NASA Stennis Space Center
Integrated System Health Management
Test Bed and Development Capabilities

FERNANDO FIGUEROA, RANDY HOLLAND, and DAVID COOTE
NASA John C. Stennis Space Center
COLLABORATORS

- Dan Duncavage, NASA JSC (ITP Project Manager).
- Paula Hensarling, NASA SSC (Contractor).
- Randy Holland, NASA SSC (Project Manager, SSC).
- Lester Langford, NASA SSC (Contractor).
- Angel Lucena, NASA KSC.
- Shreekanth Mandayam, Rowan University (Co-Investigator).
- Ajay Mahajan, Southern Illinois University (Co-Investigator).
- Carlos Mata, NASA KSC (Contractor).
- Bill Maul, NASA GRC (Contractor and Co-Investigator).
- Greg McVay, NASA SSC (Contractor).
- Pam Mullenix, NASA KSC
- Rebecca L Oostdyk, NASA KSC (Contractor).
- Han Park, JPL (Co-Investigator).
- Jose Perotti, NASA KSC (Co-Investigator).
- Joe Ponyik, NASA GRC.
- Mark Schwabacher, NASA ARC (Co-Investigator).
- Harvey Smith, NASA SSC (Contractor).
- Don Nickles, David Rauth, Sathya Bandari, and Mark Turowski: Rowan University.
Integrated System Health Management (ISHM) is a capability that focuses on determining the condition (health) of every element in a complex system (detect anomalies, diagnose causes, prognosis of future anomalies), and provide data, information, and knowledge (DIaK) – *not just data* – to control systems for safe and effective operation. This capability is currently done by large teams of people, primarily from ground, but needs to be embedded on-board systems to a higher degree to enable NASA's new Exploration Mission (long term travel and stay in space), while increasing safety and decreasing life cycle costs of spacecraft (vehicles; platforms; bases or outposts; and ground test, launch, and processing operations).
Leonard Nicholson, the Northrop Grumman-Boeing team's deputy program manager.

- "The CEV we plan to build will benefit not so much from a single, technical breakthrough but rather from evolutionary improvements in structural technologies, electronics, avionics, thermal-management systems, software and integrated system health management systems over the past 40 years."

- CEV will use two fault-tolerant subsystems and integrated system health management systems to allow it to detect, isolate and recover from subsystem failures. By comparison, Apollo generally had only single fault tolerance.
• The last Delta 4 to fly was the heavy-lift version, which blasted off from Cape Canaveral Air Force Station in December of last year. However, during what looked like a flaw-free ride to space, its first stage failed and its payload -- a mock weight simulating a satellite -- ended up 10,000 miles short of its target.

• The problem: fuel sloshing inside the booster caused some sensors to believe the rocket's tanks had run dry, shutting down the first-stage engines earlier than expected.

This is a case when a decision to shut down engines is done with limited information that does not take advantage of integrated awareness brought about by ISHM capability. Other relevant conditions such as the pressure in the tanks, signs of leakage in the tank and valves/pipes attached to it, other indicators that the engines and surrounding elements may (or may not) be entering a regime associated with fuel starvation, etc. could have been considered.
To increase the safety, affordability and sustainability of Exploration missions through Integrated Health Management of complex, mission-critical vehicles and systems.
**LAYERS REPRESENTING HOW ISHM IS CURRENTLY PERFORMED**

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>International Space Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle/ Test Stand</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer 2</th>
<th>Rocket Engine Test Stand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astronaut/ Test Conductor</td>
<td></td>
</tr>
</tbody>
</table>

| Layer 3 | |
|---------||
| Control Room |

| Layer 4 | |
|---------||
| Back Control Room |

RELEASED - Printed documents may be obsolete; validate prior to use.
ISHM Testbeds & Prototypes at NASA SSC

Objectives
- Mature Integrated System Health Management (ISHM) technologies.
- Develop an integrating architecture embodying intelligent elements.
- Develop prototype intelligent sensors.
- Mature/validate ISHM technologies on operational testbeds.
- Focus on large scale systems-of-systems (demonstration).
- Provide portability to other Exploration Systems and Space Operations applications.

Benefits
- Trusted degree-of-safety determination
- Trusted margin of operation
- Reliable, integrated awareness of health of system’s elements
- Validated data with unquestionable integrity
- Anomaly detection traceable to source

Approach
- Develop/mature core technologies
  - Intelligent integration architecture
  - Software environment
  - Intelligent sensors
- Establish testbeds: Rocket Engine Test Stands.

