensor data and information to detect anomaly indicators. Currently VISE can detect noise level and limit violations. Spike and flat signal detection will be incorporated soon. The VISE computer sends time-stamped sensor data and health events to the ISHM computer (or any other user) using the IEEE 1451.1 standard for smart sensors and actuators. The ISHM Model uses an IEEE 1451.1 Gateway to communicate with the VISE according to the standard. That means that the ISHM Model can request for TEDS information, or update TEDS in the VISE. The ISHM Model could even configure sensors if the VISE was replaced by physical intelligent sensors. The schematic shows 1451 sensors (intelligent sensors) that could be connected directly to the bus and be part of the system as plug&play elements. These sensors are not currently installed, but prototypes exist that are being tested and validated.

Upon reception of IEEE 1451 packets from the VISE, the ISHM Model populates the sensor objects with the data and timestamp, and health-related events. The events are also sent to nodes on RC trees to perform diagnostics and determine effects. The operator interfaces with the ISHM Model via the System Health and Status Display.

Data from the J-2X Powerpack tests has been acquired in real-time using the VISE. Flow of data and health to the ISHM Model is expected to be demonstrated in the June-July 2008 timeframe.

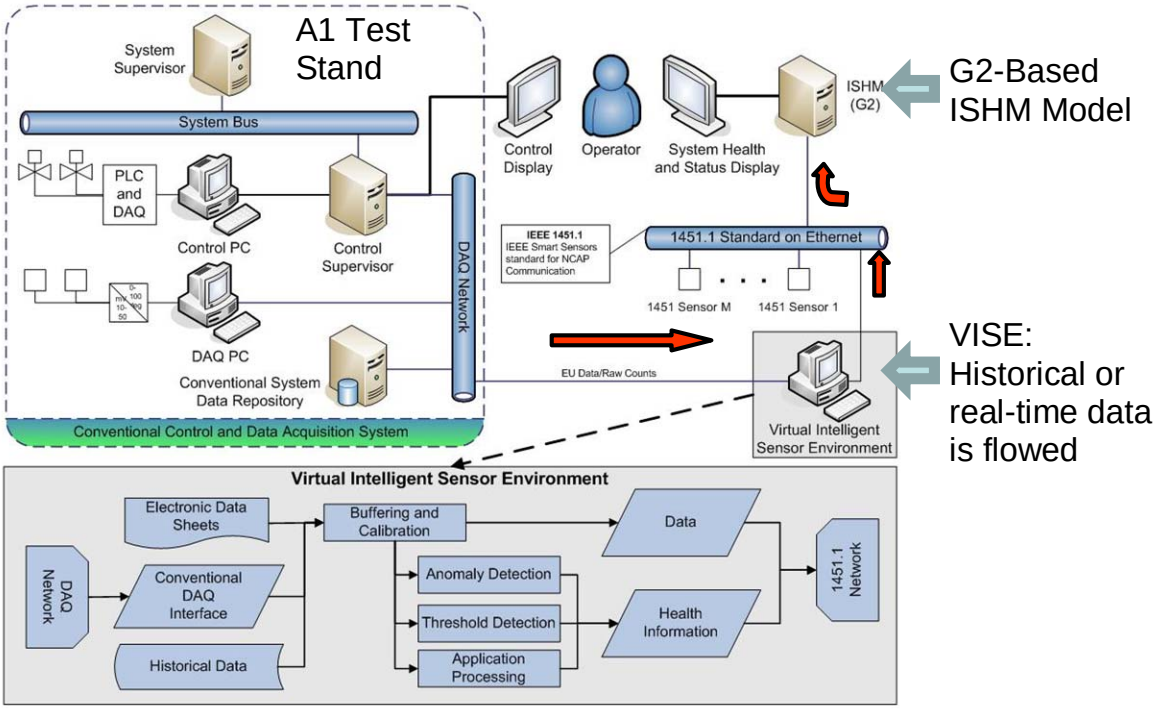

Figure 5. ISHM System Configuration.

III. Predictive Model

The predictive model chosen for this project is the J-2X Detailed Transient Model or DTM. The J-2X DTM, as the name indicates, is a transient model that accurately models all phases of engine operation including start, mainstage (phase between start and shutdown), and shutdown. The J-2X DTM is a physics-based model and simulates processes describing rocket engine operation including heat transfer, fluid flow, combustion and valve dynamics. Flowrates, pump speeds, temperatures and pressures are modeled as time dependent differential equations that are updated at a high rate, typically 2000 Hz. Property tables, valve characteristics and turbomachinery efficiency and performance curves are also incorporated in the DTM. DTM's are used to develop safe start and

shutdown sequences and for anomaly resolution. The J-2X DTM builds on a long history of DTM's supporting most major Pratt & Whitney Rocketdyne (PWR) rocket engines.

