Integrated System Health Management: Foundational Concepts, Approach, and Implementation

Fernando Figueroa
NASA Stennis Space Center, MS

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Outline

• Motivation
• Concepts and Approaches
  – ISHM: Background/Definition
  – ISHM Model of a system
  – Detection of anomaly indicators.
  – Determination and confirmation of anomalies.
  – Diagnostic of causes and determination of effects.
  – Consistency checking cycle.
  – Management of health information
  – User Interfaces
• Implementation
• Conclusions
Support rocket engine test mission with highly reliable, accurate measurements; reduced costs; etc.
Requirements Driving ISHM

Through comprehensive and continuous vigilance

- Improve quality
  - By more accurately understanding the state of a system.

- Minimize costs
  - Of configuration
  - Of repair and calibration
  - Of operations

- Avoid downtime
  - By predicting impending failures
  - By timely intervention
  - By faster diagnosis and recovery

- Increase safety (protect people and assets)
ISHM Objectives

• Use available data, information, and knowledge to
  – Identify system state
  – Detect anomalies
  – Determine anomaly causes
  – Predict system impacts
  – Predict future anomalies
  – Recommend timely mitigation steps
  – Evolve to incorporate new knowledge

ISHM implementation is a problem of “management” of data, information, and knowledge (DlaK) focused on achieving the objectives of ISHM
Concepts and Approach
ISHM is Being Done Now ... But

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>International Space Station</th>
<th>Rocket Engine Test Stand</th>
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<tbody>
<tr>
<td>Vehicle/Test Stand</td>
<td>![ISS Image]</td>
<td>![Rocket Engine Test Stand Image]</td>
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<td><strong>Signal threshold violation detection</strong></td>
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<td>Astronaut/Test Conductor</td>
<td>![Astronaut/Test Conductor Image]</td>
<td>![Astronaut/Test Conductor Image]</td>
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<td><strong>Added DIaK from on-board users.</strong></td>
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<td>Control Room</td>
<td>![Control Room Image]</td>
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<td><strong>Added DIaK from broad group of experts.</strong></td>
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<td>Back Control Room</td>
<td>![Back Control Room Image]</td>
<td>![Back Control Room Image]</td>
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<tr>
<td><strong>Added DIaK resources from larger community</strong></td>
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Intelligent Element Processes

Intelligent Control Processes

Data, Information, and Knowledge Management Architecture for ISHM (Information Architecture)

Intelligent Subsystem Processes

Intelligent Sensor Processes

Intelligent Control Processes

Intelligent Component Processes

Intelligent System Processes

Actuator
Classic architecture describing how systems are built

Sample System

Generic System

System of Systems

Pump
Motor
Bearing
Tanks
Valves
Sensors

Sub-system
Sub-system
Sub-system

Site
Correspondence between elements in the ISHM Information Architecture and processes taking place in a system.
SSC Integrated System Health Management (ISHM) Capabilities

- **Anomaly Detection**: Leaks, etc.
- **Intelligent Sensors**: IEEE Standard + Health
- **Embedding of Predictive Models**
- **Root Cause Analysis**
- **Integrated Awareness**: 3-D Health Visualization of MTTP
- **ISHM Models (Embedded Data, Information, and Knowledge)**: MTTP Implementation
- **Health Anomaly Database**: Health Electronic Data Sheets, Repository of anomalies
Detection and Confirmation of Anomalies
Consistency Checking Cycle

Intelligent System Subsystem Processes

Activated Model

Tank Processes:
Over-Pressurization
Leaking
Pressure collapse

Fill Pressurization

Valve Processes:
Opening
Closing
Leaking

Intelligent Components

Health

Intelligent Sensor Processes

Oxidizer Processes

Activated Model
MTTP Embedded DlaK
Root-Cause Tree

Leak within the active range of is2_processes-equipment
Gas Detection Alarm

Leak a-sub-component-of is2 processes-equipment

Abnormally changing pressure

Leak through an-isolation-valve-of is2 valve

Abnormally changing pressure encompassing is2 flow subsystem

Pressure sensor
Virtual Intelligent Sensors

- Provides benefits of ISHM capabilities to existing data acquisition systems by adding Virtual Intelligent Sensor capability.
ISHM Implementations
Generic Architecture to implement ISHM capability for systems with conventional equipment, with option to incorporate advanced smart/intelligent sensors and actuators.
Top level view of the ISHM model of the Launch Complex 20 Facility at NASA Kennedy Space Center
Sensor anomaly indicators detected by an intelligent sensor during a pump test using the LC-20 facility at NASA Kennedy Space Center