Contacts
- Fernando Figueroa (Fernando.Figueroa-1@nasa.gov).
- Randy Holland (Randy.R.Holland@nasa.gov).
- John Bailey (John.W.Bailey@nasa.gov).

RELEASED - Printed documents may be obsolete; validate prior to use.
ISHM – FUNCTIONAL CAPABILITY LEVEL (FCL)

ISHM FCL indicates how well a system performs the following suite of functions leading to complete knowledge of the condition of every element in a system (sensors, components, and processes).

- Determines quality, accuracy, and reliability of data (in the case of sensors).
- Detects anomalous behavior of system elements.
- Determines the cause of anomalous behaviors (diagnostics).
- Predicts future anomalies (prognosis).
- Guides operating procedures to avoid human mistakes.
- Recommends reasonable courses of action to fix problems.
- Provides an integrated view of the system.
- Stores relevant information pertaining to system performance and health for use by investigation teams.
ISHM capability is evolutionary. It begins at a low FCL and approaches 100% capability, but never reaches it.

At each FCL the Technology Readiness Level should be 9 (proven and operational technology).
ISHM capability is primarily a data, information, and knowledge (DIaK) management problem, integrated throughout a system.

The following capability must be met:

• Distributed storage.
• Distributed processing.
• Distributed intelligence.
• Availability of DIaK to any element as needed.
• Simultaneous execution of multiple processes representing models that contribute to the determination of the condition of each element in the system.
CORE ELEMENTS

- Architecture, taxonomy, and ontology (ATO) for DIaK management.
- Standards.
Open Systems Architecture Enables Health Management for Next Generation System Monitoring and Maintenance

Development Program -White Paper - Fred M. Discenzo (Rockwell Automation, Cleveland, OH), William Nickerson (Oceana Sensors, State College, PA), Charles E. Mitchell (Boeing Phantom Works, Long Beach, CA), Kirby J Keller (Boeing Phantom Works, Saint Louis, MO) www.osacbm.org
CORE ELEMENTS: Architecture, taxonomy, and ontology (ATO) for DIaK management

SoS as Hierarchical Network of Distributed Intelligent Elements
CORE ELEMENTS: ATO for DIaK Management

Process models are generic. Components contribute boundary conditions (containment).

Valve Processes:
- Opening
- Closing
- Leaking

Tank Processes:
- Fill
- Pressurization
- Over-Pressurization
- Leaking
- Pressure collapse

System of Systems
Intelligent System
Intelligent Process
Intelligent Sensors
Bus

RELEASED - Printed documents may be obsolete; validate prior to use.
IEEE-1451.X smart sensor showing the transducer element (XDCR) supported by the TIM, which is in turn interfaced to the NCAP via the TII. The TIM also stores various electronic data sheets.
SYSTEMATIC IMPLEMENTATION

- Engineering Design Processes.
- Implementation of core elements.
- Systematic augmentation of capability.
Insertion of ISHM capability must be considered throughout the design process, from concept to product, to operations, to maintenance, and to decommission.

ISHM-Enabled elements must respond to the following questions:

- What is the set of information that may be useful to help determine the condition of the element? For example, potential failure modes.
- What may be needed to detect known failures? For example, sensors mounted in key locations, algorithms, integrated models, etc.
- How may one approach detection of unknown failures? For example, use consistency checks.
Sketch of Work Phasing

Note: The relative thickness of each bar is not to scale, they merely represent the shape of the cost curve for each element.

SE&I
IM&S
ISHM
Ontology & Taxonomy
Operations
Trade Studies
DDT&E
Ops & Sustaining
Interrelationship Between Traditional Avionics Systems, Time Critical ISHM and Advanced ISHM

Time Critical ISHM System

Where traditional avionics systems become uncontrollably complex is in handling the interactions between multiple systems and in providing significant FDIR capabilities. Time Critical ISHM is a deterministic and verifiable method of handling first failure responses and intersystem interactions.

Advanced ISHM

Advanced ISHM provides toolsets designed to speed human-driven diagnostics of complex system failures and interactions. Relying on model-based and data mining techniques, it:
- isolates likely candidate failure causes
- prognosticates possible workarounds and repairs
- predicts degradation caused future failures

Humans

Direct mission and solve problems beyond the reach of automated systems with the help of automated, diagnostic and prognostic tools.

