Intelligent Integrated System Health Management

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Presentation at Louisiana Tech

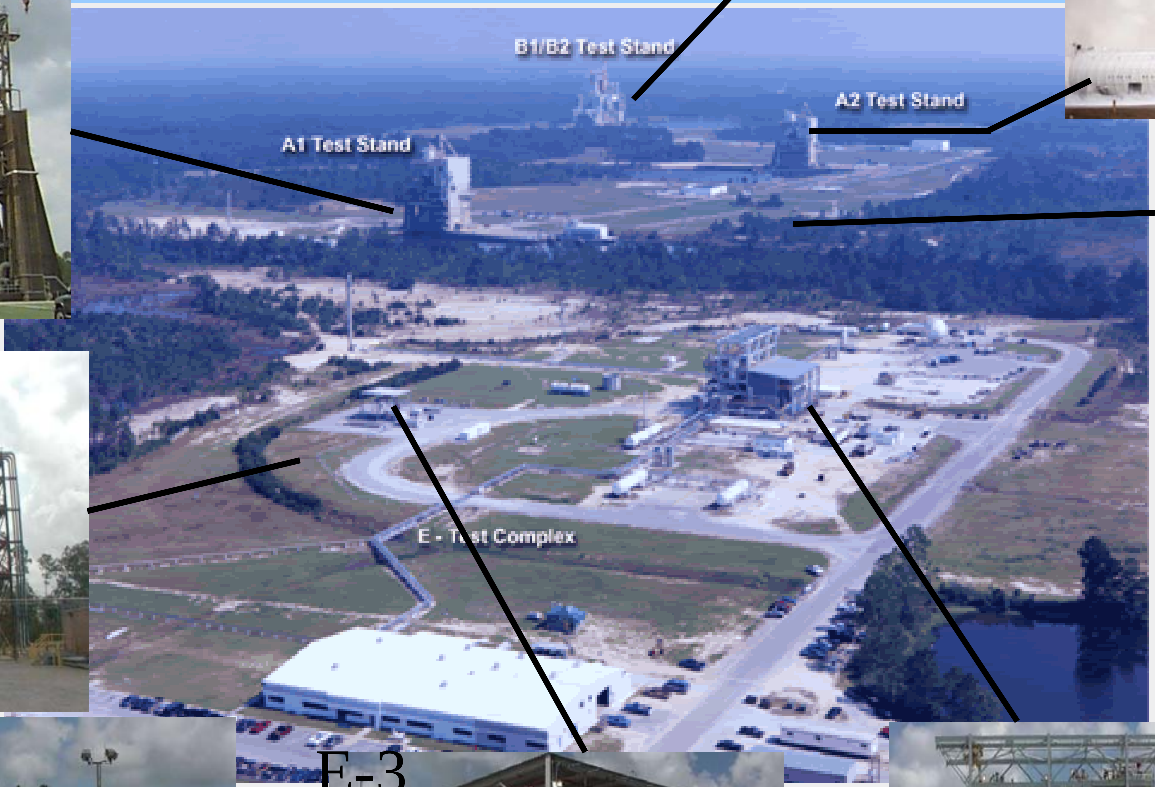
February 3, 2012

Support the rocket engine test mission with sustainable facilities that produce unquestionable measurements, affordably.

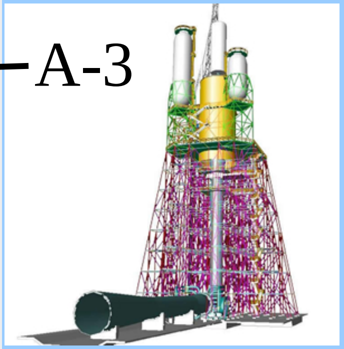
B-1/B-2

A-2

A-1



A-3



Others:

- High-pressure Gas
- Industrial Water

E-2

E-3

E-1

Outline

- ISHM Definition.
- ISHM Capability Development.
  - ISHM Knowledge Model.
  - Standards for ISHM Implementation.
  - ISHM Domain Models (ISHM-DM's).
  - Intelligent Sensors and Components.
- ISHM in Systems Design, Engineering, and Integration.
- Intelligent Control for ISHM-Enabled Systems.

Requirements Driving ISHM

Through comprehensive and continuous vigilance

- Improve quality
  - By more accurately understanding the state of a system.
- Minimize costs
  - Of configuration
  - Of repair and calibration
  - Of operations
- Avoid downtime
  - By predicting impending failures
  - By timely intervention
  - By faster diagnosis and recovery
- Increase safety (protect people and assets)

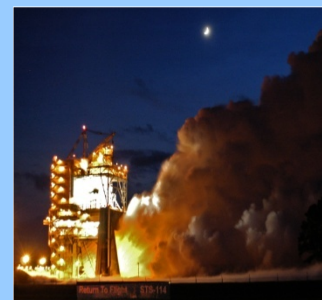
ISHM Objectives

- Use available data, information, and knowledge to
  - Identify system state
  - Detect anomalies
  - Determine anomaly causes
  - Predict system impacts
  - Predict future anomalies
  - Recommend timely mitigation steps
  - Evolve to incorporate new knowledge

ISHM implementation is a problem of "management" of data, information, and knowledge (DIaK) focused on achieving the objectives of ISHM

John C. Stennis Space Center
ISHM Partnerships for Rocket Propulsion testing
A community of Expertise and Technologies

Rocket Engine Test Stand



PENNSTATE

NASA KSC

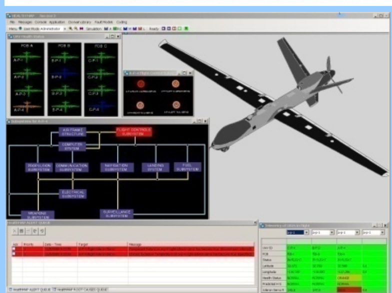
Open Systems Architectures

Prognostics & Anomaly Detection

Pratt & Whitney
A United Technologies Company

NASA ARC

GENERAL ATOMICS
ELECTROMAGNETIC SYSTEMS



Proximal Cause Analysis

Rowan University

Integrated Awareness

ISS Testbed

NASA JSC

IEEE 1451 Smart & Intelligent Sensors

MOBITRUM
Brings you mobility®

NASA KSC

ATK

INVOCON, INC.
Innovative Concepts in Systems Engineering

NVE
NVE CORPORATION

Rowan University

COLLEGE OF TECHNOLOGY
University of Houston

TOSS
plug-and-play

Concepts for iISHM

THE CAPABILITY MUST BE CREDIBLE AND AFFORDAB LE

- Intelligent System: Manages data, information, and knowledge (DIaK) to achieve its mission (Manage: storage, distribution, sharing, maintenance, processing, reasoning, and presentation)

- iISHM:
  - Employs knowledge about the system embodying “systems thinking” (captures interactions among elements of the system).
  - Is continuously vigilant.
  - Is comprehensive in assessing health of each element of a system.
  - Is systematically evolutionary to achieve higher and higher functional capability levels (increasing effectiveness).

- In order to make this capability possible, the health management system needs to incorporate “intelligence.”

ISHM Definition

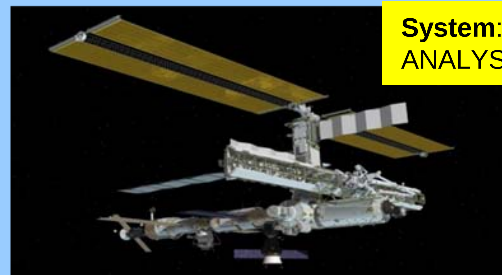
- Its own discipline, or sub-discipline under Aerospace Systems Design, Engineering, and Integration.
- Management of data, information, and knowledge (DIaK) with the purposeful objective of determining the health of a system (Management: storage, distribution, sharing, maintenance, processing, reasoning, and presentation).
- ISHM is akin to having a broad-base team of experts who are all individually and collectively observing and analyzing a complex system, and communicating effectively with each other in order to arrive at an accurate and reliable assessment of its health.

People-Based ISHM is Being Done Today

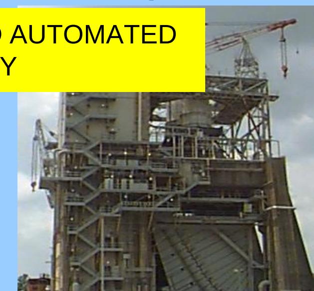
MOVE CAPABILITY TOWARD LEVELS 2 AND 1
DECREASE NEED FOR SUPPORT FROM LOWER LAYERS

International Space Station | Rocket Engine Test Stand

Layer 1
Vehicle/ Test Stand



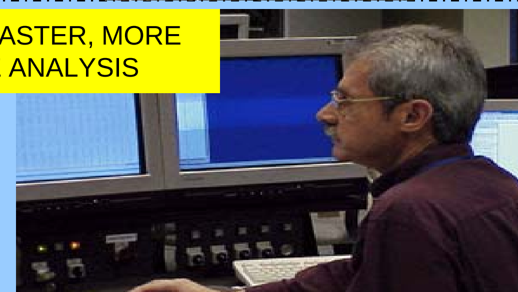
System: ON BOARD AUTOMATED ANALYS CAPABILITY



Signal threshold violation detection

Layer 2
Astronaut/ Test Conductor

Operator: FASTER, MORE ACCURATE ANALYSIS



Added DIaK from on-board users.

Layer 3
Control Room

Support: FASTER, MORE ACCURATE ANALYSIS
Decreased Need

Added DIaK from broad group of experts.

Layer 4
Back Control Room

Support: FASTER, MORE ACCURATE ANALYSIS
Decreased Need

Added DIaK resources from larger community

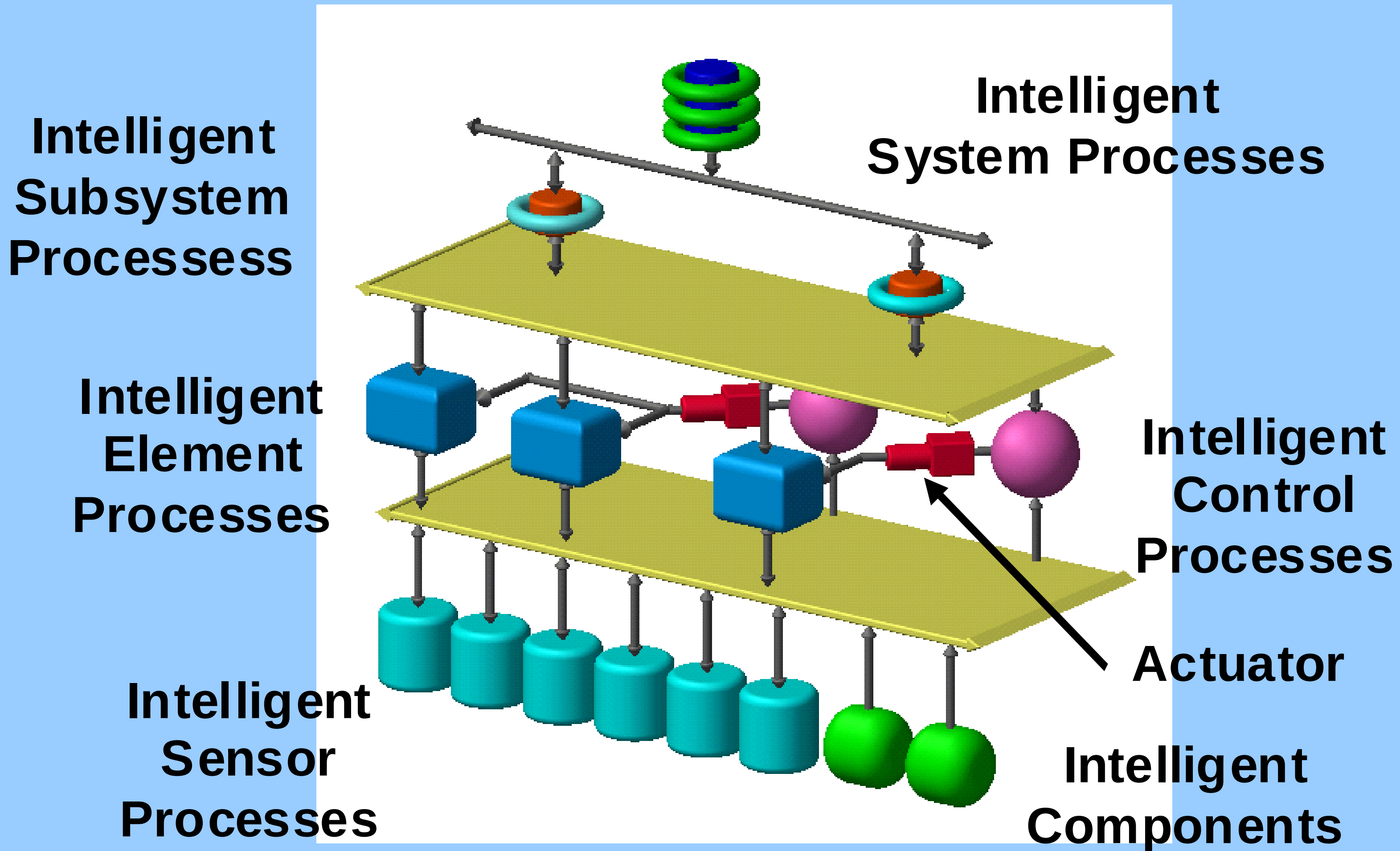
Determination of Health

- Use available SYSTEM-WIDE data, information, and knowledge (DIaK) to
  - Identify system state.
  - Detect anomaly indicators.
  - Determine and confirm anomalies.
  - Diagnose causes and determine effects.
  - Predict future anomalies.
  - Recommend timely mitigation steps.
  - Evolve to incorporate new knowledge.
  - Enable integrated system awareness by the user (make available relevant information when needed and allow to dig deeper for details).
  - Manage health information (e.g. anomalies, redlines).
  - Capture and manage usage information (e.g. thermal cycles).
  - Capture and manage design life and maintenance schedule.
  - Enable automated configuration.
  - Implement automated and comprehensive data analysis.
  - Provide verification of consistency among system states and procedures.

