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An Assessment of Integrated Health Management (IHM) Frameworks

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Abstract. In order to meet the ever increasing demand for energy, the United States (U.S.) nuclear industry is turning to life extension of existing nuclear power plants (NPPs). Economically ensuring the safe, secure, and reliable operation of aging nuclear power plants presents many challenges. The 2009 Light Water Reactor Sustainability Workshop identified online monitoring of active and structural components as essential to the better understanding and management of the challenges posed by aging nuclear power plants. Additionally, there is increasing adoption of condition-based maintenance (CBM) for active components in NPPs. These techniques provide a foundation upon which a variety of advanced online surveillance, diagnostic, and prognostic techniques can be deployed to continuously monitor and assess the health of NPP systems and components. The next step in the development of advanced online monitoring is to move beyond CBM to estimating the remaining useful life of active components using prognostic tools. Deployment of prognostic health management (PHM) on the scale of a NPP requires the use of an integrated health management (IHM) framework—a software product (or suite of products) used to manage the necessary elements needed for a complete implementation of online monitoring and prognostics. This paper provides a thoughtful look at the desirable functions and features of IHM architectures. A full PHM system involves several modules, including data acquisition, system modeling, fault detection, fault diagnostics, system prognostics, and advisory generation (operations and maintenance planning). The standards applicable to PHM applications are indentified and summarized. A list of evaluation criteria for PHM software products, developed to ensure scalability of the toolset to an environment with the complexity of a NPP, is presented. Fourteen commercially available PHM software products are identified and classified into four groups: research tools, PHM system development tools, deployable architectures, and peripheral tools.

1. Introduction

As of March 2012, there were 436 nuclear power plants (NPPs) operating in the commercial global fleet [1]. The average age of these plants, which started operation with 30- or 40-year licenses, is now over 26 years [2]. To meet the increasing demand for electricity with an aging fleet, there is a growing interest in longer term operation (LTO) of these valuable existing resources, in addition to building new plants.

As of April 2012, fourteen of the 104 plants in the United States (U.S.) [3] had moved into extended operation (past 40 years); license extensions to operate from 40–60 years have now been granted for 71 plants at 40 sites. An additional 15 plants at 11 other sites are currently undergoing review to extend their licenses to 60 years, and 14 more are expected to apply for license extensions in the next five years [4]. Many other countries are also considering an additional 10 or 20 years of operation for their plants. Although the U.S. Nuclear Regulatory Commission (NRC) recently approved plans to build the first two new NPPs in the U.S. in more than 30 years, their primary focus remains on the long-term operability of existing NPPs. In fact, the U.S. is now considering a second 20–year license extension (from 60–80 years) for the current NPP fleet.

The safe, secure, and reliable operation of aging NPPs presents many challenges. There have been various meetings discussing the issues, including a 2009 Light Water Reactor Sustainability (LWRS) Workshop, which identified online monitoring of active and structural components as essential to the better understanding of the challenges posed by aging NPPs [5]. Operators of these aging NPPs need information on the condition of structures, systems, and components to better manage power-plant life holistically, adjusting operating conditions to reduce the impact of stressors that cause degradation. In managing systems in plants there is increasing adoption of condition-based maintenance (CBM) for active components. Such techniques provide a foundation upon which a variety of advanced online

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surveillance, diagnostic, and prognostic techniques to continuously monitor and assess the health of NPP systems and components can be deployed.

Active components are managed under a maintenance rule. The use of online monitoring for fault detection and diagnosis in a condition-based approach identifies components that need to be replaced or repaired based on condition, rather than age. Current practice uses signatures and pattern recognition to identify anomalies and off-normal conditions. Moving beyond identification of "faults" is the development of fault degradation models and prognostic methods that provide estimates of remaining useful life. The deployment of prognostic methods allows for use of more proactive Prognostic Health Management (PHM) strategies, where components are opportunistically repaired or replaced based on the estimated time of failure. The aerospace and defense communities have demonstrated that PHM can bring significant advantages in terms of availability, enhanced safety, and reduced fleet operation costs [6],[7]. CBM is successfully being deployed in nuclear plants and the implementation of these proactive prognostic technologies in NPPs is expected to benefit the quest to maintain high capacity factor, shorten planned outages (currently about 40 days), maintain safety, and facilitate life extension in existing plants.

