Tutorial
Integrated Systems Health Management (ISHM)
Enabling Intelligent Systems

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The author also expresses his profound appreciation to the many individuals that, through insightful discussions and interactions, have enriched his understanding of ISHM.
Outline

• Context of the Tutorial.
• ISHM Definition.
• ISHM Capability Development.
  – ISHM Knowledge Model.
  – Standards for ISHM Implementation.
  – Software to develop ISHM Domain Models (ISHM-DM’s).
  – Intelligent Sensors and Components.
• Sensor Optimization and Placement for ISHM.
• ISHM in Systems Design, Engineering, and Integration.
• Intelligent/Adaptive Control for ISHM-Enabled Systems.
• Verification and Validation Considerations.
Context of the Tutorial
Adaptability from an Integrated System Perspective

• Intelligent/Adaptive System: Manages data, information, and knowledge (DIAK) to achieve its mission (Manage: storage, distribution, sharing, maintenance, processing, reasoning, and presentation)

• An attribute or quality of intelligent/Adaptive systems should be to posses a health management capability that:
  – Employs knowledge about the system embodying “systems thinking” (captures interactions among elements of the system).
  – Is continuously vigilant.
  – Is comprehensive in assessing health of each element of a system.
  – Is systematically evolutionary to achieve higher and higher functional capability levels (increasing effectiveness).

• In order to make this capability possible, the health management system needs to incorporate “intelligence.”
ISHM Definition


- Management of data, information, and knowledge (DIAK) with the purposeful objective of determining the health of a system (Management: storage, distribution, sharing, maintenance, processing, reasoning, and presentation).

- ISHM is akin to having a broad-base team of experts who are all individually and collectively observing and analyzing a complex system, and communicating effectively with each other in order to arrive at an accurate and reliable assessment of the health of each element of the system.
Humans

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

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.

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.

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
### People-Based ISHM is Being Done Today

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>International Space Station</th>
<th>Rocket Engine Test Stand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle/Test Stand</td>
<td><strong>System:</strong> ON BOARD AUTOMATED ANALYSIS CAPABILITY</td>
<td></td>
</tr>
<tr>
<td>Layer 2</td>
<td>Astronaut/Test Conductor</td>
<td></td>
</tr>
<tr>
<td><strong>Operator:</strong> FASTER, MORE ACCURATE ANALYSIS Decreased Need</td>
<td></td>
<td><strong>Support:</strong> FASTER, MORE ACCURATE ANALYSIS Decreased Need</td>
</tr>
<tr>
<td>Layer 3</td>
<td>Control Room</td>
<td></td>
</tr>
<tr>
<td>Layer 4</td>
<td>Back Control Room</td>
<td></td>
</tr>
</tbody>
</table>

**International Space Station**
- **System:** ON BOARD AUTOMATED ANALYSIS CAPABILITY
- **Operator:** FASTER, MORE ACCURATE ANALYSIS Decreased Need

**Rocket Engine Test Stand**
- **Support:** FASTER, MORE ACCURATE ANALYSIS Decreased Need

- **Signal threshold violation detection**
- **Added DIaK from on-board users.**
- **Added DIaK from broad group of experts.**
- **Added DIaK resources from larger community**

**MOVE CAPABILITY TOWARD LEVELS 2 AND 1**
**DECREASE NEED FOR SUPPORT FROM LOWER LAYERS**

**International Space Station Rocket Engine Test Stand**
- People-Based ISHM is Being Done Today
- System: ON BOARD AUTOMATED ANALYSIS CAPABILITY
- Operator: FASTER, MORE ACCURATE ANALYSIS
- Support: FASTER, MORE ACCURATE ANALYSIS
- Decreased Need

**Layer 1**
- Vehicle/Test Stand

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**International Space Station Rocket Engine Test Stand**
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**Layer 3**
- Control Room

**Layer 4**
- Back Control Room
Determination of Health

- Use available SYSTEM-WIDE data, information, and knowledge (DiK) to
  - Identify system state.
  - Detect anomaly indicators.
  - Determine and confirm anomalies.
  - Diagnose causes and determine effects.
  - Predict future anomalies.
  - Recommend timely mitigation steps.
  - Evolve to incorporate new knowledge.
  - Enable integrated system awareness by the user (make available relevant information when needed and allow to dig deeper for details).
- Manage health information (e.g. anomalies, redlines).
- Capture and manage usage information (e.g. thermal cycles).
- Capture and manage design life and maintenance schedule.
- Enable automated configuration.
- Implement automated and comprehensive data analysis.
- Provide verification of consistency among system states and procedures.
A plethora of Data, Information, and Knowledge (DIaK) must be applied to achieve high functional capability level (FCL) health management.

