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NASA

Intelligent Systems Health Management Technical Interchange Meeting

Sensors for Industry Conference

Houston, Texas
February 8 – 10, 2005

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Findings of the Workshop Breakout Sessions

This report presents data and summarizes the results from a technical interchange meeting (TIM) held coincident with the 2005 Sensors for Industry Conference. This annual conference is sponsored by the ISA and the IEEE Instrumentation and Measurement Society. This TIM was held on February 8-10, 2005, Marriott Houston Hobby Airport, Houston, Texas, USA. Reference to the conference is available at http://www.siconference.org/.

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Workshop Background and Description

Integrated System Health Management (ISHM) presents real opportunities for significant improvements in reliability, cost-benefits, and safety for future space exploration missions and is applicable to many large-scale industrial systems. Lessons from the Apollo, Challenger and Columbia accidents demonstrate that complete, accurate assessment of real-time vehicle state is required to provide the reaction framework needed for crew and mission assurance. NASA has recognized the potential of ISHM technologies and has supported development of specific subsystems and component technologies. ISHM is also an emergent core technology for many of the advanced commercial and military avionic platforms under development. The timing is right to integrate the available ISHM technologies, refining and maturing them for insertion first into ground support facilities, then into space-based facilities, and finally as key enablers for Moon and Mars missions. The ISHM SIcon/05 sessions explore important technology components, bringing practitioners and researchers together to advance this field.

The goals of the TIM were to:

1. Inform partners (industry, academia, other public and private entities) about NASA's ISHM technology development and maturation activities under the new Exploration Mission Systems Directorate.

2. Understand the contributions of partners external to NASA, especially those fund recipients under the Human and Robotic Technology Broad Agency announcement, on their ISHM related projects.

3. Explore how we may all benefit and leverage each other's efforts.

4. Identify technology gaps needed to meet the requirements of Project Constellation for future exploration systems missions.

The structure of the TIM consisted of keynote speakers; two sequential plenary sessions that each addresses internal and external ISHM work; and six breakout sessions to address in detail key technical issues surrounding ISHM:

1. Plenary Speaker (Dan Duncavage).

2. Paper Sessions.
    a. NASA ISHM projects (Figueroa).
    b. External partners and others ISHM projects (Crow).

3. Workshop Sessions.
    a. Integration architectures/frameworks for ISHM (Figueroa).
    b. Smart Sensors (Perotti).
    c. Health Anomaly Databases (Schmalzel).
    d. Health Detection Algorithms (Schwabacher).
    e. Communications Protocols (Brisco).
    f. Integration and Validation (Duncavage).

Plenary Presentations of Internal and External Work In ISHM

Internal Session: ISHM Work and Technology Inside of NASA
Chair: Fernando Figueroa, Stennis Space Center 228/688-2482

Session overview: The Exploration Systems Mission Directorate has identified Integrated System Health Management (ISHM) technologies as key components to design exploration systems for the mission to go back to the Moon and explore Mars. Requirements to achieve this mission include improvements in safety, life-cycle costs, and autonomous operation of exploration systems. These improvements can be met only if ISHM technologies permeate design of new spacecraft, space platforms, settlements on the Moon and Mars, and advanced test and operations ground systems. The session will include papers that describe current research and technology by NASA to develop ISHM technologies.

Intelligent Systems Health Management Testbed Dan Duncavage Johnson Space Center, Houston Texas 281/792-5478 daniel.p.duncavage@nasa.gov

Integrated Health Management with Intelligent Networked Elements (IHNIE) Prototype
Fernando Figueroa, NASA Stennis Space Center, 228/688-2482 Fernando.Figueroa-1@nasa.gov

Smart Sensors Jose Perotti, Kennedy Space Center 321/867-6746 Jose.M.Perotti@nasa.gov

Algorithms for Intelligent Elements Bill Maul, Analex Engineering/NASA Glenn Research Center, Cleveland, OH 216/977-7496

External Session: ISHM Work and Technology Outside of NASA
Chair: Ed Crow Penn State Applied Research Laboratory 814/863-9887

NASA is intent in using the best technology and expertise, and relies heavily on external partners. Industry, Universities, Laboratories, private organizations, and Federal and State Institutions, are asked to participate in Broad Agency Announcements, and other venues, to develop new technologies that focus on achieving NASA's Missions. The session included papers that describe ISHM technologies being developed by the ISHM community, in particular by those partners that have been awarded funds for research and technology in support of the Human and Robotic Technologies Program.

Intelligent Component Health Management: An Architecture for the Integration of IVHM and Adaptive Control Gabor Karsai, Gautam Biswas, Sharif Abdelwahed, Nag Mahadevia, ISIS, Vanderbilt University, Nashville, TN 37235; Kirby Keller, Scott Black, The Boeing Company, St. Louis, MO 63166 *[Speaker: Gabor Karsai (615) 343-7471/2 gabor.karsai@vanderbilt.edu]*

Intelligent Systems Health Management for Increase Autonomy, Reduced Operational Risk and Improved Capability Karl Reichard, Jeff Banks, Eddie Crow, Lora Weiss Penn State University Applied Research Laboratory, State College, PA 16804 [*Speaker: Karl Reichard 814/963-1008 kmr5@psu.edu*]

Integrated System Health Management for Exploration Mission Systems Carlos Garcia-Galan, Honeywell DSES, Houston TX (321)784-5485 carlos.garcia-galan@honeywell.com

Intelligent Vehicle Health Management for Air Force Space Systems Mark Derriso USAF Air Vehicles Directorate, Air Force Wright Aeronautical Laboratory, Dayton OH (937) 904- 6876 mark.derriso@wpafb.af.mil

Description of Workshop Sessions and Questions

Following is a description of each of the breakout sessions and questions addressed during the facilitated discussions among all audience members.