Implementation of PHM in existing NPPs poses many challenges, however, and to be accepted must be initially demonstrated with a deployment of a minimum of additional sensing capabilities. The Electric Power Research Institute (EPRI) has already demonstrated the feasibility of online monitoring at several participating U.S. nuclear power plants, including those at Harris, Limerick, Salem, Sequoyah, Three Mile Island, and V.C. Summer [8],[9]. Additionally, online monitoring has also been implemented in Europe, both at British Sizewell B and Electricité de France nuclear facilities [9]. There are already known to be significant opportunities to deploy new technologies when upgrades, including modernization of instrumentation and control systems, are implemented at existing facilities. The economic benefit from a predictive maintenance program can be demonstrated from a cost/benefit analysis. An example is the program for the Palo Verde Nuclear Generating Station [10]. An analysis of the 104 U.S. legacy systems has indicated that monitoring and diagnostics has the potential for savings of over $1B per year when applied to all key equipment [11].

The availability of low-cost wireless sensor technologies makes the broad deployment of PHM across the U.S. nuclear industry more feasible, enabling rapid deployment of multiple sensors for condition monitoring. There has been research work that established feasibility of its use in pump monitoring, where wired and wireless data were collected on the same systems [12]. To date, wireless sensor technologies have been implemented in a few U.S. NPPs, including those at Limerick, San Onofre, and Comanche Peak [13],[14]. In addition, work has also been conducted to demonstrate the technology with rotating equipment in research reactors [15].

Current state-of-the-art for online monitoring in NPPs includes leak monitoring and systems that measure reactor noise, acoustic signals, and vibration in various forms [16]. Measurements of several reactor environmental parameters (e.g., temperature, pressure, neutron flux) also occur online [17]. Additionally, some aspects of sensor calibration are also addressed with online monitoring activities [16],[18]. When the state-of-the-art is reviewed [19],[20], it appears that many, if not all, active components (e.g., pumps, valves, motors, etc.) in a NPP can potentially be well managed, routinely diagnosed, analyzed, and upgraded as needed using a combination of periodic and online CBM. However, opportunities exist to both centralize monitoring and employ more advanced and predictive or prognostic technologies, which can reduce operation and maintenance costs, and potentially maintain a high capacity factor as well, as these plants enter extended operation. The use of more automated and online monitoring and analysis activities also has the advantage of potentially better using limited staff resources and reducing worker dose.

As attention turns to longer-term operation, interest is increasing in understanding the fundamental degradation signatures for both active and passive components and how these components relate to the underlying degradation phenomena. The ability to successfully manage the passive systems and structures in NPPs is seen as critical to the goal of long-term operability [21],[22]. These passive components can also benefit from the deployment of prognostic methods that utilize many of the same algorithms as those used with active components.

A complete PHM implementation encompasses a broad array of functions, ranging from data acquisition to advisory generation. An integrated health management (IHM) framework is a software product (or suite of products) used to facilitate implementation of and interaction between the individual elements of the system. Section 2 of this paper summarizes the relevant standards and presents a list of criteria for the assessment of architectures. Section 3 provides an overview of 14 commercially available architectures that are being considered for, or have been applied to, problems relevant to NPP deployment.

2. IHM Architectures

Implementation of PHM on a system or subsystem of any scale within a NPP will require the use of a prognostics architecture, i.e., a software product (or suite of products) used to bring together and implement the necessary pieces for a complete PHM implementation. This broad definition includes condition monitoring and diagnostics in addition to prognostics; hence, a more appropriate terminology would be an IHM framework.