The ISHM Domain Model (ISHM-DM) encompasses DIaK and the tools to implement ISHM capability.
Classic architecture describing how systems are built

System of Systems

Sample System
- Pump
- Motor
- Bearing
- Tanks
- Valves
- Sensors

Generic System
- System
  - Sub-system
  - Sub-system
  - Sub-system

Site
• DIAK in the ISHM-DM are associated with software objects that represent process models that take place in objects and/or collections of objects that encompass a system of interest.

• Process models are organized as objects in a hierarchical network (ISHM DIAK Architecture), to reflect levels of complexity as processes take place involving single elements, subsystems, or the entire system.
  – Local processes using local DIAK are at the bottom of the hierarchy.
  – Processes using increasing DIAK occupy higher levels in the network.
ISHM DIAK Architecture (DIAKA)
Detection and Confirmation of Anomalies
Consistency Checking Cycle

Intelligent System Process

Intelligent Subsystem Processes

Activated Model

Intelligent Process

Intelligent Sensor Processes

Health

Activated Model

Intelligent Component

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

Valve Processes:
- Opening
- Closing
- Leaking
ISHM Capability Development

Standards for ISHM

• IEEE 1451 Family of Standards for Smart Sensors and Actuators. Lead by NIST (Dr. Kang Lee).

• OSA-CBM (Open Systems Architecture for Condition Based Maintenance). Developed by industry and government, and transferred to the MIMOSA (Machine Information Management Open Standards Alliance) organization.

• OSA-EIA (Open Systems Architecture for Enterprise Application Integration). MIMOSA organization.

ISHM capability must integrate DIAK across physical, virtual, and discipline boundaries. This is not possible in an affordable manner unless standards are used to achieve plug&play and interoperability.
ISHM Capability Development

Standards for ISHM

IEEE 1451 Family of Standards
(supporting different physical interfaces and configurations)

User Network

Network node

IEEE 1451.1 and 1451.0
NCAP or Instrument

IEEE 1451.4

MicroLAN1-wired Interface

Point-to-Point

Tim node

IEEE 1451.2

Serial Interface
(UART, SPI, I2C)

S = Sensor or Actuator
T = TEDS

IEEE 1451.1 and 1451.0
NCAP

IEEE 1451.1 and 1451.0
NCAP or gateway

IEEE 1451.1 and 1451.0
NCAP/TIM

Supporting Wireless Communication Protocols:
- 802.11 (WiFi)
- 802.15.1 (BlueTooth)
- 802.15.4 (ZigBee)
- 6LowPAN

Wireless Sensor

IEEE 1451.5

Tag

Wireless Air Interface
Ex: ISO18000 and others

Sensor-integrated RFID

Kang Lee/NIST/March 2011
ISHM Capability Development
Standards for ISHM

OSA-CBM (MIMOSA)

Advisory Generation
- Operations and maintenance advisories, capability forecast assessments, recommendations, evidence, and explanation.
- Future health grade, future failures, recommendations, evidence and Explanation.
- Health grade, diagnosed faults and failures, recommendations, evidence and explanation.
- Current enumerated state indicator, threshold boundary alerts, and statistical analysis data with timestamp and data quality
- Descriptor data with timestamp and data quality
- Digitized data with timestamp and data quality

Prognostics Assessment

Health Assessment

State Detection

Data Manipulation

Data Acquisition
Architecture for pilot ISHM system implemented at NASA Kennedy Space Center, Launch Complex 20 (LC-20) showing the use of IEEE 1451.1, OSA-CBM, and OSA-EAI standards
Software to develop ISHM Domain Models (ISHM-DM’s)

A software system for ISHM capability should support all core capabilities by integrating systematically DlA.K through the ISHM-DM

• **Object orientation**: object representation of system physical elements and associated process models is the best way to embed DlA.K in a systematic and in an organized manner.