ISHM Architectures (Figueroa)—*Integration architectures and frameworks (A&F) for intelligent health management are key to develop ISHM systems. A&F must support efficient management of data, information and knowledge so that these are available at the right time and within the proper context. Management of data, information, and knowledge includes storage, updating, modification, distribution, expansion, evolution, etc.*

Q1: Identify ISHM architectures/frameworks you know of (or any of its similar names, e.g. Prognostics Health Management, Embedded Diagnostics/Prognostics, Condition Based Maintenance, Intelligent Vehicle Health Management, Health Monitoring)
Q2: What are the distinguishing characteristics of an ISHM architecture?
Q3: Is it practical to have a single architecture for ISHM?

Smart Sensors (Perotti)- *Autonomous smart sensors can assume significant roles in an ISHM architecture. A smart sensor shares similarities with a "non-smart" sensor in that they both produce measurement data; the smart sensor differs because it also possesses sufficient computing power to perform algorithmic assessment of its state to inform higher-level process(es) of the estimated quality of the data and of the ability of the smart sensor to perform its functions. Models for intelligent sensors need to be developed that include embedded health evaluation knowledge bases and associated assessment algorithms along with methodologies to embed learning of new concepts and behaviors. Other sensor issues include the need for novel total-system calibration methods to address the distributed voltage reference problem (i.e., every smart sensor has an individual voltage reference compared to the conventional data acquisition model where one-or few-high accuracy references are shared). Similarly, methods need to be developed to provide clock synchronization protocols for improving time references between sensors such as using IEEE 1588.*

Q1: What are your expectations of a smart sensor? Are they being met?
Q2: What type and level of embedded capability do you think a smart sensor should have?
Q3: What is the impact/benefit of a smart sensor?

Health Anomaly Databases (Schmazel)- *Detection of health and other types of fault behaviors in complex systems requires that a library of representative faults and fault signatures is available to those working in the ISHM field. Participants will describe their experience with developing such health databases and solicit ideas for ways to expand the available resources in this area and make them widely available. Expanding the general framework of the IEEE 1451.N series, opportunities exist to extend the innovation of the transducer electronic data sheet (TEDS) structure to include a health electronic data sheet (HEDS) that supports the ISHM architecture.*

Q1: What transitional fault>>failure data sources exist? Who? Where?
Q2: How do we ensure getting data we need for ISHM development by piggy-backing on component/subsystem life testing that occurs as a normal course in program development?
Q3: How do we make fault>>failure data available to a broad community of ISHM developers and respect the claims of proprietary information by contractors?

Health Detection Algorithms (Schabacher)- *Embedding health metrics into smart sensors and other portions of an ISHM architecture requires that health anomalies from available databases be cataloged. Algorithms to detect anomalies must accommodate available hardware and software resources. Algorithm performance measures need to be developed so that appropriate algorithms can be selected for a given ISHM application.*

Q1. What are measures of effectiveness and measures of performance for ISHM?
Q2. Is ISHM algorithm commonality possible? [e.g. can a pump health monitoring algorithm for a rocket engine test stand be the same as for one on the International Space Station (ISS) and the Crew Exploration Vehicle (CEV)?
Q3. Identify ISHM algorithms you know of? What is missing?

Communication Protocols (Watson, Brisco)- *Comparison and selection of communication protocols to best support ISHM applications can be based on existing standards or may utilize special-purpose protocols developed by NASA or a particular industry. For example, TCP/IP or UDP are available standard protocols; Marshall Space Flight Center has developed a time-triggered protocol to support mission-critical control loops. The performance of ISHM networks under representative loading needs to be evaluated to ensure that adequate performance is available.*

Q1:   What standards exist that apply to ISHM systems?
Q2: What needs must be addressed by new protocols to be suitable to support ISHM functionality?
Q3: What kind of interfaces are needed between ISHM and human control? Between ISHM and autonomous control?

Integration and Validation (Workshop)- *The separate components of an ISHM need to be integrated in such a manner as to preserve functionality and avoid unnecessary conflict or inefficiency when combined together. Important elements include the operating system environment, overall computational and input/output bandwidth, etc. Similarly, an ISHM system needs a methodology to validate design decisions and to predict performance. An ISHM test suite can consist of simulation tools and physical test facilities such as those available at a number of NASA centers.*

Q1: How should ISHM requirements be specified?
Q2: How could an ISHM capability be validated?
Q3: How should benefits versus cost of ISHM capability be measured and determined?

Breakout Session Workshop Findings

The workshop employed a special process using peer-to-peer interviews followed by facilitated discussions. This method is especially suited for efficient and effective capture of information from an expert knowledge base. It's a technique consisting of a sequence of peer-to-peer interviews using questions specially crafted around the topic of interest to reveal base information. This step is followed by a facilitated discussion among the subject matter experts to debate and discuss the information. Thereafter, the information is organized by subgroup and category concluding with prioritization exercises and final group consensus building. See later section in this report for a description of this process- "The Great Rotation"

ISHM Architectures (Figueroa)- *Integration architectures and frameworks (A&F) for intelligent health management are key to develop ISHM systems. A&F must support efficient management of data, information and knowledge so that these are available at the right time and within the proper context. Management of data, information, and knowledge includes storage, updating, modification, distribution, expansion, evolution, etc.*

ISHM Architectures (Figueroa)

> **1. Identify ISHM architectures/frameworks you know of (or any of its similar names, e.g. Prognostics Health Management, Embedded Diagnostics/Prognostics, Condition Based Maintenance, Intelligent Vehicle Health Management, Health Monitoring)**

Roll-Up Summary
• UCAP
• DDAC
• PITEX (X-34)
• Embedded Diagnostics
• Condition based
• DIAMOND II
• G2
• ARINC 60L
• OSA/CBM
• ARINC 624
• (2) JSF
• Livingstone
(2) X-33
VISIMBR
Northstar 6M
(3) 777 Central PRDC.
IFFE 1451.N
• HUMS
• SSME/DISCOVERY EXPS-Post-fit
• SSP
• SARAA (ISS)
• To/TAES (test stand)

- DATA – SIMILANT
- Space Ship One
- ISHM – SSC – HYAE E-1(g2)
- CEV-IVHM
- SLI-IVHM
- OSP-IVHM

TRUTH: Hierarchical Bottom-up
Framework
SSC:
    System
    Processor
    Sensor
    T. Global Diag S=1
Los Almos
    Operation Evaluation
    Cleansing
    Fusion
    Feature

