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NASA Stennis Space Center Integrated System Health Management Test Bed and Development Capabilities

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ISHM DEFINITION

Integrated System Health Management (ISHM) is a capability that focuses on determining the condition (health) of every element in a complex System (detect anomalies, diagnose causes, prognosis of future anomalies), and provide data, information, and knowledge (DIaK) – *not just data* – to control systems for safe and effective operation. This capability is currently done by large teams of people, primarily from ground, but needs to be embedded on-board systems to a higher degree to enable NASA's new Exploration Mission (long term travel and stay in space), while increasing safety and decreasing life cycle costs of spacecraft (vehicles; platforms; bases or outposts; and ground test, launch, and processing operations).

ishm_complete.avi

ISHM RELATED NEWS ARTICLES

Leonard Nicholson, the Northrop Grumman-Boeing team's deputy program manager.

- "The CEV we plan to build will benefit not so much from a single, technical breakthrough but rather from evolutionary improvements in structural technologies, electronics, avionics, thermal-management systems, software and integrated system health management systems over the past 40 years."

- CEV will use two fault-tolerant subsystems and integrated system health management systems to allow it to detect, isolate and recover from subsystem failures. By comparison, Apollo generally had only single fault tolerance.

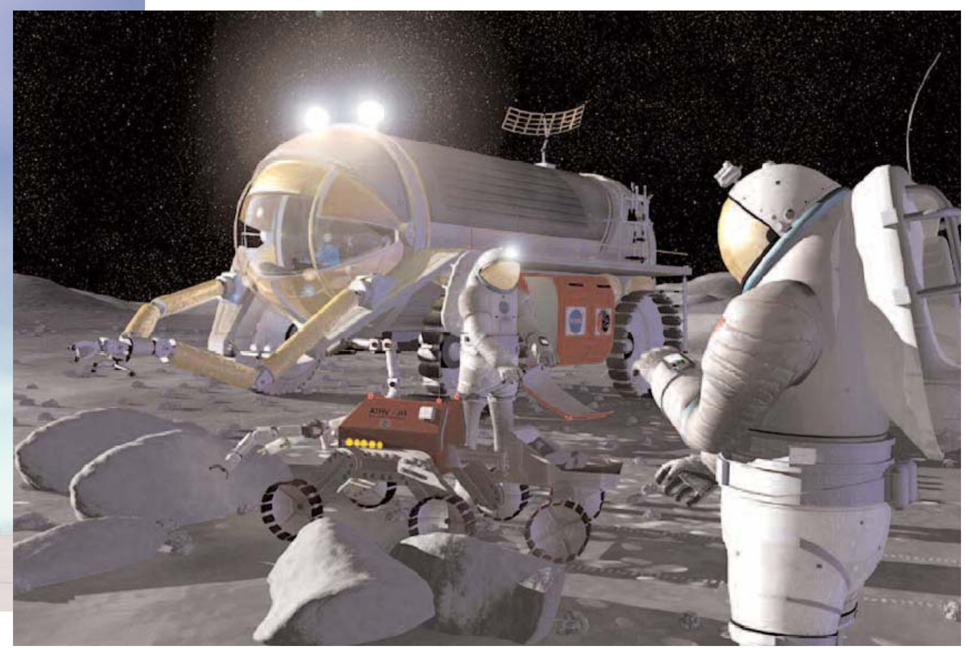
ISHM RELATED NEWS ARTICLES

- The last Delta 4 to fly was the heavy-lift version, which blasted off from Cape Canaveral Air Force Station in December of last year. However, during what looked like a flaw-free ride to space, its first stage failed and its payload -- a mock weight simulating a satellite -- ended up 10,000 miles short of its target.
- The problem: fuel sloshing inside the booster caused some sensors to believe the rocket's tanks had run dry, shutting down the first-stage engines earlier than expected.

This is a case when a decision to shut down engines is done with limited information that does not take advantage of integrated awareness brought about by ISHM capability. Other relevant conditions such as the pressure in the tanks, signs of leakage in the tank and valves/pipes attached to it, other indicators that the engines and surrounding elements may (or may not) be entering a regime associated with fuel starvation, etc. could have been considered.

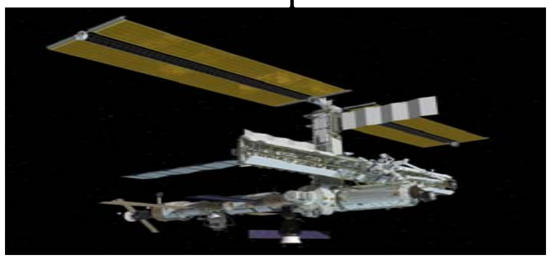
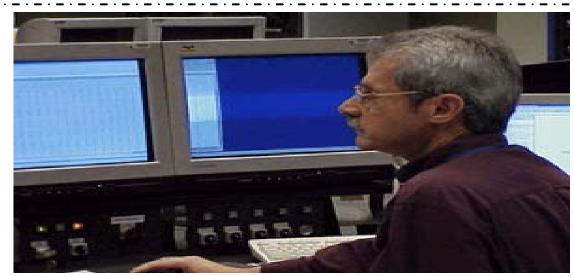
ISHM VISION FOR EXPLORATION

To increase the safety, affordability and sustainability of Exploration missions through Integrated Health Management of complex, mission-critical vehicles and systems.



LAYERS REPRESENTING HOW ISHM IS CURRENTLY PERFORMED

Stennis Space Center

	International Space Station	Rocket Engine Test Stand
<u>Layer 1</u> Vehicle/ Test Stand		
<u>Layer 2</u> Astronaut/ Test Conductor		
<u>Layer 3</u> Control Room		
<u>Layer 4</u> Back Control Room		

ISHM Testbeds & Prototypes at NASA SSC

Stennis Space Center

Objectives

- Mature Integrated System Health Management (ISHM) technologies.
- Develop an integrating architecture embodying intelligent elements.
- Develop prototype intelligent sensors.
- Mature/validate ISHM technologies on operational testbeds.
- Focus on large scale systems-of-systems (demonstration).
- Provide portability to other Exploration Systems and Space Operations applications.

Benefits

- Trusted degree-of-safety determination
- Trusted margin of operation
- Reliable, integrated awareness of health of system's elements
- Validated data with unquestionable integrity
- Anomaly detection traceable to source

Approach

- Develop/mature core technologies
  - Intelligent integration architecture
  - Software environment
  - Intelligent sensors
- Establish testbeds: Rocket Engine Test Stands.

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ISHM – FUNCTIONAL CAPABILITY LEVEL (FCL)

ISHM FCL indicates how well a system performs the following suite of functions leading to complete knowledge of the condition of every element in a system (sensors, components, and processes).

- Determines quality, accuracy, and reliability of data (in the case of sensors).
- Detects anomalous behavior of system elements.
- Determines the cause of anomalous behaviors (diagnostics).
- Predicts future anomalies (prognosis).
- Guides operating procedures to avoid human mistakes.
- Recommends reasonable courses of action to fix problems.
- Provides an integrated view of the system.
- Stores relevant information pertaining to system performance and health for use by investigation teams.

ISHM – FUNCTIONAL CAPABILITY LEVEL (FCL) AND TECHNOLOGY READINESS LEVEL (TRL)

ISHM capability is evolutionary. It begins at a low FCL and approaches 100% capability, but never reaches it.

At each FCL the Technology Readiness Level should be 9 (proven and operational technology).

CORE ELEMENTS: CAPABILITIES NEEDED

ISHM capability is primarily a data, information, and knowledge (DIaK) management problem, integrated throughout a system.

