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

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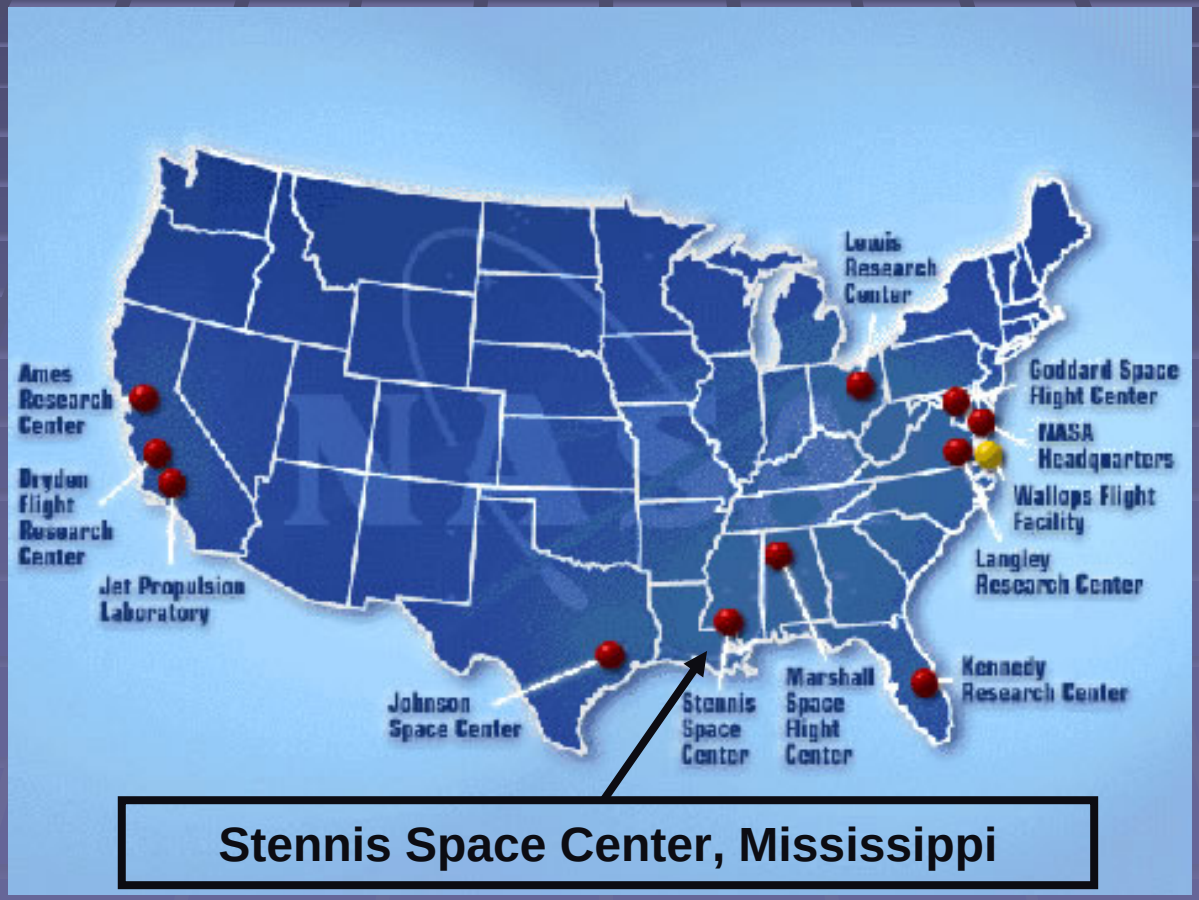
# Outline

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

# NASA Centers

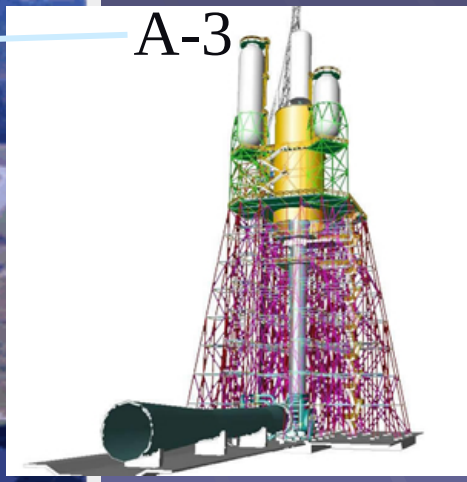


Rocket engine testing at NASA-Stennis is distributed over a 13,500 acre (5,500 ha.) site +120,000 acre (48,500 ha.) noise abatement easement

B-1/B-2

A-1

A-2



A-3

E-2

E-3

E-1

# 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)

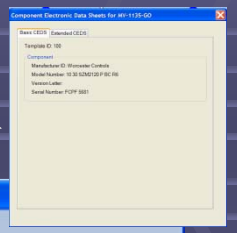
# Technologies and Tools for ISHM

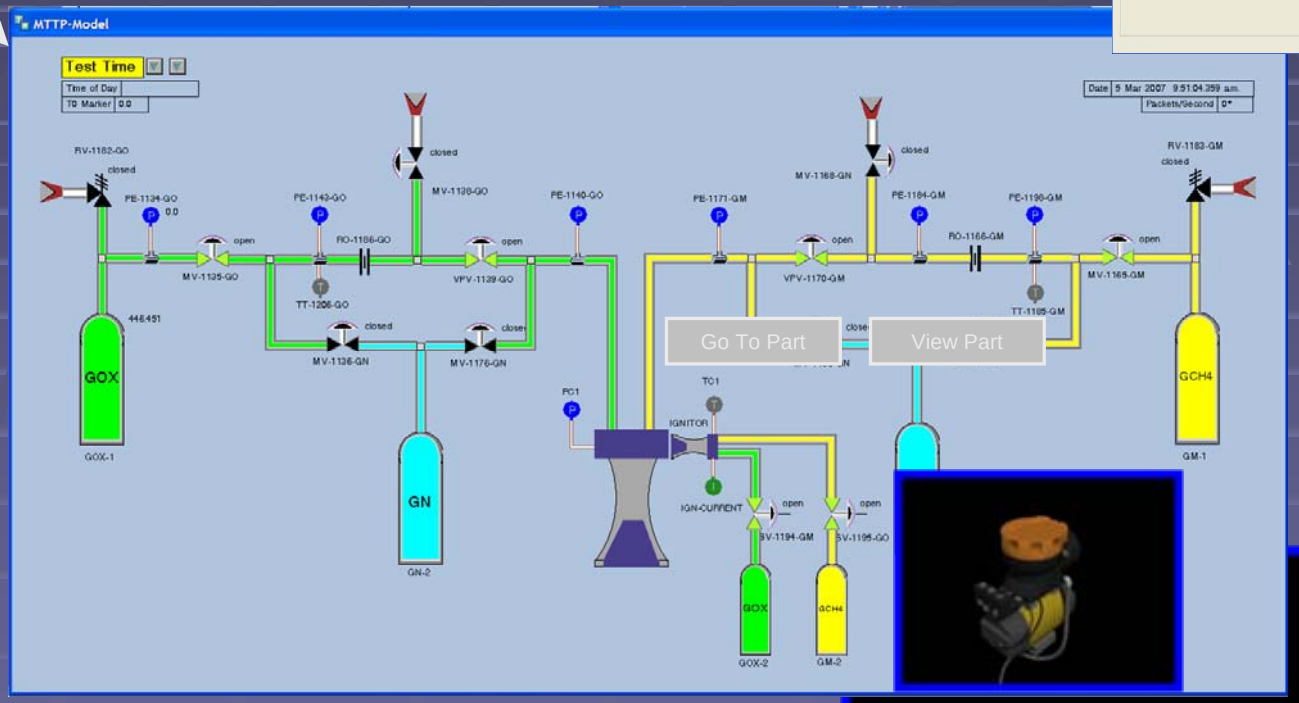
- ISHM Architecture
- Health assessment database
- Anomaly detection methods
- Predictive modeling
- Root cause analysis
- Intelligent elements
- Integrated awareness