• **Distribution of ISHM-DM’s within and across networks**: ISHM-DM’s might be distributed among processors connected to a network, simply because it is necessary to use parallel processing, and/or ISHM-DM’s might be created by different people in various geographic locations
TAXONOMY/ONTOGONY OF OBJECT ORIENTED IMPLEMENTATION

**Variables**
- **Object**
- **Component**
  - Tank
  - Valve
- **Sensor**
  - Pressure
  - Temperature
- **Process**
  - Tank
  - Pipe
- **Instances**
  - PRES-TOP
  - TEMP-TOP
- **LOX-E1-01**
  - Sensors:
    - Top Pressure
    - Bottom Pressure
    - Top Temperature
    - Bottom Temperature
  - Processes:
    - Pressurize
    - Fill
  - Specifications:
    - Capacity
  - Contents:
  - Condition:

**Specs**
- **Capacity**

**Rules**
- **Contents**
- **Condition**

**Information Fusion**
- **Analytical**
- **Statistical**
- **Qualitative**

**Inheritance**
- Conceptual understanding of process in sensor
Software to develop ISHM Domain Models (ISHM-DM’s)

A software system for ISHM capability should support all core capabilities by integrating systematically DIAK through the ISHM-DM

- **Distribution across processing units**: Since multiple process models are expected to be running at any given time, the software environments should support parallel processing.

- **Inference engine**: Many tasks require an inference engine. Reasoning and decision making leading to anomaly detection, diagnostics, effects, and prognostics; require contextual integrity and cause-effect analysis using heterogeneous data and information.
Software to develop ISHM Domain Models (ISHM-DM’s)

A software system for ISHM capability should support all core capabilities by integrating systematically DIAK through the ISHM-DM

• **Integrated management of distributed DIAK**: DIAK must be managed in a way to allow embodiment of systems thinking across elements and subsystems. Often this is enabled by definitions of relationships among elements of systems that can be physically visible (i.e. attached to, belong to a system); or more abstracted relationships, as it relates to involvement by groups of objects in process models.

• **Definition of dynamic relationships among objects for use in reasoning**: Often, the framework for reasoning and application of process models changes dynamically with configuration changes, stages of operation, etc.
Software to develop ISHM Domain Models (ISHM-DM’s)

A software system for ISHM capability should support all core capabilities by integrating systematically DIaK through the ISHM-DM

• **Iconic representation of systems objects with visible and virtual links (relationships) used to provide intuitive representation of reasoning and context:** The mix of object orientation and iconic representation of DIaK provides the ability to intuitively visualize interrelationships and dig deep into details of the ISHM system. As complexity increases, graphical programming and visualization become essential.
ISHM Domain Model of a Hydraulic System, including a Rule example

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 + MinDelta) then change the control icon-color of $P$ to red and inform the operator that “Noise Level Unacceptable - [(the pressure-sensor)]”
CSG ISHM Domain Model: User Interfaces

Transducer Electronic Data Sheet

Viewing Windows

Blueline Active Monitors

Redline Active Monitors

Blueline Alarm Queues

Redline Alarm Queues

CSG LOX System

CSG IPA System

CSG Water System
CSG ISHM Domain Model: Blueline/Redline User Interfaces
CSG ISHM Domain Model:
Redline Event Handling
<table>
<thead>
<tr>
<th>ID #</th>
<th>Item-Functional Identification</th>
<th>Function</th>
<th>Failure Modes and Causes</th>
<th>Mission Phase-Operational Mode</th>
<th>Failure Effects</th>
<th>Failure Detection Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Process Equipment</td>
<td>Fluid feed subsystem</td>
<td>Leak</td>
<td>Sealed subsystem maintaining pressure</td>
<td>Pressure leak</td>
<td>Decreasing pressure measurement</td>
</tr>
</tbody>
</table>

**Mission Phase-Operational Mode:**
- Local Effects
- Next Level Effects
- Higher Level Effects

**Failure Effects:**
- Pressure leak
- Decreasing pressure measurement
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
“The IEEE (Institute of Electrical and Electronics Engineers) 1451 smart transducer interface standards provide the common interface and enabling technology for the connectivity of transducers to microprocessors, control and field networks, and data acquisition and instrumentation systems. The standardized TEDS specified by IEEE 1451.2 allows the self-description of sensors and the interfaces provide a standardized mechanism to facilitate the plug and play of sensors to networks. The network-independent smart transducer object model defined by IEEE 1451.1 allows sensor manufacturers to support multiple networks and protocols. Thus, transducer-to-network interoperability is on the horizon. The inclusion of P1451.3 and P1451.4 to the family of 1451 standards will meet the needs of the analog transducer users for high-speed applications. In the long run, transducer vendors and users, system integrators and network providers can all benefit from the IEEE 1451 interface standards [1].”