OSA
    Process
    System   DATA INTERFACE
    Sub
    Sensor
TREND:
    New, more dynamic, more STDS-OSA, Data XCNG

Oral Report for Architectures - Q1

Observations
- 777 best example
- SHM has always been there (e.g. BIT), current focus on integration
- 3-layer architecture (includes sensors) vs 2-layer (subsystem/system)
- Open system architecture (multiple functional layers)
- Process model architectures
- Data driven architectures
- Temporal architectures

Truths
- hierarchical architectures

Trends
- more dynamic, more standards, OSA

2. What are the distinguishing characteristics of an ISHM architecture?

Roll-Up Summary
1.
- interface protocol
- system-level function /organization
- subsystem health management algorithms
- standard interface
2.
- diagnostics/prognostics
- artificial intelligence
- automated maintenance/supportability
- collect/process data – decision/training
- use a smart sensor
3.
- data gathering/interpretation
- current state
- action needed
1.
- distributed and hierarchical
- object-oriented
- wide range of data rate accommodations
2.
- distributed processes
- object-oriented
- multi-protocols (well defined)
- limited # of general functions
- distinct layers (comm.. BTU layers)
- sensors/comm/application layers
- middleware
3.
- integration of components
- information provider
- hierarchical system
- different users (may)
- flight control real-time
- scalable
- timely response
- modular
- sensor identification
- sensor coverage to detect faults
- integrate to isolate faults
- standard protocols/hardware/platforms
- passive or active
- flexible
- robust
- ensemble of interfaces

- data driven
- operating system
- centralized or distributed processing
- data buses
- data formats
- every element is integrated to the top level with intelligence
- real-time failure detection correction
- enter systems coordination
- trend analysis at a high level
- distributed expertise with high-level information sent to an integrator for decision.

Oral Report for Architectures - Q2

Observations
- Interface protocol
- Diagnostics/prognostics
- Data gathering
- Distributed/hierarchical
- Distributed processes
- Integration of components

3. Is it practical to have a single architecture for ISHM?

Roll-Up Summary

YES
- One generic architecture that is tailored
- Although SoS might require different layers. V & V favors a common architecture
- Generic functional architecture defines roles and interfaces
- Common architecture with modular components
- Common starting point, but be prepared to modify it to suit specific system
- Highest level, may need modification at lower levels

NO
- ISHM is too broad a term, depends on system application
- Provided there are sufficient network resources
- Sub-systems may require different architecture 11x3
- Different ISHM's may have different goals
- Won't work for flight systems. May be OK for ground systems/test beds. Different hardware, Operating Systems need different architectures.
- Not practical across different systems but should be for vehicle
- Architecture must be application specific

Definition of architecture different to different people
Common Ontology needed
Single environment such as G2 may be OK but different tools are needed for different architecture

Oral Report for Architectures - Q3

Observations
- 9 yes, 10 no
- Difficult to answer the question without a definition of architecture and definition of "generic"
- Different system goals make it difficult to use common architecture
- How specific is a common architecture – what does it mean to use a common architecture
- Look to construction industry for analogy – a house is more like a house than it is like a hotel
- Looking at building analogy – consider roles of architect, engineer, building codes, construction workers, etc.

Smart Sensors (Perotti)- *Autonomous smart sensors can assume significant roles in an ISHM architecture. A smart sensor shares similarities with a "non-smart" sensor in that they both produce measurement data; the smart sensor differs because it also possesses sufficient computing power to perform algorithmic assessment of its state to inform higher-level process(es) of the estimated quality of the data and of the ability of the smart sensor to perform its functions. Models for intelligent sensors need to be developed that include embedded health evaluation knowledge bases and associated assessment algorithms along with methodologies to embed learning of new concepts and behaviors. Other sensor issues include the need for novel total-system calibration methods to address the distributed voltage reference problem (i.e., every smart sensor has an individual voltage reference compared to the conventional data acquisition model where one-or few-high accuracy references are shared). Similarly, methods need to be developed to provide clock synchronization protocols for improving time references between sensors such as using IEEE 1588.*

Smart Sensors

1. What are your expectations of a smart sensor? Are they being met?

Roll-Up Summary
- Low PWF (multi-alt)
- Self-cal - self ID (TEDS)
- Noise Filtering
- Built in algorithm capable
- Convert to engineering units
- Window
- Self diagnosis
- Fault tolerance
- BW reduction
- Parameterization
- Compensation/linearization
- Intelligent data transfer (right data/right time/right quantity)
- Exchange data, information and knowledge
- Networking capability (multi mode) (communication)
- Long life
- Sensor, function (don't forget!)

HEALTH
- Quality of data
- Self health (self diagnosis)
- Anomalies

SHARED
- Smarts not in sensor
- Smarts in sensor

Oral Report for Smart Sensors – Q1

Observations
- Low power, multiple types of power (Trend)
- Self-calibration (truth)
- Self-identification (truth)
- Built-in algorithm capabilities
- Self-diagnostics/qualification
- Networking capability (truth – but different opinions on type of network)
- Long life (trend)
- Sensor functionality (truth)
- Quality of data (truth)
- Self-health (truth)
- Smarts in sensors, compared to smarts in node (truth)

2. What type and level of embedded capability do you think a smart sensor should have?

Roll-Up Summary
• Digitize/process data/data reduction
• Trending
• Requires U controller
• Knowledge base of behaviors and capabilities
• Send data – raw or filtered
• Provide confidence level of data
• Auto-calibration
• Memory/storage
• Ability to customize for application
• Self-ID
• Have a generic module for different types of sensors
• Fault detection at the processor level
• Communication with neighbor and higher level sensors
• Power management
• Time synchronization
• Compatibility with legacy sensors
• Report data and sensor health
• Bi-directional communication (for uploading parameters)
• Self-powered
• Wireless communication
• Reliability of sensor – reliability of system
• Secondary sensors for health determination
• Self-healing
• Re-program sensor
• Data collection dependent on system state