Careful evaluation of available products is necessary to avoid the use of limited or stovepipe applications and ensure long-term success of the prognostics implementation. There have been many reviews of prognostic methodologies and algorithms available in the literature, including a recent review by Peng, Dong, and Zuo [23]. In 2006, Hines and Seibert [9] identified software systems suitable for sensor calibration in NPPs; however, there appear to have been no publically available comprehensive assessments of commercially available IHM frameworks for the nuclear industry.

2.1. Applicable Standards, Specifications, and Formats

Technical standards and specifications are used to create a common framework within a chosen field or application, including establishing common terminology, communications protocols, and functionalities. The use of standards promotes interoperability and minimizes redesign of similar systems [24].

The following standards, specifications, and formats have been identified as relevant to prognostics: ISO–13374, ISO–13381, ISO–18435, SAE AIR5871, the Machinery Information Management Open Standards Alliance (MIMOSA) Open Systems Architecture for Condition-based Maintenance (OSA-CBM), MIMOSA Open Systems Architecture for Enterprise Application Integration (OSA-EAI), and the Diagnostic Markup Language (DiagML). In addition, there are PHM standards currently under development by professional organizations like the IEEE Reliability Society.

ISO–13374 is a collection of standards that define a general condition monitoring architecture (framework) for machines. Part 1 [25] focuses on general procedures; Part 2 [26] focuses on data processing; and Part 3 [27] is in development, and covers communication [28]. Together, these three parts define six layers or blocks of functionality within a condition monitoring system. The functions of the blocks summarized below are discussed in more detail in [29].

The first three blocks are typically technology specific (e.g., vibration monitoring, temperature monitoring, electrochemical monitoring) and provide these functions:

1. ***Data Acquisition (DA):*** *converts an output from the transducer to a digital parameter representing a physical quantity and related information (such as the time, calibration, data quality, sensor configuration, and data collector utilized).*

2. ***Data Manipulation (DM):*** *performs signal analysis, computes meaningful descriptors, and derives virtual sensor readings from the raw measurements.*

3. ***State Detection (SD):*** *facilitates the creation and maintenance of normal baseline "profiles," searches for abnormalities whenever new data are acquired, and determines in which abnormality zone, if any, the data belong (e.g., alert or alarm).*

The second three blocks combine human concepts with monitoring technologies in order to assess the current health of the machine, predict future failures, and provide recommended action steps to operations and maintenance personnel:

4. ***Health Assessment (HA):*** *diagnoses any faults and rates the current health of the equipment or process, considering all state information.*

5. ***Prognostics Assessment (PA):*** *determines future health states and failure modes based on the current health assessment and projected usage loads on the equipment and/or process, as well as remaining useful life.*

6. ***Advisory Generation (AG):*** *provides actionable information regarding maintenance or operational changes required to optimize the life of the process and/or the equipment.*

ISO–13381 provides general guidelines for the development of machinery prognostics, addressing terminology, concepts, uncertainty, and degradation modeling [30].

ISO–18435 describes an integration model and interfaces to facilitate integration of CBM-related information with operating and environmental information to support optimal decision-making for effective and efficient manufacturing [28].

SAE AIR5871 applies to the prognostics of gas turbine engines [31]. The standard also defines prognostics terminology, explains potential benefits and limitations of prognostics, and provides general guidelines for the use of prognostics using existing condition monitoring systems. Examples are included in this standard.

MIMOSA OSA-CBM is an implementation of the ISO-13374 functional specification [29]. OSA-CBM uses the Unified Modeling Language (UML) to define the standard, separating the information from the technical interfaces used to exchange or communicate the information. This implementation allows vendors and integrators to implement the most appropriate technologies for their application.

MIMOSA OSA-EAI defines a data repository for asset management [32]. The OSA-EAI database includes information about engineering, maintenance, operations, and reliability.