“Intelligent Sensor” is a “Smart Sensor” with the ability to provide the following functionality: (1) measurement, (2) measure of the quality of the measurement, and (3) measure of the “health” of the sensor. The better the sensor provides functionalities 2 and 3, the more intelligent it is.
ISHM Capability Development

Intelligent Sensors and Components

Typical Process Models for Sensors

- Noise Level Assessment and History
- Spike Detection and History
- Flat Signal Detection and History
- Response Time Characterization
- Intermittency Characterization and History
- Physical Detachment Characterization and History
- Regime Characterization and History
- Curve Fit on Identified Regimes

“Intelligent Sensor” is a “Smart Sensor” with the ability to provide the following functionality: (1) measurement, (2) measure of the quality of the measurement, and (3) measure of the “health” of the sensor. The better the sensor provides functionalities 2 and 3, the more intelligent it is.
The Virtual Intelligent Sensor Environment (VISE) converts all classic sensors installed in a rocket engine test stand into “intelligent sensors.”
ISHM Capability Development

Intelligent Sensors and Components

Example Intelligent Sensor Implementations

Mobitrum
www.mobitrum.com

Smart Sensor Systems
www.smartsensorsystems.com

Esensors
www.eesensors.com

NIST
www.mel.nist.com
Sensor selection and Placement for ISHM

• When developing an ISHM capability from the ground up, one must optimize sensor suites to achieve maximum functional capability (anomaly detection, diagnosis, effects, prognostics).
Sensor selection and Placement for ISHM

Systematic Sensor Selection Strategy (S4) is a model-based procedure for systematically and quantitatively identifying the sensor compliment that optimally achieves the health assessment goals of a system (Reference 14 of the paper).
ISHM in Systems Design, Integration, and Engineering (SDI&E)

- SDI&E practices are employed to build complex systems.
- SDI&E for aerospace systems has developed into its own discipline, although theories and concepts have not been adequately formalized in an academic sense.
- The role of ISHM in SDI&E is linked to the concept of ISHM-DM’s, whereby every element that is part of a system comes with its own ISHM-DM that can be rolled-up into an overall system ISHM-DM in a plug&play approach.
- When two elements are assembled, the ISHM-DM of each element is incorporated into the ISHM-DM of the assembly. In this manner, DIAK compartmentalized in each element becomes immediately available and useful to the ISHM-DM of the assembly.
ISHM in Systems Design, Integration, and Engineering (SDI&E)

ISHM concept for systems integration of ISHM-DM’s
Intelligent Control for ISHM-Enabled Systems

• Control of complex systems that are ISHM-enabled is a nascent area, simply because ISHM itself is also relatively new.
• The objective is for the control function to make use of system health information in order to achieve its objectives.

The paradigm implies that control systems become users of health information, while at the same time making use of actuators to help further improve determination of the system health.
Intelligent Control for ISHM-Enabled Systems

Example Application (Reference 18 of the paper)
The need to use knowledge, and hence inference engines; and the complexities of parallel processing and reconciliation of potentially inconsistent outcomes that lead to anomaly determination; requires advances in verification and validation of the ISHM capability itself.
Backup Slides
Health Assessment Database System (HADS)

- Health Electronic Data Sheets (HEDS)
- Repository of anomalies and algorithms
- Transducer Electronic Data Sheets (TEDS)
- Historical test data and analysis results
- Provides ease of data analysis and data trending

![Health Assessment Database System (HADS)]
HADS Browser Application

HADS Browser Capabilities

- Allows longitudinal analyses and comparisons with previous test results
- Viewing usage statistics on monitored elements
  - cycle times on valves
  - mean time to failure
- Viewing anomalous events/data trends
- Viewing TEDS

Analog Data – 3 tests, multiple channels

Digital Data – 3 tests, multiple channels

Anomalous Data – 2 tests, 1 channel

TEDS Data
CSG ISHM Domain Model: Top Layer View
CSG ISHM Domain Model:
Transducer Data Plots

Streaming data plots from selected sensors
CSG Anomalies Detected

- Evidence of TC degradation detected by VISE anomaly detection
- Advanced notification to determine the health of the whole system before beginning a test
## List of Anomaly Detection Capabilities

