Intelligent Sensors and Components for On-Board ISHM

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Support rocket engine test mission with highly reliable, accurate measurements.
New Needs: Constellation Systems

Aries V: Cargo Launch Vehicle

- ~130-mT payload capacity
- 4.4-Mlb gross lift-off weight
- 358 ft in length

Lunar Habitat

Aries I: Crew Launch Vehicle

- ~25-mT payload capacity
- 2-Mlb gross lift-off weight
- 309 ft in length

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

Upper Stage
- 292-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

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

Composite Shroud

Earth Departure Stage
- LOX/LH2
- One J2X Engine
- Al-Li Tanks/Structures

Interstage

Five Segment RSRBs

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

Ares V Cargo Launch Vehicle

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Rocket Engine Test Stand Technology Roadmap

- FY05: ISHM Testbed
- FY06: Embedded Smart Sensors
- FY07: Smart Components
- FY08: ISHM System Integration into test RETS
- FY09: ISHM System Integration into Large-scale RETS

Test Stand of the Future

Intelligent Test Stand

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System-of-System
Integrated Systems Health Management (ISHM)
R&D PROGRAM: Co-Development of a Centralized G2-based IIHMS System with Highly Autonomous Sensors

**High Level Controller**

- Processes or Systems
- Process/System Bus
- Sensor Bus
- Highly Autonomous Sensors

**G2 ISHM**

- **Ap Code** (MATLAB)
- Conventional Sensors
- Highly Autonomous Sensors
  - *Smart Sensors* (Hardware, Software)

**Development Path**

**G2**

**ISHM**

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Key Components & Technologies

- **SSC Test environment**
  - Production and developmental rocket engine testing—many different facilities, many sensors and actuators
  - Long documentation history of transducer/actuator failures, fault signatures
  - Physical model opportunities—e.g., Trailer-mounted test stand (TMTS) for development/prototyping and validation

- **Knowledgeware system software- Gensym G2**

- **Smart sensors**
  - Network-enabled embedded processors w/ operating systems and high-level language development tools
  - IEEE 1451.2: Smart transducer interface for sensors and actuators—Transducer to μP communication protocols and transducer electronic data sheet (TEDS)
  - IEEE 1588, Precision clock synchronization protocol for networked measurement and control systems
IEEE-1451 Model of Smart Sensor: STIM <-> NCAP

STIM: Smart Transducer Interface Module
TII: Transducer Independent Interface
NCAP: Network Capable Application Processor
Prototype Smart Sensor Arch:

ADC, Cygnal C8051F300, Etc.

iButton

TEDS & HEDS

Type K

H2O2 Temp Mon

TCs

TC Signal Conditioning & Health Monitoring

AD595

Embedded Processor & Software (OS + Ap)

I2C, SPI

Data

10BaseT TCP/IP

STIM & NCAP

PC: Process, IIHMS Analysis Support (MATLAB)

IIHMS

PC: Sensor IEF, IDM

G2

Test Stand Data

Data + Health

Hub

Embedded Processor & Software (OS + Ap)

I2C, SPI

Data
Sensor Architecture

- Embedded processor architecture
  Z-World Rabbit 2000
- Embedded operating system
  - Dynamic C
  - MicroC/OS-II (FAA RTCA DO-178B)
- Sensor system partition (mono-, multi-processor)
  - Redundant EP architecture
- Library functions
  - Network, Basic math, I/O
  - Health assessment
Generic Smart Sensor


Ethernet Core NCAP + Custom STIM piggy-back card

Sensor function:
3-axis Accelerometer
Smart Sensor Issues

- Uncertainties of smart sensors
  - Uncertainty in data domain
  - Uncertainty in the time domain

- Health-Enabled smart sensors
  - Evolving catalog of fault behaviors
  - Algorithms for health assessment
SSC Test Environment:

Discrepancy Reports (DRs)

- Rigorous method of documentation to identify and solve problems—especially sensor/actuator failures
- Complete files available for test stands
- DR Review methodology
- +150 DRs reviewed/summarized from E1 focusing on sensor problems and descriptions
- Failure ("health") descriptors (Aerospace Corp.)

