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Integrated System Health Management (ISHM): Systematic Capability Implementation

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Abstract* – This paper provides a credible approach for implementation of ISHM capability in any system. The requirements and processes to implement ISHM capability are unique in that a credible capability is initially implemented at a low level, and it evolves to achieve higher levels by incremental augmentation. In contrast, typical capabilities, such as thrust of an engine, are implemented once at full Functional Capability Level (FCL), which is not designed to change during the life of the product. The approach will describe core ingredients (e.g. technologies, architectures, etc.) and when and how ISHM capabilities may be implemented. A specific architecture/taxonomy/ontology will be described, as well as a prototype software environment that supports development of ISHM capability. This paper will address implementation of system-wide ISHM as a core capability, and ISHM for specific subsystems as expansions and evolution, but always focusing on achieving an integrated capability.

I. INTRODUCTION

The term Integrated System Health Management (ISHM) is used to describe 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. In the case of NASA, 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 functional capability level (FCL) indicates how well a system can perform the following suite of functions:

List of functions:

- Evaluate condition of system elements.
- Detect anomalies and their causes.
- Identify overall system state.
- Predict system impacts.
- Recommend responses to mitigate anomaly and failure effects.
- Communicate contextual and timely DIaK and situational awareness to system elements and system operators.

Implementation of ISHM capability is not a once-and-done task. It has to be systematic and evolutionary. Affordable and sustainable systems must, by definition, have embedded ISHM capability. The following sections describe an approach defined by three activities that form the basis for implementation of a credible on-board ISHM capability. These activities are: Definition of the core elements, systematic implementation approach, and the role of supporting infrastructure such as testbeds.

II. CORE ELEMENTS FOR ISHM IMPLEMENTATION

ISHM capability is primarily a data, information, and knowledge (DIaK) management problem, integrated throughout a system. Attempts to implement ISHM in the past have primarily focused on data, and have not emphasized integration across all elements that make up a system. The following capability must be met:

Capability list:

- 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.

Figure 1. Distributed Hierarchical Architecture with Intelligent Elements

A. *Architecture, taxonomy, and ontology (ATO) for DIaK management.*

In order to implement credible ISHM capability, ATO to meet the capabilities cited in the list above must be defined. Typically, architectures have been centralized and focused on data. Hence, data from all sensors is individually wired to a central signal processing unit, for use in control and monitoring activities. This approach has worked well, but ISHM for higher complexity systems, can be more efficiently developed using distributed and/or hierarchical architectures. The need and urgency to define a common architecture for ISHM is evident from efforts supported by the industrial community and the Department of Defense. These entities have engaged in defining an architecture (as well as standards and an ontology) for condition-based maintenance, denominated Open Systems Architecture for Condition-Based Maintenance or OSU-CBM [1] (Figure 1). Such architecture is distributed, but not hierarchical, or at least, hierarchy is not mandated by the architecture. This approach is advantageous in that any element is linked to another element directly over the same bus, but it can result in inefficiencies as a consequence of higher processing requirements for each element and very high bus traffic. Another suitable architecture for ISHM is shown in Figure 2 [2]. This distributed-hierarchical architecture (DHA) can be used to represent any complex system, and includes the necessary paths and elements to meet the requirements in the list above. Intelligent Sensors and Components [2,3] share a bus that provides connectivity among them, as well as with processes and controllers. The architecture is "Process-Centered," since process models are central to the performance of ISHM related tasks as described in the list under the Introduction Section. The definition of process is generic as it may represent an analytical equation, a logic rule, a Fuzzy Logic representation of a process, statistical relationships, etc.

The DHA is also defined in terms of "Intelligent Elements." This is necessary, because the underlying inspiration for the system is that each element be capable of determining its health, using local DIaK as much as possible, but accessing global DIaK when needed.

Although the elements in the DHA appear to be physical units, they may be implemented as virtual entities. In fact, the entire DHA may be implemented in one central processing unit, using virtual elements such as virtual intelligent sensors, virtual intelligent components, etc. In this manner, one may apply the DHA to legacy systems without physically changing any of its elements.