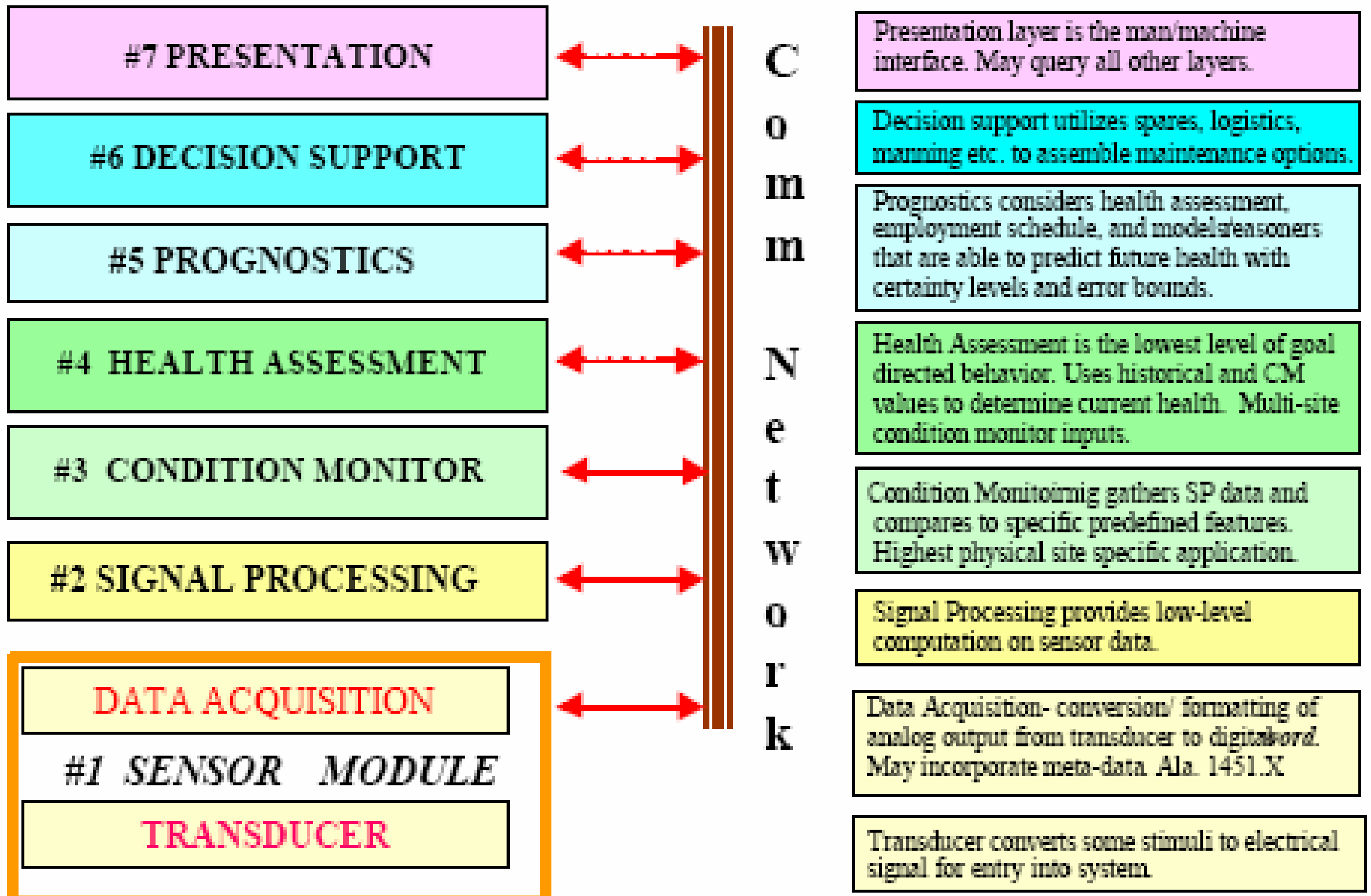
The following capability must be met:

- Distributed storage.
- Distributed processing.
- Distributed intelligence.
- Availability of DIaK to any element as needed.
- Simultaneous execution of multiple processes representing models that contribute to the determination of the condition of each element in the system.

CORE ELEMENTS

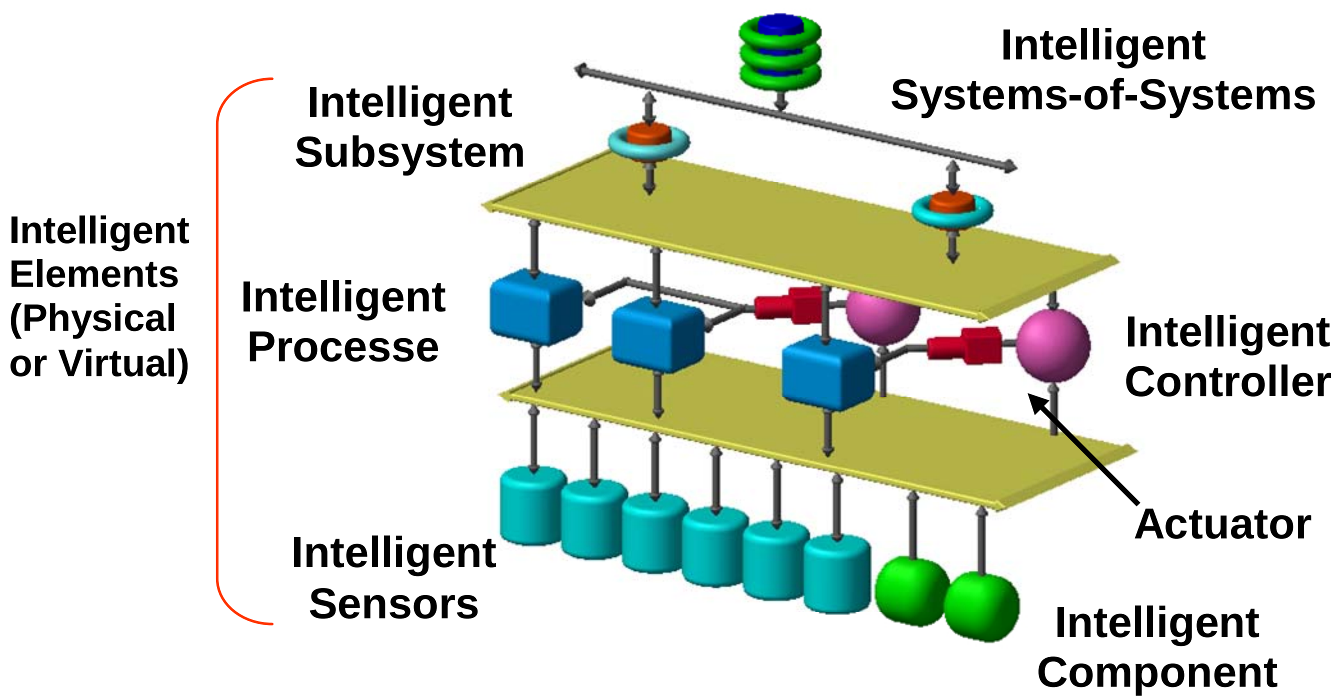
- Architecture, taxonomy, and ontology (ATO) for DIaK management.
- Standards.