Oral Report for Smart Sensors – Q2

Observations
- digitize and process data
- embedded knowledge base/database
- transmit capability
- auto-calibration
- customizable
- communication
- time synchronization
- compatible with legacy sensors
- self powered
- wireless communications

3. What is the impact/benefit of a smart sensor?

Roll-Up Summary
- Required Distribution network (extra resources such as wiring
- Still need raw data @ high tiers
- Increase needed bandwidth
- Faster failure response times
- Might reduce computational request for high-level tier
- Longer time between calibration
- Significant reduce bandwidth processing requirements for rest of system
- Enable increase system complexity
- Adds a level of fault tolerance (locally)
- Provides increase reliability
- No single point of failure
- Distribute intelligence
- Performs like a firewall for anomalies
- Power management
- Modular
- Cost, size, complexity, power (negative impacts)
- More reliability, processing power, plug & play calibration/self-calibration, (positive impacts)
- Wireless
- Send only good data to next level
- Identities its problems based on data & knowledge
- Self-diagnosis – improve system effectiveness and overall $
- Increase availability
- Data conversion on sensors
- Programmable for different tasks
- Increase initial cost but decrease life cycle $
- Improved maintainability
- Improved measured accuracy
- Improved process and system reliability
- Reduced $
- Physical phenomena captured without delay

- Enables/helps ISHM overall
- Impact of a smart sensor is reduced bandwidth
- Saves weight
- Increases weight
- Reduces power
- Increases power
- Impact to infrastructure
- Impact to maintenance culture

Complexity – adds and enables
Reliability increase trend
Not being designed for hostile environments

Oral Report for Smart Sensors – Q3

Observations
- Requires distributed network resources (-)
- Still need raw data (-)
- Reduces BW requirements on the rest of the system (trend)
- Reduces complexity / increases complexity
- Increases reliability (trend)
- Better ability to localize anomalies
- Cost, size, complexity, power (+/-)
- Drive wireless technology
- Decreased lifecycle cost
- Improved measurement accuracy
- Saves weight / Increases weight
- Impact to maintenance culture
- Adoption of smart sensors affects overall system complexity (+/-)

Smart Sensors – group discussion
- Question about whether intelligence should be embedded at the sensor level or shared at a higher level
- Smart sensors are an enabling technology for ISHM
- Is a "smart sensor" really a smart sensor or a subsystem that includes sensors and processing (integration of separate components)
- Sensors have set BW so you don't want to lose sensor data BW in order to build in intelligence
- Need to define smart sensor versus smart sensor node
- Need to consider costs and other issues related to making "smart" sensors rated for the target environment. Issue is qualification of transducer verses transducer + processor.
- Embedding algorithms in the sensor will impact software V&V requirements because SW is isolated at the sensor instead of running on a shared computing platform.

Health Anomaly Databases (Schmazel)- *Detection of health and other types of fault behaviors in complex systems requires that a library of representative faults and fault signatures is available to those working in the ISHM field. Participants will describe their experience with developing such health databases and solicit ideas for ways to expand the available resources in this area and make them widely available. Expanding the general framework of the IEEE 1451.N series, opportunities exist to extend the innovation of the transducer electronic data sheet (TEDS) structure to include a health electronic data sheet (HEDS) that supports the ISHM architecture.*

Health Anomaly Databases

1. What transitional fault>>failure data sources exist? Who? Where?

Roll-Up Summary
- Shuttle PSRM Test Database and Burn Rate Motor Database (shuttle program or No. 1)
- Stennis DR database – NASA SSC
- Electronic industry should have a database (i.e. UL)
- Non aerospace – e.g. cement plan in South Africa that uses G2 and Smart Sensors
- PRACA – ISS, KSC? Problem recording and corrective action
- FAA anomaly report system   - airlines
- Repository of simulate fault information
- CAMS (Maintenance Database) Air Force
- REMIS – Air Force
- SSME/ACTS Boeing/MSFC
- Boeing airplanes (Seattle)
- Automotive Industry (Ford, GM – North Star)
- Data from vendors (should require it)
- AEDC, ARC, Plumbrook (GRC), LaRC
- Nuclear Industry
- Chemical 1
- DOE PHM COE Initiative Sandia NL
- RSG8 Boeing Canoga
- MSFC Test Systems failure data
    Operational data reduction center (ODRC) – complete database, not just anomalies
- Mukutart/DOD
- Launch facilities (Vanderburgh, Wallops, Kodiak)
- International community

Oral Report for Databases – Q1

Observations
- Shuttle and ISS data bases at NASA
- Commercial companies
- Government labs

Industry groups (Nuclear, electronics)

2. How do we ensure getting data we need for ISHM development by buggy-backing on component/subsystem life testing that occurs as a normal course in program development?

Roll-Up Summary

- Need data sets that contain faults
- For simulated data need real characteristics
- Complete data set information
- Standardize data format
- Available on server for multiple users with sorting capability
- Organization responsible for tracking and recording faults (management/commitment)
- Management agreement from vendors for anomaly data available (deliverables)
- Access to the expert
- Flow down ISHM requirements to SS level
- Provide funding to collect historical data from other programs/sources
- ISHM part of design process
- Standardize anomaly description
- Access to all historical data

Oral Report for Databases – Q2

Observations (trends)
- Need data that contains faults
- Complete data set information
- Need organization responsible for tracking and recording faults (need management commitment)
- Need vendor buy-in to provide anomaly data (truth)
- Funding needed to collect data

3. How do we make fault>> failure data available to a broad community of ISHM developers and respect the claims of proprietary information by contractors?