<table>
<thead>
<tr>
<th>Anomaly/Behavior</th>
<th>Demonstrated Cause</th>
<th>Detection Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaks (pipes, valves, etc.)</td>
<td>Various</td>
<td>Checking for pressure leaks using the concept of Pressure Subsystems.</td>
</tr>
<tr>
<td>Valve state undetermined</td>
<td>Defective feedback sensor</td>
<td>Determines valve state by checking consistency of command, feedback, open/close switches, and pressure conditions upstream and downstream.</td>
</tr>
<tr>
<td></td>
<td>Controller failure</td>
<td></td>
</tr>
<tr>
<td>Valve oscillation</td>
<td>Fluid contamination in hydraulic supply</td>
<td>Compare running standard deviation of command versus feedback.</td>
</tr>
<tr>
<td></td>
<td>Seat seizure</td>
<td></td>
</tr>
<tr>
<td>Excessive noise, spikes, etc.</td>
<td>Interference</td>
<td>Running standard deviation exceeds set limits. Thresholds violations during short time spans (compared to sensor time-constant).</td>
</tr>
<tr>
<td>Degradation</td>
<td>Wear, aging</td>
<td>Trend detection using curve fitting and determination of time-constants.</td>
</tr>
<tr>
<td>Prediction-Measurement</td>
<td>Various</td>
<td>Use predictive model (e.g. from Modeling &amp; Analysis Group) to predict sensor values and compare with measurements.</td>
</tr>
<tr>
<td>mismatch</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Short-Time Fourier Transform Segmentation

Figure 1. Simulated input signal

Figure 2. Short-time FT 9s window
<table>
<thead>
<tr>
<th>Valve State</th>
<th>Command</th>
<th>Feedback</th>
<th>Open limit</th>
<th>Closed Limit</th>
<th>Associated Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>True</td>
<td>False</td>
<td>Agree with model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Healthy</td>
</tr>
<tr>
<td>Closed</td>
<td>Closed</td>
<td>Closed</td>
<td>False</td>
<td>True</td>
<td>Agree with Model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Healthy</td>
</tr>
</tbody>
</table>
Checking for Pressure Leaks

1. Wait for Valve State Change
2. Do Closed Elements Form a Boundary?
3. Mark All Elements of PS SUSPECT for Leak Anomaly
4. For Each Element:
   - Change Health Parameters in Leak Process Model to SUSPECT
5. Define Pressurizable Subsystem
6. Do Sensors Indicate a Change in Pressure?
7. Root-Cause-Analysis
8. For Each PS:
   - Check All Pressure Sensors
   - Root Cause
Runtime Predictive Modeling
Intelligent Sensors

Process: HP LOX - Start: 2/5/01, 13:08  End: 2/6/01, 8:45
Sensors: E1HPLOXP1: Pressure, Strain-Gauge. Loc: Top
          E1HPLOXP2: Pressure, Piezoelectric. Location: Bottom
          E1HPLOXT1: Temperature, Thermocouple K, Loc: Top
          E1HPLOXT2: Temperature, Thermocouple K, Loc: Bott
          E1HPLOXV1: Valve position, Loc: Bottom

PROCESS RELATED CONDITION MONITORING
Behavior discrepancies
E1HPLOXP1: spike
E1HPLOXP1: disturbance
E1HPLOXP1: disturbance
E1HPLOXT1: high noise

Sensor E1HPLOXP1: Pressure, Strain-Gauge - Process: HP LOX
Start: 2/5/01, 13:08  End: 2/6/01, 8:45

<table>
<thead>
<tr>
<th>Condition Monitoring</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>flat-with-noise</td>
<td>normal, occurrences: 5</td>
</tr>
<tr>
<td>step-up</td>
<td>normal, occurrences: 2</td>
</tr>
<tr>
<td></td>
<td>Exp. time-constant: 0.50s</td>
</tr>
<tr>
<td></td>
<td>Spec. time-constant: 0.52s</td>
</tr>
<tr>
<td>sensor-disturbance</td>
<td>occurrences: 5</td>
</tr>
<tr>
<td></td>
<td>Exp. time-constant: 0.50s</td>
</tr>
<tr>
<td></td>
<td>Spec. time-constant: 0.52s</td>
</tr>
<tr>
<td></td>
<td>Limit-violation-count since 1/3/01, 3:45: 7</td>
</tr>
<tr>
<td>flat-with-noise</td>
<td>normal, occurrences: 6</td>
</tr>
<tr>
<td>spike</td>
<td>Spike-count since 1/3/01, 3:45: 35</td>
</tr>
<tr>
<td>sensor-disturbance</td>
<td>Occurrences: 6</td>
</tr>
<tr>
<td></td>
<td>Exp. time-constant: 0.55s</td>
</tr>
<tr>
<td></td>
<td>Spec. time-constant: 0.52s</td>
</tr>
<tr>
<td></td>
<td>Limit-violation-count since 1/3/01, 3:45: 8</td>
</tr>
<tr>
<td>drift-with-noise</td>
<td>normal, occurrences: 3</td>
</tr>
<tr>
<td></td>
<td>drift-slope: -0.05 PSI/s</td>
</tr>
<tr>
<td></td>
<td>expected drift with temp: -0.001 PSI/s</td>
</tr>
<tr>
<td></td>
<td>warm-up period: 2 hr.</td>
</tr>
<tr>
<td></td>
<td>time-since-turn-on: 5 hr. 45 min</td>
</tr>
<tr>
<td></td>
<td>expected-wear-drift: -0.005 PSI</td>
</tr>
<tr>
<td></td>
<td>op-time-since-last-cal: 54 hr</td>
</tr>
<tr>
<td>step-down</td>
<td>normal, occurrences: 2</td>
</tr>
<tr>
<td></td>
<td>Exp. time-constant: 0.51s</td>
</tr>
<tr>
<td></td>
<td>Spec. time-constant: 0.52s</td>
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</tbody>
</table>
**Intelligent Sensors**