# 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





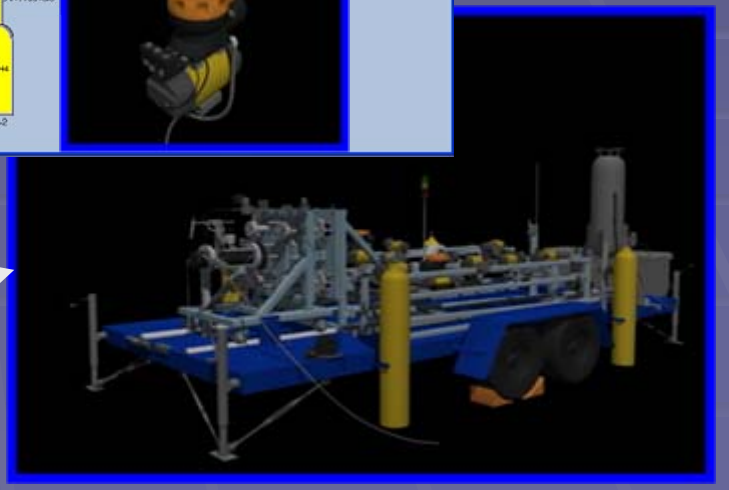

**Anomaly Detection**:
Leaks, etc.

**Intelligent Sensors**: IEEE Standard+Health

**Embedding of Predictive Models**

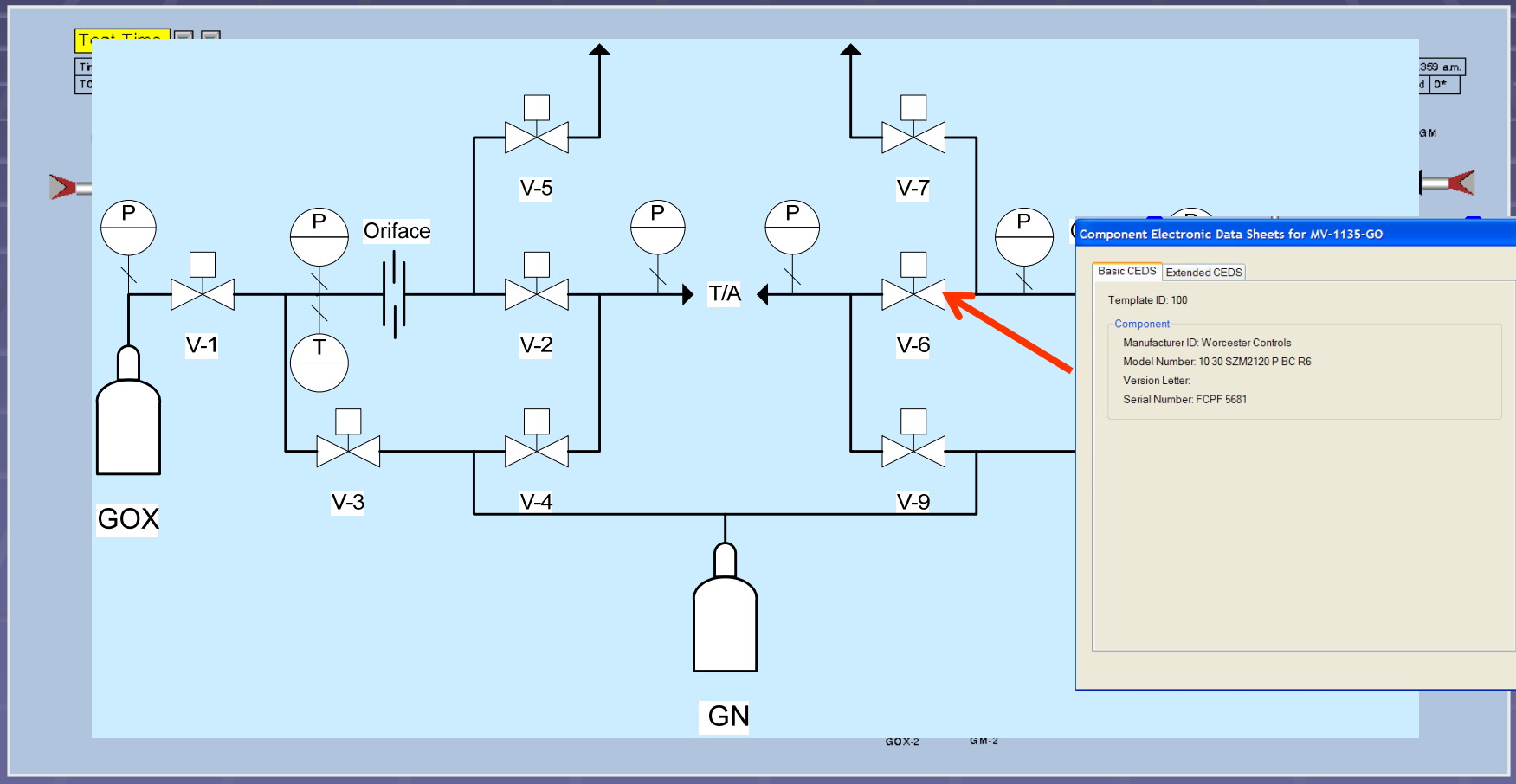
**Root Cause Analysis**

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



# ISHM Enabling Technologies: ISHM Architecture

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




Populated by component objects with associated xEDS…

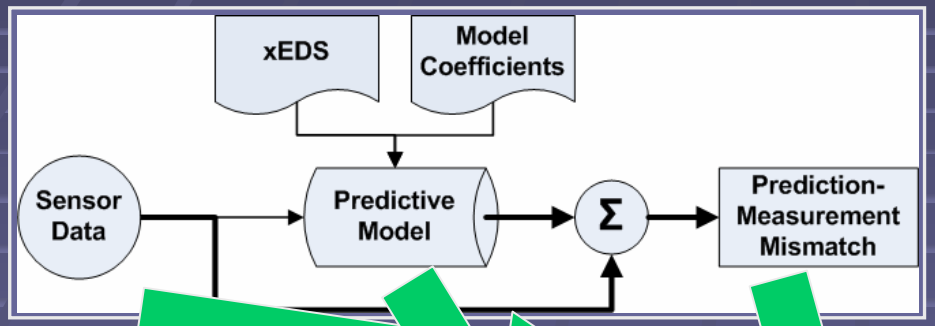
# ISHM Enabling Technologies: Health Assessment Database