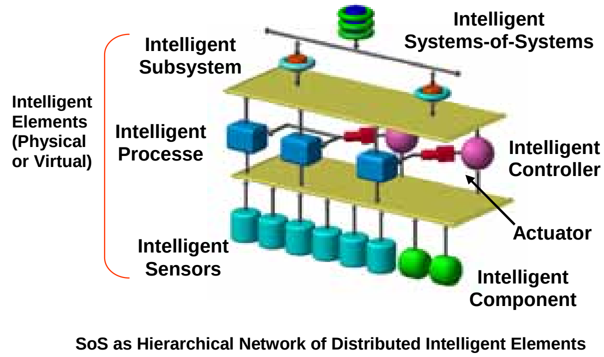

Figure 2. Distributed Hierarchical Architecture with Intelligent Elements

A taxonomy based on the DHA should make possible the List of Capabilities in Section II in a way that supports incremental capability augmentation and incremental expansion. An object-oriented taxonomy is well suited, since the elements in the architecture can be defined as object entities with embedded local assets and communication attributes to determine their own health. Along with object orientation, a suitable software environment is needed with

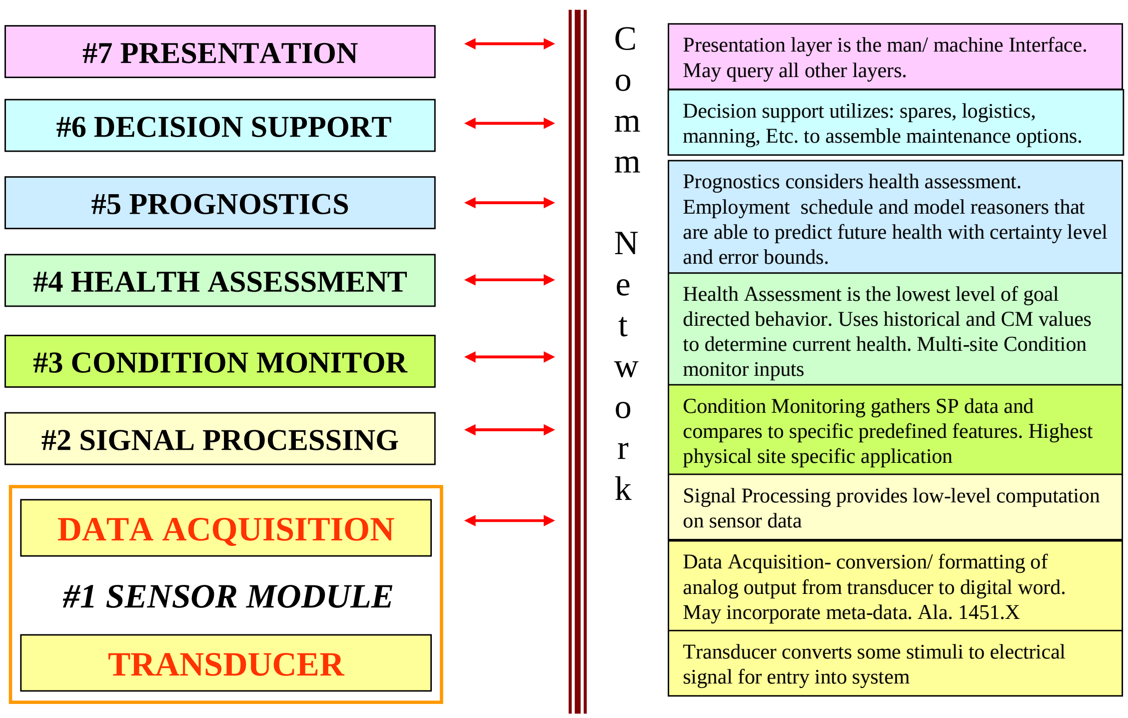

Figure 1. Open Systems Architecture Enables Health Management for Next Generation System Monitoring and Maintenance Development Program [1].

tools to manage DIaK. These tools should include those normally available in artificial intelligence applications (inference engine, structures for management of symbolic and qualitative information), as well as tools for analytical/engineering applications.

Ontology also needs to be defined, since a specific language is needed to ensure effective and accurate communication. Ontologies are implemented by standards and protocols. An example is the TEDS or Transducer Electronic Data Sheet standard (IEEE 1451.x). This standard defines a common set of specification-related words and the means to organize, store, and share information normally available in specification sheets and/or manuals.

B. Standards

Standards to manage DIaK are currently being developed by IEEE and others [1-4]. These standards need to be augmented to include health information, and also to cover other elements, such as components (valves, etc.), actuators, controllers, and processes.

