Making Smart Sensors Intelligent: Building on the IEEE 1451.x Standards

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Outline

- Integrated Systems Health Management and the Role of Intelligent Sensors
- Intelligent Sensors
- The Role of IS in Future Space Flight
NASA Centers

Stennis Space Center, Mississippi
Rocket engine testing at NASA-Stennis is distributed over a 13,500 acre (5,500 ha.) site +120,000 acre (48,500 ha.) noise abatement easement.
ISHM Requirements

- Improve quality
  - By making better and more reliable measurements

- Minimize costs
  - Of reconfiguration between test articles
  - Of repair and calibration

- Avoid downtime
  - By predicting impending failures
  - By timely intervention

- Increase safety (protect people and assets)
Technologies and Tools for ISHM

- ISHM Architecture
- Health assessment database
- Anomaly detection methods
- Predictive modeling
- Root cause analysis
- Intelligent elements
- Integrated awareness
A View of an ISHM Application

ISHM Models (Embedded Data, Information, and Knowledge):
MTTP Implementation

Health Assessment Database:
Health Electronic Data Sheets
Repository of anomalies

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 Enabling Technologies: ISHM Architecture

The Piping & Instrumentation Diagram (P&ID) for a system... is translated to a G2 (Gensym) model...

Populated by component objects with associated xEDS...
ISHM Enabling Technologies: Health Assessment Database

- Historical data records
  - Nominal
  - Anomalous

- Algorithm repository
  - Complex for implementation at upper ISHM architecture levels
  - Simplified for embedding in Intelligent Sensor

- Electronic Data Sheets (EDS)
  - Transducer Electronic Data Sheets (TEDS)
  - Health Electronic Data Sheet (HEDS)
  - Component EDS (CEDS)
  - Others
ISHM Enabling Technologies: Anomaly Detection

- NASA (Glenn Research Center)
  - Developed as part of Atlas-Centaur pneumatic and hydraulic system post-flight analysis (’80’s)
    - Noise Events
    - Spike Events
    - Flat-line Events
    - Level Shift Events
    - Drift Events

- Open literature
ISHM Enabling Technologies: Predictive Modeling

Measurement data...Are compared with model predictions...
Within the ISHM model is a root cause analysis layer...
Example Leak RCA

A decreasing pressure measurement associated with a pressurizable subsystem is used to reason about the possible cause/effects.
Pressure Leaks

- Leaks are critical in hydraulic systems
- One approach for leak detection:

```
<table>
<thead>
<tr>
<th>Wait for Valve State Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
</tr>
<tr>
<td>Do Closed Elements Form a Boundary?</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>Define Pressurizable Subsystem</td>
</tr>
<tr>
<td>Pressurizable Subsystems</td>
</tr>
<tr>
<td>PS</td>
</tr>
<tr>
<td>PS</td>
</tr>
<tr>
<td>PS</td>
</tr>
<tr>
<td>For Each PS</td>
</tr>
<tr>
<td>Check All Pressure Sensors</td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td>Do Sensors Indicate a Change in Pressure?</td>
</tr>
<tr>
<td>No</td>
</tr>
<tr>
<td>Mark All Elements of PS SUSPECT for Leak Anomaly</td>
</tr>
<tr>
<td>For Each Element</td>
</tr>
<tr>
<td>Change Health Parameters in Leak Process Model to SUSPECT</td>
</tr>
<tr>
<td>Root-Cause-Analysis</td>
</tr>
<tr>
<td>Root Cause</td>
</tr>
</tbody>
</table>
```
ISHM Enabling Technologies: Integrated Awareness

- User interface
  - Minimize information overload
  - Provide navigation through 3D structure
  - Spatial relationships between components
  - Maintenance guide
Definition of an Intelligent Sensor

An Intelligent Sensor consists of a Smart Sensor augmented by support for application-specific algorithms and associated electronic data sheets (xEDS).

That means, we first have to deal with Smart Sensors…
A Smart Sensor adheres to one of the IEEE 1451.x Standards; for distributed systems, important to have a network capable application processor (NCAP)

- IEEE 1451.0 Defines a set of common commands, operations and Transducer Electronic Data Sheets (TEDS) for the family of IEEE 1451 standards
- IEEE 1451.1 Defines a common object model describing the behavior of a Network Capable Applications Processor (NCAP)
More IEEE 1451.X Smart Sensor Standards

- IEEE 1451.2 Defines a transducer to NCAP transducer independent interface (TII) and TEDS for a point-to-point configuration of transducer interface modules (TIMs)
- IEEE 1451.3 Defines a transducer to NCAP interface and TEDS for multi-drop transducers
- IEEE 1451.4 Defines a mixed-mode interface for analog transducers with analog and digital operating modes; simplest 1451 model
- IEEE 1451.5 Defines a TII interface and TEDS for wireless transducers
- IEEE P1451.6 Defines a TII interface and TEDS using the controller area network (CAN)
- IEEE P1451.7 Defines an RFID interface
IEEE 1451 – Smart Sensor

NCAP

Ethernet Stack (Hardware)

Ethernet Interface

IEEE 1451.1
Base Client Port
Base Publisher Port

IEEE 1451.{2-6}
physical standard w/ T-Block

Physical Standard Abstraction Layer

Physical Standard
(Hardware)

Transducer Independent Interface (TII)

Sensors

IEEE 1451.1 Application

Transducer Electronic Datasheets (TEDS)