DiagML is a fully Extensible Markup Language (XML) schema that defines a format for transferring diagnostic information [33]. DiagML was produced by DSI International and TYX Corporation. DiagML has been used in a wide variety of commercial applications. Impact Technologies, Boeing, and NASA's Jet Propulsion Laboratory have all developed projects demonstrating the use of DiagML.

2.2. Assessment Criteria

In order to assess the suitability of commercially available IHM frameworks for use in NPPs, a list of desired features has been developed. These features are based on the authors' experiences in software development and PHM. They are meant to provide a foundation for evaluating architectures, rather than an exhaustive set of mandatory features. Every application will have its own unique set of requirements based on the demands of the associated industry:

1. ***Open, modular architecture.*** *The architecture should be independent of the selection of diagnostic or prognostic algorithms, so that a change in the desired algorithm can be quickly and easily accomplished. This includes having well-published interfaces allowing researchers to create algorithms that will work with the architecture.*

2. ***Platform independence.*** *The architecture should not be tied to any single computer platform, but rather should be able to operate on as many platforms as possible.*

3. ***Graphical user interface (GUI).*** *Control room or other site staff could easily be overwhelmed by the amount of data available to them. A well-designed GUI is necessary so that the technician or operations and maintenance professional does not miss critical information.*

4. ***Web-based tool set.*** *The use of web applications promotes flexibility in the system by allowing ready access to information over a computer network.*

5. ***Scalability.*** *The product must be scalable to systems that range from the single motor or pump to subsystems within a plant (e.g., those that comprise a service water system) or modules that combine to comprise a full NPP.*

6. ***Compatibility with existing or emerging standards and specifications.*** *Standards and specifications are used to promote interoperability and minimize redundancy. Existing prognostics standards and specifications are listed in Section 2.1.*

3. COTS Products

For the most efficient utilization of funding resources, use of a commercially available IHM framework would be ideal. Candidate products (or sets of products) developed by thirteen manufacturers were identified initially, based on discussions with experts in the field, review of the literature, and internet search. Due to space constraints, the full results are not presented in this paperis paper; a summary of the product features and a description of each product can be found in [34]. Product analysis was based on information available as of July 2011 in product fact sheets and brochures, on company websites, and, in some cases, through direct communication with the vendors.

The reviewed products were divided into four categories: (i) research tools, (ii) PHM system development tools, (iii) deployable architectures, and (iv) peripheral tools. Research tools include codes and algorithms that are useful for prototyping new methods, investigating feasibility, or performing small-scale studies. These codes tend to not scale well to full systems and lack the development support necessary for actual implementation. PHM system development tools include products designed to aid in the development of monitoring systems, but do not typically run analysis with online data. Deployable architectures are those systems that appear to be readily scalable to large, complex systems; be fully supported by the vendor for system development and implementation; and include most or all of the modules included in a PHM system.

3.1. Research Tools

Several of the systems considered are actually research tools, not deployable PHM architectures. The PEM and PEP toolboxes from the University of Tennessee are designed for fast prototyping of monitoring, fault detection, and prognostic models. This is to allow easy comparison across candidate models, support development of new techniques and algorithms, and present proof-of-principle for small scale systems. The toolboxes are not written to be robust enough for deployment on an actual system of any scale. Similarly, Watchdog Agent, developed at the Center for Intelligent Maintenance Systems at the University of Cincinnati, provides a set of tools for fast prototyping of monitoring, fault detection and diagnostics, and prognostics algorithms. However, this product is built on National Instruments' LabVIEW software and is not expected to scale well to the systems and subsystems that comprise a NPP.

