Standards for Prognostics and Health Management (PHM) Techniques within Manufacturing Operations

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ABSTRACT

Prognostics and health management (PHM) technologies reduce time and costs for maintenance of products or processes through efficient and cost-effective diagnostic and prognostic activities. These activities aim to provide actionable information to enable intelligent decision-making for improved performance, safety, reliability, and maintainability. Thoughtful PHM techniques can have a dramatic impact on manufacturing operations, and standards for PHM system development, data collection and analysis techniques, data management, system training, and software interoperability need to exist for manufacturing. The National Institute of Standards and Technology (NIST) conducted a survey of PHM-related standards applicable to manufacturing systems to determine the needs addressed by such standards, the extent of these standards, and any commonalities as well as potential gaps among the documents. Standards from various national and international organizations are summarized, including those from the International Electrotechnical Commission, the International Organization for Standardization, and SAE International. Finally, areas for future PHM-related standards development are identified.

1. PHM ENABLES SMART MANUFACTURING

Prognostics and health management (PHM) systems and technologies enable maintenance action on products and processes based on need, determined by the current system condition via diagnostic analyses and/or the expected future condition through prognostic methods. PHM techniques are in contrast to the use of schedules (i.e., preventative maintenance) where maintenance is conducted on specific time intervals (United States Army, 2013). PHM aims to reduce burdensome maintenance tasks while increasing the availability, safety, and cost effectiveness for the products and processes to which it is applied. In this sense, PHM enables smart manufacturing by optimizing maintenance operations via data collection, diagnostics, and prognostics as well as usage monitoring.

1.1. National Strategic Needs in Manufacturing

The United States is beginning to gain ground in reestablishing its manufacturing dominance through research and development in a wide-range of advanced technologies. Additive manufacturing, robotics, data analytics, cloud computing, and intelligent maintenance are just a few evolutionary technologies that are actively being refined. These technologies can have a tremendous impact on U.S. manufacturing that would "increase productivity, efficiency and innovation, speed-to-market, and flexibility" (Ludwig & Spiegel, 2014).

The National Institute of Standards and Technology (NIST) is focused on advancing, documenting, and standardizing industry practices in many of these new technologies. Standards have a well-documented history of impact within the national and global manufacturing community (Ludwig & Spiegel, 2014). NIST has a strong history of working with industry to develop standards and guidelines to promote best practices and further manufacturing competitiveness (Bostelman, Teizer, Ray, Agronin & Albanese, 2014, Hunten, Barnard Feeney & Srinivasan, 2013, Lee, Song & Gu, 2012, Marvel & Bostelman, 2013). Much of NIST's work in the manufacturing sector lies within the NIST Engineering Laboratory (EL).

One of EL's manufacturing projects is *Prognostics and Health Management for Smart Manufacturing Systems* (PHM4SMS), which was initiated in 2013 (National Institute of Standards and Technology, 2014). The goal of this five-year effort is to develop and document methods, protocols, best practices, and tools to enable robust, real-time diagnostics and prognostics in manufacturing environments. These outputs will provide manufacturers with uniform guidelines to identify the complex system, sub-system, and component interactions within smart manufacturing so they can understand the specific influences of each on process performance metrics and data integrity. Increased operational efficiency will be achieved through this greater understanding of the system, its constituent elements, and the multitude of relationships present.

1.2. PHM Needs and Challenges

Figure 1 shows a flowchart of the general process of PHM system development with certain standards listed for reference purposes. PHM system development begins with cost and dependability analyses to determine the components to monitor. The data management system is then initialized for collection, processing, visualization, and archiving of the maintenance data. Once the measurement techniques are established, the diagnostic and prognostic approaches are developed and tested to ensure that the desired goals are achieved. Finally, personnel are trained during the iterative process of system validation and verification before final system deployment.