Traditional Avionics Systems

Traditionally designed subsystems form the basis of this architecture. This type of design has proven to be extremely reliable and predictable when used within its limits. Provided that the software complexity remains in a region where determinism is reasonably guaranteed, only evolutionary change is necessary.
SYSTEMATIC IMPLEMENTATION

Implementation of Core Elements

Implement Architecture/Taxonomy/Ontology and define standards that make possible the following functionality.

- Distributed storage.
- Distributed processing.
- Distributed intelligence.
- Availability of DIaK to any element as needed.
- Simultaneous execution of multiple processes representing models that contribute to the determination of the condition of each element in the system.
SYSTEMATIC IMPLEMENTATION

Systematic augmentation of capability

1. Initial capability of an ISHM system might just be a support capability that makes easily available to the user.
   - TEDS … Transducer Electronic Data Sheet
   - HEDS … Health Electronic Data Sheet.
   - AEDS … Actuator Electronic Data Sheet.
   - CEDS … Component Electronic Data Sheet.

2. implement process models (rules, algorithms, etc.) and begin to employ reasoning to infer health related information in an integrated manner
Definition of appropriate testbeds must consider the following:

- ISHM testbeds are about determining all failure modes of a system, whereas other testbeds are about making sure a system does not fail under expected operating conditions.
- It is not possible to reproduce a complete set of anomalies.
- Many anomalies are not known.
- Users do not trust some AI oriented ISHM technologies.
- Users do not think ISHM capability is needed.
TESTBED REQUIREMENTS: RETS AND ISS

- RETS/ISS central role for developing and validating ISHM Technologies.
  - Extensive historical data and information to define a solid baseline prior to ISHM implementation.
    - Discrepancy reports (key knowledge of failure modes for HM Systems).
    - Test/Telemetry data (means of validation).
  - Expert Test Engineers (key component to build knowledge bases and to experience and acknowledge ISHM benefits – should become advocates of the technology).
  - Complete and well understood models and documentation.
  - Suitable for staged implementation, e.g. the GN subsystem, followed by the RP subsystem, and so on.
  - Non intrusive implementation.
- RETS/ISS can be established as permanent sites to test new ISHM elements such as “intelligent sensors,” “intelligent components,” system integration frameworks, etc. Adding new sensors or making modifications in RETS is much less complicated than in the case of flight hardware.
- RETS mirror the same tight integration found in the flight systems tested in these facilities (facilities replicate vehicle propulsion subsystems).
SUSTAINABLE DEVELOPMENT AND VALIDATION PROCESS

Stennis Space Center

Research Laboratory

Monitor
Detect
Diagnose
Mitigate
Integrated Awareness
Predict

Safe
Flexible
Modular
Evolutionary
Reliable
Affordable

RELEASED - Printed documents may be obsolete; validate prior to use.
On-board ISHM capability should be developed by migrating proven capability and technologies validated in operational ground testbeds.
TAXONOMY/ONTOMOLOGY OF OBJECT ORIENTED IMPLEMENTATION

Classes:
- Component
  - Tank
  - Valve
- Sensor
  - Pressure
  - Temperature
- Process
  - Electrical Resistance and Temperature
  - Tank
  - Pipe
- Pressurize
- Fill

Instances:
- LOX-E1-01
  - Sensors:
    - Top Pressure
    - Bottom Pressure
    - Top Temperature
    - Bottom Temperature
  - Processes:
    - Pressurize
    - Fill
  - Specs:
    - Capacity
  - Rules:
  - Contents:
  - Condition:

PRESSURIZE
Information Fusion:
- Analytical
- Statistical
- Qualitative

Rules:

Inheritance of conceptual understanding of process in sensor

RELEASED - Printed documents may be obsolete; validate prior to use.
**ISHM Capability on the E1 Test Stand Hydraulic System**

When the standard deviation of the reading of any pressure-sensor P during the last 5 seconds > (the standard deviation of the reading of P during the last 2 minutes + MinDEnTA) then change the control icon-color of P to red and inform the operator that "Noise Level Unacceptable - [(the pressure-sensor)]"
DEFINE RELATIONSHIPS TO EMBED INTELLIGENCE

- Information Extraction and Fusion (IEF).
- Inference and Decision Making (IDM).