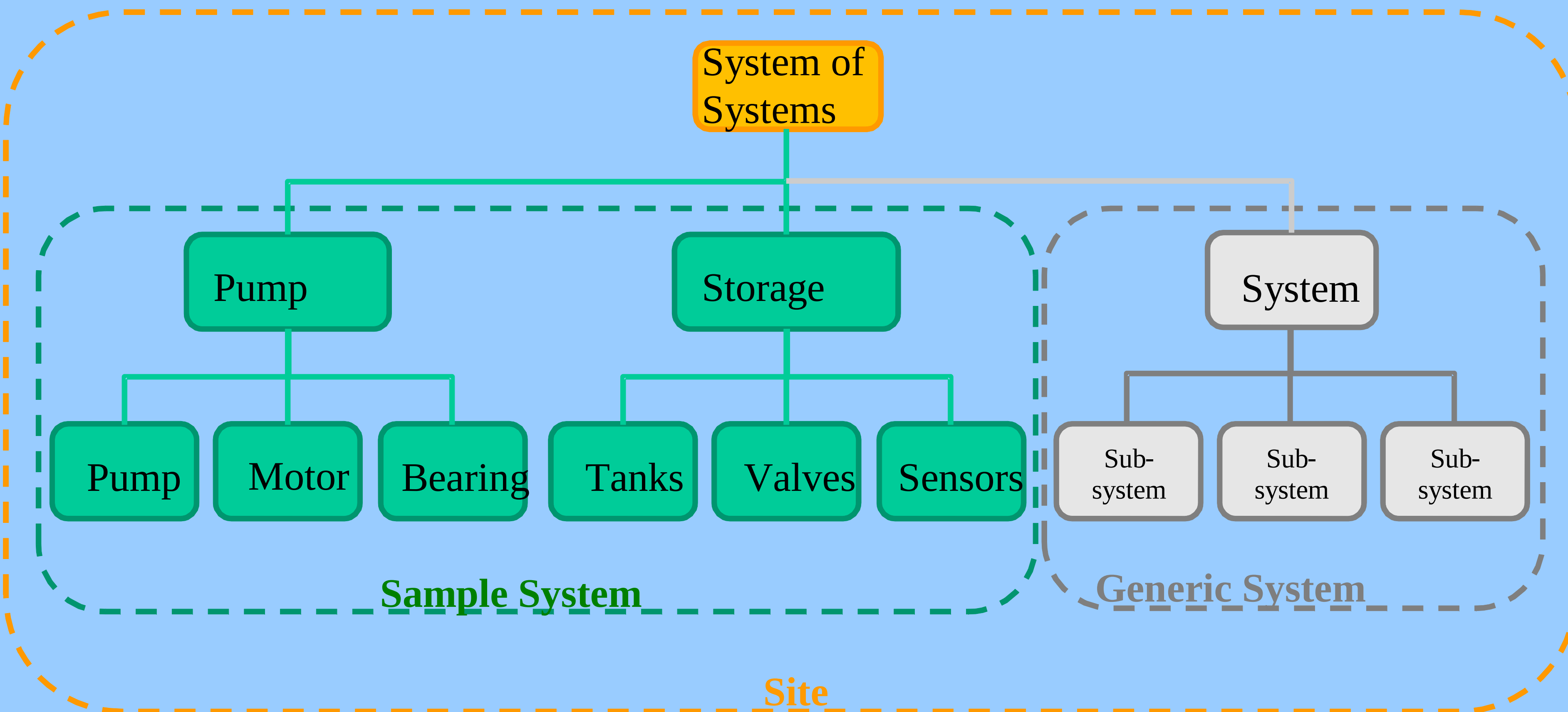
ISHM Capability Development
ISHM Knowledge Model

- A plethora of Data, Information, and Knowledge (DIaK) must be applied to achieve high functional capability level (FCL) health management.
- The ISHM Domain Model (ISHM-DM) encompasses DIaK and the tools to implement ISHM capability.

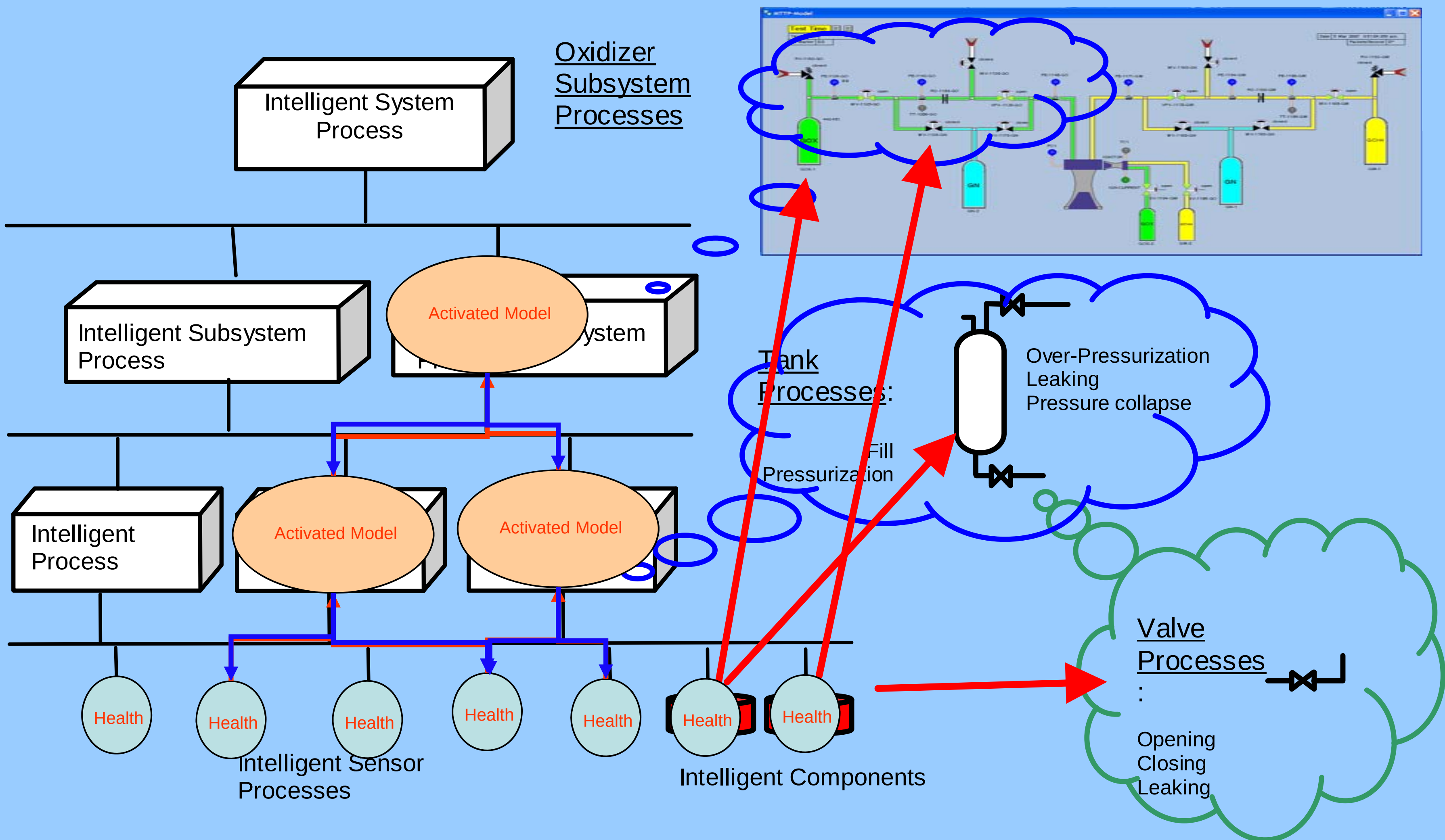
Data, Information, and Knowledge Management Architecture for ISHM (Information Architecture)



Classic architecture describing how systems are built



Detection and Confirmation of Anomalies
Consistency Checking Cycle



ISHM Capability Development

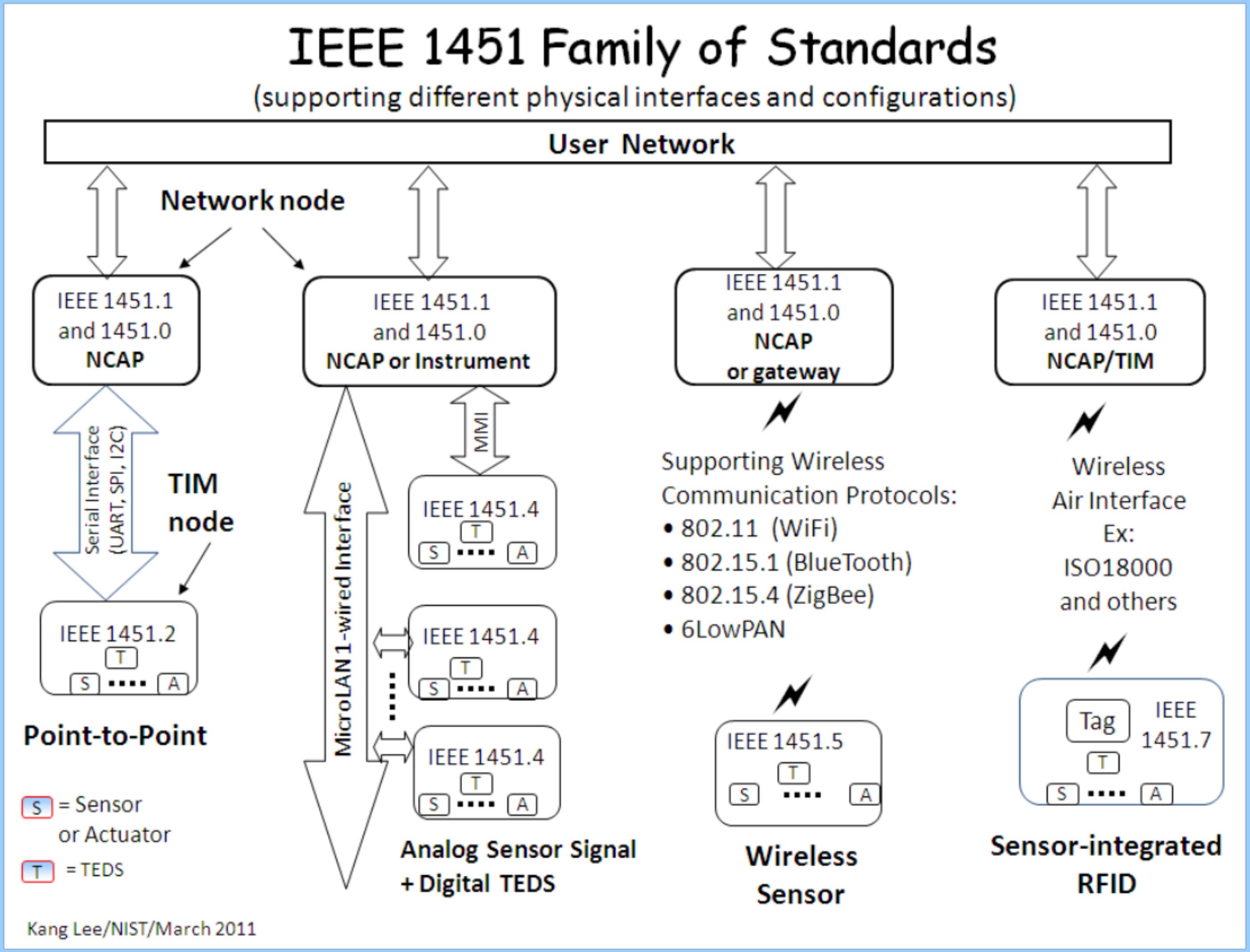
Standards for ISHM

- IEEE 1451 Family of Standards for Smart Sensors and Actuators. Lead by NIST (Dr. Kang Lee).
- OSA-CBM (Open Systems Architecture for Condition Based Maintenance). Developed by industry and government, and transferred to the MIMOSA (Machine Information Management Open Standards Alliance) organization.
- OSA-EIA (Open Systems Architecture for Enterprise Application Integration). MIMOSA organization.

ISHM capability must integrate DIaK across physical, virtual, and discipline boundaries. This is not possible in an affordable manner unless standards are used to achieve plug&play and interoperability.

ISHM Capability Development

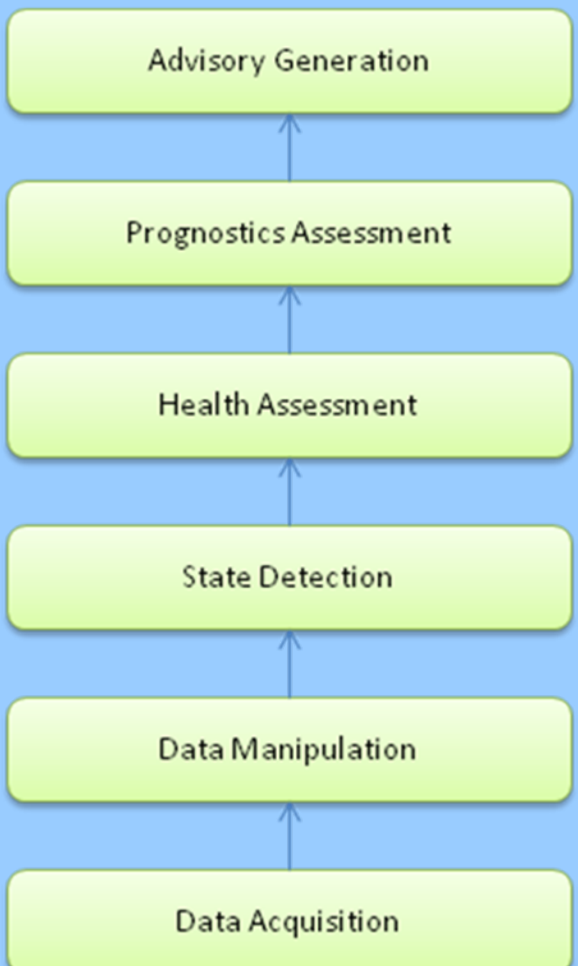
Standards for ISHM



ISHM Capability Development

Standards for ISHM

OSA-CBM (MIMOSA)



Operations and maintenance advisories, capability forecast assessments, recommendations, evidence, and explanation.

Future health grade, future failures, recommendations, evidence and Explanation.

Health grade, diagnosed faults and failures, recommendations, evidence and explanation.