- 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

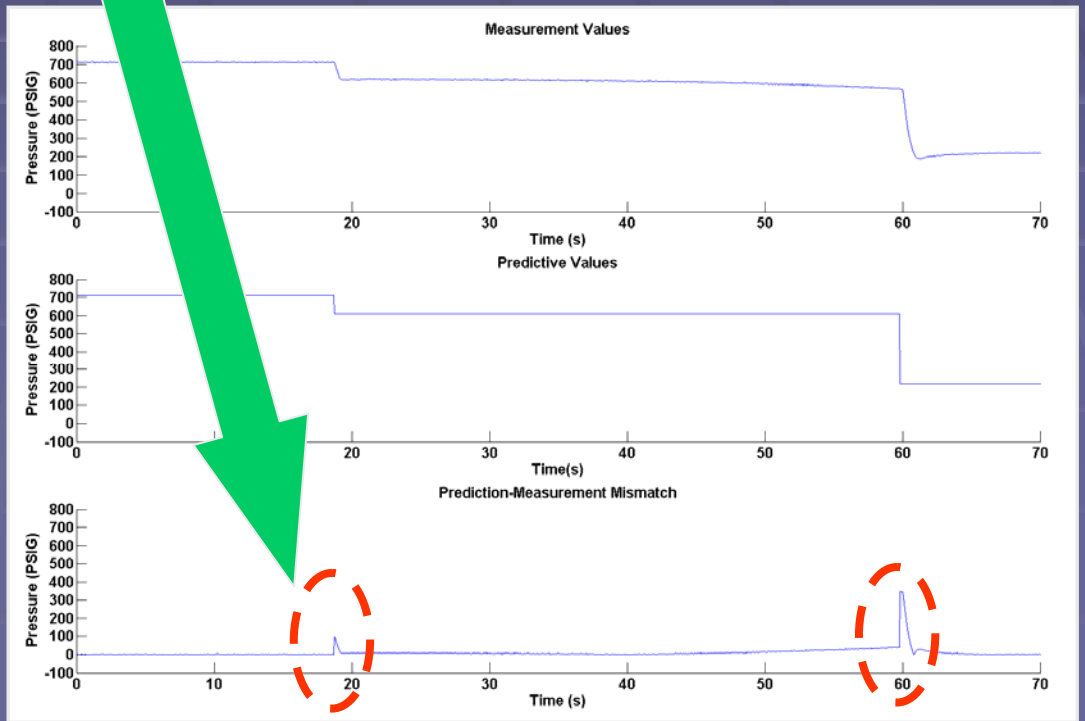
- NASA (Glenn Research Center)
  - Developed as part of Atlas-Centaur pneumatic and hydraulic system post-flight analysis (’80’s)
    - Noise Events
    - Spike Events
    - Flat-line Events
    - Level Shift Events
    - Drift Events
- Open literature