**Example Signal**

**Process RELATED CONDITION MONITORING**

<table>
<thead>
<tr>
<th>Behavior discrepancies</th>
<th>E1HPLOXP1: spike</th>
<th>E1HPLOXP1: disturbance</th>
<th>E1HPLOXP1: disturbance</th>
<th>E1HPLOXT1: high noise</th>
</tr>
</thead>
</table>

**Sensors:**
- E1HPLOXP1: Pressure, Strain-Gauge. Loc: Top
- E1HPLOXP2: Pressure, Piezoelectric. Location: Bottom
- E1HPLOXT1: Temperature, Thermocouple K, Loc: Top
- E1HPLOXT2: Temperature, Thermocouple K, Loc: Bottom
- E1HPLOXV1: Valve position, Loc: Bottom

**Process:** HP LOX - Start: 2/5/01, 13:08  End: 2/6/01, 8:45

**Sensors:** E1HPLOXP1: Pressure, Strain-Gauge.  Loc: Top  
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E1HPLOXV1: Valve position, Loc: Bottom

**Condition Monitoring**

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<th>Event Type</th>
<th>Occurrence Details</th>
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<tbody>
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<td>flat-with-noise</td>
<td>normal, occurrences: 5</td>
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</table>
| step-up             | normal, occurrences: 2  
Exp. time-constant: 0.50s  
Spec. time-constant: 0.52s |
| sensor-disturbance  | occurrences: 5  
Exp. time-constant: 0.50s  
Spec. time-constant: 0.52s  
Limit-violation-count since 1/3/01, 3:45: 7 |
| flat-with-noise     | normal, occurrences: 6                                                             |
| spike               | Spike-count since 1/3/01, 3:45: 35                                                 |
| sensor-disturbance  | Occurrences: 6  
Exp. time-constant: 0.55s  
Spec. time-constant: 0.52s  
Limit-violation-count since 1/3/01, 3:45: 8 |
| drift-with-noise    | normal, occurrences: 3  
drift-slope: -0.05 PSI/s  
expected drift with temp: -0.001 PSI/s  
expected-warm-up-drift: -0.005 PSI  
   warm-up period: 2 hr.  
   time-since-turn-on: 5 hr. 45 min  
   expected-wear-drift: -0.005 PSI  
   op-time-since-last-cal: 54 hr |
| step-down           | normal, occurrences: 2  
Exp. time-constant: 0.51s  
Spec. time-constant: 0.52s |
**Intelligent Sensors**

**Example Signal**

**Sensor E1HPLOXP1:** Pressure, Strain-Gauge - Process: HP LOX  
Start: 2/5/01, 13:08  End: 2/6/01, 8:45

<table>
<thead>
<tr>
<th>Condition Monitoring</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat-with-noise</td>
<td>normal, occurrences: 5</td>
</tr>
</tbody>
</table>
| step-up              | normal, occurrences: 2  
Exp. time-constant: 0.50s  
Spec. time-constant: 0.52s |
| sensor-disturbance   | occurrences: 5  
Exp. time-constant: 0.50s  
Spec. time-constant: 0.52s  
Limit-violation-count since 1/3/01, 3:45: 7 |
| flat-with-noise      | normal, occurrences: 6 |
| spike                | Spike-count since 1/3/01, 3:45: 35 |
| sensor-disturbance   | Occurrences: 6  
Exp. time-constant: 0.55s  
Spec. time-constant: 0.52s  
Limit-violation-count since 1/3/01, 3:45: 8 |
| drift-with-noise     | normal, occurrences: 3  
Drift-slope: -0.05 PSI/s  
Expected drift with temp: -0.001 PSI/s  
Expected-warm-up-drift: -0.005 PSI  
Warm-up period: 2 hr.  
Time since turn-on: 5 hr. 45 min  
Expected-wear-drift: -0.005 PSI  
Op-time since last cal: 54 hr |
| step-down            | normal, occurrences: 2  
Exp. time-constant: 0.51s  
Spec. time-constant: 0.52s |