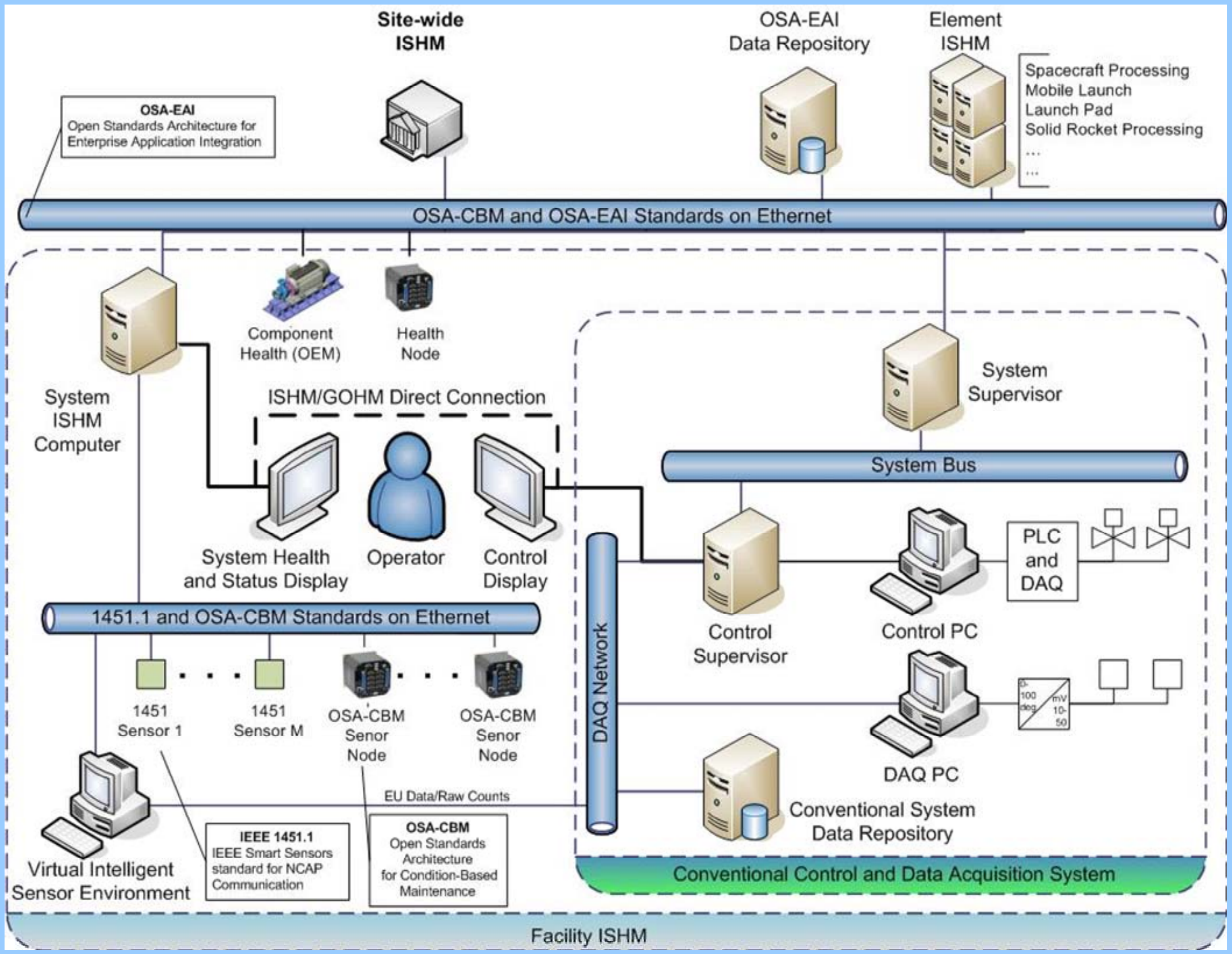
Current enumerated state indicator, threshold boundary alerts, and statistical analysis data with timestamp and data quality

Descriptor data with timestamp and data quality.

Digitized data with timestamp and data quality.

ISHM Capability Development

Standards for ISHM



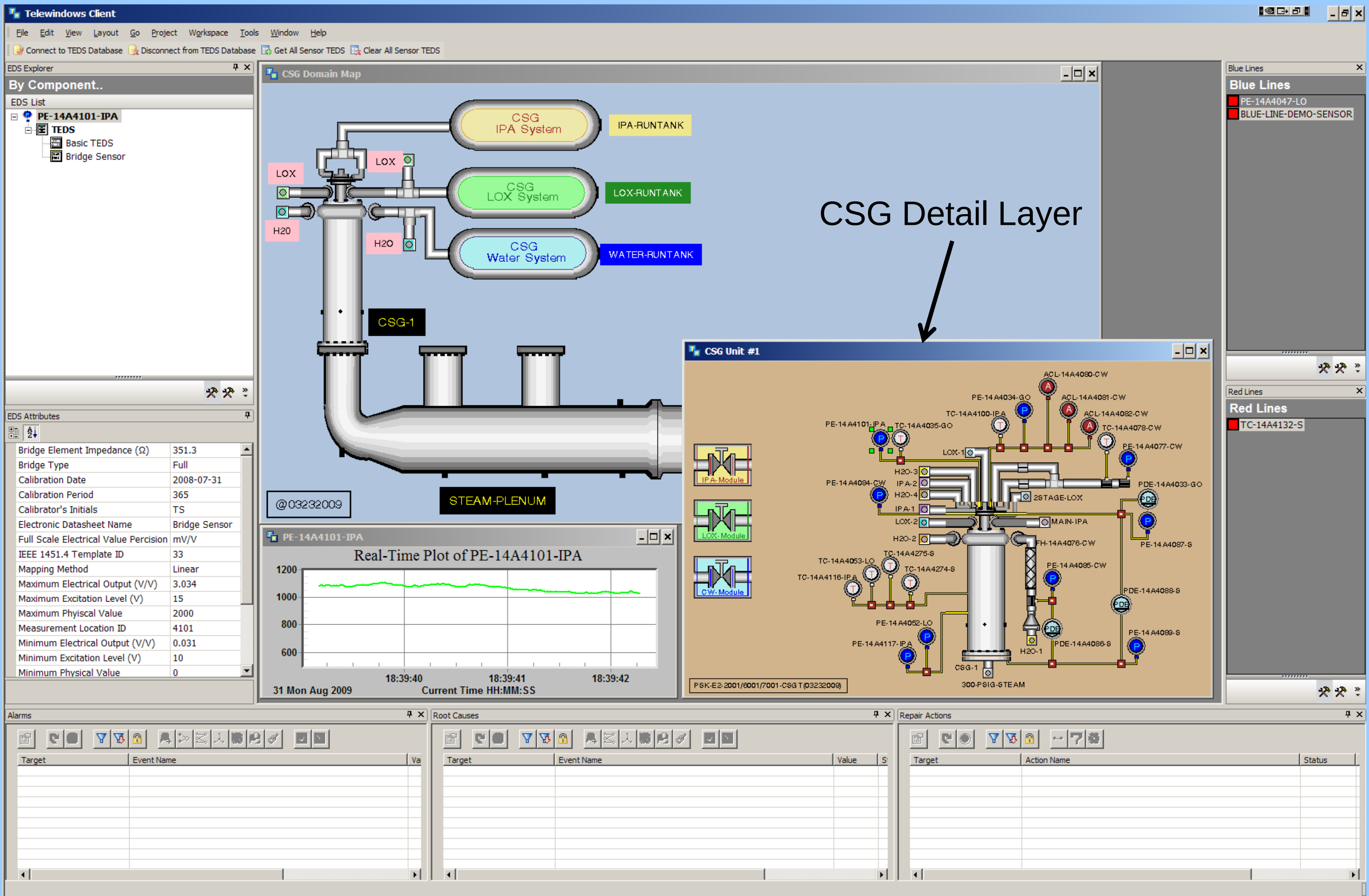
Architecture for pilot ISHM system implemented at NASA Kennedy Space Center, Launch Complex 20 (LC-20) showing the use of IEEE 1451.1, OSA-CBM, and OSA-EAI standards

Software to develop ISHM Domain Models (ISHM-DM’s)

A software system for ISHM capability should support all core capabilities by integrating systematically DIaK through the ISHM-DM

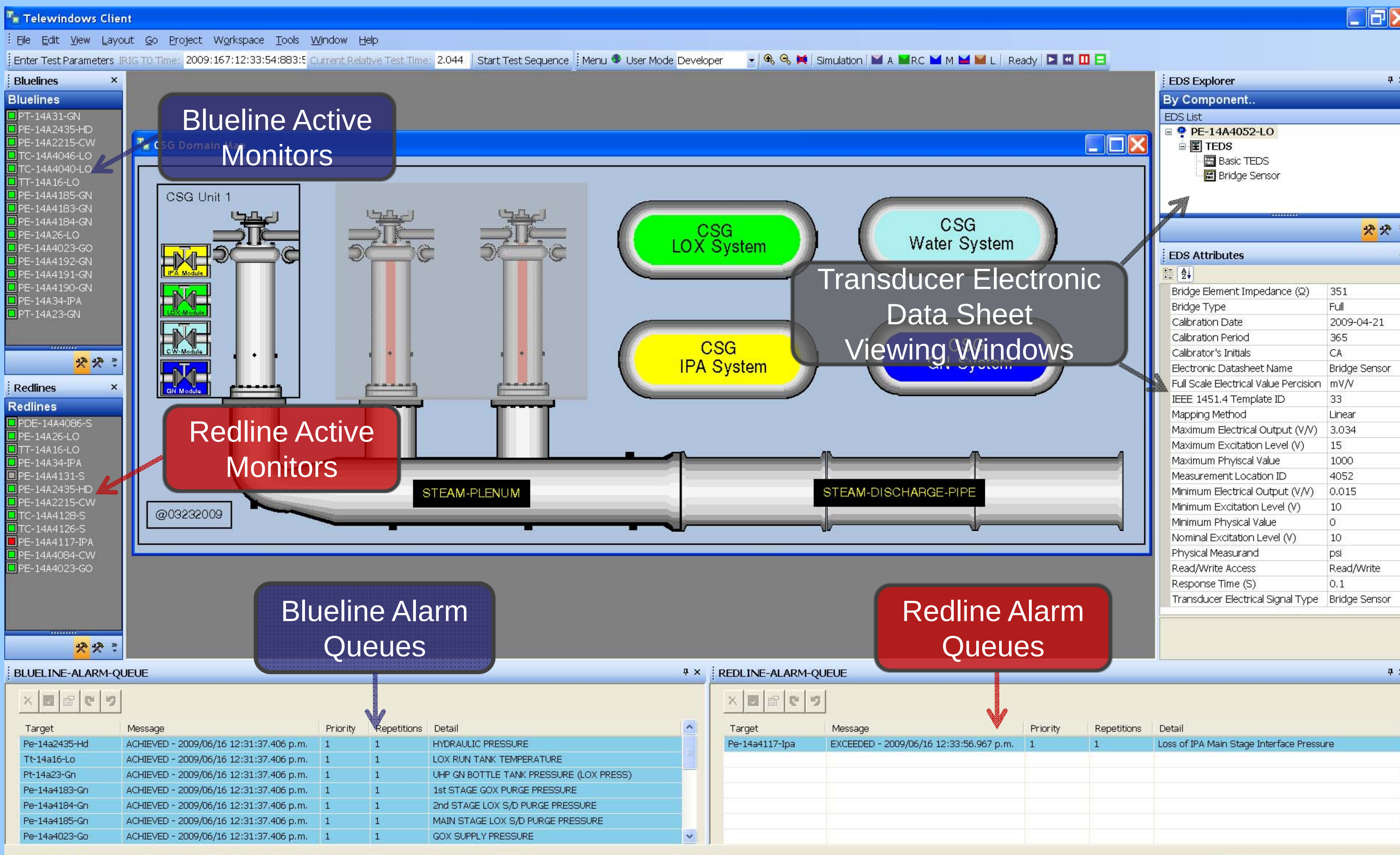
- ***Iconic representation of systems objects with visible and virtual links (relationships) used to provide intuitive representation of reasoning and context***: The mix of object orientation and iconic representation of DIaK provides the ability to intuitively visualize interrelationships and dig deep into details of the ISHM system. As complexity increases, graphical programming and visualization become essential.