# ISHM Enabling Technologies: Predictive Modeling




Measured data…

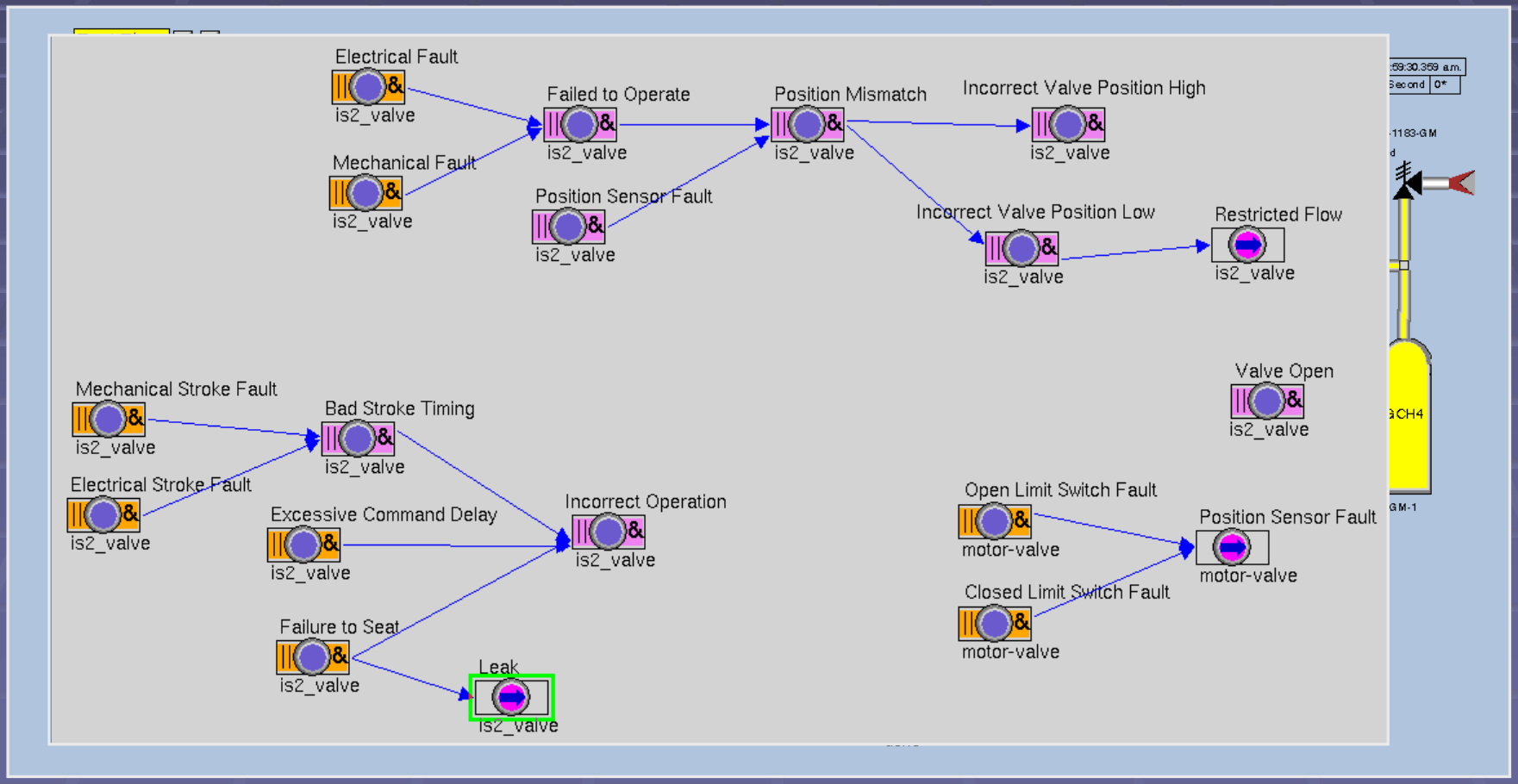
Model predictions…



# ISHM Enabling Technologies: Root Cause Analysis

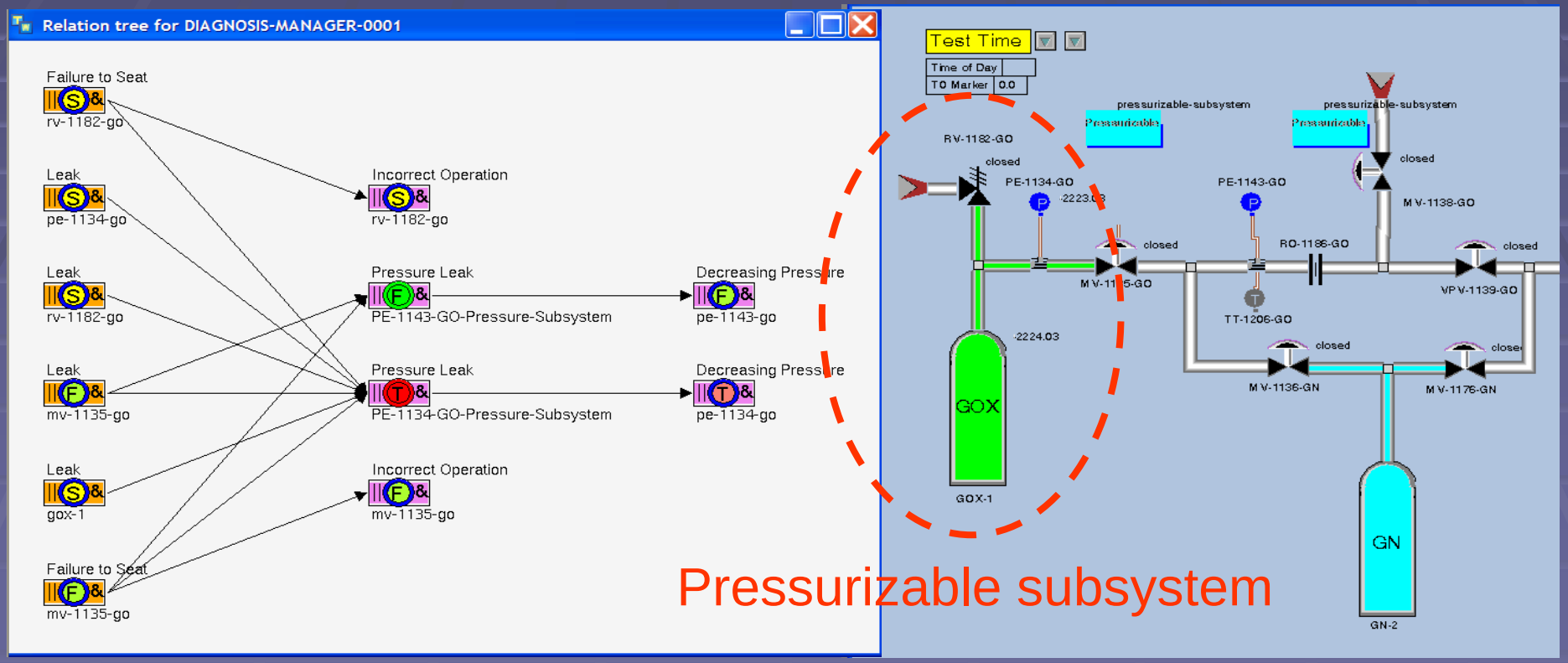
Within the ISHM model is a root cause analysis layer…