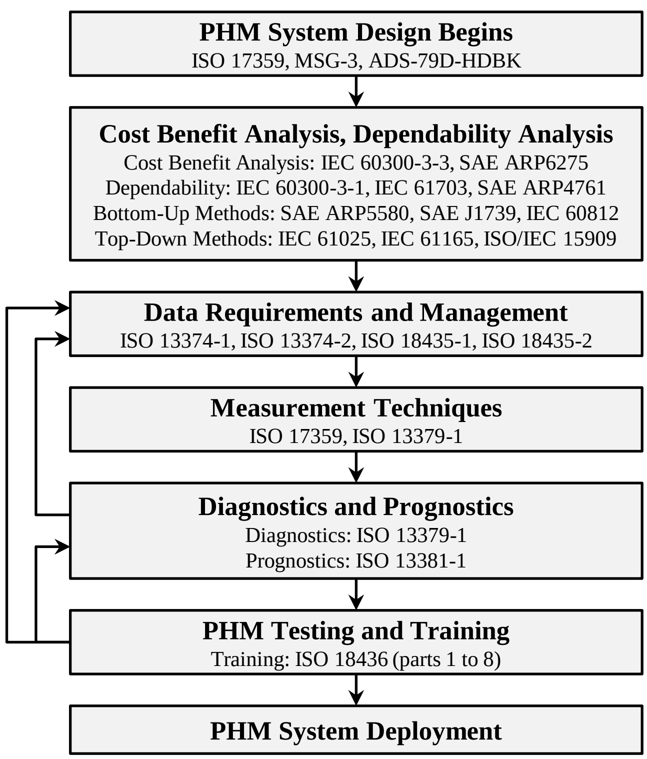

Figure 1. General PHM system development process and associated standards.

Several needs and challenges exist for PHM system development. PHM is dependent on maintenance-related data collection and processing for components or subsystems, so standards about data acquisition and processing are needed to influence the requirements for PHM systems development (United States Army, 2013). Standards for PHM are needed for harmonized terminology, consistency of the PHM methods and tools, and compatibility and interoperability of PHM technology. Standards also help provide guidance in the practical use and development of PHM techniques (Mathew, 2012). The creation of PHM systems is still difficult due to the inter-related tasks of design engineering, systems engineering, logistics, and user training (United States Army, 2013).

1.3. NIST PHM Efforts

PHM systems need to be developed, verified, and validated before implementation to enable improved decision-making for performance, safety, reliability, and maintainability of products and processes. However, standards appear to be lacking for PHM system development, data collection and analysis techniques, data management, system training, and software interoperability. The PHM4SMS project at NIST intends to help to serve a role in the development of such standards. The first step is to identify the existing pertinent standards, and this paper summarizes the results of such a review (Vogl, Weiss & Donmez, 2014).

2. PUBLISHED STANDARDS

Multiple organizations publish standards related to PHM for manufacturing products or processes. Table 1 lists the organizations that have published standards, while Table 2 (see Section 3) and Table 3 (see Appendix) categorize the developing or existing standards, respectively, related to PHM for manufacturing. All tables are organized according to topics based on the PHM process steps seen in Figure 1: ‘Overview’, ‘Dependability analysis’, ‘Measurement techniques’, ‘Diagnostics and Prognostics’, ‘Data management’, ‘Training’, and ‘Applications’. If a standard has an ‘X’ mark in a corresponding general topic column within a table, then that standard is largely applicable within that category. Some of the standards outline broad approaches for PHM (marked in the ‘Overview’ category) or are specific in guidance for PHM within a given application (marked in the ‘Applications’ category). Other standards focus on dependability analysis, measurement techniques, diagnostics and/or prognostics, PHM data management, or training related to maintenance of systems. The lists of standards are not exhaustive, yet are comprehensive enough for those in the manufacturing fields.

As seen in Table 1, the standards were typically developed by a technical committee (TC) or subcommittee (SC) of various national and international organizations: the Air Transport Association (ATA), the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE), the

International Organization for Standardization (ISO), the Machinery Information Management Open Standards Alliance (MIMOSA), SAE International, and the United States Army (US Army).

Table 1. PHM-related standards organizations.

Organization	Committee/ Subcommittee	Overview	Cost and Dependability analyses	Measurement techniques	Diagnostics and Prognostics	Data management	Training	Applications
ATA	MSG	X						X
IEC	56	X	X					
IEEE	RS	X						
ISO	TC 108/SC 2			X				
ISO	TC 108/SC 5	X		X	X	X	X	
ISO	TC 184/SC 4					X		
ISO	TC 184/SC 5				X	X		
ISO/IEC	JTC 1/SC 7		X					
MIMOSA	——					X		
SAE International	AQPIC		X					
SAE International	E-32	X			X			X
SAE International	G-11r	X	X					
SAE International	HM-1	X	X	X	X			X
US Army	Aviation Engineering	X		X	X			X

The following sections summarize the published standards in categories that are broad in scope: Overview, Dependability Analysis, Measurement Techniques, Diagnostics and Prognostics, and Data Management. Because they are outside the scope of NIST's current focus, Cost-, Training-, and Application-focused standards are not summarized.

2.1. Overview

Standards with general guidance about the creation of PHM systems are indicated under the 'Overview' category within Table 3. Such standards are a natural starting point during the creation of PHM systems, because these documents outline the factors influencing condition monitoring and provide guidance for the monitoring of components and/or sub-systems.