Roll-Up Summary

- Legal agreement (non-disclosure)
- Transform data to hide any proprietary information
- Limit access (firewalls)
- Need to mandate in contracts
- Create data access permission by group affiliation
- Pay for the data
- Mandated in contract
- Central repository with controlled access
- Make a database of composite data
- Creating a test program to generate fault data available to everyone (IEEE Buyer Test)
- If we can build a strong end-user coalition, (Data, DOD, Automotive, Oil) sharing can be mandated to vendors (provide waiting period to vendor affected by failure before information is made public)
- Make it available to people that need to know
- Liability issue is key

Oral Report for Databases – Q3

Observations
- Legal agreement
- Transform data to hide proprietary aspects
- Limit access
- Mandate in contracts and pay for the data
- Make data available to people who need it

Databases - Comments
- Only capture the data that we actually need to avoid proprietary information that might be included but not needed
- Create databases with different levels of access for different levels of proprietary content
- Liability is an issue – don't want provider of information to have a liability later because someone found something in the data. Need to hide details that would result in liability to the provider/manufacturer
- Power-by-the-hour (e.g. GE aircraft engines) was driven by warranty considerations
- Want to limit amount of nominal "good" data and concentrate on data with faults in it

Health Detection Algorithms (Schabacher)- *Embedding health metrics into smart sensors and other portions of an ISHM architecture requires that health anomalies from available databases be cataloged. Algorithms to detect anomalies must accommodate available hardware and software resources. Algorithm performance measures need to be developed so that appropriate algorithms can be selected for a given ISHM application.*

Health Detection Algorithms

1. What are measures of effectiveness and measures of performance for ISHM?

Roll-Up Summary

ROBUSTNESS

- How far in advance can you detect fault
- False positive/negative
- Frequency of detection
- Failure coverage
- Repeatability of fault detection
- Fault isolation
- Time to id fault
- Stability
- Time to respond to fault
- Environment range (of ISHM system)
- Efficient use of sensors
- Confidence in detection
- Avoid over-building system
- Decrease cost (system)
- COST – benefits
- Envelope of performance
- System availability
- SLOC
- Does it enable architectures not otherwise achievable?
- Scalability of algorithms
- Efficient use of
    - processor
    - memory
    - comm./network
    - PWR

COST ISSUES

- MTBF
- MTTR – turnaround time
- LCC

Response to unknown faults

Averted faults

Oral Report for Health Detection Algorithms – Q1

Observations
- Robustness (truth)
- Predictive capability
- Pfa and Pd
- Failure coverage
- Repeatability
- Fault isolation
- Efficient use of sensors
- Fundamental question about whether we are talking about and can separate ISHM algorithms and ISHM systems
- Cost (truth) – should reduce overall system cost and lifecycle cost
- System availability
- Single lines of code (SLOC)
- Scalability
- Efficiency of use

Response to unknown faults (system characteristic

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2. Is ISHM algorithm commonality possible? e.g. can a pump health monitoring algorithm for a rocket engine test stand be the same as for one on the International Space Station (ISS) and the Crew Exploration Vehicle (CEV)

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Roll-Up Summary
YES • Basic algorithm applicable but model changes • Possible but not preferable • At high level/with tools that can be applied to tailored to specific applications • If components are similar or processes are similar • Similar to software reuse • Shell/framework is portable but needs to be tailored to specific component • Portable if sensor independent and computationally efficient (design for worst case) • Prior experience applicable to new component NO • Depends on specifics of individual component • Depends on criticality   - critical request better monitoring YES/NO • depends on component failure modes

Oral Report for Health Detection Algorithms – Q2

Observations
- Yes and No
- Depends on composition of system
- Algorithm might be applicable with different reference models
- Possible but may not be preferable
- Depends on criticality
- Yes if components and processes are similar
- Can probably apply down (from more critical to less critical) but maybe not the other way
- Reusability may depend on approach to health monitoring (monitor individual components and integrate results versus monitoring entire processes)
- Ability to develop generic, reusable functions may be limited by time criticality and need to streamline code execution (executing more functions takes longer)

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3. Identify ISHM algorithms you know of? What is missing?

Roll-Up Summary

TRUTHS
- Beam
- Livingstone/Hyde
- Shine
- Rodon
- Teams
- Ladder Logic
- FDIR
- AIMS
- Prognostics & HMS
- AHMS (SSME)
- OPAD
- Case Based Reason
- Rule Based Reason
- RTVMS/ARTEMS
- LEM
- BIT testing
- Bearing Monitors
- BCA
- Power Generator Health Mgmt
- Image Processing for engine plume
- Test Stand Health monitoring algorithms
- AI Diagnostics relationship between components
- Detecting known & unknown faults
- Hydraulic system with ISHM SSC
- Redline detection
- Voting logic to avoid false alarms

TRENDS
  - CLASSES
- Model based reasoning
- Physics based algorithms
- Hybrid systems
- Statistical
- Neural Networks
  - MISSING
- Prognostics
- Integration/combination routines
- Scalable software
- System level reasoning
- System level capability after faults
- Common language for describing health
- Unified modeling language for ISHM, IVHM, NMS, etc.

NOVEL IDEAS
- Trends between data sets (long term)
- Prediction maintenance
- No gold standard for ISHM so no standard for ISHM algorithms so all have to be developed from scratch

Health Detection Algorithms – Q3

Observations
  - List of different algorithms and approaches (truths – because they exist)
  - Classes of algorithms
  - Missing
    o Prognostics
    o Integrating and combining algorithms at system level
    o Scalability
    o System level reasoning
    o Common language for describing health
    o Unified modeling language for health
  - Systems
    o Hydraulic systems
    o Redline detection
  - Missing
    o No gold standards
    o Ways to compare algorithms
  - Can we have algorithms without databases to compare performance

Communication Protocols (Brisco)- *Comparison and selection of communication protocols to best support ISHM applications can be based on existing standards or may utilize special-purpose protocols developed by NASA or a particular industry. For example, TCP/IP or UDP are available standard protocols; Marshall Space Flight Center has developed a time-triggered protocol to support mission-critical control loops. The performance of ISHM networks under representative loading needs to be evaluated to ensure that adequate performance is available.*

Communication and Protocols

1. What standards exist that apply to ISHM system?

Roll-Up Summary

- Synch   1553   1773   RS485,232
              NTP   TTP   PTP
- Asynch   Ethernet, 1451, CAN, TCP/IP UDP   NDDS
- Many out there, none exclusive
- CAN, CORBA object exchange
- NATO STANAG (Naval Vessels)