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## Sample fault behavior descriptions

- **Overscale**
- **Hashy, Noisy**
- **Readings deviate from expected**
  - Polarity
  - Value
- **Suspected alias**

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th>Probe</th>
<th>Description</th>
<th>Fix</th>
</tr>
</thead>
<tbody>
<tr>
<td>184</td>
<td>8/29/2000</td>
<td>TE-202-IGM</td>
<td>Reads over scale entire duration of recording</td>
<td>Replaced amp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-103B-CHM</td>
<td>Reads over scale entire duration of recording</td>
<td>Checked connections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-103B-INJ</td>
<td>Becomes very hashy at T+1s. Possible loose conn.</td>
<td>Checked connections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-103E-INJ</td>
<td>Reads over scale entire duration of recording</td>
<td>Checked connections: Swapped amp</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-103L-INJ</td>
<td>Reads around -260°F entire duration of recording. Very noisy</td>
<td>Checked connections. Reconnect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-104-CHM</td>
<td>Reads opp dir of TE-105-CHM and gets noisy at T+2s</td>
<td>TC wired backwards</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-203A-INJ</td>
<td>Prob. Has TC leads swapped and a loose connection</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-204A-INJ</td>
<td>Should be close to 204B. It goes in the opp. Direction</td>
<td>MSID file error, wrong units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TE-204B-INJ</td>
<td>Appears to be identical data to TE-204B-INJ</td>
<td></td>
</tr>
</tbody>
</table>

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Summary of Typical Fault Behaviors

- Limits (signal, noise) - (High, Low)
- Saturation (High, Low)
- Bandwidth (signal, noise)
- Spike noise limit
- Attack, $t_r$ (Max, Min)
- Decay, $t_f$ (Max, Min)

- Nominal values (Mean, Variance)
- Alias
- Impossibility
- Instrumentation
  - Flat
  - Static (offset) error
  - Gain (slope) error
Fault Behaviors Modified by Phase

- Condition faults and values modified by context of the measurement—i.e., the state of the process or system modifies interpretation of signal/fault properties.

- Example system state diagram:
  - Idle
  - Pre-test (chill down)
  - Test
  - Post-test
  - Maintenance
  - Abort
Example Fault Behaviors: Condition

- Impossible
- +Saturation
- -Saturation

- Noise
- Attack Max/Min
- Expected
- Decay Max/Min
- Spike
Phase Modifies Condition

Define, quantify, and model condition codes for each phase

Example: During **Idle**, expect Max/Min Attack/Decay to be function of environmental forcings; During **Pre-Test chill down**, expect Max/Min Attack/Decay to be function of internal (pipe flow) forcings
Uncertainties of Smart Sensors

Problem: *Shared references of existing data acquisition systems are replaced with distributed—non shared—references*

1. Signal conditioning building (SCB) provides controlled environment for centralized data acquisition system (DAS) 2 that converts signals from test stand transducers such as thermocouples 3. A smart sensor would be placed on the test stand similar to existing 4-20 ma transmitters 4.
Timing

- Deterministic structure of conventional DAS makes time-stamping easy
- Nondeterministic networks supporting smart sensors makes time-stamping difficult
- New standard, IEEE-1588
IEEE-1588

- For spatially-localized networks (e.g., Test stand)
- $\mu$s to sub-$\mu$s accuracy
- Applicable to high- and low-end devices
- Local oscillators are synchronized to reference oscillator(s) by measuring network transport delays
Recommendations & Future Work

- Development
  - Expert system (G2)
  - Baseline smart sensor (incl. HEDS)
  - Network issues

- Test support
  - Smart sensor evaluation (Vref, Time)

- Application
  - Lab
  - Field
Recap: G2-centric View

PC w/ G2

Knowledge Base

NCAP Bridge

PC GOAL Bridge

IP ADD 1

IP ADD 2

Private Ethernet (TCP/IP)

Ethernet Hub

SSC Ethernet

For now, no trusted links to SSC net.

Autonomous Smart Sensor

STIM

iButton

Precision Reference

Sensor Subsystems (ADC, SC, etc.)

Z-World NCAP w/ TEDS, HEDS

MATLAB Bridge

MATLAB

PC w/ MATLAB

MATLAB

Ethernet

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Task: Models

- Sensor data fusion and health assessment
  - Artificial Neural Nets (ANNs)
  - Wavelet transforms for feature extraction
- Models for failures; methods for detection
Smart Sensor Development

- Design/Implement smart sensor suite
  - Smart sensor architecture
  - TEDS/HEDS
  - Selected smart sensor
### Task: HEDS Extensions to IEEE-1451

**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>
Adapting IEEE-1451 for HEDS

- Full catalog/analysis of exemplar sensor (and actuator) faults
- Codify fault conditions and system phases
- Define HEDS as TEDS extensions
- Submit to IEEE-1451 WG
Task: Networking

- Timing per IEEE-1588
- Modeling of large number of sensors
Sensor Test Suite

- Smart Sensor development/validation suite
  - NCAP w/ TII to support arbitrary STIM
  - Characterization capability
    - ENOB: Oven capability (-55°C to +125°C)
    - Jitter: Timing capability