3.2. PHM System Development Tools

Three products can be considered PHM system development tools: eXpress (DSI International), MADe (PHM Technology), and PHM Design (Impact Technologies). eXpress was originally designed as a tool for design assessment and optimization for the purpose of fault detection and diagnostics. It has since evolved with some online capabilities, but its core function remains evaluating a system design, either new or legacy, in terms of diagnostic ability. MADe is a suite of tools with a similar purpose. The MADe suite can be used to simulate system failures, track faults as they progress to failure and propagate through the system, optimize sensor placement for maximum detection and diagnosis, and generate fault symptom patterns based on the failure simulation and chosen sensor suite. Finally, PHM Design can be used to identify appropriate targets for prognostic monitoring, optimize the sensor suite, and evaluate the prognostic and diagnostic coverage of a proposed PHM system. While these tools are not directly useful as PHM systems, they can be used to guide and inform system development for pilot studies.

3.3. Deployable Architectures

Several products or suites of products represent deployable system monitoring architectures. Five of these architectures do not appear to include prognostic estimates, and it is unclear how easy it would be to incorporate third party prognostic algorithms: eXpress, FAMOS (Scientech), Operational Insight and Equipment Condition Monitor (Matrikon), OstiaEdge (ESRG), and PlantAPS (Smart Signal). SureSense (Expert Microsystems) includes the full health monitoring suite, but does not provide advisory generation. Both Optimized Systems and Solutions Inc. (OSyS) and Impact Technologies provide a pair of tools that seem to employ all six models when used in tandem: AOC and EHM, and SignalPro and ReasonPro, respectively. Each of these products has its own advantages and disadvantages.

The multi-agent system approach (University of Strathclyde) is very promising for developing an open, modular PHM system that scales to large, complex plants. However, this approach has not yet been developed into a commercially available product.

One additional product was identified after the initial product assessment. Analysis and Measurement Services Corporation (AMS) developed OLM, a comprehensive system that can perform calibration verification and determine equipment, sensor, and plant process health. OLM was developed specifically for use in NPPs, and is scalable to an unlimited amount of sensors. It integrates static and dynamic analysis under a common software framework, and has a web-based user interface. Empirical modeling, redundant sensor analysis, and noise analysis algorithms are incorporated in OLM. The OLM static and dynamic techniques are being used commercially at the Sizewell B plant in the United Kingdom to facilitate the extension of transmitter calibration intervals [15]. In addition, AMS has performed case studies to demonstrate the use of the OLM system at four reactor units in the U.S. under Department of Energy (DOE) grant number DE-FG02-06ER84626. The OLM system currently incorporates data acquisition, system modeling, fault detection, and fault diagnostics; incorporation of prognostics is in progress.

3.4. Peripheral Tools

IBM's Maximo is an Enterprise Asset Management tool that has some basic data acquisition and signal thresholding capabilities, as well as engines for identifying appropriate maintenance actions and scheduling. Maximo should not be considered a PHM system; however, it is designed with interoperability in mind. It presents a useful hub for displaying and aggregating the results of third party systems. In fact, the Matrikon products are designed to communicate with Maximo, and it is expected that other products do or will interact with Maximo in the future.

4. Conclusions

This review is not intended to recommend any individual product for use in NPPs, nor is it meant to provide a list of all commercially available IHM architectures. Rather, it is meant to educate the reader on the availability of COTS IHM architectures, as well as to provoke thoughtful consideration into the desirable features of prognostic architectures. Careful evaluation of available products is necessary to avoid the use of applications with limited or stovepipe functionality and to ensure long-term success of the prognostics implementation. This review has focused on COTS products, as use of a commercially available IHM framework would logically provide the most efficient utilization of funding resources. It is likely that the most sustainable product would result from partnership with a software company to specifically design a product to meet the needs of a NPP. As an example, EPRI has contracted with Expert Microsystems to develop such a product for use by EPRI members in the commercial power industry (both nuclear and fossil fuel). The EPRI product, named the Fleet-Wide Prognostic and Health Management (FW-PHM) Suite, is a web-based, integrated tool environment designed for compatibility with power utility business processes. The EPRI FW-PHM Suite is currently in beta-testing by EPRI members.

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