Oral Report for Communication Protocols – Q1

Observations
- Synchronous and Asynchronous fabrics exist
- Data link protocols (Ethernet)
- Communication/Network protocols (TCP-IP)
- High level protocols riding on top of the network protocols
- Many protocols out there, but none are exclusive
- Need for time determinism for time critical control
- Need for open standards for non-time critical control
- ISHM requirements probably fall under both time critical and non-time critical categories
- Non-time critical typically costs less so only make things time critical if absolutely necessary

2. What needs must be addressed by new protocols to be suitable to support ISHM functionality?

Roll-Up Summary

- Scalability (easily)
- Deterministic
- Reliable
- Fast
- Ease of integration between systems with different communication requirements
         (legacy systems)
- Fault – tolerant
- Support large # of nodes
- Wiring/weight concerns

- Time synchronization support
- Standardization of health information communication
- Easy to interface
- Disagree with having <u>NEW</u> protocol
- Need standardization
- Flexibility to handle new development
- Robust physical components (more margin)
- Low error rate
- Variable packet size
- Reconfigurable
- Speed/bandwidth
- Support different levels of abstraction (raw data vs. highly processed data)
- Autonomous and asynchronous communication for high level information
- TEDS capable
- Must address health information of sensor as well as data
- Time – stamping
- Support distributed calibration cap
- Standard changes with ISHM level
- Need large database with tools for query (smart engineering)
- Accommodate different levels of time synchronization

Oral Report for Communication Protocols – Q2

Observations
- Ease of integration (truth)
- Standardization of health information (trend)
- Support both raw and processed data
- TEDS capable
- Must address health information for sensors with data (trend)
- Standard may be different for different levels of the health management system
- Accommodate different levels of time synchronization

> **3. What kind of interfaces are needed between ISHM and human control? Between ISHM and autonomous control?**

Roll-Up Summary
<u>Human</u>
- Visual
- Interactive
- Tactile
- Voice – for hands-free
- Hierarchical drill-down
- Intuitive
- Touch-screen
- Provide support information
- Continuous state & health information
- Virtual-reality/multimodal

- Alarm
- Ability to trouble shoot –corrective action & associated procedures

<u>Autonomous</u>
- Close-loop time critical
- Confidence
- Operator intervention
- Adjustable

  Non-Time Critical
  - Asynchronous control
  - Support the diagnostics based on probabilities
  - Common communication protocol

Oral Report for Communication Protocols – Q3

Observations
  - Broken down into ISHM-human interface and ISHM-autonomy interface
  - Human interface
    o Visual (hands free)
    o Interactive
    o Voice (hands free)
  - Autonomous
    o Closed-loop for TC control
    o Need confidence information
    o Need to provide for operator intervention – asynchronous
    o Support diagnostics
    o Common communication protocol between ISHM and control

Communication Protocols – Comments
  - Are we suggesting that we need to have multiple communication protocols on a single aircraft? What are the implications on spacecraft design, complexity, cost, etc.
  - Space station uses multiple protocols
  - Using standards reduces cost of software development – particularly if you can reuse software modules developed for ground applications

Integration and Validation (Workshop)- *The separate components of an ISHM need to be integrated in such a manner as to preserve functionality and avoid unnecessary conflict or inefficiency when combined together. Important elements include the operating system environment, overall computational and input/output bandwidth, etc. Similarly, an ISHM system needs a methodology to validate design decisions and to predict performance. An ISHM test suite can consist of simulation tools and physical test facilities such as those available at a number of NASA centers.*

Integration and Validation

1. How should ISHM Requirements be specified?

Roll-Up Summary

- From systems group
- Program level – trickle-down
- Reliability/Availability Goals
- Practice – difficult to estimate/accuracy
- Interoperability
- Data-Sharing
- Degree of Integration
- Requirements specified with functional capability – response time requirements
- Ops concept

NASA - level 1 requirements
-     ▪ availability
-   - level 2
-     ▪ reliability (MTTF,R)
-     ▪ turnaround (MTTR)

Contractor - level 3
Responses ▪ technical approach
-     ▪ specific technology

- Coverage of anomalies
- Knowledge and information content
- Interface requirements for integration
- Process improvement

Oral Report Integration and V&V – Q1

Observations
- Two perspectives – 1) Functional Engineering POV
  - Systems group
  - Program level
  - Reliability/availability – difficult to estimate beforehand
  - Interoperability
  - Data sharing
  - Degree of integration

- How NASA does it – from Ops concept
  o Level 1 (rolled up from level 2)
    ▪ Availability
  o Level 2
    ▪ Reliability (MTTF)
    ▪ Turnaround (MTTR and recertification time)
  o Level 3 (how the contractor responds)
    ▪ Technical approach
    ▪ Specific technologies

2. How could an ISHM capability be validated?

Roll-Up Summary
- Different V & V requirements based on criticality
  - careful evaluation of criticality
- Software simulation
- Hardware-in-the loop
- Component testing
- System level testing
- Formal verification for software (mathematical)
- Measure resource usage
- Look for opportunities for non-interference to reduce V & V requirements
- Need to simulate impact or influence of other subsystems
- 3-ways to test ability to center faults
  1. simulation in software
  2. induce fault in hardware
  3. run to failure
- ISHM system vs. subsystem validation

Integration and V&V – Q2

Observations
- Should have different V&V requirements based on level of criticality (Truth)
- Several different levels of testing (Truth)
  o Software simulations
  o HW in the loop
  o Component testing
  o System level testing

3. How should benefits versus cost of ISHM capability be measured and determined?

Roll-Up Summary

- Define a Baseline
  - Figures of Merit # of anomaly detection
    - Availability
    - Reliability
    - Safety
    - Expendability
    - Cost savings
    - Cost of building
    - Cost of maintenance
- Measuring of differences to baseline according to the figure of merits
- Estimate Impacts
- Business goals
  - in depth economic analysis
- Tested vs. actual system
  - based on some metrics identity problem, cost of lost opportunity avoid problem, cost of wasted resources detect problem quicker, salvage the mission, more usage of system
- Costs of ISHM
  - software
  - mass
  - power
  - increased processing & storage, BW development of new hardware
  - Cost historical information (prognostics)
  - Cost of validation/verification
  - Cost of operator training
- Tie into net present value of future unrecoverable failures (very difficult)