Pilot ISHM Implementation Chemical Steam Generator (CSG)



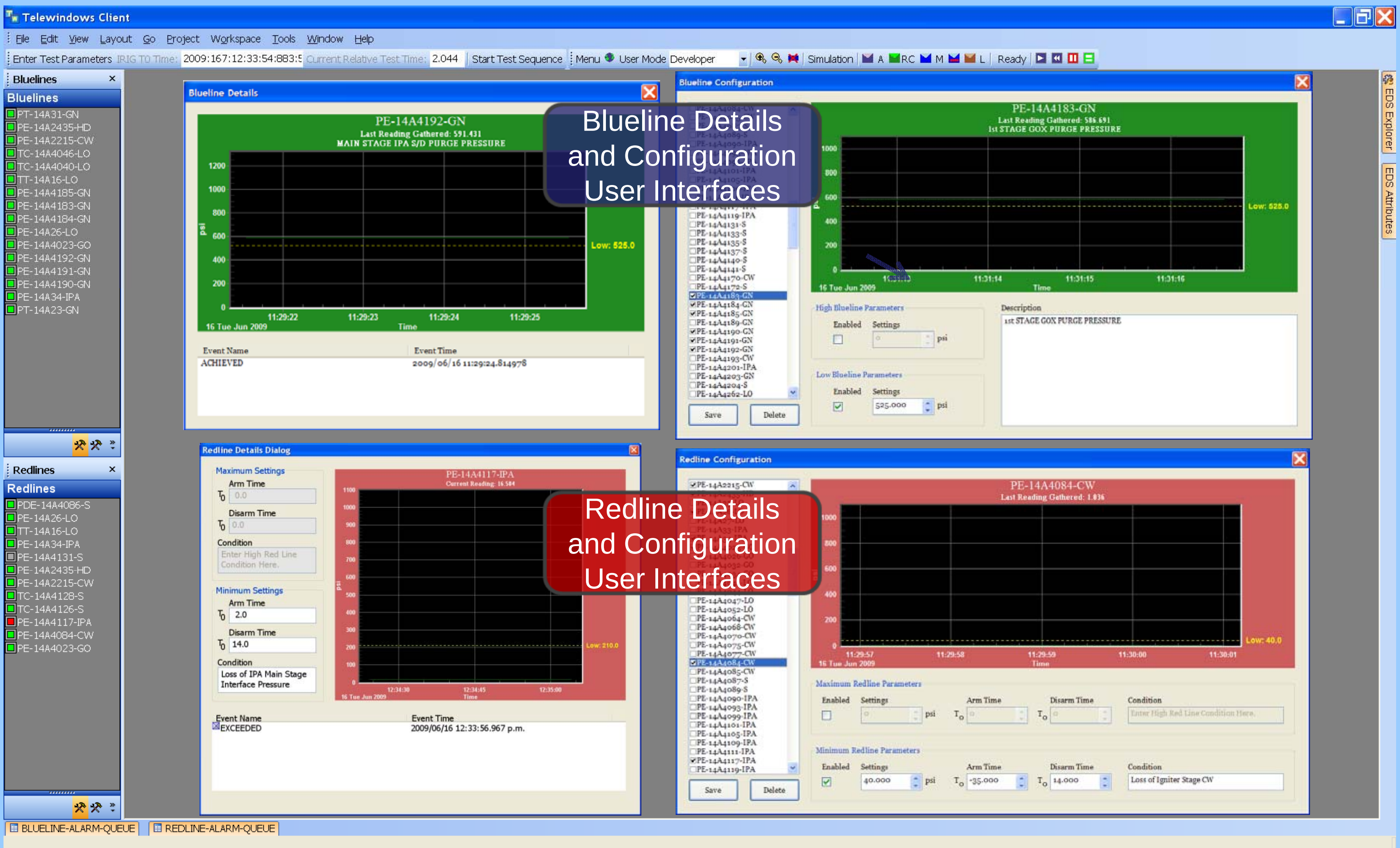
CSG ISHM Domain Model:

User Interfaces

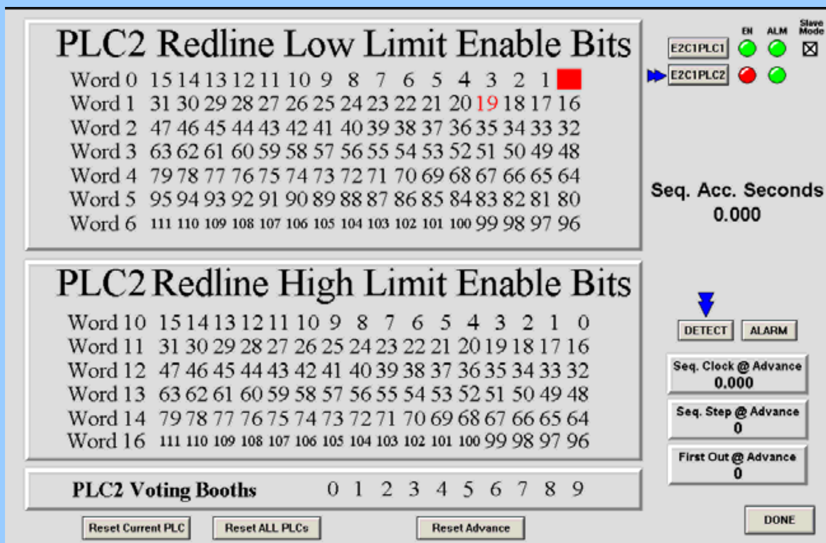


CSG ISHM Domain Model:

Blueline/Redline User Interfaces



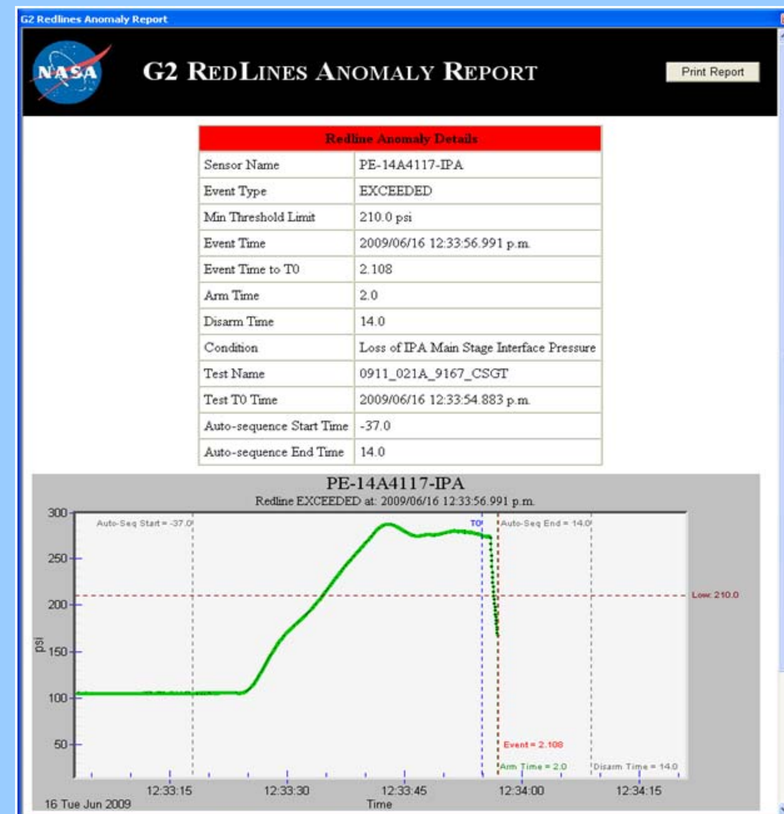
Example Redline Handling



E2 Control Room Redlines UI

- Requires extensive expertise in interpreting events
- Analysis of events takes considerable time and effort
- Only viewed by selected personnel at control room facility

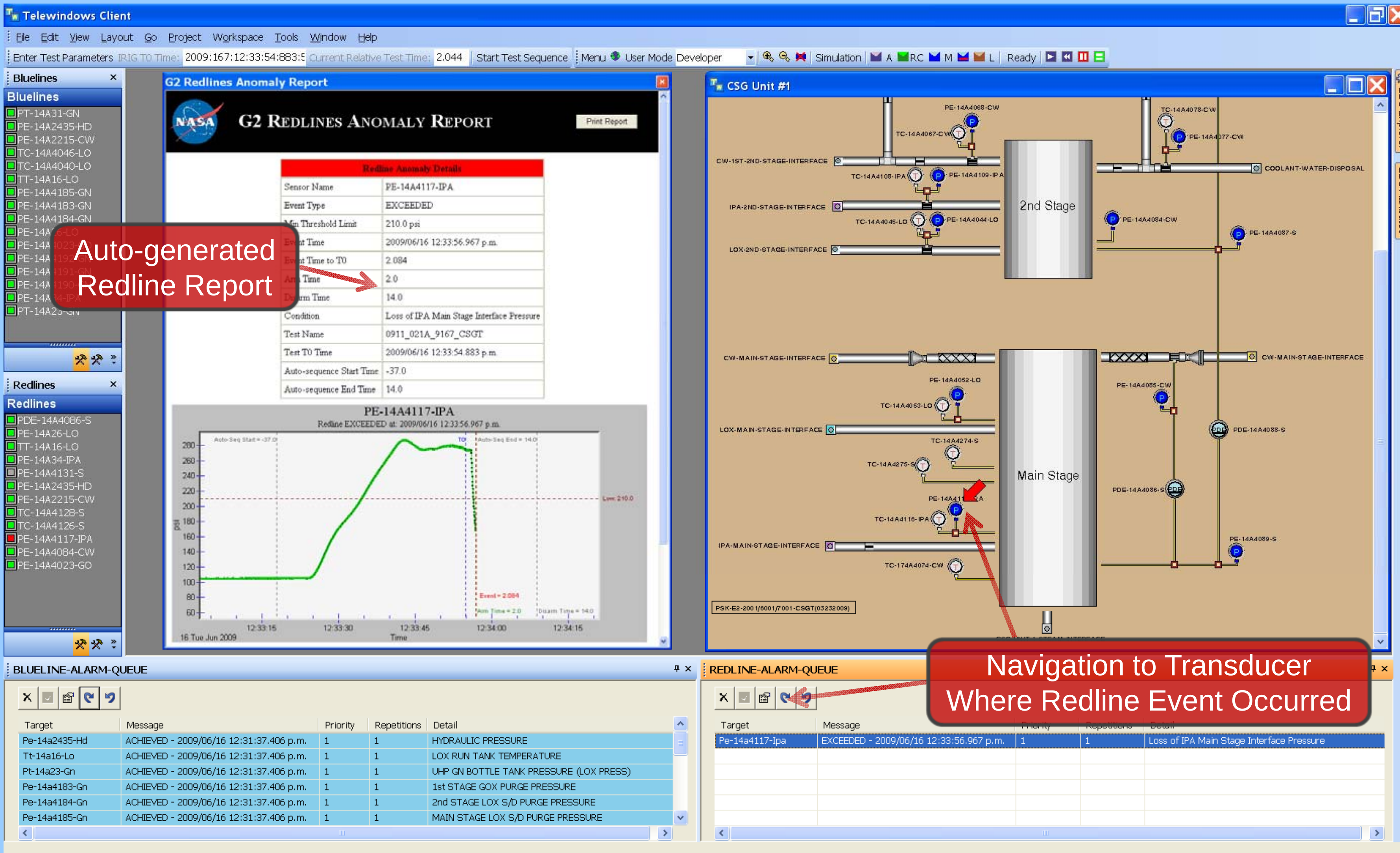
VS.



ISHM CSG Model Redlines UI

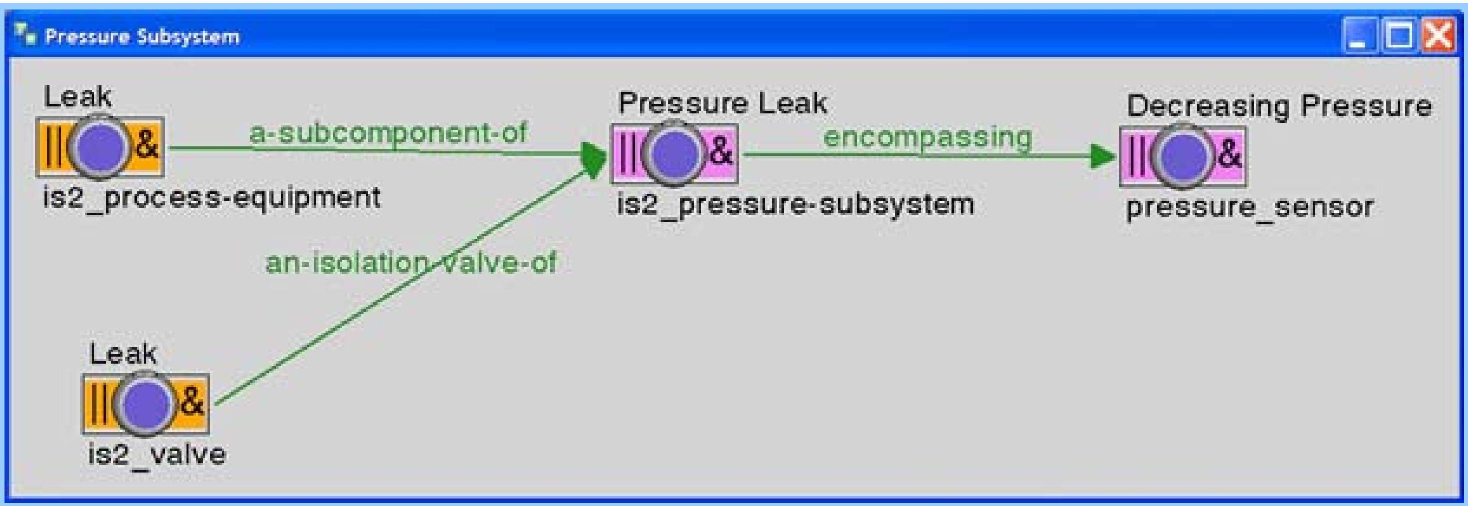
- Provides easily recognizable details of events
- Immediately accessible to all personnel at control room facility, hardcopy printouts allow for ease of distribution and record keeping
- Additional event and test parameters and associated data are depicted

CSG ISHM Domain Model:
Redline Event Handling



Failures Modes and Effects Analysis (FMEA) MIL-STD-1629A(2) NOT 3

ID #	Item-Functional Identification	Function	Failure Modes and Causes	Mission Phase-Operational Mode	Failure Effects			Failure Detection Method
					Local End Effects Effects	Next Higher Level		
	Process Equipment	Fluid feed subsystem	Leak	Sealed subsystem maintaining pressure		Pressure leak	Decreasing pressure measurement	Identify sealed subsystem, and check pressure sensors for decreasing pressure.



ISHM Capability Development

Intelligent Sensors and Components

Smart Sensor/Actuator (NIST)

"The IEEE (Institute of Electrical and Electronics Engineers) 1451 smart transducer interface standards provide the common interface and enabling technology for the connectivity of transducers to microprocessors, control and field networks, and data acquisition and instrumentation systems. The standardized TEDS specified by IEEE 1451.2 allows the self-description of sensors and the interfaces provide a standardized mechanism to facilitate the plug and play of sensors to networks. The network-independent smart transducer object model defined by IEEE 1451.1 allows sensor manufacturers to support multiple networks and protocols. Thus, transducer-to-network interoperability is on the horizon. The inclusion of P1451.3 and P1451.4 to the family of 1451 standards will meet the needs of the analog transducer users for high-speed applications. In the long run, transducer vendors and users, system integrators and network providers can all benefit from the IEEE 1451 interface standards [1].".

"Intelligent Sensor" is a "Smart Sensor" with the ability to provide the following functionality: (1) measurement, (2) measure of the quality of the measurement, and (3) measure of the "health" of the sensor. The better the sensor provides functionalities 2 and 3, the more intelligent it is.

