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
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

**Anomaly Detection:** Leaks, etc.

**Intelligent Sensors:** IEEE Standard + Health

**Health Assessment Database:**
- Health Electronic Data Sheets
- Repository of anomalies

**Integrated Awareness:**
- 3-D Health Visualization of MTTP

**Embedding of Predictive Models**

**Root Cause Analysis**

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Leak a-subcomponent-of m2_process-equipment
Pressure Leak encompassing m2_pressure-subsystem
Decreasing Pressure pressure_sensor
ISHM Enabling Technologies: ISHM Architecture

The Piping & Instrumentation Diagram (P&ID) for a system...

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 to determine anomalies.

Diagram:

- Sensor Data → Predictive Model → Prediction-Measurement Mismatch
- xEDS → Model Coefficients → Predictive Model
- Measurement Values vs Predictive Values vs Prediction-Measurement Mismatch
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:
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...
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)
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

IEEE 1451.1 Application

IEEE 1451.1 Base Client Port
Base Publisher Port

Physical Standard Abstraction Layer

Physical Standard Interface (TII)

Transducer Electronic Datasheets (TEDS)

Network Hardware

transducer interface

Sensors

NCAP

Ethernet Stack (Hardware)

Ethernet Interface

NCAP
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
IEEE 1451.1 - Information Model

```
IEEE1451_Root

+GetClassName()
+GetClassID()

IEEE1451_Entity

+GetObjectTag()
+SetObjectTag()
+GetObjectID()
+GetObjectName()
+GetDispatchAddress()
+GetOwningBlockObjectTag()
+GetObjectProperties()
+Perform()

IEEE1451_Block

+GetGroupIds()
+SetGroupIds()
+GetBlockMajorState()
+GetBlockManufacturerID()
+GetBlockModelNumber()
+GetBlockVersion()
+GoActive()
+GoInactive()
+Initializer()
+Reset()
+GetNetworkVisibleServerObjectProperties()
+RegisterNotifyOnUpdate()
-DeregisterNotifyOnUpdate()

IEEE1451_Component

+SpecifyRuleBasis()

IEEE1451_Service

-SpecifyRuleBasis()
```
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 (1st, 2nd)
  - 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

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

Mobitrum
www.mobitrum.com

Smart Sensor Systems
www.smartsensorsystems.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
### 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></td>
<td><strong>Data structure related data sub-block</strong></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></td>
<td><strong>Application related data sub-block</strong></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></td>
<td><strong>Data integrity data sub-block</strong></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

Ares V: Cargo Launch Vehicle

- ~130-mT payload capacity
- 7.4-Mlb gross liftoff weight
- 358 ft in length

Ares V Cargo Launch Vehicle

- LOx/LH2
- One J2X+ Engine
- Al-Li Tanks/Structures

Earth Departure Stage

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

Upper Stage
- 260-Mlb 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

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

Five Segment RSRBs

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