OPEN SYSTEMS ARCHITECTURE FOR CONDITION-BASED MAINTENANCE (OSA-CBM)



Open Systems Architecture Enables Health Management for Next Generation System Monitoring and Maintenance Development Program -White Paper - Fred M. Discenzo (Rockwell Automation, Cleveland, OH), William Nickerson (Oceana Sensors, State College, PA), Charles E. Mitchell (Boeing Phantom Works, Long Beach, CA), Kirby J Keller (Boeing Phantom Works, Saint Louis, MO) **www.osacbm.org**

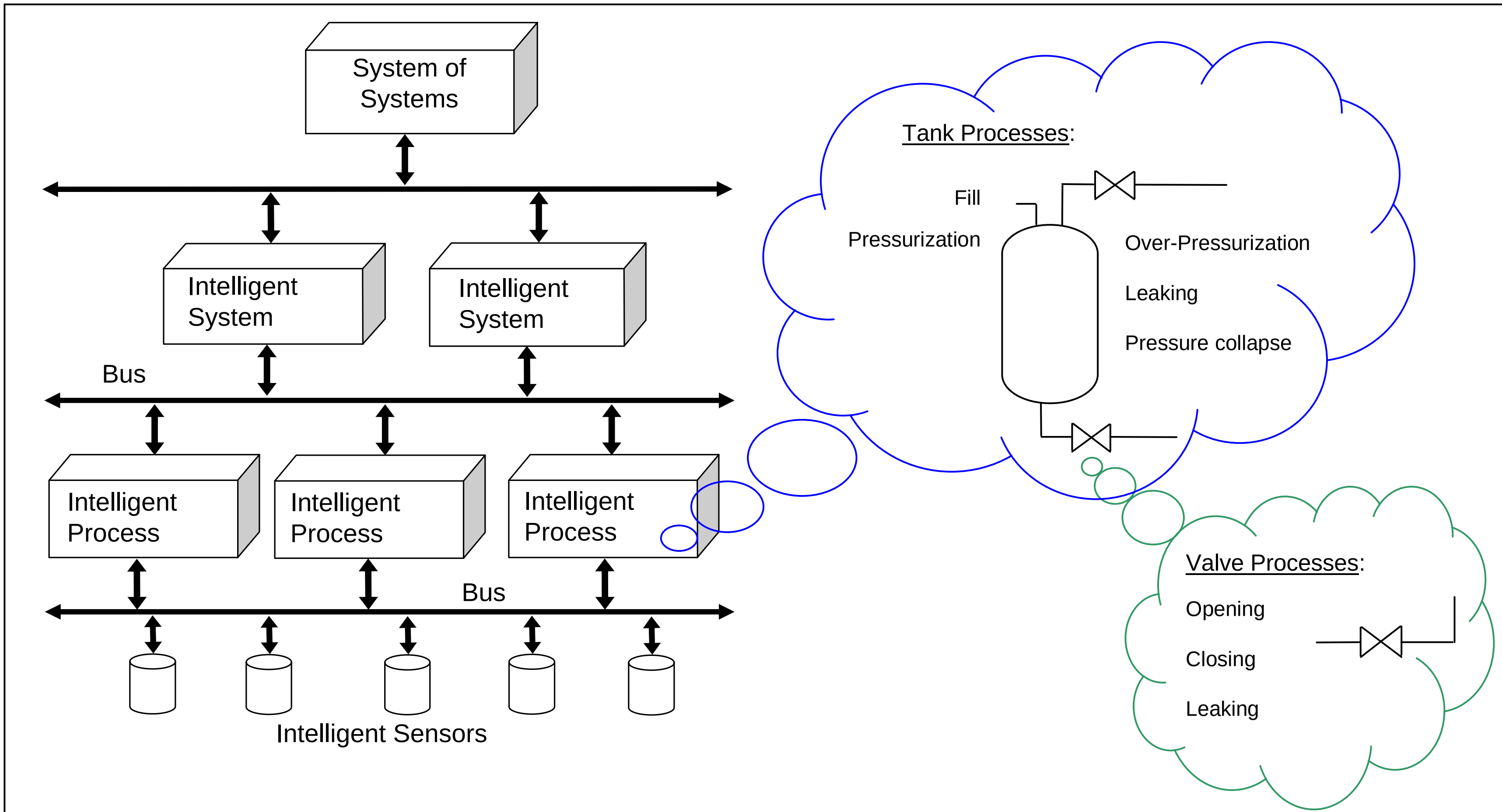
CORE ELEMENTS: Architecture, taxonomy, and ontology (ATO) for DIaK management



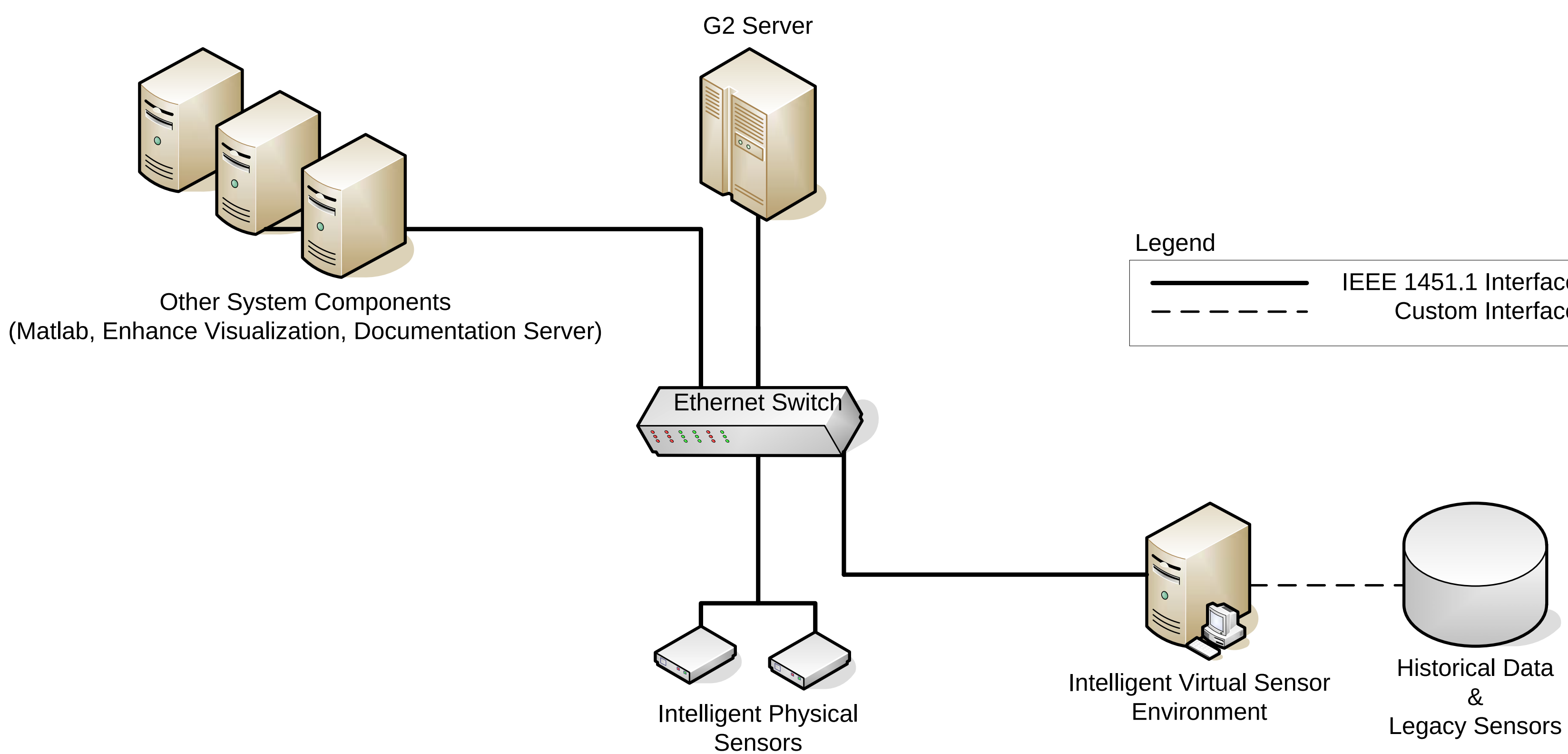
SoS as Hierarchical Network of Distributed Intelligent Elements

CORE ELEMENTS: ATO for DIaK Management

Process models are generic. Components contribute boundary conditions (containment).