Oral Report Integration and V&V – Q3

Observations
- Define baseline and figures of merits
- Measure differences to baseline and estimate impacts of differences
- Need to have business goals (e.g. what does sustainability mean?)
- Need to define costs of ISHM
  - Development
  - Testing
  - Personnel training
- Tie cost of future potential failures into NPV
  - Example – cost of return to flight

THE GREAT ROTATION PEER-TO-PEER PROCESS DESCRIPTION

SUBTILE:
A classic design that enables large groups of people to discuss important organizational issues in a short period of time

SYNOPSIS:
In any planning process the ability to diagnose an organization's real issues is a key element to a successful strategic plan. Unfortunately, many organizations use only traditional tools (questionnaires, small focus groups) to try to uncover what is on people's minds.

Many leaders and administrators want to involve employees and other stakeholders in diagnosing issues and discussing potential strategies. Their dilemma is that they are not sure how to accomplish this in focused and efficient ways. They fear the chaos, disagreement, and waste of time that can easily be the result when large numbers of people are gathered to discuss issues.

The Great Rotation activity provides a successful way to engage large groups of people in a productive, collaborative, and highly participative manner. It allows for full participation of all participants and provides the structure necessary for the discussion to stay focused and on track. The activity stimulates thinking, develops listening skills, fosters collaboration, and identifies common ground.

GOALS of the Great Rotation:
- To gather information from all the participants in a relatively short period of time
- To prioritize information and develop common ground
- To identify organizational issues that need to be dealt with effectively
- To insure the full participation of all the participants in the diagnostic activity

Simply defined, the Great Rotation is a large group discussion that enables participants to create meaningful information, diagnose the organization's issues, and engage in problem solving.

The Great Rotation - Goals

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GOALS of the Great Rotation:

- Insure the full participation of all the participants
- Gather information in a relatively short period of time
- Prioritize information and develop common ground
- Identify organizational issues that need to be dealt with effectively
- Quickly summarize the results for sponsors to act upon
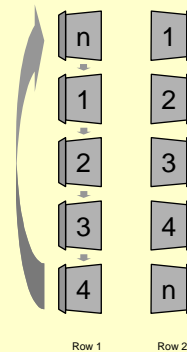
THE ACTIVITY:
(Explained assuming 40 participants)

1. The facilitator must decide the important questions that need to be discussed by the participants. The questions will create the heart of the interview design. The following are some questions that have proven to be effective in a planning process.
- Please identify at least three things this organization does well, and, in your opinion should continue to do.
- From your perspective, what are three things that limit the effectiveness of this organization?
- What have you heard from customers that worry you most?
- If you were the boss, what are three things you would try to change immediately in order to improve organizational effectiveness?
- What are some opportunities in the marketplace that we should be taking advantage of?
- What are some ways we can continue to improve communication throughout this organization?
- Why do you continue to work here?
- What do you believe are the truly "lived" values of this organization?

2. Arrange chairs in pairs of rows facing one another, with the number in each row determined by the number of questions to be discussed. In the example below, we have 5 questions for 40 participants. In this case, there would be 4 Row 1's and 4 Row 2's.

Step 1 – if you have 5 questions put 5 seats in a row with 5 seats facing them
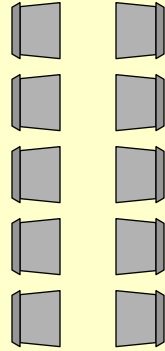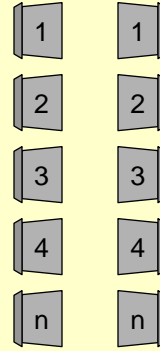
Step 2 – assign one question to each peer according to their seat
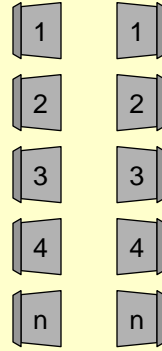
**Step 3** – make peers feel more comfortable using a team ice breaker

Row 1	Row 2

Row 1	Row 2
1	1
2	2
3	3
4	4
n	n

Row 1	Row 2
1	1
2	2
3	3
4	4
n	n

If you have some extra participants, you can put them on the end of Row 1, because this row will not move during the activity.

3. Have participants sit in the chairs. Make sure there is a piece of paper with one of the questions printed at the top of the page in each chair. Each person in each row will have one question that is his or her question for the entire exercise, and will interview the person sitting across from him or her on that question.

4. Row 1 will begin interviewing Row 2. Participants should take notes regarding what the interviewees have to say and can probe to make sure they understand the responses. At the end of 5 minutes, they will switch roles, and Row 2 will then interview Row 1 for 5 minutes.

ARL Penn State — The Great Rotation – Execute

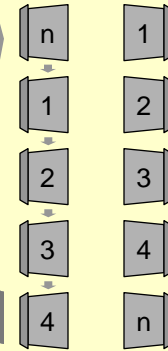Step 4 – peers in row 1 ask their questions to peers in row 2 and record answers (3-5 minutes)
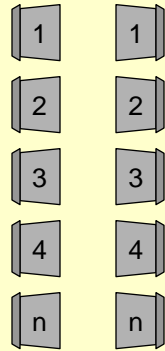
Step 5 – peers in row 2 ask their questions to peers in row 1 and record answers (3-5 minutes)
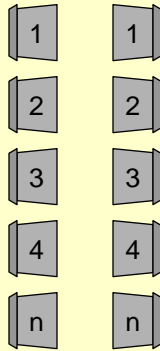
Step 6 – peers in row 1 rotate. *Repeat* for each question (total time is n x 10 minutes)

Result – each peer has answered each question once and has collected n answers to their question

5. After people in Row 1 and Row 2 have asked and answered the questions (10 minutes), the participants in Row 2 are asked to move one seat to the right and the person at the end of the row rotates to the rear. The people in Row 1 remain stationary.
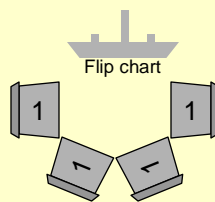
6. Now each person has another person to interview on his or her question and the opportunity to be interviewed on another question. This process continues until all the participants have been interviewed on all the questions. Each participant will have interviewed 5 other people. You now have a 100% sample from everyone in the room.