![Graphs showing temperature, noise detection result, disconnect detection result, and out-of-range detection result over time.](image)
Screenshot of the ISHM model of the LC-20 facility at KSC showing detection of a valve leak created by opening the valve manually.
Expanded causal-directed graph generated by the detection of a leak in the subsystem where a valve was opened manually (injected leak)

Causal directed graph dynamically generated from events detected during the simulated leak at GNCP104
Pilot ISHM Implementation
Chemical Steam Steam Generator (CSG)
Pilot ISHM Implementation

Chemical Steam Generator (CSG)
Pilot ISHM Implementation
Chemical Steam Generator (CSG)
Conclusions

- A sound basis to guide the community in the conception and implementation of ISHM capability in operational systems was provided.
- The concept of “ISHM Model of a System” and a related architecture defined as a unique Data, Information, and Knowledge (DIaK) architecture were described. The ISHM architecture is independent of the typical system architecture, which is based on grouping physical elements that are assembled to make up a subsystem, and subsystems combine to form systems, etc.
- It was emphasized that ISHM capability needs to be implemented first at a low functional capability level (FCL), or limited ability to detect anomalies, diagnose, determine consequences, etc. As algorithms and tools to augment or improve the FCL are identified, they should be incorporated into the system. This means that the architecture, DIaK management, and software, must be modular and standards-based, in order to enable systematic augmentation of FCL (no ad-hoc modifications).
- A set of technologies (and tools) needed to implement ISHM were described. One essential tool is a software environment to create the ISHM Model. The software environment encapsulates DIaK, and an infrastructure to focus DIaK on determining health (detect anomalies, determine causes, determine effects, and provide integrated awareness of the system to the operator). The environment includes gateways to communicate in accordance to standards, specially the IEEE 1451.1 Standard for Smart Sensors and Actuators.
Backup Slides
MTTP End-to-End System
Methane Thruster Testbed Project
A1 and J2-X ISHM MODEL
Runtime Predictive Modeling

- Sensor Data
- Predictive Model
- xEDS
- Model Coefficients
- Prediction-Measurement Mismatch

![Graphs showing sensor data, predictive model, and prediction-measurement mismatch over time.](image)
Checking for Pressure Leaks

- Wait for Valve State Change
  - No
  - Do Closed Elements Form a Boundary?
    - Yes
      - Define Pressurizable Subsystem
    - No
- Pressurizable Subsystems
  - For Each PS
    - Mark All Elements of PS SUSPECT for Leak Anomaly
      - For Each Element
        - Change Health Parameters in Leak Process Model to SUSPECT
        - Do Sensors Indicate a Change in Pressure?
          - Yes
            - Check All Pressure Sensors
          - No
        - Root-Cause-Analysis
          - Root Cause
Electronic Datasheets

- Electronic Data Sheets (EDS)
  - Transducer Electronic Data Sheets (TEDS)
    - Calibration
  - Health Electronic Data Sheet (HEDS)
    - Codified fault conditions and system phases
    - Key detection algorithms w/ parameters
  - Component EDS (CEDS)
    - Manufacturing details
    - Engineering data
    - Traceability
  - Other EDS
Intelligent Sensors have embedded ISHM functionality and support Smart Sensor standards.

- **Smart sensor**
  - NCAP (Go Active, Announce)
  - Publish data
  - Set/Get TEDS

- **Intelligent sensor**
  - Set/Get HEDS
  - Publish health

- **Detect classes of anomalies using:**
  - Using statistical measures
    - Mean
    - Standard deviation
    - RMS
  - Polynomial fits
  - Derivatives (1\textsuperscript{st}, 2\textsuperscript{nd})
  - Filtering—e.g., Butterworth HP
  - FFT—e.g., 64-point
  - Algorithms for
    - Flat
    - Impulsive ("spike") noise
    - White noise
  - Other (ANN, etc.)