Network Hardware

transducer interface
TEDS

- The transducer electronic data sheet provides the means to tag a sensor with a description.
  - Manufacturer
  - Serial number
  - Calibration status
  - Coefficients
  - Physical location

- Offers practical means for reducing costs/errors associated with measurement system configuration
Making a Smart Sensor Intelligent

- Capable of embedding algorithms; for example, for ISHM:
  - Noise detection (broadband, bandlimited, spike)
  - Instrumentation anomalies
    - Flat line
    - Drift
  - Sensor anomalies
    - Open/short
    - Debondment
Augmenting Core IEEE 1451 Functions

- **NCAP**
  - Publish normal data + health

- **Extended TEDS**
  - Health electronic data sheet (HEDS)
    - Set_HEDS
    - Get_HEDS
  - Component electronic data sheet (CEDS)
    - Set_CEDS
    - Get_CEDS
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
  - Algorithms for
    - Flat
    - Impulsive (“spike”) noise
    - White noise
  - Other (ANN, etc.)
Example ISHM-Enabled Intelligent Sensors

**Hardware**
- 3-Ch Thermocouple
- 24-bit ADC
- 8-bit μP
- 1 MB RAM/Flash
- SPI
- Ethernet (802.3af)

**IEEE 1451 & O/S**
- NCAPBlock_Go_Active
- NCAP_Block_Go_InActive
- Request_NCAPBlock_Announcement
- NCAPBlock_Announcement
- PublishNormalData

**ISHM**
- Mean, Std dev, Min/Max, RMS
- dv/dx, d²v/dx²
- Poly fit
- Bu HPF (13th)
- 64-pt FFT
- Anomalies: Flat, Spike, Noise

**Rowan University**

**PublishNormalData+Health**
**Channel_Sample_Rate**
**Get_HEDS • Set_HEDS • Get_TEDS • Set_TEDS**
Other Smart Sensors—Some w/ Intelligent Sensor Capabilities

Smart Sensor Systems
www.smartsensorsystems.com

Mobitrum
www.mobitrum.com

Esensors
www.eesensors.com

NIST
www.mel.nist.com
ISHM Enabling Technologies: Intelligent Sensors

- Unfortunately, Intelligent Sensors are not widely available; to realize IS benefits in a system populated with conventional sensors, create a Virtual IS.
- The Virtual Intelligent Sensor is software that mimics IS behavior and allows use of conventional sensors and data acquisition systems.

![Diagram of Intelligent Sensors and Data Acquisition System (DAS)]
## Data Structure Model for IEEE-1451

<table>
<thead>
<tr>
<th>Field No.</th>
<th>Description</th>
<th>Type</th>
<th>No. of Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data structure related data sub-block</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Extension: TEDS length</td>
<td>U32L</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Extension TEDS ID Number</td>
<td>U16E</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>Extension TEDS version number</td>
<td>U16E</td>
<td>2</td>
</tr>
<tr>
<td><strong>Application related data sub-block</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fields 4-8 repeat for each health condition.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Phase code</td>
<td>U8C</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Condition code</td>
<td>U8C</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Detection algorithm + arguments</td>
<td>STRING</td>
<td>Varies</td>
</tr>
<tr>
<td><strong>Data integrity data sub-block</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Checksum for the extension TEDS</td>
<td>U16C</td>
<td>2</td>
</tr>
</tbody>
</table>
Timing in Sensor Networks

- Need to provide time synchronization across multiple IS nodes in order to time-align measurements
- IEEE-1588 in distributed networks
  - For spatially-localized networks (e.g., Test stand, Space vehicle, Labs)
  - μs to sub-μs accuracy
  - Local oscillators synchronized to reference oscillator(s) by measuring network transport delays

http://ieee1588.nist.gov/
The Role of IS in Future Space Flight

**Ares I: Crew Launch Vehicle**
- ~25-mT payload capacity
- 2-Mlb gross liftoff weight
- 309 ft in length

**Upper Stage**
- 260-klb Liquid Oxygen/Liquid Hydrogen (LOX/LH₂) Stage
- 5.5-m Diameter
- Aluminum-Lithium (Al-Li) Structures
- Instrument Unit and Interstage
- RCS / Roll Control for First Stage Flight
- CLV Avionics System

**Upper Stage Engine**
- Saturn J-2 Derived Engine (J-2X)
- Expendable

**First Stage**
- Derived from Current Shuttle Reusable Solid Rocket Motor/Booster (RSRM/B)
- Five Segments/Polybutadiene
- Acrylonitrile (PBAN) Propellant
- Recoverable
- New Forward Adapter

**Ares V Cargo Launch Vehicle**
- ~130-mT payload capacity
- 7.4-Mlb gross liftoff weight
- 358 ft in length

**Earth Departure Stage**
- LOx/LH₂
- One J2X+ Engine
- Al-Li Tanks/Structures

**Upper Stage Engine**
- Saturn J-2 Derived Engine (J-2X)
- Expendable

**Core Stage**
- LOx/LH₂
- Five RS68 Engines
- Al-Li Tanks/Structures

**Composite Shroud**
- Interstage
- Five Segment RSRBs

**LSAM**

**Ascent Stage Descent Stage**
Intelligent Sensors in Space

- Space-qualified intelligent sensors
  - Size, mass, power constraints
    - Trade spaces: Minimized wiring, distributed computing, distributed intelligence
  - Integrated with guidance, navigation & control (GN&C) architecture
  - Bus structure/protocol
    - Bandwidth, reliability

Lunar Habitat
Constellation: Return to the Moon

VTS_06_1.VOB