ISHM Capability Development
Intelligent Sensors and Components

Typical Process Models for Sensors

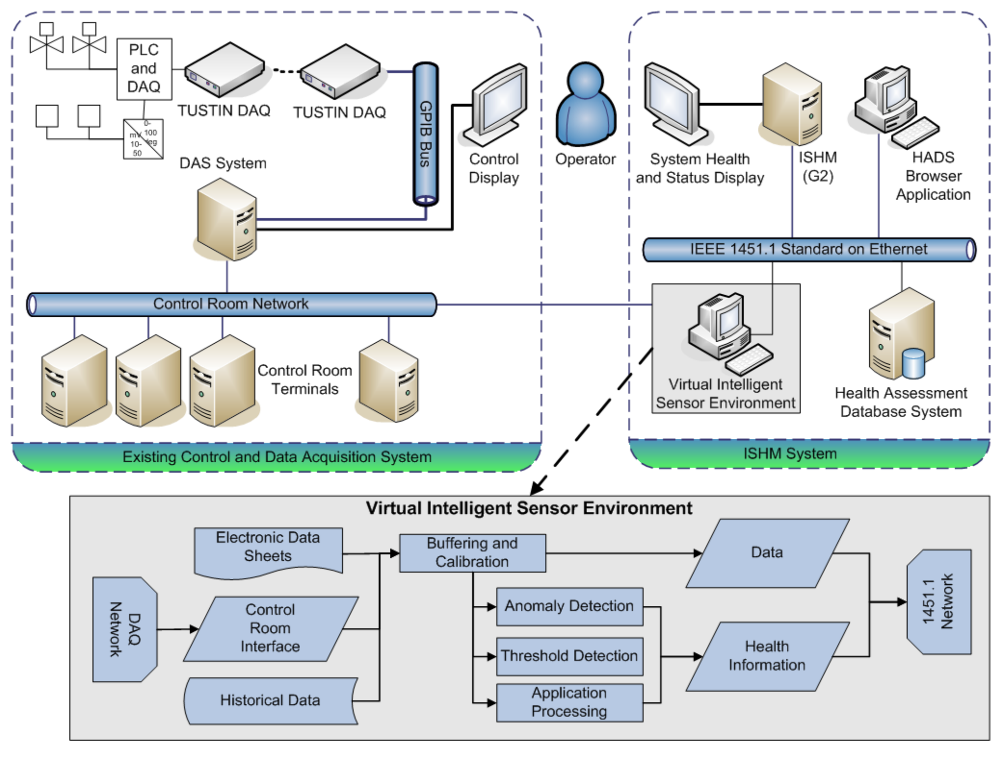
- Noise Level Assessment and History
- Spike Detection and History
- Flat Signal Detection and History
- Response Time Characterization
- Intermittency Characterization and History
- Physical Detachment Characterization and History
- Regime Characterization and History
- Curve Fit on Identified Regimes

"Intelligent Sensor" is a "Smart Sensor" with the ability to provide the following functionality: (1) measurement, (2) measure of the quality of the measurement, and (3) measure of the "health" of the sensor. The better the sensor provides functionalities 2 and 3, the more intelligent it is.

ISHM Capability Development

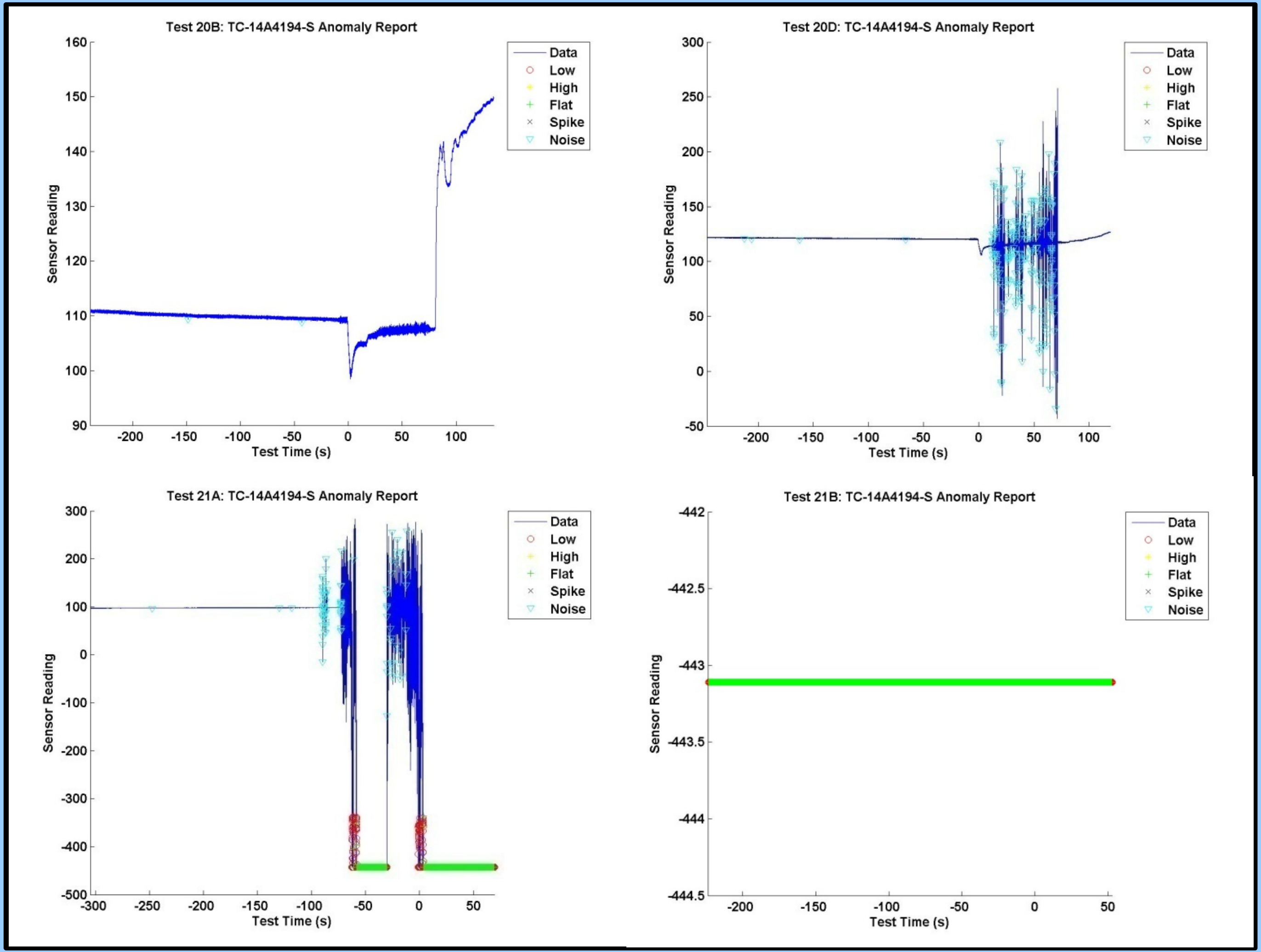
Intelligent Sensors and Components

Example Intelligent Sensor Implementations



The Virtual Intelligent Sensor Environment (VISE) converts all classic sensors installed in a rocket engine test stand into “intelligent sensors.”

CSG Anomalies Detected



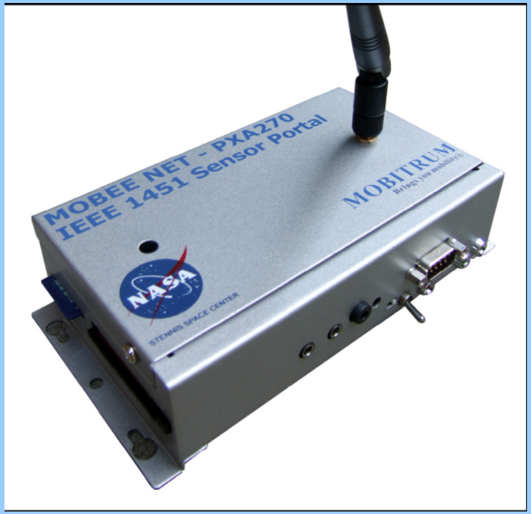
- Evidence of TC degradation detected by VISE anomaly detection
- Advanced notification to determine the health of the whole system before beginning a test

Transducer Anomaly Report Graphs for one sensor in four consecutive tests.

ISHM Capability Development

Intelligent Sensors and Components

Example Intelligent Sensor Implementations



Mobitrum

www.mobitrum.com

Smart Sensor Systems

www.smartsensorsystems.com

NIST

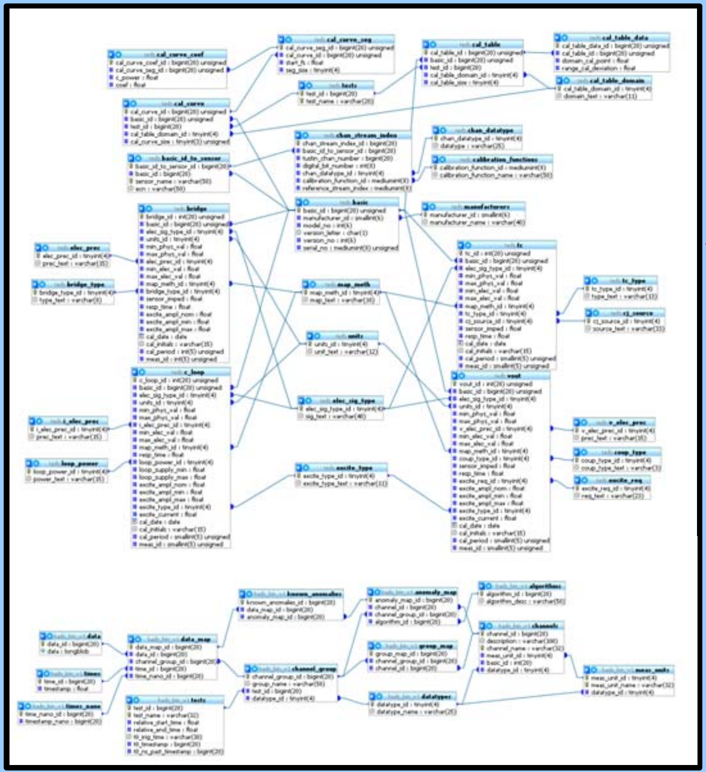
www.mel.nist.com

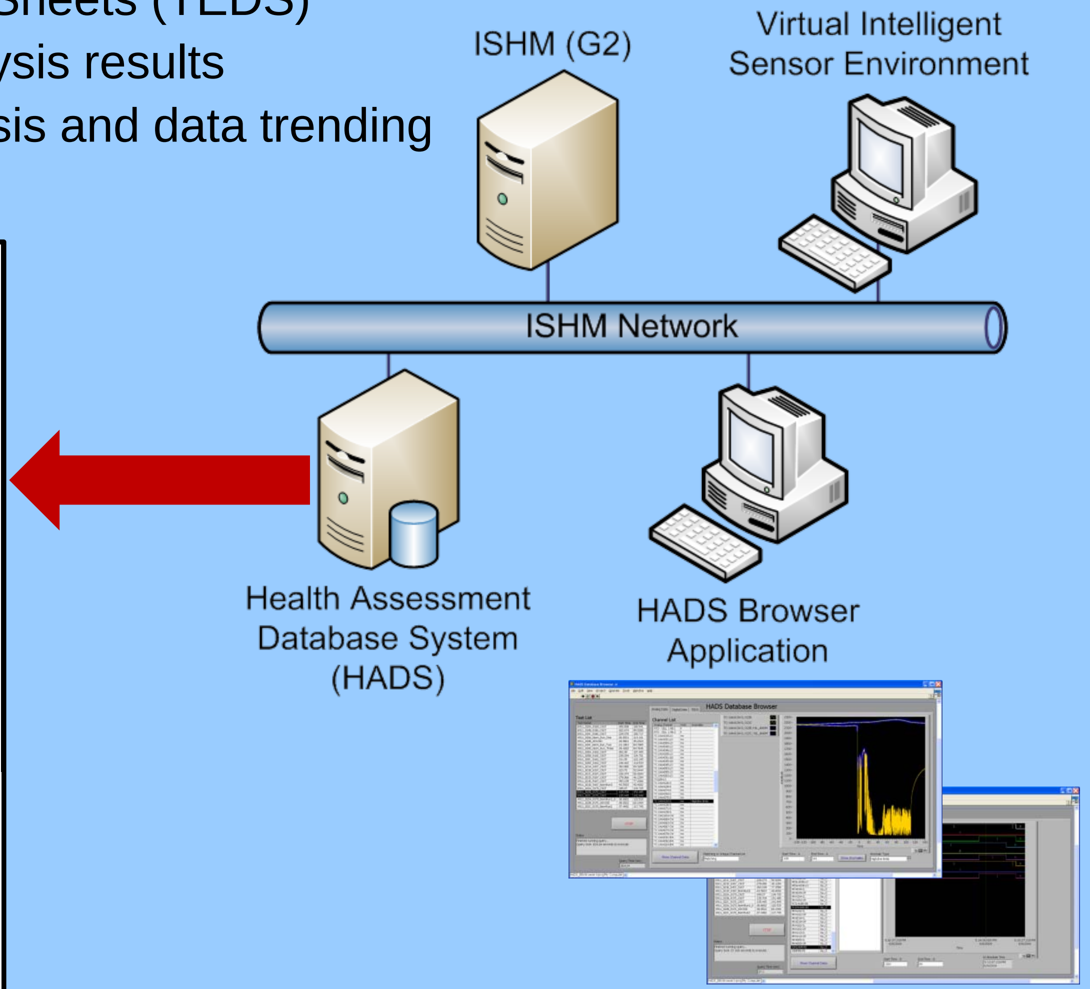
Esensors

www.eesensors.com

Health Assessment Database System HADS

- Health Electronic Data Sheets (HEDS)
- Repository of anomalies and algorithms
- Transducer Electronic Data Sheets (TEDS)
- Historical test data and analysis results
- Provides ease of data analysis and data trending