**Process:** HP LOX - Start: 2/5/01, 13:08  End: 2/6/01, 8:45

**Sensors:**  
- E1HPLOXP1: Pressure, Strain-Gauge. Loc: Top  
- E1HPLOXP2: Pressure, Piezoelectric. Location: Bottom  
- E1HPLOXT1: Temperature, Thermocouple K, Loc: Top  
- E1HPLOXT2: Temperature, Thermocouple K, Loc: Bottom  
- E1HPLOXV1: Valve position, Loc: Bottom

**Behavior discrepancies:**  
- E1HPLOXP1: spike  
- E1HPLOXP1: disturbance  
- E1HPLOXP1: disturbance  
- E1HPLOXT1: high noise  

**CLOSE**
• Extract continuously intuitive descriptions of all signals before, during, and after tests (create a complete and meaningful record).

• Identify, diagnose, and propose remedies to abnormal or potentially abnormal conditions occurring in all test-stand components (sensors, actuators, processes).

**INTELLIGENT ISHM**

**Record:** pre-test, step-up, sensor disturbance, steady state, spike, steady-state, sensor-disturbance, drift, step-down

**Abnormal Conditions:** sensor-disturbance, spike, sensor-disturbance

**Potential Abnormal Conditions:** drift.
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.
Intelligent Sensors

- 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
  - Wavelet Transforms (segmentation)
  - Algorithms for
    - Flat
    - Impulsive (“spike”) noise
    - White noise
  - Other (ANN, etc.)
Humans
Direct mission and solve problems beyond the reach of automated systems with the help of automated, diagnostic and prognostic tools.

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

Interrelationship Between Traditional Avionics Systems, Time Critical ISHM and Advanced ISHM

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.
The wedge of work currently performed by humans necessitates a very large and complex operations infrastructure. Long term recurrent ops cost savings can only be realized through dramatically more capable tools.
Initial ISHM Capabilities Breakout

Initially, the Time-Critical ISHM system will integrate the functions of FDIR and add only a small wedge of capability. Advanced ISHM will speed the human-directed troubleshooting efforts.

As Advanced ISHM technologies mature to a certifiable state, more are added to the Time-Critical portion, further relieving the human workload and therefore cost.
Evolved ISHM Capabilities

As Advanced ISHM technologies mature to a certifiable state, more are added to the Time-Critical portion, further relieving the human workload and therefore cost.

Traditional Avionics System
- Constant activity
- Nominal operations
- Deterministic
- Autonomous, but monitored

Time Critical ISHM
- Covers first failure
- Deterministic
- Advises humans on all actions

Advanced ISHM Assisted Humans
- ISHM takes no actions except human alerts
- Advises and assists humans
- Speculative

Intersystem coordination & first failure response.

Nominal system functions

Imminent failures and very complex or new failures.
Cost Savings from Advanced Systems

Reliability

Complexity of System

Current ISS Ops Cost

Traditional Avionics System

Traditional + Time Critical ISHM

Traditional + Time Crit ISHM + Adv ISHM

Reliability Requirement

All slack must be carried by Humans
"The C&DH system is vulnerable to instability under heavy load conditions. The ISS has developed operational guidelines that control this problem. This is an acceptable mode of operation during the construction phase of the ISS. But is not adequate for conducting scientific research in a production environment in which many activities execute concurrently. Recommendation 01-20a indicated that NASA should "Gain an improved understanding of the range of commanding problems that lead to constraints on the system." Although the Panel believes that NASA is making progress on this recommendation, the Panel plans to reexamine the issue in the coming year. Recommendation 01-20a is continuing."

ISHM technologies being matured include real time and design-time tools which assist in uncovering the state space of software and hardware-software interactions

"Recommendation 01-20c renews the earlier concern about the adequacy of the current C&DH architecture and component performance. The recommendation is "Evaluate potential architectures that would improve the systems stability and robustness and ensure safe operations. Implement architecture improvements as soon as it is prudent to do so." Therefore Recommendation 01-20c is continuing."

One purpose of advanced components of ISHM is to address those faults and errors which are too complex to be programmed into a deterministic system. ISHM increases the robustness by accelerating and improving the ability of operators to handle complex faults.