The J-2X DTM underwent modification to enable it to run in "real-time" mode. In real-time mode, the DTM will respond in real world clock time to external stimuli such as changes in valve position and engine inlet conditions. The latter will comprise the interface to the test stand model. Advances in computer processor technology have made this possible due to the fast update rate required to maintain numeric stability. Real-time is achieved if a model advances in time (step time) at the same rate as a wall clock. If a processor can perform all calculations in a step time or less, then the model is real-time capable. The step time should also be consistent and set to the longest measured step time corresponding to the longest logical path. Shorter frames are then padded to provide a deterministic step time. The J-2X DTM, or any DTM for that matter, was not optimized for real-time operation. Changes that were required include streamlining model code, limiting or eliminating model diagnostic output, and fixing the step time. The J-2X DTM currently uses a variable step time to maintain numeric stability so deterministic timing is not possible. Real-time DTM operation is required when communication to other real-time components of a system is required such as hardware-in-the-loop testing or for online monitoring of an engine and test stand. Near real-time operation has been demonstrated indicating full real-time operation is feasible in the near future. The modified DTM now has the designation J-2X Detailed Real-Time Model or DRTM.

The DRTM was modified to enable failure mode simulation. Failure modes are modeled as changes to the flowpath of the DRTM (e.g. leaks) or modification of engine parameters (e.g. turbine efficiency) representative of failure signatures. Sensor characteristics, such as lag and bit toggle, and process noise were also modeled to better replicate engine operation. A simulation of cavitation due to low inlet pressure was also added to the DRTM as the primary test stand/engine interface fault mode. As the inlet pressure falls below a certain level, the propellant begins to vaporize and pump performance drops dramatically.

IV. Automated Fault Detection and Isolation

One goal of this work is to use data-driven methods to automatically detect and isolate faults in the J-2X. It was decided to use decision trees, since they tend to be easier to interpret than other data-driven methods. The decision tree algorithm automatically "learns" a decision tree by performing a search through the space of possible decision trees to find one that fits the training data. The particular decision tree algorithm used is known as C4.5[8]. Simulated J-2X data from the DRTM was used to "train" and test the decision tree. Fifty-six DRTM simulations were performed for this purpose, with different leak sizes, different leak locations, and different times of leak onset. To make the simulations as realistic as possible, they included simulated sensor noise, and included a gradual degradation in both fuel and oxidizer turbine efficiency. A decision tree was trained using 11 of these simulations, and tested using the remaining 45 simulations. In the training phase, the C4.5 algorithm was provided with labeled examples of data from nominal operation and data including leaks in each leak location. From the data, it "learned" a decision tree that can classify unseen data as having no leak or having a leak in one of the five locations. In the test phase, the decision tree produced very low false alarm rates and low missed detection rates on the unseen data. It had very good fault isolation rates for three of the five simulated leak locations, but it tended to confuse the remaining two locations, perhaps because a large leak at one of these two locations can look very similar to a small leak at the other location. ARC delivered the decision tree to SSC for integration with G2 and deployment to the A1 test stand.

V. On-Going Implementation

Work is continuing to achieve a core ISHM capability for the A1 Test Stand and the J-2X Engine. It is expected that the capability will be systematically augmented to support, as a pilot activity, testing of the engine. Further augmentation of the capability should occur throughout the initial test phase, so that the ISHM capability might actually work in a validation/operational mode during the later tests.

VI. Conclusion

A pilot implementation of ISHM capability that integrates the A1 Test Stand at NASA Stennis Space Center and the J-2X Engine is being developed. The implementation includes integration of three core elements contributed by partners NASA SSC, PWR, and NASA ARC. NASA SSC is developing an ISHM Model of the test stand and engine, and has put in place the infrastructure to support real-time ISHM capability at the test stand. PWR is providing a transient predictive model of the engine for incorporation as a tool to improve health management. NASA ARC has used data-driven methods to automatically detect and isolate faults in the J-2X. Data from tests of the J-2X Engine Powerpack is being acquired at the VISE (which encompasses the intelligent sensor portion of the

ISHM Model), and the ISHM Model is 95% ready (only needing validation with test data). ISHM capability incorporating the PWR model will initially be done in non-real-time, but real-time synchronization of the PWR model outputs with the ISHM model are expected to be accomplished by the time engine testing begins. Systematic augmentation of ISHM capability will occur first during the initial test phase (intensely), and throughout the test program. The objective is to provide health management support to the J-2X test program.

For additional background and context related to the ISHM implementation described in this paper, the reader might consult references 9-11.

Acknowledgments

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