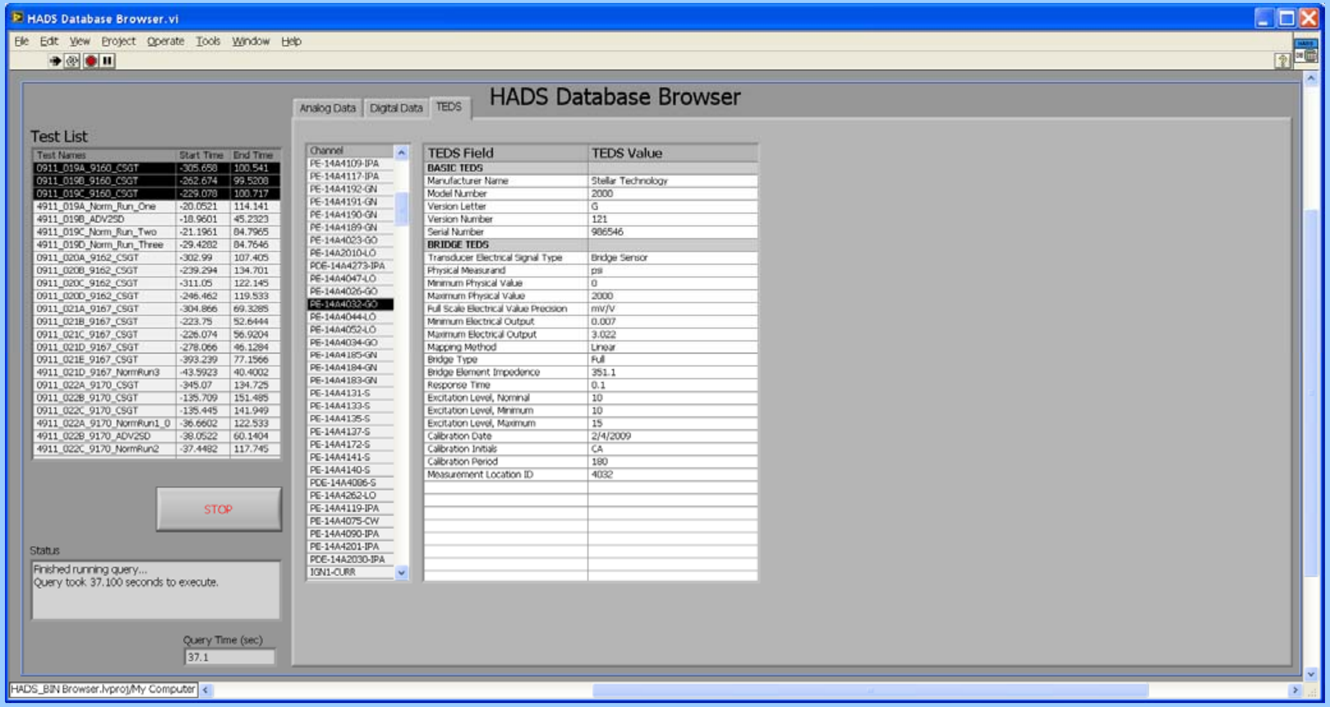




HADS Browser Application

HADS Browser Capabilities

- Allows longitudinal analyses and comparisons with previous test results
- Viewing usage statistics on monitored elements
  - cycle times on valves
  - mean time to failure
- Viewing anomalous events/data trends
- Viewing TEDS

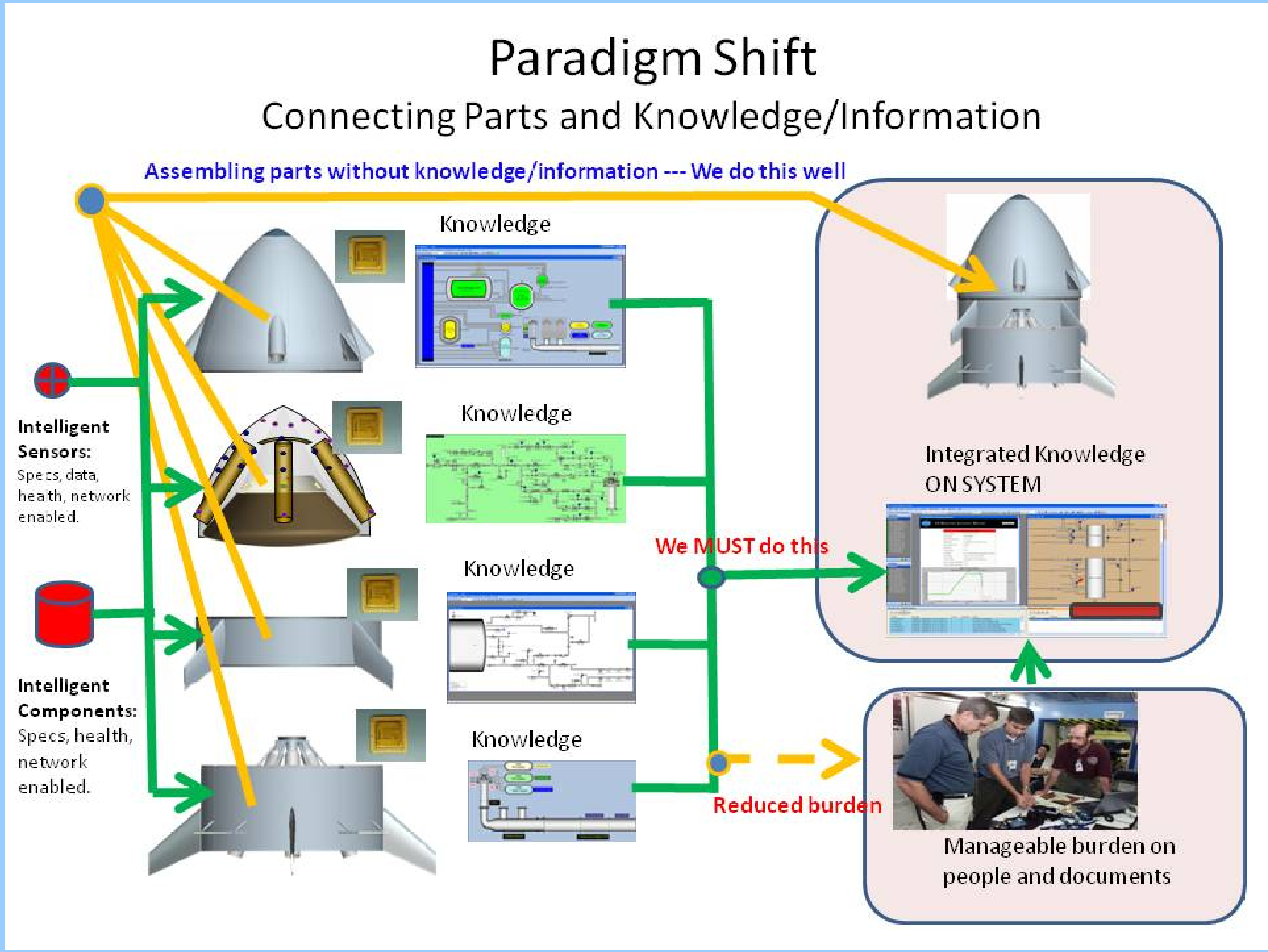


Analog Data – 3 tests, multiple channels
Digital Data – 2 tests, 1 channel

ISHM in Systems Design, Integration, and Engineering (SDI&E)

- SDI&E practices are employed to build complex systems.
- SDI&E for aerospace systems has developed into its own discipline, although theories and concepts have not been adequately formalized in an academic sense.
- The role of ISHM in SDI&E is linked to the concept of ISHM-DM's, whereby every element that is part of a system comes with its own ISHM-DM that can be rolled-up into an overall system ISHM-DM in a plug&play approach.
- When two elements are assembled, the ISHM-DM of each element is incorporated into the ISHM-DM of the assembly. In this manner, DIaK compartmentalized in each element becomes immediately available and useful to the ISHM-DM of the assembly.

ISHM in Systems Design, Integration, and Engineering (SDI&E)



ISHM concept for systems integration of ISHM-DM's

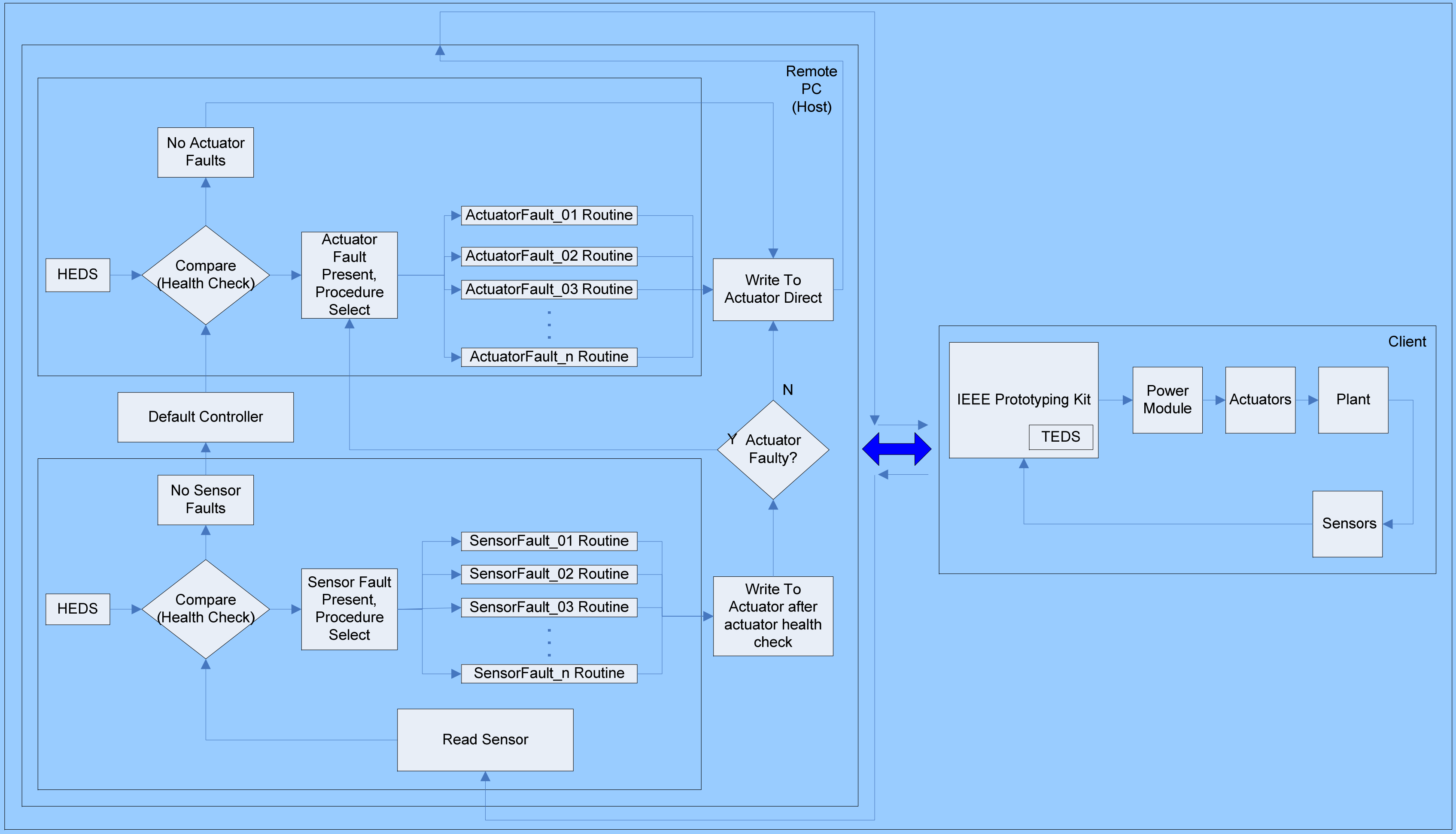
Intelligent Control for ISHM-Enabled Systems

- Control of complex systems that are ISHM-enabled is a nascent area, simply because ISHM itself is also relatively new.
- The objective is for the control function to make use of system health information in order to achieve its objectives.

The paradigm implies that control systems become users of health information, while at the same time making use of actuators to help further improve determination of the system health

Intelligent Control for ISHM-Enabled Systems

Example Application (Reference 18 of the paper)



Conclusions

- A sound basis to guide the community in the conception and implementation of ISHM capability in operational systems was provided.

- The concept of “ISHM Model of a System” and a related Data, Information, and Knowledge (DIaK) architecture were described. The ISHM architecture is independent of the typical system architecture, which is based on grouping physical elements that are assembled to make up a subsystem, and subsystems combine to form systems, etc.

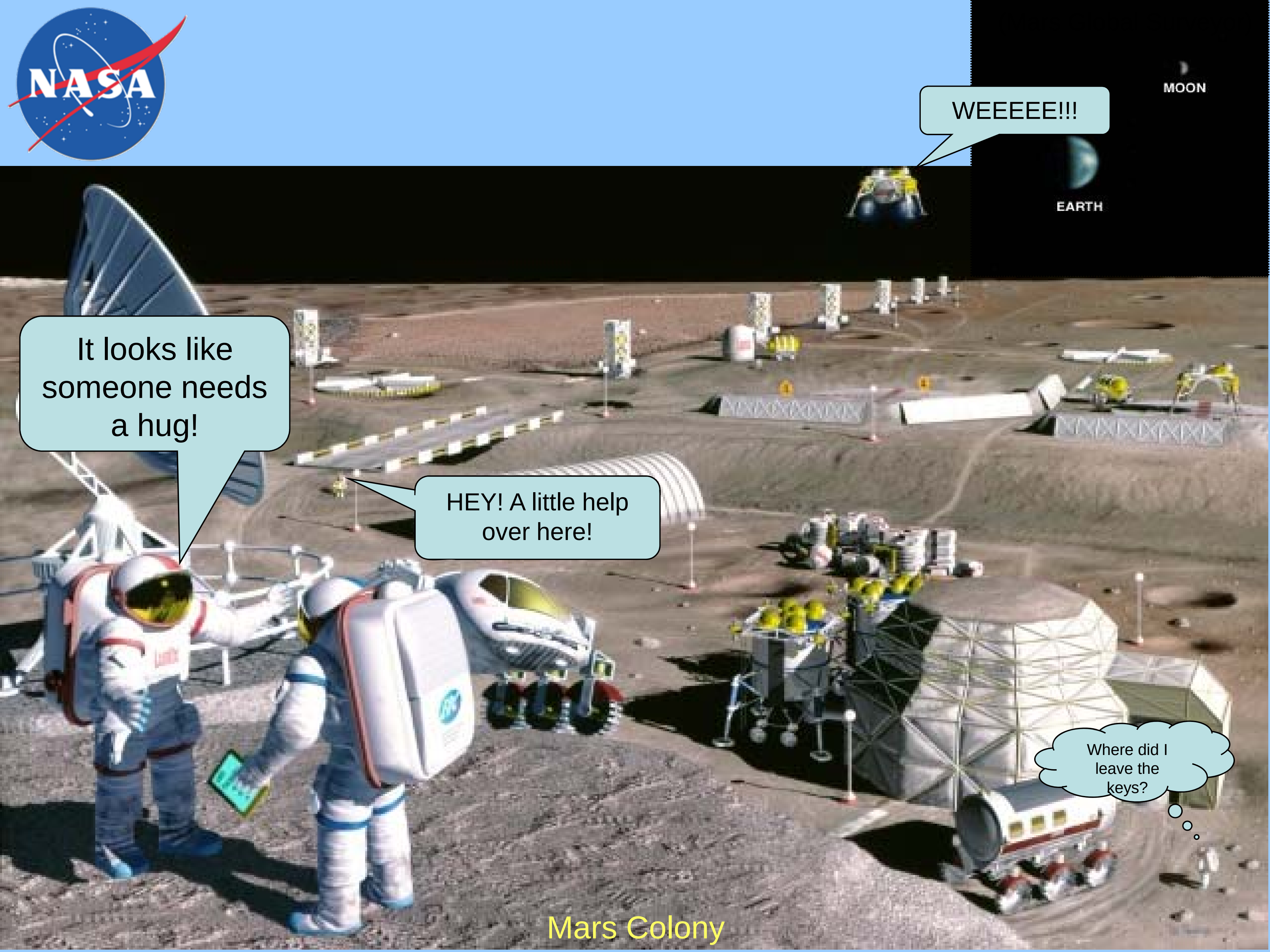
- It was emphasized that ISHM capability needs to be implemented first at a low functional capability level (FCL), or limited ability to detect anomalies, diagnose, determine consequences, etc. As algorithms and tools to augment or improve the FCL are identified, they should be incorporated into the system. This means that the architecture, DIaK management, and software, must be modular and standards-based, in order to enable systematic augmentation of FCL (no ad-hoc modifications).