**ARL** Penn State — The Great Rotation – Structure Information

Step 7 – peers individually organize their notes
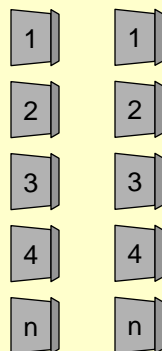
Step 8 – peers meet in numbered groups for 30-60 minutes to discuss, analyze and classify results and record conclustions

Step 9 – one peer from each numbered group provides a 5-10 minute summary to the overall group

Flip chart

Each team selects
-facilitator
-scribe
-timekeeper
-briefer
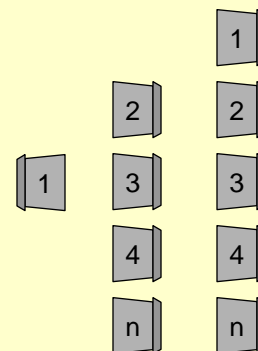
7. The next step is to have all the participants sit quietly with their data for about 10 minutes and organize their information. They are to look for Truths, Trends, and Unique Ideas. Truths are defined as those answers they received from every person they interviewed. Trends represent answers that were given consistently by at least half of the persons interviewed. Unique Ideas are ideas that were communicated by one individual, but represent a different or unique approach, perspective, or idea.

8. After individuals have organized their information into Truths, Trends, and Unique Ideas, have participants join with others who have the same question. In this model you would identify 5 stations (one for each question) throughout the room, and have 8 participants at each station.
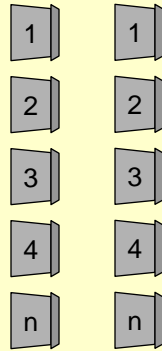
9. Tell these smaller groups to pool their information and reach agreement as a group on the Truths, Trends and Unique Ideas for their question. (They should remember that each small group of 8 now represents the input of all the participants, for their particular question). Their goal in the next 30 minutes is to discuss the information and put the Truths, Trends, and Unique Ideas for their question on newsprint.

When participants are working with others who have the same question, make sure that you identify for each group: one <u>presenter</u> who will present the group's information to the larger audience; one <u>recorder</u> whose job is to capture the group's information on newsprint; one <u>timekeeper</u> who will remind the group about the time left for the task (about every 10 minutes); and one <u>facilitator</u> whose job it is to keep the group on the task at hand and insure everyone's participation. Having these specific roles defined and people identified enables the group to self-manage.

Let groups struggle with what is a Truth, Trend or Unique Idea. It is their data. It was formulated from their questions and they know better than you whether it is a truth or not. Encourage the groups to disclose information.

10. The most important instruction to give is for the group to prepare a presentation of its data for the large group. They must pick a spokesperson to represent the issues to the larger group clearly and concisely. Encourage the group to prepare a 2– to 3–minute skit on some aspect of the data. The creativity and humor released from this exercise stimulates a tired group, and the presentations are usually hilarious, followed by a serious presentation of real issues. It is often easier for a group to hear tough data if it can laugh at itself and not take itself too seriously.
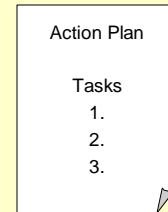
ARL Penn State

The Great Rotation – Prioritize and Take Action

Step 10 – peers individually assign priority to the list of needs

1 1
2 2
3 3
4 4
n n

Row 1   Row 2

Step 11 – facilitator summarizes priorities and provides report to sponsor

Summary Report

Priorities
1.
2.
3.
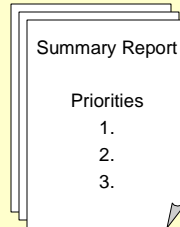
Step 12 – sponsor distributes report, request feedback and develops action plan

Action Plan

Tasks
1.
2.
3.

11. After all the presentations, the facilitator can lead a short discussion about people's reactions to the information presented. This helps brings closure to the activity.

12. Participants need to know where all this valuable information will go. They have worked hard and generated quality data. The facilitator needs to be able to explain to them what the next steps will be.

TIME REQUIRED:

15 minutes	Introduction, goals, and explaining the logistics of the meeting.
60 minutes	Participants interview each other for 5 minutes per question. In this example, the rotation would take 60 minutes. You need to allow time for people to move from chair to chair.
10 minutes	Participants organize their data by self.
30 minutes	Participants work with other people who have the same question and create Truths, Trends and Unique Ideas. Allow extra time if you have groups do skits.
30 minutes	5 minutes per group presentation
15 minutes	Facilitator leads a short discussion on participants' reactions.

Total time: approximately 2.5 hours.

TIPS FOR THE FACILITATOR:

1.   Having participants help you create the questions is both strategic and collaborative. You can choose a small team of 4 to 6 participants and spend 30 minutes coming up with the best questions possible. Participants appreciate knowing that hey are dealing with questions that have been designed for their particular situation.

2.   The quality of the questions is a key element in this activity. If you ask engaging and tough questions, you will get excellent information and build credibility. If the questions are nice and safe, you will get okay information and lose a wonderful opportunity to engage participants' minds and hearts.

3.   Do not attempt to run this activity if someone is missing from one of the chairs. Either cut out a question from all the groups or get someone to sit in the empty chair.

4.   Logistics is a key element of this design. Make sure you have everything very well organized.

   • Have enough paper and pens for all participants.
   • Make sure the stations and easels are set up before participants with the same question get together.
   • Make sure that before the small groups begin their work they have identified the self–managed roles of presenter, recorder, timekeeper and facilitator.

5.   Interviewers must be clear on their roles. The goal is to listen and accurately record the respondent's opinions. Participants must resist the urge to discuss or debate the ideas being shared.