That describes cause/effect relationships…



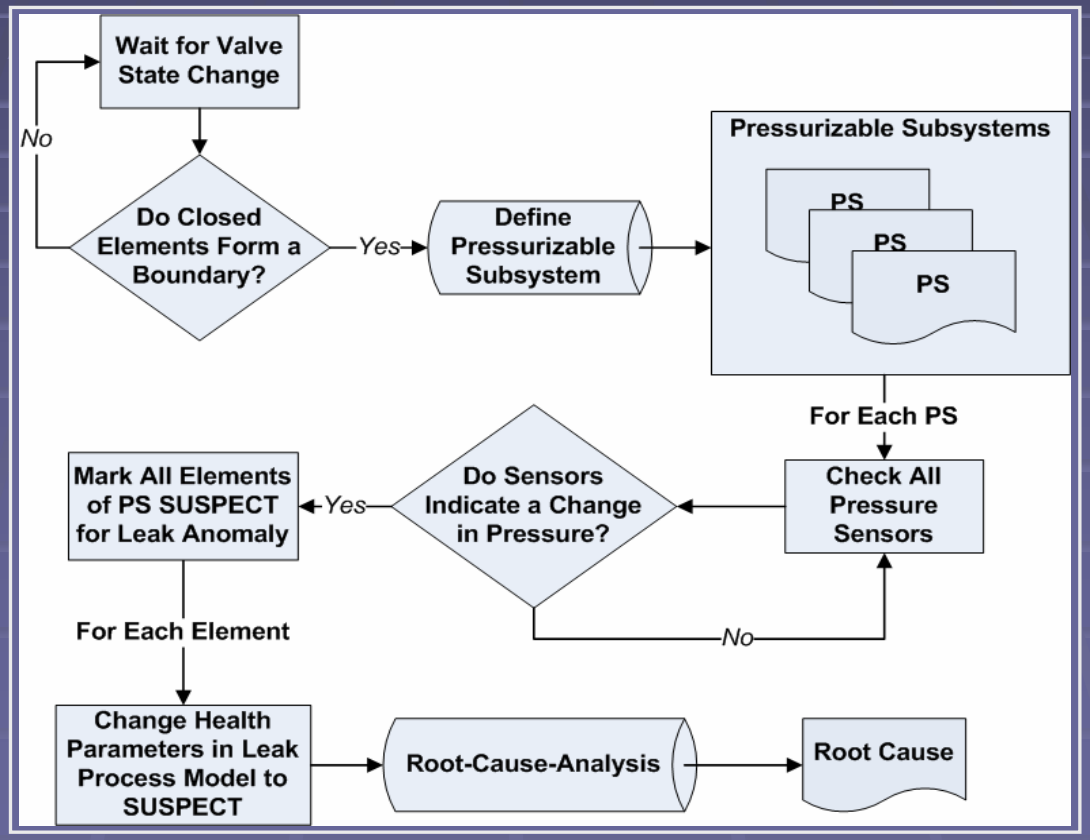
# Example Leak RCA

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



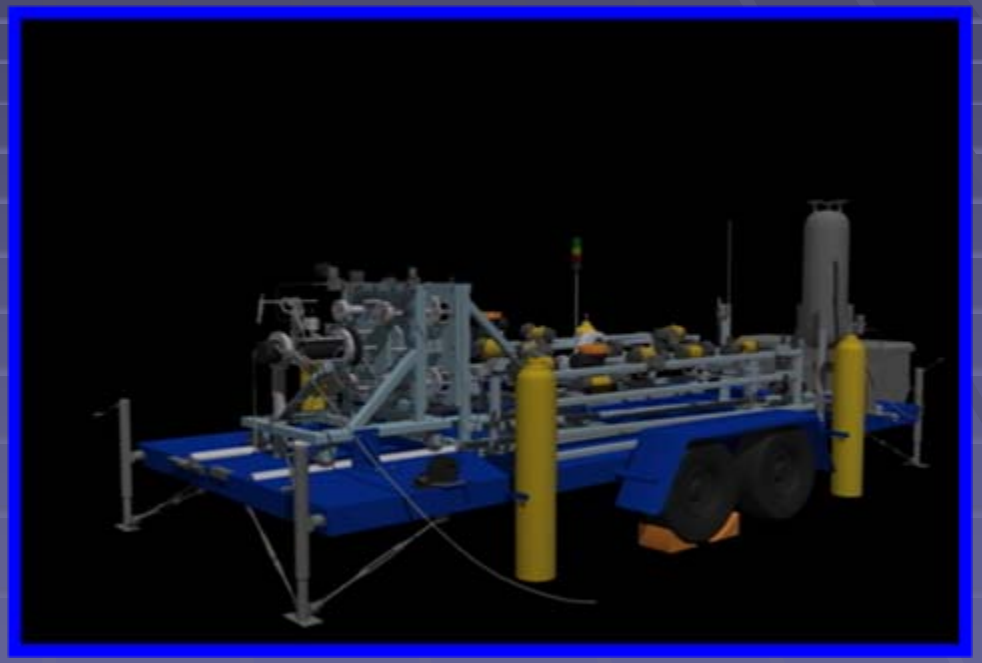
# Pressure Leaks

- 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



# 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…

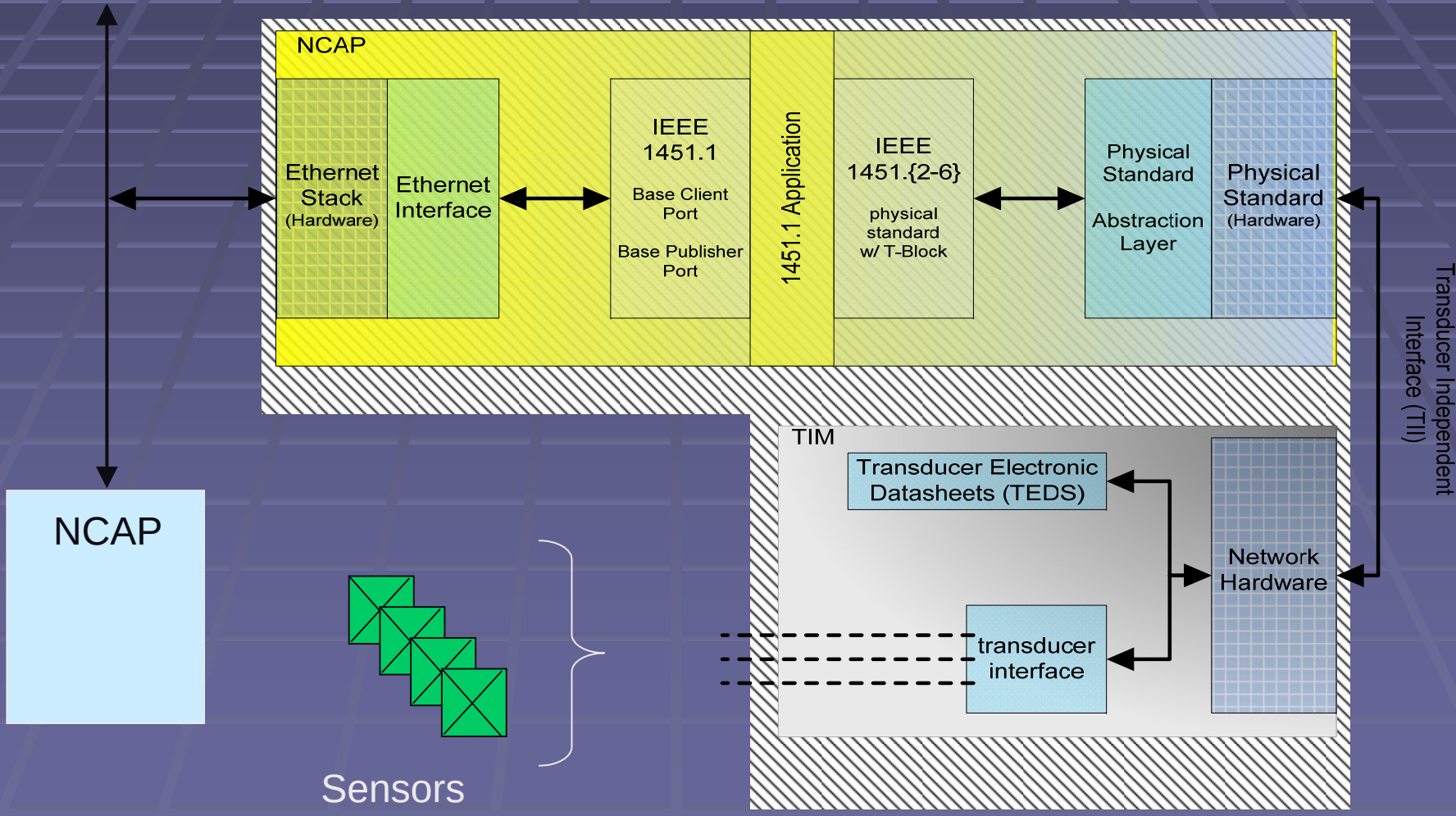
# Smart Sensors

- 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)