- A set of technologies (and tools) needed to implement ISHM were described. One essential tool is a software environment to create the ISHM Model. The software environment encapsulates DIaK, and an infrastructure to focus DIaK on determining health (detect anomalies, determine causes, determine effects, and provide integrated awareness of the system to the operator). The environment includes gateways to communicate in accordance to standards, specially the IEEE 1451.1 Standard for Smart Sensors and Actuators

Challenges and Opportunities

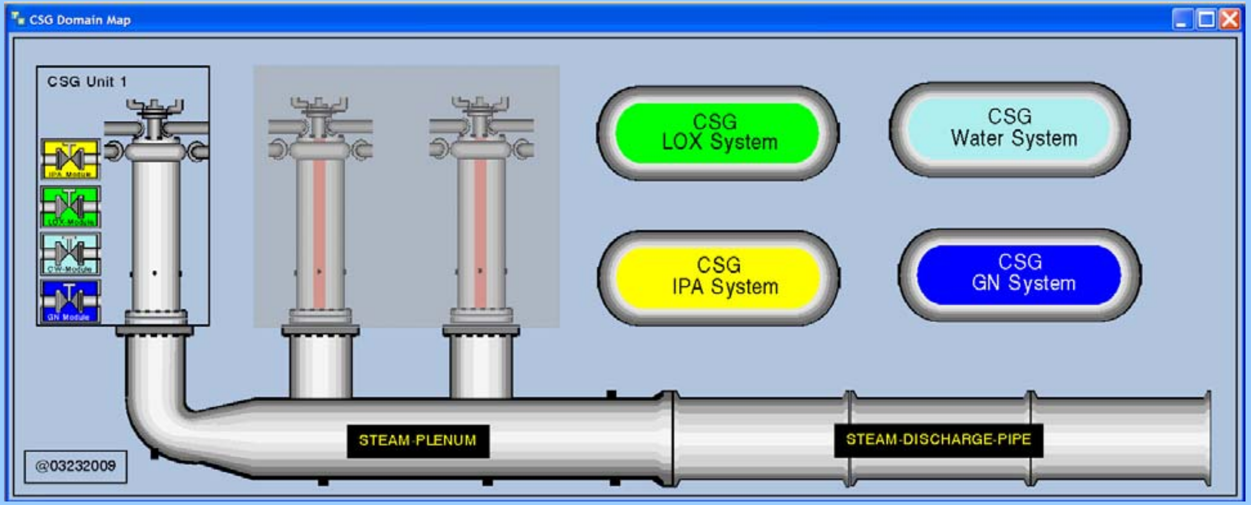
- EDUCATION
  - Inclusion of ISHM in the design process (Design for ISHM).
  - ISHM concept as a knowledge-based capability.
  - Software environments to build ISHM models.
  - Physics of failure.
  - Anomaly detection (algorithms, approaches, strategies).
  - Failure modes and effects analysis (FMEA) and root-cause tree analysis concepts and automation.
  - Software environments supporting processing within networked intelligent elements and standards-based interaction.
  - User interfaces: “integrated awareness of system elements.”

- RESEARCH
  - ISHM incorporates multiple disciplines: physics modeling or modeling of any phenomena occurring in a system, algorithm development, knowledge systems, user interfaces, software environments, intelligent systems, standards, network capabilities, etc.
  - Laboratory/pilot implementations (e.g. university power plant) for validation of the research. Very few “low functional capability” ISHM systems have been implemented (Space Shuttle Main Engine, Boeing 777 are the more visible cases). Experimental validation will bring high visibility to potential users/investors (NASA, DoD, DoE, Chemical and Oil industries, power plants, ships, etc.).
  - ISHM is in its infancy, but can develop very fast. Three notable annual conferences specific to ISHM are on- going:
    - ISHM Conference (usually in Covington Ky. Or Cincinnati, OH), started by AFRL (In its fifth year or so).
    - Prognostics and Health Management Annual Conference (its second event to take place at the end of September, in San Diego).
    - AIAA Infotech@jAerospace Conference has added ISHM as a technical area.
  - ISHM capability can be implemented and validated without disturbing on-going normal operations.


MOON
EARTH
WEEEEE!!!
It looks like someone needs a hug!
HEY! A little help over here!
Where did I leave the keys?
Mars Colony

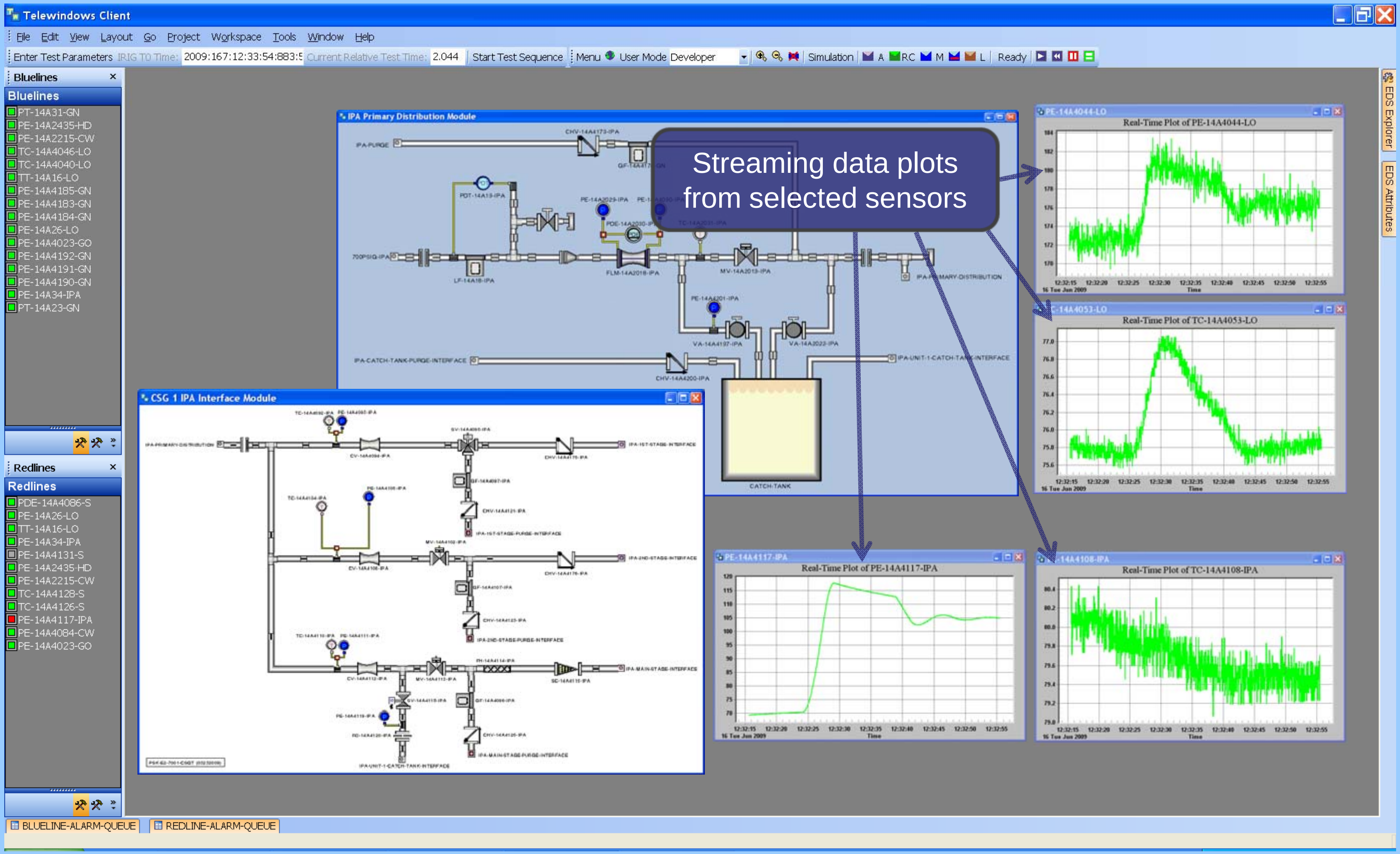
Backup Slides

CSG ISHM Domain Model:
Top Layer View

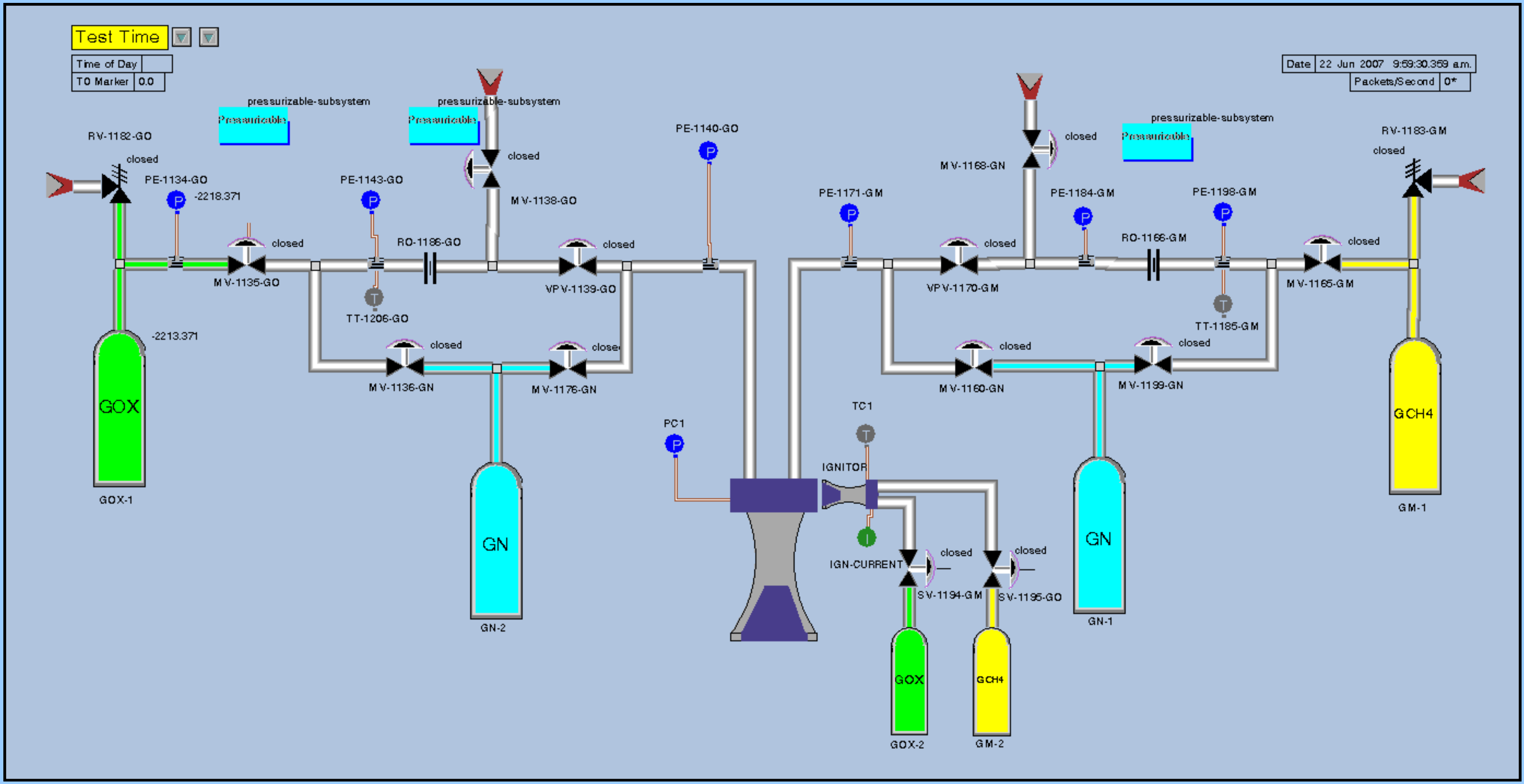


ISHM Domain Model
Top Layer

CSG ISHM Domain Model:
Transducer Data Plots



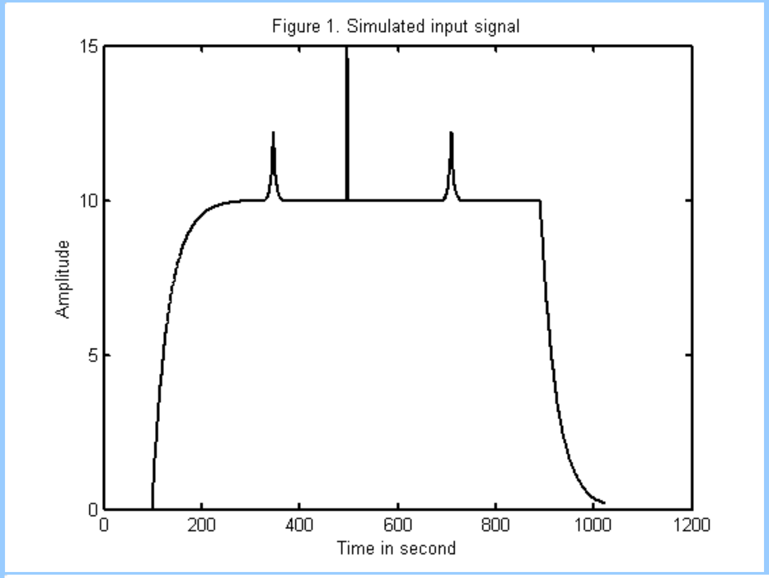
Elements of an ISHM System:
ISHM Model - Proximate Cause Analysis

