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

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54th International Instrumentation Symposium
Pensacola, FL USA
5-8 May 2008
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
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 that describes cause/effect relationships...
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
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 P1451.7Defines an RFID interface
IEEE 1451 – Smart Sensor
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
- \( dv/dx, \frac{d^2v}{dx^2} \)
- Poly fit
- Bu HPF (13\(^{th}\))
- 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

NIST
www.mel.nist.com

Esensors
www.eesensors.com
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)
  - \( \mu s \) to sub-\( \mu s \) 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

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
- 200-kib 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
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
Constellation: Return to the Moon

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Discussion