# 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

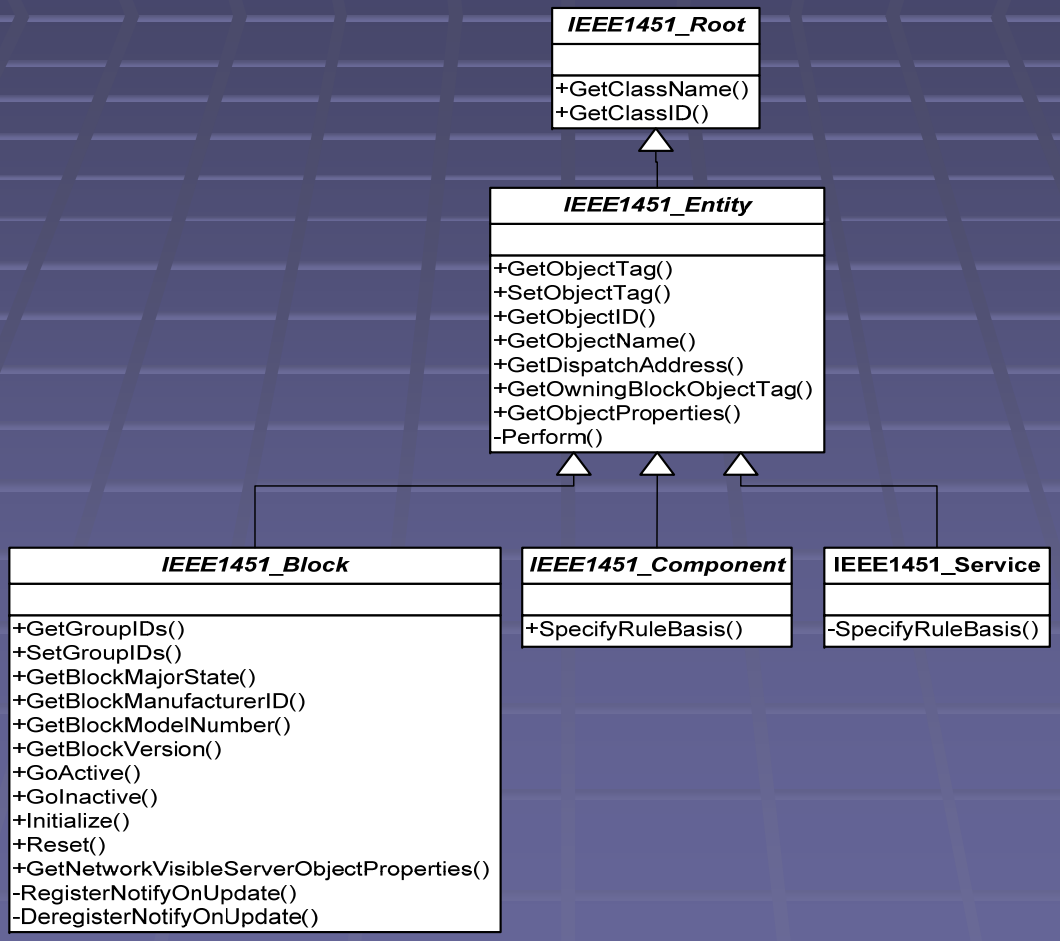
# IEEE 1451 – Smart Sensor



# 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



# Making a Smart Sensor Intelligent

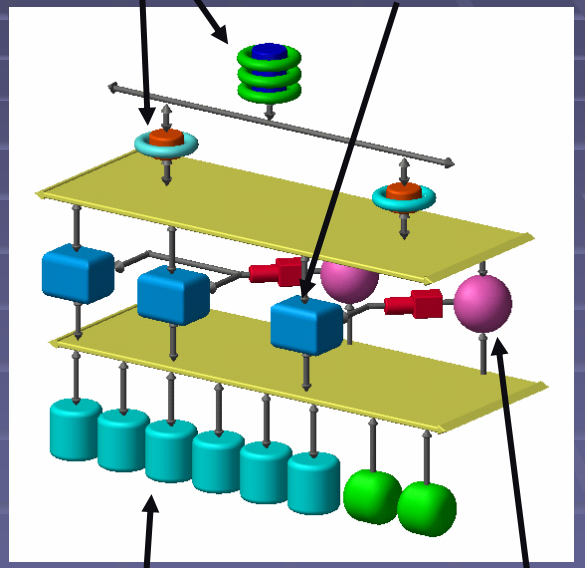
- Capable of embedding algorithms; for example, for ISHM:
  - Noise detection (broadband, bandlimited, spike)
  - Instrumentation anomalies
    - Flat line
    - Drift
  - Sensor anomalies
    - Open/short
    - Debondment

# 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

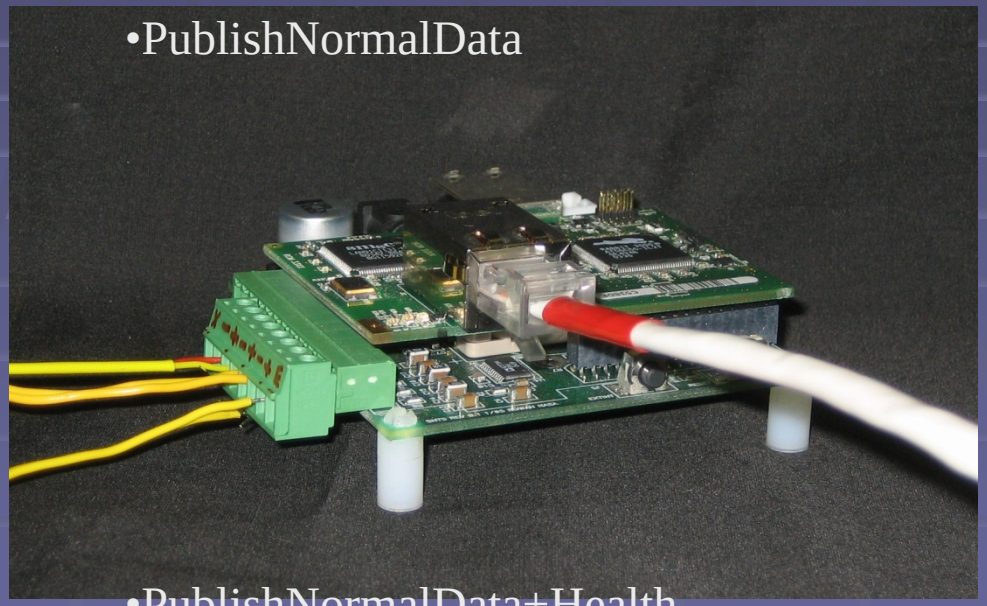
- Smart sensor
  - NCAP (Go Active, Announce)
  - Publish data
  - Set/Get TEDS
- Intelligent sensor
  - Set/Get HEDS
  - Publish health
- Detect classes of anomalies using:
  - Using statistical measures
    - Mean
    - Standard deviation
    - RMS
  - Polynomial fits
  - Derivatives (1st, 2nd)
  - 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

**IEEE 1451 & O/S**

- NCAPBlock_Go_Active
- NCAP_Block_Go_InActive
- Request_NCAPBlock_Announcement
- NCAPBlock_Announcement
- PublishNormalData



- PublishNormalData+Health
- Channel_Sample_Rate
- Get_HEDS •Set_HEDS •Get_TEDS •Set_TEDS