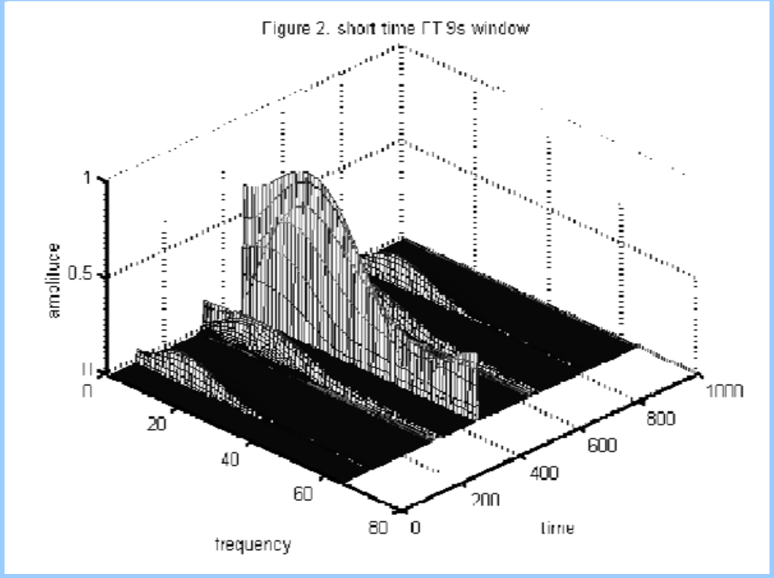


List of Anomaly Detection Capabilities

Anomaly/Behavior	**Demonstrated Cause**	**Detection Approach**
Leaks (pipes, valves, etc.)	Various	Checking for pressure leaks using the concept of Pressure Subsystems.
Valve state undetermined	Defective feedback sensor Controller failure	Determines valve state by checking consistency of command, feedback, open/close switches, and pressure conditions upstream and downstream.
Valve oscillation	Fluid contamination in hydraulic supply	Compare running standard deviation of command versus feedback.
Valve stuck	Fluid contamination in hydraulic supply Seat seizure	Feedback remains horizontal while command changes.
Excessive noise, spikes, etc.	Interference	Running standard deviation exceeds set limits. Thresholds violations during short time spans (compared to sensor time-constant).
Degradation	Wear, aging	Trend detection using curve fitting and determination of time-constants.
Prediction-Measurement mismatch	Various	Use predictive model (e.g. from Modeling & Analysis Group) to predict sensor values and compare with measurements.

Short-Time Fourier Transform Segmentation

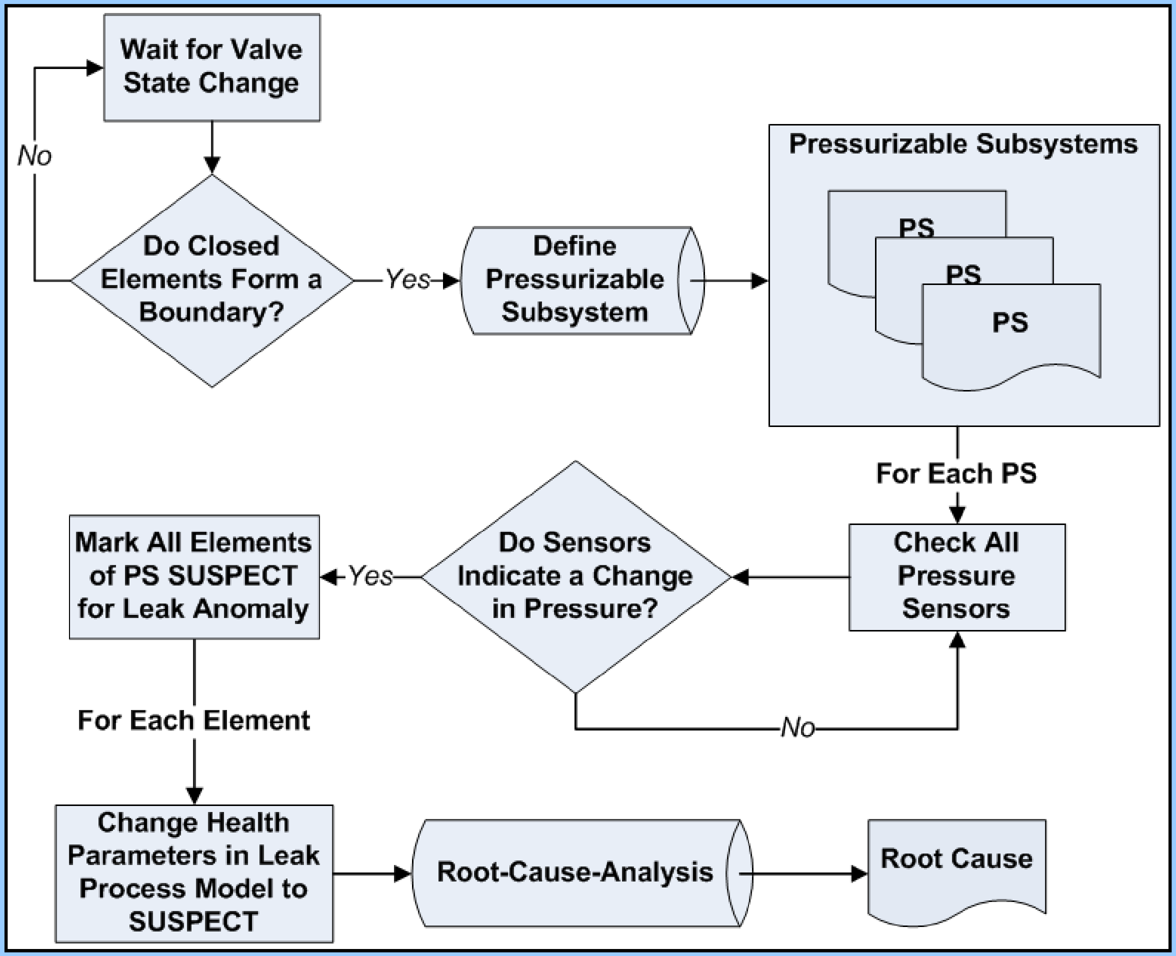




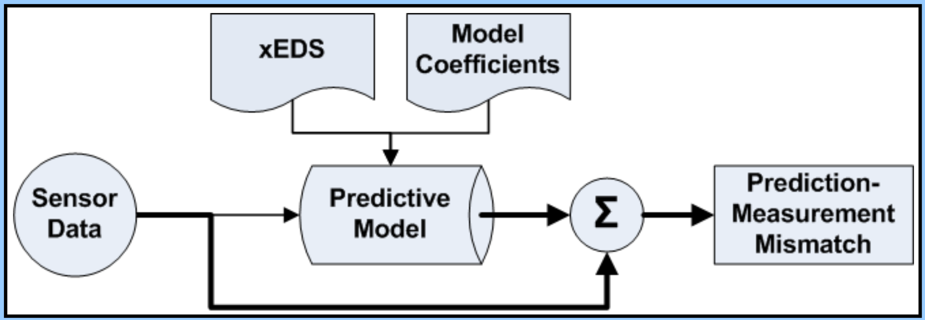
Determining Valve-State

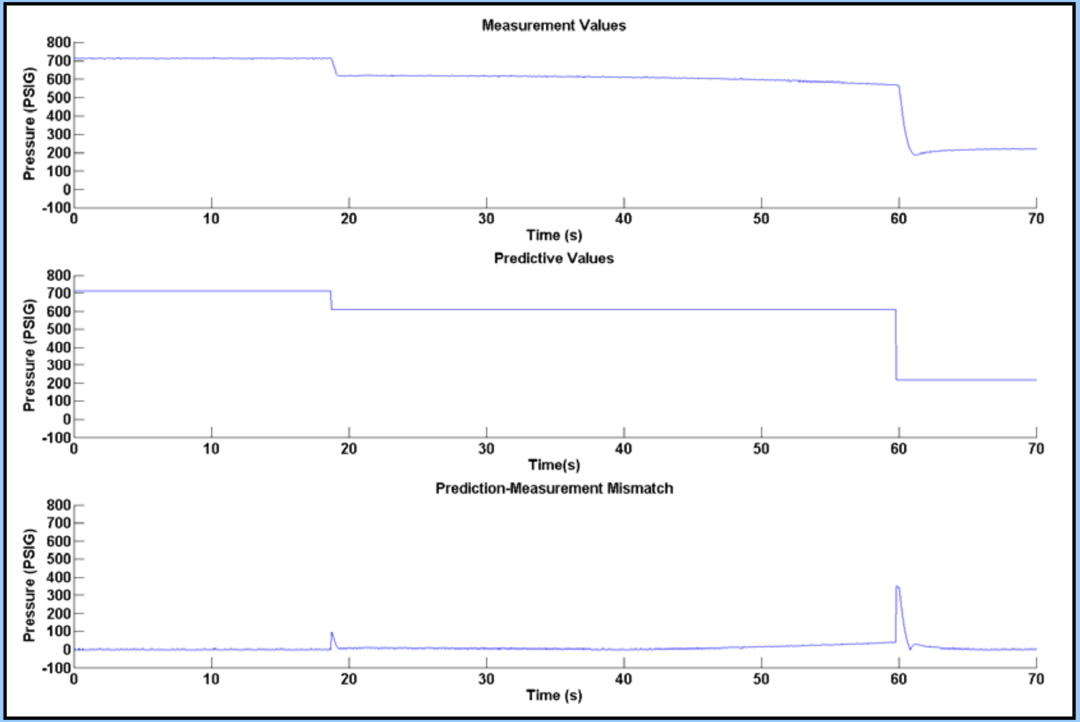
Valve State	**Command**	**Feedback**	**Open limit**	**Closed Limit**	**Associated Sensors**
Open	Open	Open	True	False	Agree with model
	Healthy				
Closed	Closed	Closed	False	True	Agree with Model
	Healthy				

Checking for Pressure Leaks



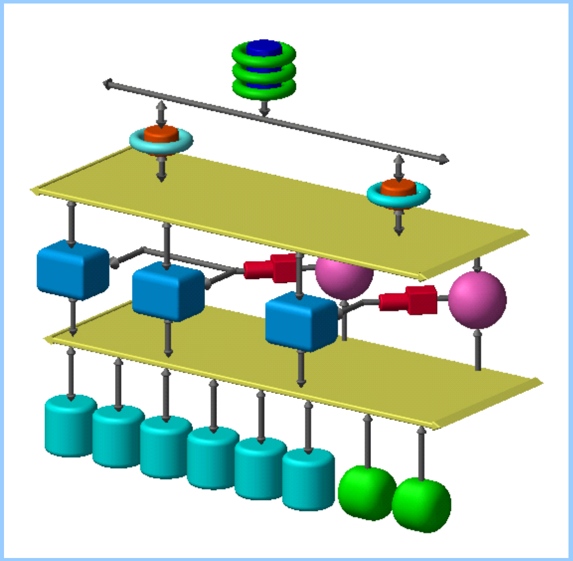
Runtime Predictive Modeling





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^{st}, 2^{nd})
  - Filtering—e.g., Butterworth HP
  - FFT—e.g., 64-point
  - Wavelet Transforms (segmentation)
  - Algorithms for
    - Flat
    - Impulsive (“spike”) noise
    - White noise
  - Other (ANN, etc.)



Intelligent Sensors have embedded ISHM functionality and support ***Smart Sensor*** standards

Software to develop ISHM Domain Models (ISHM-DM's)

A software system for ISHM capability should support all core capabilities by integrating systematically DIaK through the ISHM-DM

- ***Object orientation***: object representation of system physical elements and associated process models is the best way to embed DIaK in a systematic and in an organized manner.
- ***Distribution of ISHM-DM's within and across networks***: ISHM-DM's might be distributed among processors connected to a network, simply because it is necessary to use parallel processing, and/or ISHM-DM's might be created by different people in various geographic locations

Software to develop ISHM Domain Models (ISHM-DM's)

A software system for ISHM capability should support all core capabilities by integrating systematically DIaK through the ISHM-DM

- ***Distribution across processing units***: Since multiple process models are expected to be running at any given time, the software environments should support parallel processing.
- ***Inference engine***: Many tasks require an inference engine. Reasoning and decision making leading to anomaly detection, diagnostics, effects, and prognostics; require contextual integrity and cause-effect analysis using heterogeneous data and information.

Software to develop ISHM Domain Models (ISHM-DM's)

A software system for ISHM capability should support all core capabilities by integrating systematically DIaK through the ISHM-DM

- ***Integrated management of distributed DIaK***: DIaK must be managed in a way to allow embodiment of systems thinking across elements and subsystems. Often this is enabled by definitions of relationships among elements of systems that can be physically visible (i.e. attached to, belong to a system); or more abstracted relationships, as it relates to involvement by groups of objects in process models.
- ***Definition of dynamic relationships among objects for use in reasoning***: Often, the framework for reasoning and application of process models changes dynamically with configuration changes, stages of operation, etc.