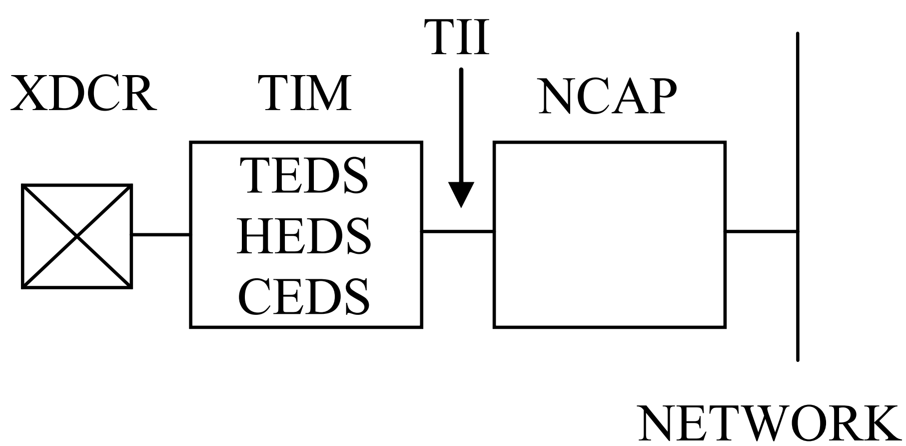


ISHM ARCHITECTURE PHYSICAL IMPLEMENTATION



CORE ELEMENTS: Standards

IEEE-1451.X smart sensor showing the transducer element (XDCR) supported by the TIM, which is in turn interfaced to the NCAP via the TII. The TIM also stores various electronic data sheets.



SYSTEMATIC IMPLEMENTATION

- Engineering Design Processes.
- Implementation of core elements.
- Systematic augmentation of capability.

Engineering Design Processes

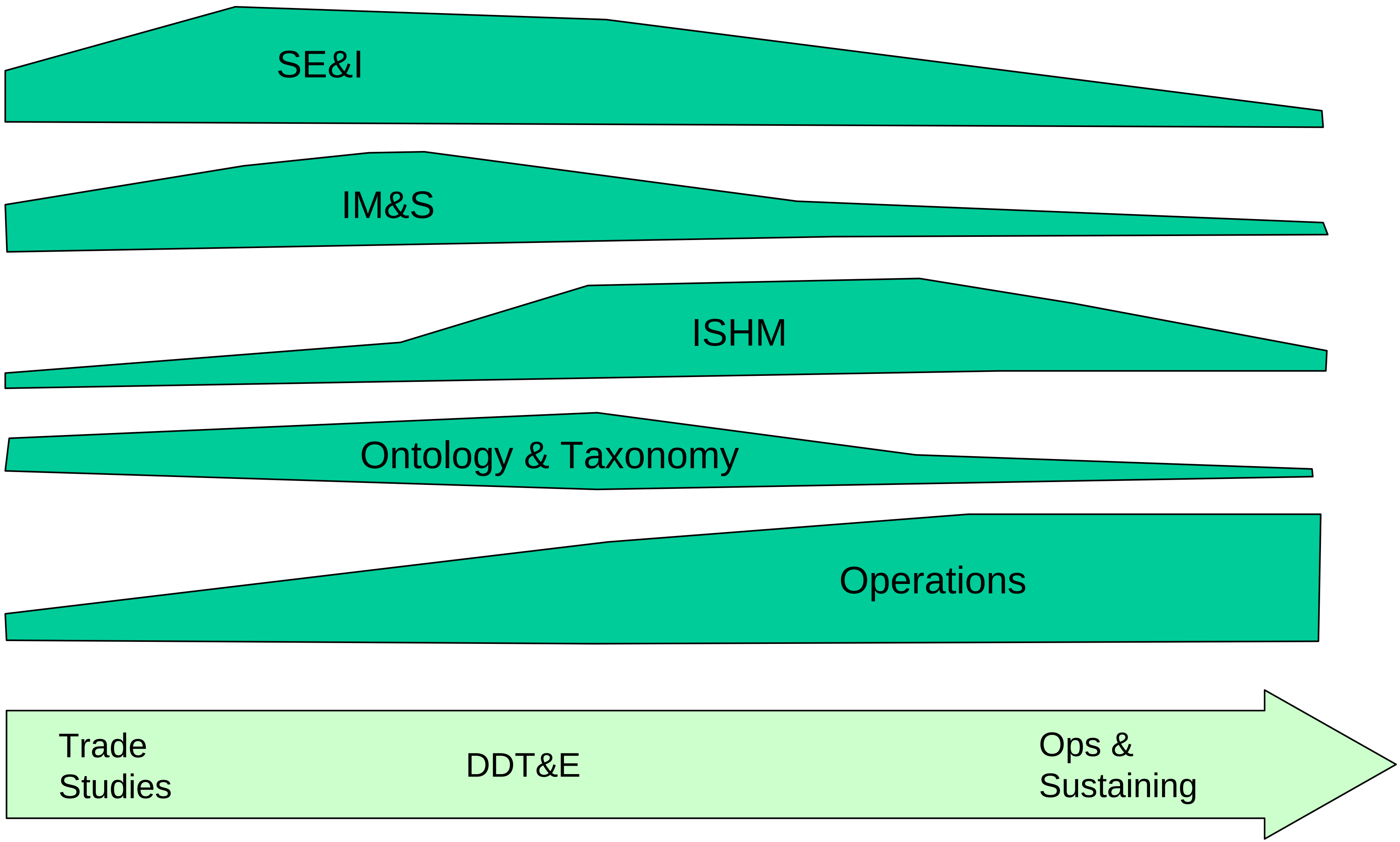
Insertion of ISHM capability must be considered throughout the design process, from concept to product, to operations, to maintenance, and to decommission.

ISHM-Enabled elements must respond to the following questions:

- What is the set of information that may be useful to help determine the condition of the element? For example, potential failure modes.
- What may be needed to detect known failures? For example, sensors mounted in key locations, algorithms, integrated models, etc.
- How may one approach detection of unknown failures? For example, use consistency checks.

Sketch of Work Phasing

Note: The relative thickness of each bar is not to scale, they merely represent the shape of the cost curve for each element.



Interrelationship Between Traditional Avionics Systems, Time Critical ISHM and Advanced ISHM

Time Critical ISHM System

Where traditional avionics systems become uncontrollably complex is in handling the interactions between multiple systems and in providing significant FDIR capabilities. Time Critical ISHM is a deterministic and verifyable method of handling first failure responses and intersystem interactions.

Humans

Direct mission and solve problems beyond the reach of automated systems with the help of automated, diagnostic and prognostic tools.

Advanced ISHM

Advanced ISHM provides toolsets designed to speed human-driven diagnostics of complex system failures and interactions. Relying on model-based and data mining techniques, it:

- isolates likely candidate failure causes
- prognosticates possible workarounds and repairs
- predicts degradation caused future failures

Traditional Avionics Systems

Traditionally designed subsystems form the basis of this architecture. This type of design has proven to be extremely reliable and predictable when used within its limits. Provided that the software complexity remains in a region where determinism is reasonably guaranteed, only evolutionary change is necessary.

SYSTEMATIC IMPLEMENTATION

Implementation of Core Elements

Implement Architecture/Taxonomy/Ontology and define standards that make possible the following funcionality.

- Distributed storage.
- Distributed processing.
- Distributed intelligence.
- Availability of DIaK to any element as needed.
- Simultaneous execution of multiple processes representing models that contribute to the determination of the condition of each element in the system.