The area of smart sensor development is active, with one important focus being the definition of sensor interfaces to allow “plug and play.” IEEE has developed an extensive set of standards for “smart sensors” including IEEE 1451.0-.5 [3]; IEEE 1451.6 is in development. The nature of these standards has been widely published [5]. For our purposes, the presence of an embedded processor in a sensor application does not automatically satisfy the definition of “smart” unless it includes some level of compliance with the IEEE 1451.X family. For example, [6] describes a “smart” sensor, but the application lacks conformance to the IEEE 1451 standards. In comparison, [7] describes a smart sensor that does conform to IEEE 1451. We suggest reserving the use of “smart” for the latter applications.

We have adopted a generalized model of the IEEE 1451 smart sensor that consists of the transducer (XDCR) hosted by a transducer interface module (TIM), which provides signal conditioning and data acquisition along with being the repository of a collection of “electronic data sheets” including transducer (TEDS), health (HEDS), and component (CEDS). The TIM communicates over a transducer independent interface (TII) with a network capable application processor (NCAP). The NCAP in turn provides network interface to the wider application system. Figure 3 shows the block diagram of a representative smart sensor.

III. SYSTEMATIC IMPLEMENTATION

Implementation of ISHM capability must follow a process, which also requires a change in mindset with respect to the classic engineering design process.

A. Engineering design process

Insertion of ISHM capability must be considered throughout the design process, from concept to product, to operations, to maintenance, and to decomission. Just like prior evolutionary changes in the design process, e.g. “Design for Manufacturing,” or “Design for Manuracturability,” or even “Design of Mechatronic Systems;” there is a need for “Design for ISHM.”

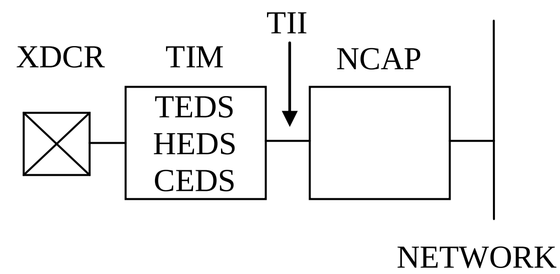

Figure 3. Block diagram of an IEEE-1451.X smart sensor showing the transducer element (XDCR) supported by the TIM, which is in turn interfaced to the NCAP via the TII. The TIM also stores various electronic data sheets.

Any product design process should be ISHM-Minded, hence, for every element of a system, one should ask 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.

When a product is provided, it should include all ISHM related information

B. Implementation of core elements

ISHM is rarely implemented at a high functional capability level (FCL). In fact, a method or approach to measure FCL has not yet been established. However, it is reasonable to assume that ISHM capability must be implemented incrementally, as it is about embedding DIaK and the ability to manage DIaK. Implementing ISHM capability on-board a system may be paralleled to a person acquiring a new skill, which takes time and is built upon initial basic skills. Hence, the question we wish to answer in this section is how to begin implementation of ISHM capability.

Regardless of whether one is embedding ISHM capability on a legacy system or a yet-to-be-built system, the following elements must be implemented:

- Architecture/Taxonomy/Ontology (ATO).

- Standards and protocols.

Beyond this, one must select a suitable software environment able to support the List of Capabilities in Section II. Once these core elements are in place, it is a matter of embedding information and knowledge, including processes and approaches, in order to have the ISHM perform the List of Functions in the Introduction Section.

C. Systematic augmentation of capability

Initial capability of an ISHM system might just be a support capability that makes easily available to the user, information that is normally provided in data sheets, manuals, and product descriptions. The IEEE 1451.x Transducer Electronic Data Sheet (TEDS) standards are especially suitable for this implementation, as far as transducers are concerned [2-5]. The standards need to be expanded to include Component electronic Data Sheet (CEDS), Actuator Electronic Data Sheet (AEDS), and perhaps others as well [2].

Next, one can begin to implement process models (rules, algorithms, etc.) and begin to employ reasoning to infer health related information in an integrated manner. For example, one may be running a running standard deviation algorithm to determine noise level in all signals. One should be able to easily compare noise levels in elements that share a physical location to infer, perhaps, that wires in one sensor are loose.