These activities require understanding (knowledge) of relationships, for example, among elements:

- Physical
- Connected to
- Part-of
- Class of
- Kind of
- Principle of operation is … process models (e.g., Tempco)
- Is made of (materials)
Intelligent Elements (sensors, components, etc.) must be networked elements (communicate according to established standards) and provide:

- Data
- Measures of data quality
- Measures of element health
- Electronic Data Sheet (EDS) information
  - Transducer (TEDS): Sensor parameters
  - Health (HEDS): Anomaly parameters
  - Component (CEDS): Component parameters
ISHM TESTBEDS AND PROTOTYPES AT SSC
CURRENT IMPLEMENTATIONS

Stennis Space Center

**ISHM-Toolkit**

- Encapsulates Data, Information, and Knowledge (DIAK) distributed throughout intelligent networked elements.
- Defined inter-element relationships are used to perform DIAK fusion (checking of inconsistencies).
- Multiple processes representing models (e.g. algorithms, rules, etc.) may run simultaneously to detect anomalies and infer health of each element.

**Testbed: E1 Rocket Engine Test Stand**

**Testbed: Portable Rocket Engine Test Stand**

RELEASED - Printed documents may be obsolete; validate prior to use.
Modeling and Simulation

Integrated Facility Simulation and Analysis
Applied Over the Test Project Life Cycle

- Analytic Tools Providing Comprehensive Propellant System Thermodynamic Modeling & Test Simulation

Integrated Performance Modeling Capabilities Substantially Improves Understanding & Knowledge of Test Systems Performance that has Translated to Efficient Test Facility Design, Activation & Test Operations

System Design

Test and Data Analysis

Fluid System Modeling & Analysis

UHP GH2 Bottles
625 ft³, 15,000 psig

MV 10A89 GH

To HP Flare

GS 10A00 GH

FCV 10A26 GH

MV 10A4269 GH

GF 10A4255 LH

LPTP FMV

To HP Flare

PE 10A1402 LH

PE 10A1402 LH

CFD Modeling & Analysis

UHP Bottle Pressure

Mixer Pressure

Interface Pressure

0 100 200 300 0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000 5200 5400 5600 5800 6000 6200 6400 6600 6800 7000

TIME SECONDS

20 mph Wind

Distance from Discharge (ft)

GH2 Activation Test
June 29, 2004

Predicted vs Actual

625 ft³, 15,000 psig

625 ft³, 15,000 psig

20 mph Wind

20 mph Wind

20 mph Wind

0

200 230 260 290 320 350 380 410 440 470 500 530 560 590 620 650 680 710 740 770 800

20 mph Wind

20 mph Wind

20 mph Wind

0

200 230 260 290 320 350 380 410 440 470 500 530 560 590 620 650 680 710 740 770 800

20 mph Wind

20 mph Wind

20 mph Wind

0
Summary ISHM Testbed Environments

SSC ISHM Testbed Environments

- Test Stand as System of Systems
- Test Stand with ISHM
  QA of facilities infrastructure; Enhance testing of Test Articles
- DACS Laboratory/Cryo Component TF
  Verification of components, sensors, data acquisition and processing systems, controls, software.

ISHM Technologies
- Integration Architecture/Framework for networked intelligent elements.
- Data/Information/Knowledge Management (storage, transmission, maintenance, evolution, suitability (context), availability (timely)).
- Intelligent Network Elements.

We Provide
- A base/flexible architecture.
- ISHM Software Development Tool.
- A database for health assessment.
  - Anomaly data.
  - Anomaly methods/algorithms.
  - DIaK.
  - Electronic data sheets.
- Intelligent Sensors.

RELEASED - Printed documents may be obsolete; validate prior to use.
• Tested two unsupervised anomaly detection algorithms on rocket propulsion data
• Detected known anomalies and unknown (but insignificant) anomalies
• Different algorithms detect different anomalies, so it’s worth running multiple algorithms.
NASA can not wait and does not need to wait to begin implementing ISHM capability onboard spacecraft, space platforms, Lunar and Mars outposts, and ground test and operations facilities. The following tasks must begin immediately:

- Refine architectures, taxonomies, ontologies, and **tools** to implement ISHM capability (e.g. an architecture that defines a complex system as a hierarchical network of distributed intelligent elements).
- Survey, compare, and define commonality standards for DIaK management on-board a system (e.g. IEEE 1451 for intelligent sensors’ communications, TEDS for intelligent sensors’ on-board information), and across multiple systems. DIaK management includes distributed storage, maintenance, and evolution; timely and contextual availability to any element of the system.
- Once architectures/taxonomies/ontologies and standards are defined, implement a low functional capability level ISHM and increase by incremental augmentation.
- Define a systems process for implementation of ISHM capability. All design/test/validate activities must include insight and methodic approaches so that each element of a system contributes to the integrated health determination of the system.
- Develop capability using laboratory testbeds, mature using operational testbeds (RETS, ISS, Launch Systems), and migrate to space systems after validation in operational testbeds.
- Define an enterprise wide ISHM testbed environment to support on-going ISHM operations from Earth, and concurrent ISHM technology development.
NASA can not wait and does not need to wait to begin implementing ISHM capability on-board spacecraft, space platforms, Lunar and Mars outposts, and ground test and operations facilities. The following tasks must begin immediately:

- **Refine architectures, taxonomies, ontologies, and tools to implement ISHM capability** (e.g. an architecture that defines a complex system as a hierarchical network of distributed intelligent elements).
- **Survey, compare, and define commonality standards for DIaK management on-board a system** (e.g. IEEE 1451 for intelligent sensors’ communications, TEDS for intelligent sensors’ on-board information), and across multiple systems. DIaK management includes distributed storage, maintenance, and evolution; timely and contextual availability to any element of the system.
- **Once architectures/taxonomies/ontologies and standards are defined, implement a low functional capability level ISHM and increase by incremental augmentation.**
- **Define a systems process for implementation of ISHM capability.** All design/test/validate activities must include insight and methodic approaches so that each element of a system contributes to the integrated health determination of the system.
- **Develop capability using laboratory testbeds, mature using operational testbeds (RETS, ISS, Launch Systems), and migrate to space systems after validation in operational testbeds.**
- **Define an enterprise wide ISHM testbed environment to support on-going ISHM operations from Earth, and concurrent ISHM technology development.**
TRANSITIONING ISHM TO SUPPORT NASA MISSIONS: DEMO

Explore and define architectures, taxonomies, ontologies, and tools to implement ISHM capability (e.g. an architecture that defines a complex system as a hierarchical network of distributed intelligent elements).

- G2 Framework
- Smart Sensors
  - RU
  - KSC
- Algorithms
  - SIU / Glenn
- HADS (DIaK Repository)
- Visualization
TRANSITIONING ISHM TO SUPPORT NASA MISSIONS: DEMO

Develop capability using laboratory testbeds, mature using operational testbeds (RETS, ISS, Launch Systems), and migrate to space systems after validation in operational testbeds.

Portable RETS

DACS Lab

E1 Test Stand

RELEASED - Printed documents may be obsolete; validate prior to use.
Survey, compare, and define commonality standards for DIAK management on-board a system (e.g. IEEE 1451 for intelligent sensors’ communications, TEDS for intelligent sensors’ on-board information), and across multiple systems. DIAK management includes distributed storage, maintenance, and evolution; timely and contextual availability to any element of the system.

- **Intelligent Sensors**
  - IEEE 1451
  - IEEE 1588

- **Electronic Data Sheets**
  - IEEE 1451 TEDS
  - Extensions to TEDS: HEDS, CEDS
Feature Detection Routines

• Developed starting around 1990 for use in SSME PTDS. Continued Use in X-33 PTDS. Also Applied to Atlas/Centaur Data.
• Moved towards Real-Time during work on Propulsion Checkout and Control System for the Integrated Propulsion Technology Demonstrator Program
• The Real-Time features demonstrated as part of automated testing demonstrator developed at Arnold Engineering Development Center.
• Routines detect:
  – Drifts (Slow transitions in average levels)
  – Level Shifts (rapid changes in data level.)
  – Spikes (Rapid, non-permanent changes in data)
  – Noise (significant increase in average variance of the data)
  – Flat Regions (significant lack of variance in data)
• In some cases, multiple routines can detect the same feature. (e.g., 3 detect level shifts, 2 detect drifts.)
• Three routines detect multiple features (drifts/level shifts (2), level shift/peak)
Sample Features Detected in SSC Test Stand Data

- Detected in Data From the 9_LDAS_0908 Test Set Received from NASA SSC
- Detected Using One Routine
- Drifts and Level Shifts Were Mutually Exclusive (i.e. no overlap)