**Hardware**

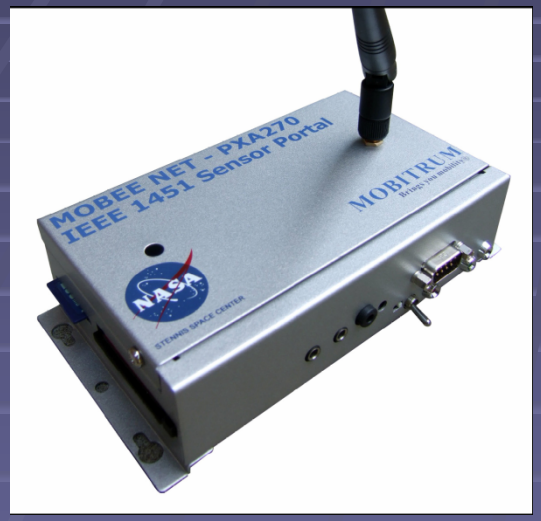
- 3-Ch Thermocouple
- 24-bit ADC
- 8-bit μP
- 1 MB RAM/Flash
- SPI
- Ethernet (802.3af)

**ISHM**

- Mean, Std dev, Min/Max, RMS
- $dv/dx$, $d^2v/dx^2$
- Poly fit
- Bu HPF ($13^{th}$)
- 64-pt FFT
- Anomalies: Flat, Spike, Noise