SYSTEMATIC IMPLEMENTATION

Systematic augmentation of capability

1. Initial capability of an ISHM system might just be a support capability that makes easily available to the user.

- TEDS … Transducer Electronic Data Sheet
- HEDS … Health Electronic Data Sheet.
- AEDS … Actuator Electronic Data Sheet.
- CEDS … Component Electronic Data Sheet.

2. implement process models (rules, algorithms, etc.) and begin to employ reasoning to infer health related information in an integrated manner

TESTBEDS AND ON-BOARD ISHM

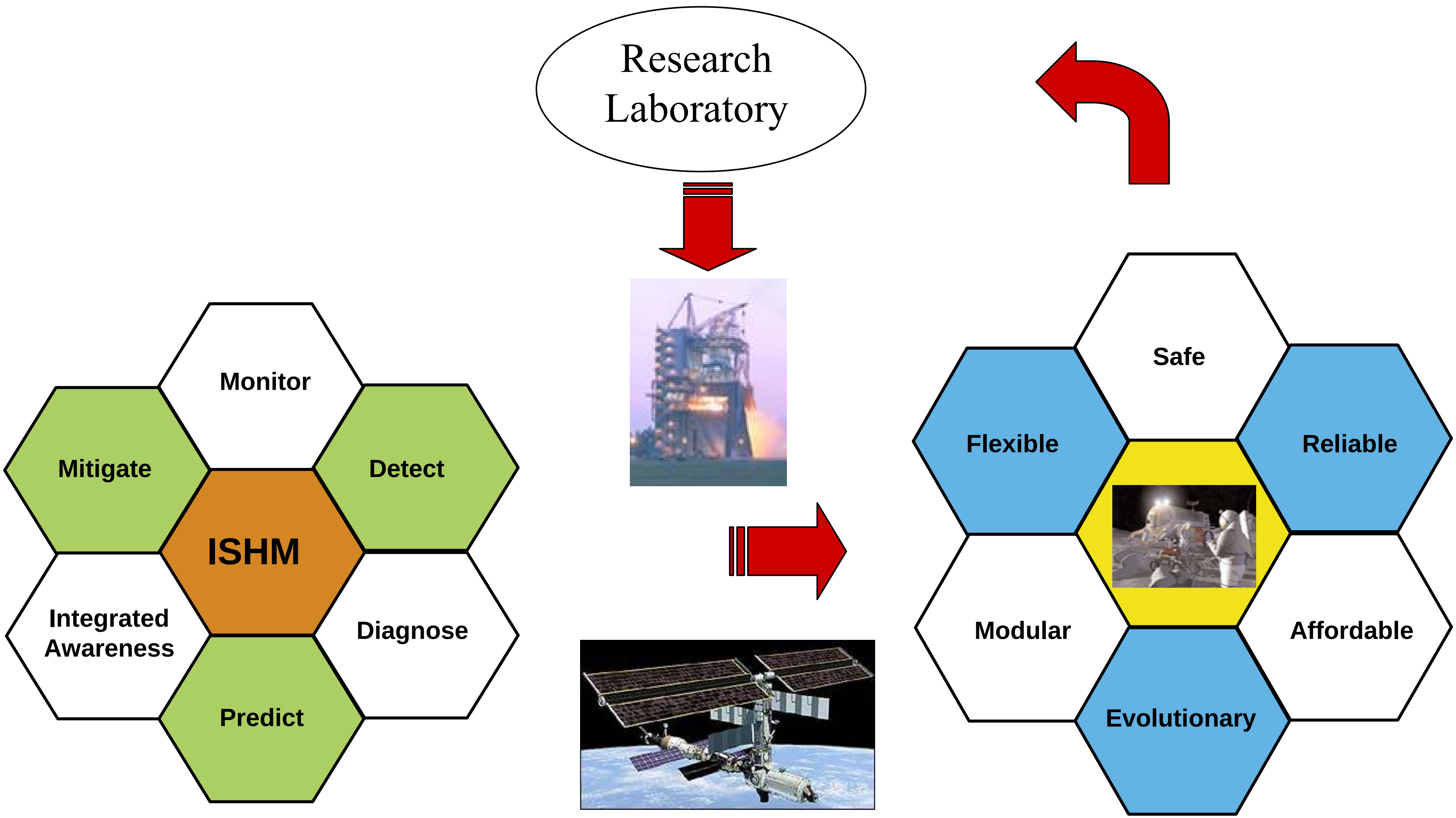
Definition of appropriate testbeds must consider the following:

- ISHM testbeds are about determining all failure modes of a system, whereas other testbeds are about making sure a system does not fail under expected operating conditions.
- It is not possible to reproduce a complete set of anomalies.
- Many anomalies are not known.
- Users do not trust some AI oriented ISHM technologies.
- Users do not think ISHM capability is needed.

TESTBED REQUIREMENTS: RETS AND ISS

- RETS/ISS central role for developing and validating ISHM Technologies.
  - Extensive historical data and information to define a solid baseline prior to ISHM implementation.
    - Discrepancy reports (key knowledge of failure modes for HM Systems).
    - Test/Telemetry data (means of validation).
  - Expert Test Engineers (key component to build knowledge bases and to experience and acknowledge ISHM benefits – should become advocates of the technology).
  - Complete and well understood models and documentation.
  - Suitable for staged implementation, e.g. the GN subsystem, followed by the RP subsystem, and so on.
  - Non intrusive implementation.
- RETS/ISS can be established as permanent sites to test new ISHM elements such as “intelligent sensors,” “intelligent components,” system integration frameworks, etc. Adding new sensors or making modifications in RETS is much less complicated than in the case of flight hardware.
- RETS mirror the same tight integration found in the flight systems tested in these facilities (facilities replicate vehicle propulsion subsystems).