The FCL of the ISHM never reaches 100%, because one can never embed enough DIaK to ensure that all possible anomalies will be detected and identified. Hence, FCL is incrementally augmented as new methods and technologies become available.

IV. TESTBEDS AND ON-BOARD ISHM

Testbeds are always needed to develop, mature, and validate products, especially products that require a high degree of reliability. Testbeds for ISHM, however, are unlike others. 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. One difficult problem is that it is impossible to reproduce all possible anomalies, or even worse, many anomalies are not known or understood. This is a key validation problem, and is just beginning to be addressed [8]. ISHM capability is built using many proven technologies, and a few core, yet un-proven technologies that address the integration, intelligence, and on-board aspects. Testbeds required to elevate the Technical Readiness Level (TRL) of technologies addressing these aspects are unique and different from typical testbeds.

A. Testbed requirements

Different types of testbeds perform functions that lead to incremental and methodic implementation of ISHM capability both, on ground operations systems, and on space platforms and vehicles. At research facilities, testbeds must be adequate to prove the technologies and capabilities under simulated scenarios, and if possible use data and information from real systems, especially from ground testbeds. At operations centers, testbeds are the complex systems within the facilities themselves (ISS, RETS, Launch Facilities). These are complex systems in operation, well characterized and documented (specifications, descriptions, procedures, models that describe the processes from multiple perspectives and at multiple degrees of granularity), with historical DIaK describing anomalies and normal operation, and algorithms to detect the anomalies. Use of ground test and operations facilities and the ISS as testbeds provides two main benefits: (1) the facilities themselves are updated/enhanced with embedded ISHM capability, and establish credibility with operators, leading to a natural migration to flight systems, and (2) the facilities are used to develop, test, and validate ISHM technologies.

A very important mode of use of operational testbeds is the Non-Interference Mode (or Shadow Mode), whereby the testbed is being used for other projects, and the ISHM system has access to all DIaK from the testbed, and can execute all the functions in the List of Functions of Section I at gradually increasing FCLs.

In the case of NASA, primary ground testbeds for ISHM include the rocket engine test stands (RETS) at the NASA Stennis Space Center in Mississippi, the International Space Station (most operations are done from ground at Mission Control), and the launch facilities with permanent systems that support launch operations at NASA Kennedy Space Center. There are many laboratory testbeds, but the Advanced Diagnostics and Prognostics Testbed (ADAPT) at Ames Research Center has been recently implemented to support ISHM R&D activities.

B. Development and validation in testbeds

Development and validation of low TRL technologies can be done in laboratory testbeds. However, development and validation of an operational ISHM requires higher complexity testbeds such as those represented by operational facilities (e.g. RETS). Not only do developers have to be satisfied with the ISHM implementation, but also users. In fact, users and developers should work together in order to implement a credible capability. It is also the most efficient approach to move the technology from operation testbeds such as RETS or the ISS to flight systems, as these technologies are carefully verified by developers and users. The issue of validation of ISHM capability is, in fact, a very difficult one. For more information on validation and verification of ISHM systems, please see [8].

C. Development of on-board ISHM capability

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

D. Sustained improvement of ISHM capability

As ISHM capability is evolutionary, that is, it is meant to achieve higher and higher FCL during the design phase, and throughout the operational/maintenance cycles of the system. This incremental augmentation of FCL needs to be supported by continuous research, development, test, and validation activities supported by the testbeds. Users and experts must continue the process of augmenting capability that is developed through the activities cited in Subsections A thru C.

V. CONCLUSION

Development of embedded ISHM capability on systems can be done now, using existing technology, and maturing the following core elements that address integration and embedding of intelligence: (1) definition of architecture, taxonomy, and ontology; (2) definition of standards and protocols for management of DIaK across all elements of a system; and (3) use of a software environment suitable for "intelligent applications," with tools for management of DIaK for networked elements, and not just data (typical scientific tools), or just qualitative information (typical artificial intelligence tools), or centralized approaches (as opposed to distributed). Furthermore, appropriate testbeds must be used at each stage of development, where operational testbeds become essential in maturing and validating the technology prior to porting to flight systems. Operational testbeds are also existing resources and do not require much investment to be used for this purpose. Furthermore, a systems approach must be followed to design, operate, maintain, and retire systems with ISHM capability. The potential benefits from this approach include increased reliability, reduced costs, and sustainable and long-life systems.

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