"Finding 01-17 Instances of anomalies in crew performance may be increasing. Recommendation 02-17: Review all data on crew performance and all root causes of crew incidents to determine if a trend is apparent. Take appropriate action."

ISHM provides the crew with two capabilities:
(a) increased insight into the system and correlations between events and (b) moving training and operations away from fixed procedures and towards problem solving and adaptable mission management.
Safety Impacts

Recommendation 02-18: Ascertain the availability of functional redundancy through dissimilar computer hardware and software for all safety-critical functions. Predicated on a prioritization of criticality, develop a program to provide requisite functional redundancy.

ISHM components can be implemented as in-band and out-of-band systems, operating on different hardware, software and design processes than the core system. The ISHM embedded system can therefore provide critical system diversity without the added cost of providing redundant disparate control systems.

"Finding 02-22: It is necessary for software assurance, of which IV&V is a part, to evolve in response to advances in information technology. Nondeterministic systems, such as those constructed from neural nets and other artificial-intelligence approaches, offer particular challenges for validation and verification. The attempt to take advantage of COTS software requires that such software be verified and validated not only in accord with its original intent, but also in case it is modified or customized for a specific application and within its new environment. Recommendation 02-22: Maintain a robust research and development effort within the NASA IV&V program. Establish reasonable and supportive funding levels for this effort. Create a research agenda in cooperation with NASA’s operational and research enterprises. Provide oversight by program and project managers to ensure that the research meets their needs."

ISHM addresses this recommendation in two ways:

1) ISHM brings the world’s leaders in artificial intelligence, information technology, and COTS together. An endogenous expertise in these areas will facilitate the development of V&V technology designed for these types of computational systems.

2) ISHM is, at its core, a runtime V&V system. The state space of any large software product is vast enough to invalidate the concept of complete testing. However, the state space of any software at a point in the runtime is calculable. Therefore, ISHM extends the viability of the formal V&V methods to the runtime environment, increasing their utility.
Hardware Software Integration: CARD Table 3.7.4.D-1 identifies "Resources provided to support PR analysis" as a 1st order I&O cost driver. The same table identifies: "Resources required to support testing and other verification activities" as a 1st order cost driver for both I&O and DDT&E.

Software Development and Integration Lab: CARD Table 3.7.5.B-1 identifies "...test rig troubleshooting and anomaly resolution support..." as a Key Product and Service.

Prime Command & Data Handling Sustaining:
CARD Table 3.4.3.2.D-1 identifies "Number and complexity of anomalies; real time anomaly resolution; unknown variable increases as more HW added on-orbit; number of PRACAS requiring C&DH expertise; amount of on-going monitoring and trending" as the #1 cost driver for this $22M/year cost element. The third driver includes: "Number and complexity of C&DH system on-orbit."

Prime Communication & Tracking, Guidance Navigation & Control and other Sustaining:
The CARD contains language for these areas that is similar to C&DH sustaining.

The #1 target of ISHM is rapid anomaly resolution. While current ISHM tools are targeted at acceleration of on-orbit anomaly resolution, the basic ISHM structure and technology is extensible to the more complex problems often faced in ground testing.
**SSTF**: CARD Section 4.3.3.2.1C: "Space Station Training Facility costs are heavily dependant on the number of training hours required for both the crew and flight controller training" and "secondary cost drivers include troubleshooting..."

*ISHM increases the ability to move training away from the large, costly integrated simulators used for troubleshooting of systems anomalies. Operating the still-required high fidelity simulators is facilitated by ISHM because many of the same ISHM components and algorithms used on the flight system are identical in the simulator.*

**Training Hours:**
The current budget for ISS Prime Crew Training is 4552 hours. Of that, 970 hours (21%) are allocated to ISS systems which are related to the ISHM target. The #1 cost driver (CARD Table 4.3.4.D-1) for Flight Operations, Training and Mission Preparation is the "Number of hours of training instruction required." This includes crew, instructor and flight controller training.

*Movement towards skills-based training has been hindered by the need for detailed system understanding. This need is driven by the lack of high level troubleshooting tools such as ISHM.*

**MCC Console**: CARD Table 4.3.4.D-1 identifies "Number of hours of on-console support," "Continuous mission support," and the number of "people who must be in MCC at a given time" as major cost drivers. It also points to this being "diminished by how many Gemini shifts are applied." Simply achieving the current POP guidelines requires the replacement of 40% of the current full shifts by Gemini in FY05.

*ISHM is absolutely required to move our operations concept away from a massive Mission Control Center towards a leaner Mission Support Center.*