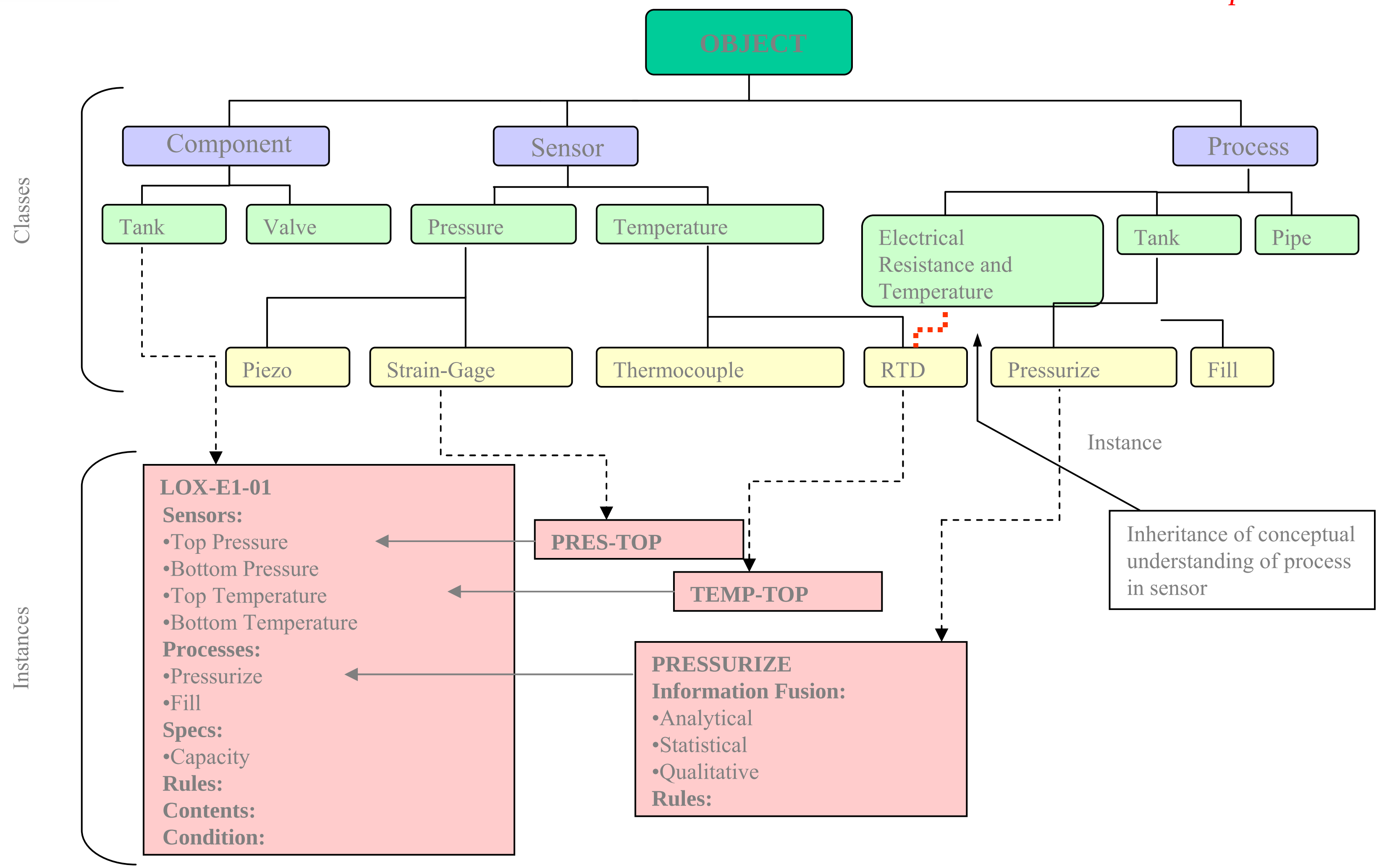
SUSTAINABLE DEVELOPMENT AND VALIDATION PROCESS



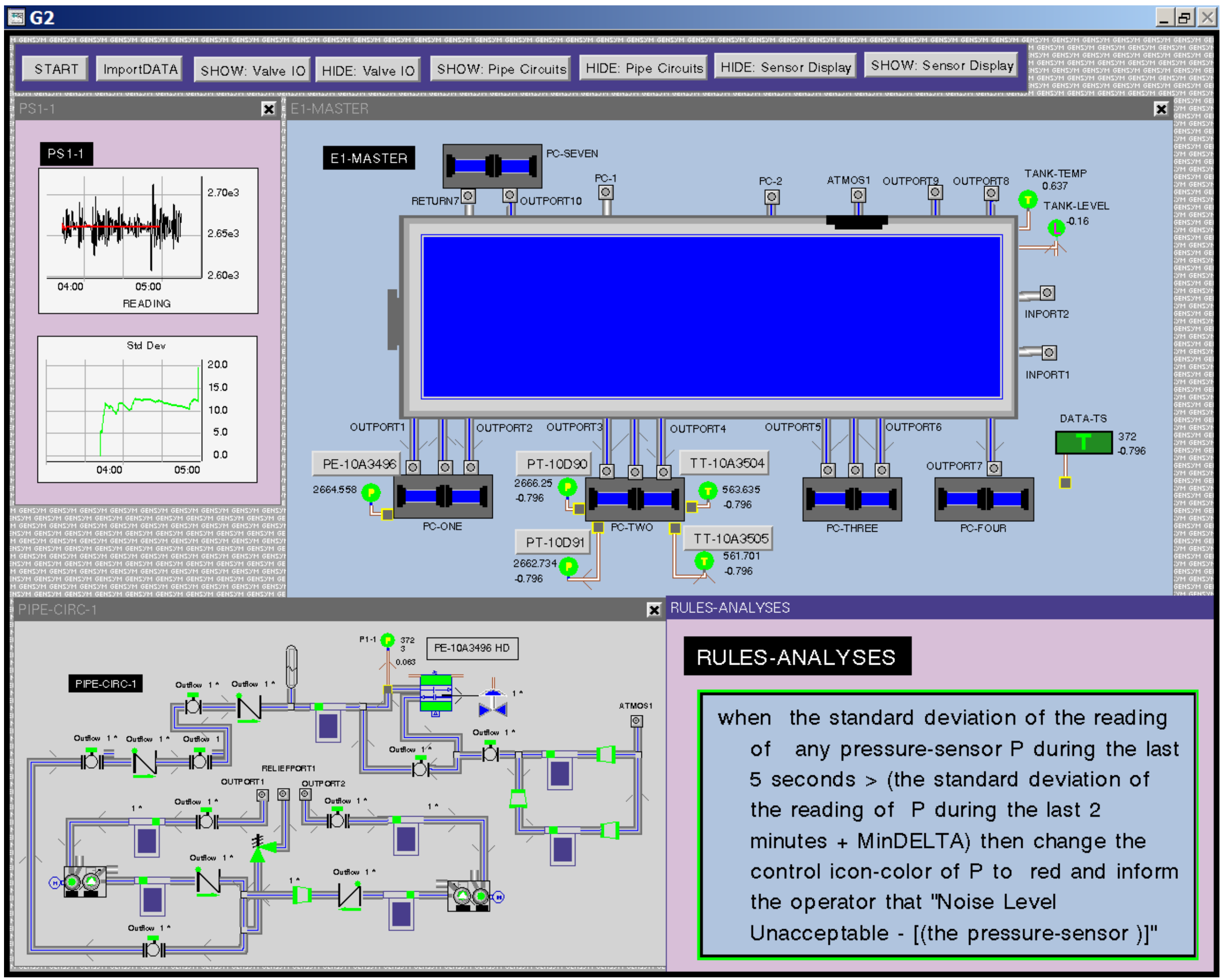
DEVELOPMENT OF ON-BOARD ISHM

On-board ISHM capability should be developed by migrating proven capability and technologies validated in operational ground testbeds.

TAXONOMY/ONTOLOGY OF OBJECT ORIENTED IMPLEMENTATION



ISHM Capability on the E1 Test Stand Hydraulic System



DEFINE RELATIONSHIPS TO EMBED INTELLIGENCE

- Information Extraction and Fusion (IEF).
- Inference and Decision Making (IDM).

These activities require understanding (knowledge) of relationships, for example, among elements:

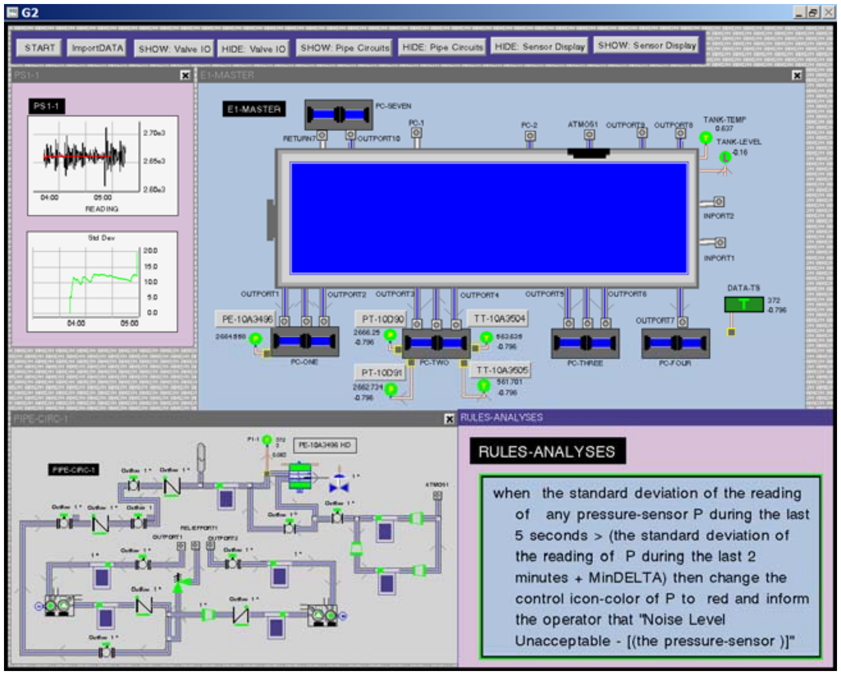
- Physical
- Connected to
- Part-of
- Class of
- Kind of
- Principle of operation is … process models (e.g., Tempco)
- Is made of (materials)