Rowan University

# Other Smart Sensors—Some w/ Intelligent Sensor Capabilities




Mobitrum

www.mobitrum.com

Smart Sensor Systems

www.smartsensorsystems.com

NIST

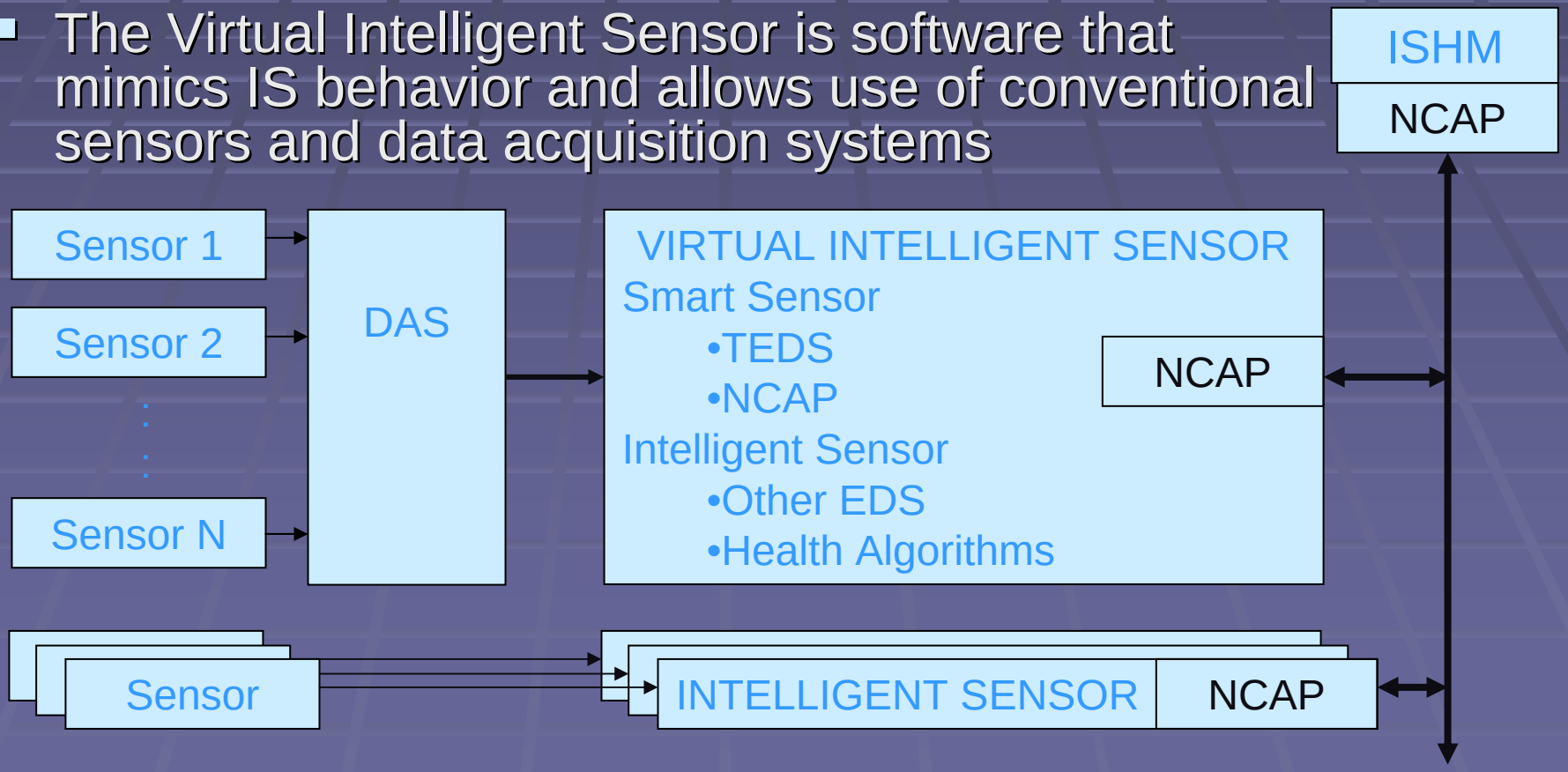
www.mel.nist.com

Esensors

www.eesensors.com

# ISHM Enabling Technologies: Intelligent Sensors

- When available, use 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



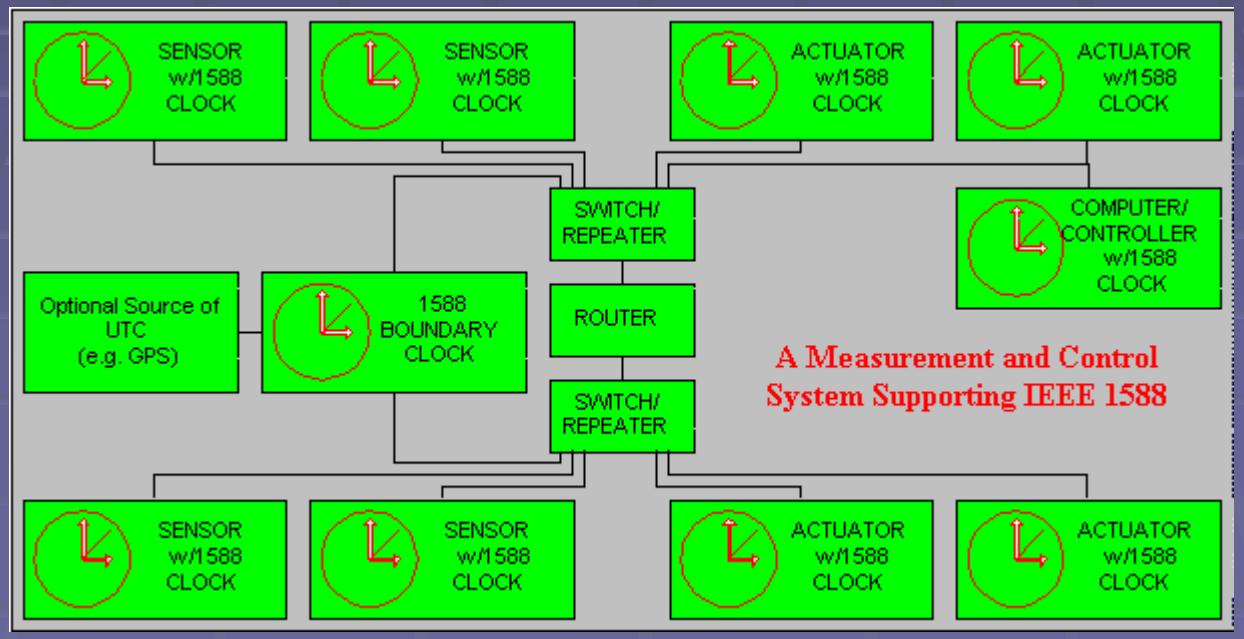
# HEDS Extensions to IEEE-1451

## Data Structure Model for IEEE-1451

| Field No. | Description | Type | No. of Bytes |
|---|---|---|---|
| | **Data structure related data sub-block** | | |
| 1 | Extension: TEDS length | U32L | 4 |
| 2 | Extension TEDS ID Number | U16E | 2 |
| 3 | Extension TEDS version number | U16E | 2 |
| | **Application related data sub-block** | | |
| | Fields 4-8 repeat for each health condition. | | |
| 4 | Phase code | U8C | 1 |
| 5 | Condition code | U8C | 1 |
| 6 | Detection algorithm + arguments | STRING | Varies |
| | **Data integrity data sub-block** | | |
| N | Checksum for the extension TEDS | U16C | 2 |

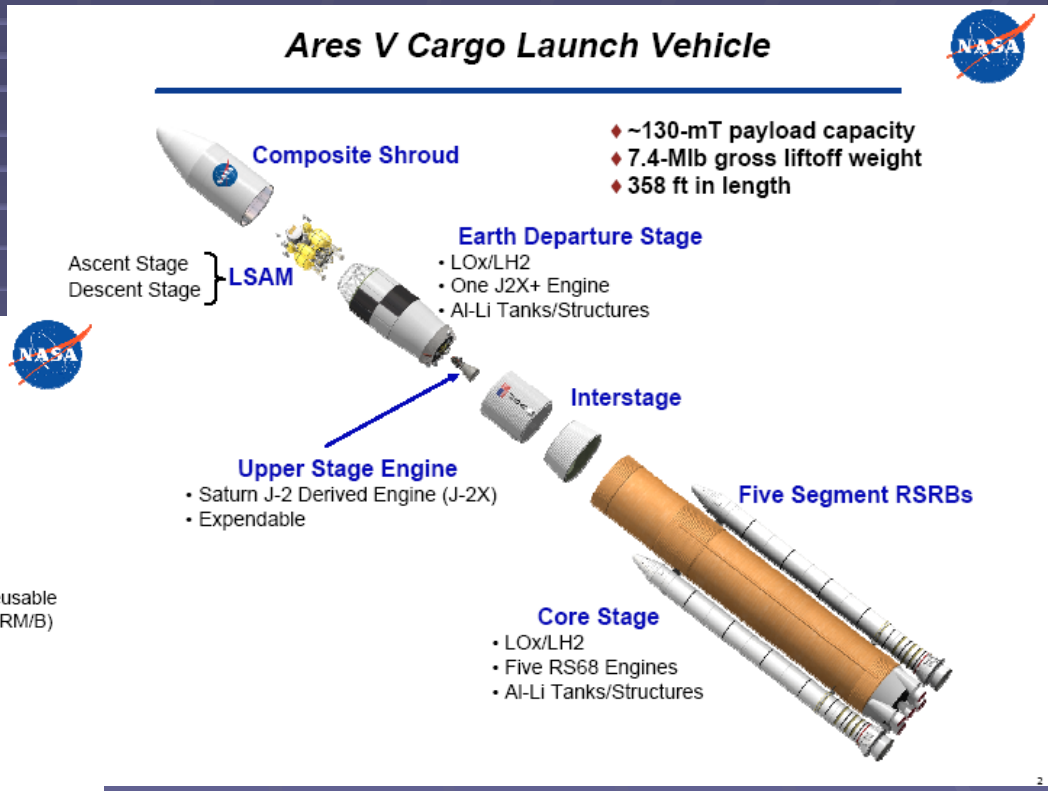
# Timing in Sensor Networks

- 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

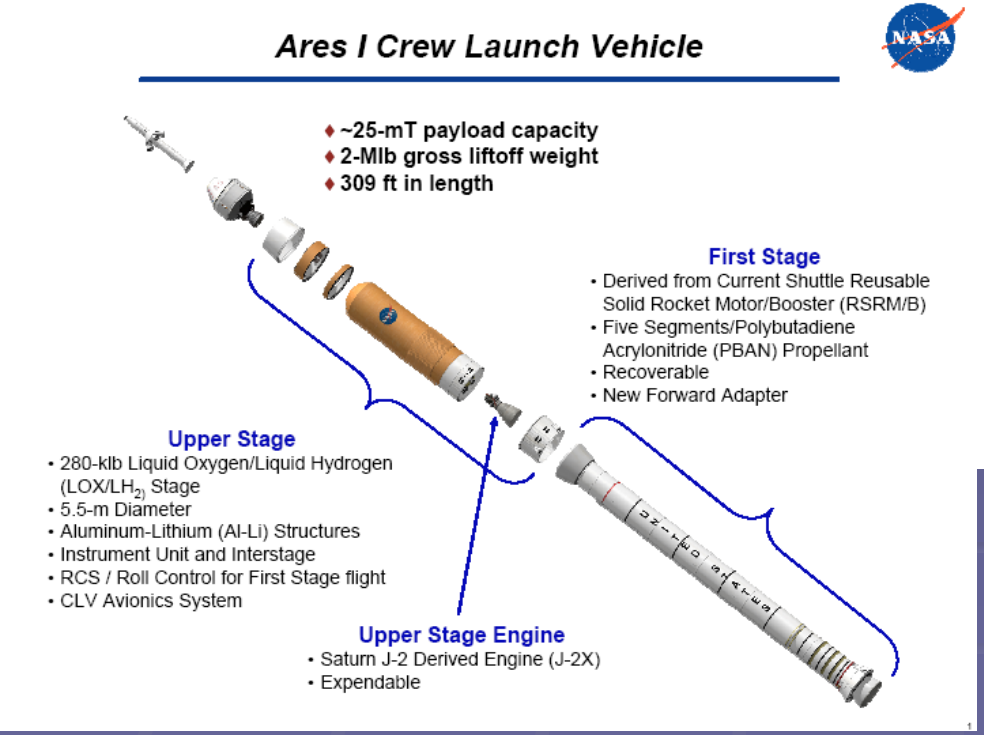



http://ieee1588.nist.gov/

# The Role of IS in Future Space Flight




Ares V: Cargo Launch Vehicle




Ares I: Crew Launch Vehicle

# 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

# Discussion