INTELLIGENT ELEMENTS
Physical and Virtual

Intelligent Elements (sensors, components, etc.) must be networked elements (communicate according to established standards) and provide:

- Data
- Measures of data quality
- Measures of element health
- Electronic Data Sheet (EDS) information
  - Transducer (TEDS): Sensor parameters
  - Health (HEDS): Anomaly parameters
  - Component (CEDS): Component parameters

ISHM TESTBEDS AND PROTOTYPES AT SSC
CURRENT IMPLEMENTATIONS



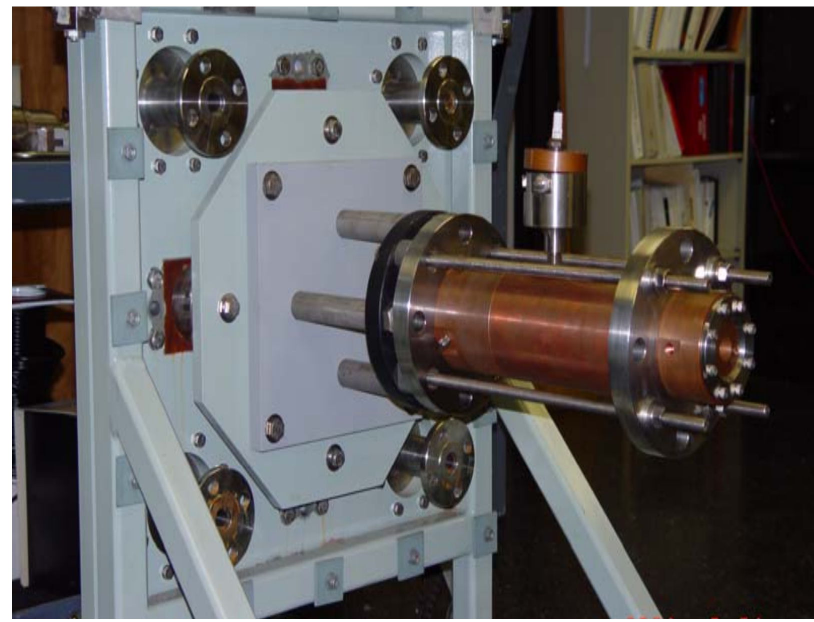
Testbed: E1 Rocket Engine Test Stand

Testbed: Portable Rocket Engine Test Stand

ISHM-Toolkit

- Encapsulates Data, Information, and Knowledge (DIaK) distributed throughout intelligent networked elements.
- Defined inter-element relationships are used to perform DIaK fusion (checking of inconsistencies).
- Multiple processes representing models (e.g. algorithms, rules, etc.) may run simultaneously to detect anomalies and infer health of each element.

Trailer-Mounted RETS



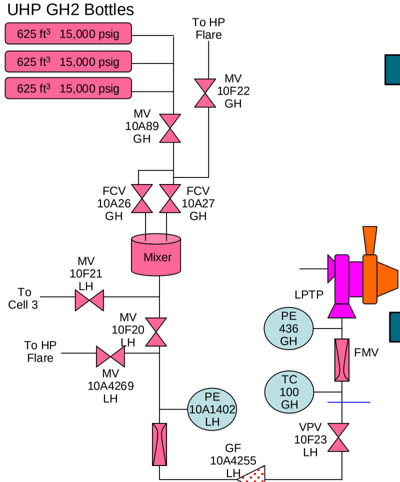
Modeling and Simulation

Integrated Facility Simulation and Analysis Applied Over the Test Project Life Cycle

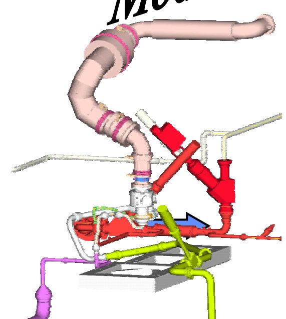
- Analytic Tools Providing Comprehensive Propellant System Thermodynamic Modeling & Test Simulation

Integrated Performance Modeling Capabilities Substantially Improves Understanding & Knowledge of Test Systems Performance that has Translated to Efficient Test Facility Design, Activation & Test Operations

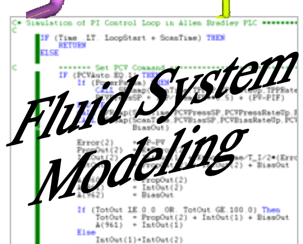
System Design



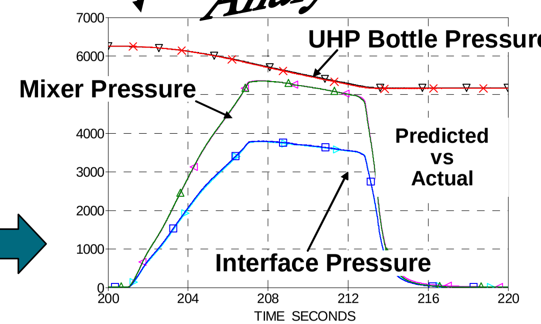
Modeling

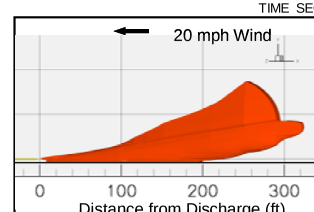


Fluid System Modeling



Test and Data Analysis





CFD Modeling & Analysis

Summary ISHM Testbed Environments

SSC ISHM Testbed Environments

Test Stand as System of Systems

Test Stand with ISHM
QA of facilities infrastructure; Enhance testing of Test Articles

DACS Laboratory/Cryo Component TF
Verification of components, sensors, data acquisition and processing systems, controls, software.

ISHM Technologies

- Integration Architecture/Framework for networked intelligent elements.
- Data/Information/Knowledge Management (storage, transmission, maintenance, evolution, suitability (context), availability (timely)).
- Intelligent Network Elements.

We Provide

- A base/flexible architecture.
- ISHM Software Development Tool.
- A database for health assessment.
  - Anomaly data.
  - Anomaly methods/algorithms.
  - DIaK.
  - Electronic data sheets.
- Intelligent Sensors.

DATA MINING - ARC

- Tested two unsupervised anomaly detection algorithms on rocket propulsion data
- Detected known anomalies and unknown (but insignificant) anomalies
- Different algorithms detect different anomalies, so it’s worth running multiple algorithms.

TRANSITIONING ISHM TO SUPPORT NASA MISSIONS

NASA can not wait and does not need to wait to begin implementing ISHM capability on-board spacecraft, space platforms, Lunar and Mars outposts, and ground test and operations facilities. The following tasks must begin immediately:

- Refine architectures, taxonomies, ontologies, and **tools** to implement ISHM capability (e.g. an architecture that defines a complex system as a hierarchical network of distributed intelligent elements).
- Survey, compare, and define commonality standards for DIaK management on-board a system (e.g. IEEE 1451 for intelligent sensors’ communications, TEDS for intelligent sensors’ on-board information), and across multiple systems. DIaK management includes distributed storage, maintenance, and evolution; timely and contextual availability to any element of the system.
- Once architectures/taxonomies/ontologies and standards are defined, implement a low functional capability level ISHM and increase by incremental augmentation.
- Define a systems process for implementation of ISHM capability. All design/test/validate activities must include insight and methodic approaches so that each element of a system contributes to the integrated health determination of the system.
- Develop capability using laboratory testbeds, mature using operational testbeds (RETS, ISS, Launch Systems), and migrate to space systems after validation in operational testbeds.
- Define an enterprise wide ISHM testbed environment to support on-going ISHM operations from Earth, and concurrent ISHM technology development.

TRANSITIONING ISHM TO SUPPORT NASA MISSIONS: DEMO

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TRANSITIONING ISHM TO SUPPORT NASA MISSIONS: DEMO

Explore and define architectures, taxonomies, ontologies, and tools to implement ISHM capability (e.g. an architecture that defines a complex system as a hierarchical network of distributed intelligent elements).

- G2 Framework
- Smart Sensors
  - RU
  - KSC
- Algorithms
  - SIU / Glenn
- HADS (DIaK Repository)
- Visualization

TRANSITIONING ISHM TO SUPPORT NASA MISSIONS: DEMO

Develop capability using laboratory testbeds, mature using operational testbeds (RETS, ISS, Launch Systems), and migrate to space systems after validation in operational testbeds.

Portable RETS

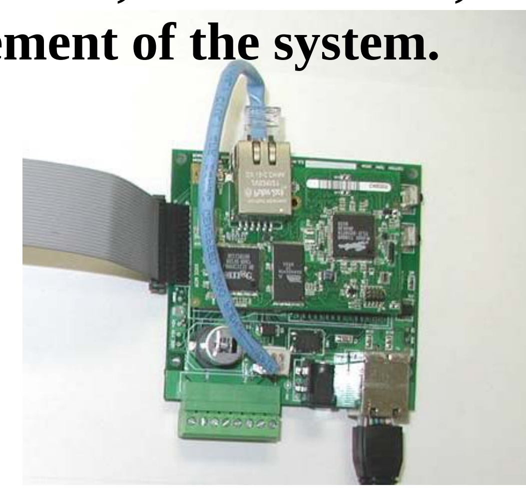
E1 Test Stand

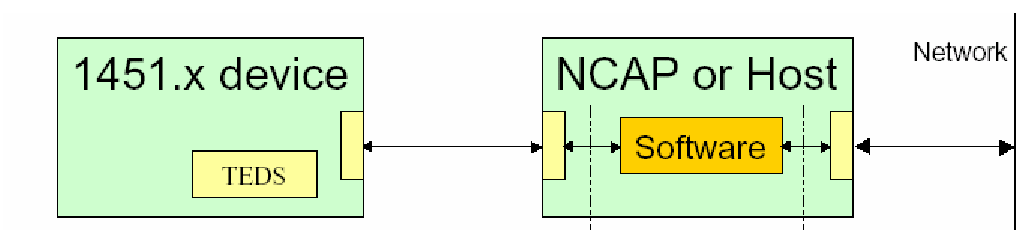
DACS Lab

TRANSITIONING ISHM TO SUPPORT NASA MISSIONS: DEMO

Survey, compare, and define commonality standards for DIaK management on-board a system (e.g. IEEE 1451 for intelligent sensors' communications, TEDS for intelligent sensors' on-board information), and across multiple systems. DIaK management includes distributed storage, maintenance, and evolution; timely and contextual availability to any element of the system.

- Intelligent Sensors
  - IEEE 1451
  - IEEE 1588
- Electronic Data Sheets
  - IEEE 1451 TEDS
  - Extensions to TEDS: HEDS, CEDS



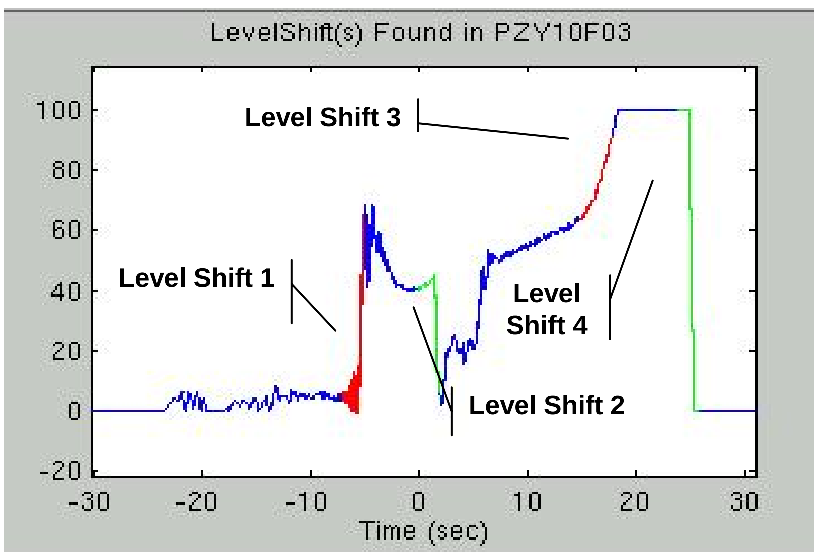


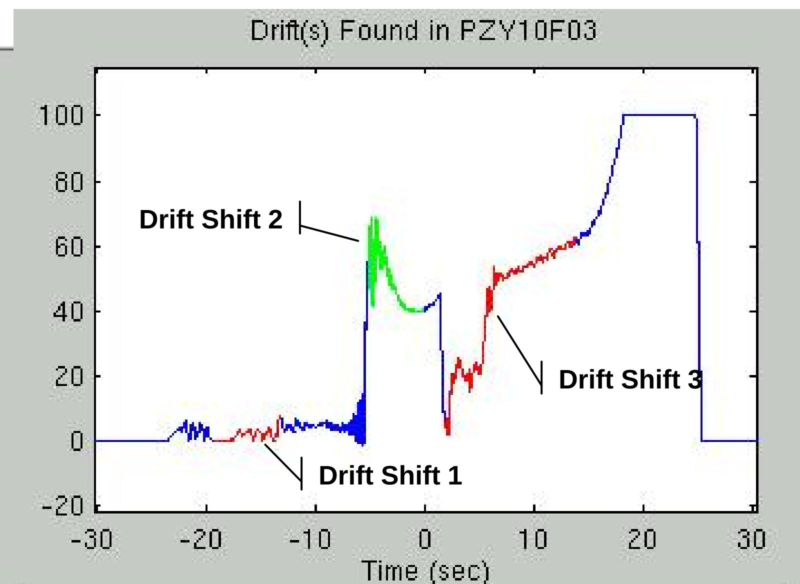
Feature Detection Routines

- Developed starting around 1990 for use in SSME PTDS. Continued Use in X-33 PTDS. Also Applied to Atlas/Centaur Data.
- Moved towards Real-Time during work on Propulsion Checkout and Control System for the Integrated Propulsion Technology Demonstrator Program
- The Real-Time features demonstrated as part of automated testing demonstrator developed at Arnold Engineering Development Center.
- Routines detect:
  - Drifts (Slow transitions in average levels)
  - Level Shifts (rapid changes in data level.)
  - Spikes (Rapid, non-permanent changes in data)
  - Noise (significant increase in average variance of the data)
  - Flat Regions (significant lack of variance in data)
- In some cases, multiple routines can detect the same feature. (e.g., 3 detect level shifts, 2 detect drifts.)
- Three routines detect multiple features (drifts/level shifts (2), level shift/peak)

Sample Features Detected in SSC Test Stand Data

- Detected in Data From the 9_LDAS_0908 Test Set Received from NASA SSC
- Detected Using One Routine
- Drifts and Level Shifts Were Mutually Exclusive (i.e. no overlap)





Health Assessment Database (DIaK Repository)