2.1.1. Manufacturing Industry

As the parent document of a group of standards that cover condition monitoring and diagnostics, ISO 17359 (International Organization for Standardization, 2011) was developed by ISO/TC 108/SC 5 ("Condition monitoring and diagnostics of machines") to provide the general procedures for setting up a condition monitoring program for all machines, e.g., the generic approaches to setting alarm criteria and carrying out diagnosis and prognosis. ISO 17359 outlines the condition monitoring procedure for a general manufacturing process, factors influencing condition monitoring, a list of issues affecting equipment criticality (e.g., cost of machine down-time, replacement cost), and a table of condition monitoring parameters (such as temperature, pressure, and vibration) for various machine types. ISO 17359 also presents multiple examples of tables showing the correlation of possible faults (e.g., air inlet blockage, seal leakage, and unbalance) with symptoms or parameter changes. Furthermore, ISO 17359 shows an example of a typical form for recording monitoring information.

2.1.2. Aircraft Industry

Another standard that provides guidance for PHM systems development is MSG-3, a document titled "Operator/Manufacturer Scheduled Maintenance Development." The Maintenance Steering Group (MSG) of the Air Transport Association (ATA) developed MSG-3, which is used for developing maintenance plans for aircraft, engines, and systems (Air Transport Association of America, 2013) before the aircraft enters service. MSG-3 is a top-down approach to determine the consequences (safety, operational, and economic) of failure, starting at the system level and working down to the component level (Adams, 2009). Failure effects are divided into five categories, and if the consequences of failure cannot be mitigated, then redesign becomes necessary. For example, the MSG-3 process led to mandatory design changes for the Boeing 787-8's in-flight control and lightning protection systems. Furthermore, the MSG-3 methodology helps improve safety while reducing maintenance-related costs up to 30 percent (Adams, 2009).

2.1.3. Military

Similar in scope to the standards just described, an Aeronautical Design Standard (ADS) Handbook (HDBK), ADS-79D-HDBK, was developed by the U.S. Army to describe the Army's condition-based maintenance (CBM) system for military aircraft systems (United States Army, 2013). CBM is the preferred maintenance approach for Army aircraft systems, yet ADS-79D-HDBK is broad enough for application in other industries to be included in the 'Overview' category of Table 3. The document provides guidance and standards for use by all Department of Defense (DoD) agencies in the development of CBM data acquisition, signal processing software, and data management. Furthermore, ADS-79D-HDBK is in the spirit of the reliability centered maintenance (RCM) methods previously used by the DoD to avoid the consequences of material failure. Failure mode, effects, and criticality analysis (FMECA) identifies where CBM should be utilized, but RCM is used to determine the most appropriate failure management strategy. Additionally, ADS-79D-

HDBK is supported by the Machinery Information Management Open Standards Alliance (MIMOSA), a United States association of industry and Government, and follows the information flow structure detailed in the ISO 13374 series (International Organization for Standardization, 2003, United States Army, 2013).

ADS-79D-HDBK defines CBM-related terms ('airworthiness', 'critical safety item', 'exceedance', etc.) and assists in the development of CBM systems for both legacy and new aircraft. Also, the standard describes the elements of a CBM system architecture with technical considerations for Army aviation in thirteen separate appendices (e.g., fatigue life management, flight test validation, vibration based diagnostics, and data integrity). These appendices help developers identify components to maintain, plan for data acquisition, perform fault testing, design the software and hardware elements, and validate CBM algorithms.

2.2. Dependability Analysis

One aspect of the generation of PHM systems outlined in Figure 1 is the determination of what components or subsystems should be redesigned, changed, or monitored due to their fault and/or failure potential. Typically, a dependability analysis involves the identification of the reliability, availability, and maintainability of the entire system, its subsystems, and its components (International Electrotechnical Commission, 2003).

Numerous methods exist to identify the failure modes of the system. Bottom-up (elements) methods are used to identify the failure modes at the component level, which are then used to determine the corresponding effect on higher-level system performance. On the other hand, top-down (functional) methods are used to identify undesirable system operations by starting from the highest level of interest (the top event) and proceeding to successively lower levels (International Electrotechnical Commission, 2003). Bottom-up dependability analysis methods include event tree analysis, failure mode and effects analysis (FMEA), and hazard and operability study (HAZOP), while top-down methods include fault tree analysis (FTA), Markov analysis, Petri net analysis, and reliability block diagrams (RBD).

2.2.1. General Guidance

IEC 60300-3-1 gives a general overview of the common dependability analysis techniques, including fault tree analysis, Markov analysis, Petri net analysis, and stress-strength analysis. IEC 60300-3-1 presents tables outlining the general applicability and characteristics of each method as well as concise summaries of each method (including benefits, limitations, and examples) in a separate informative annex (International Electrotechnical Commission, 2003). The methods can be categorized according to their purpose of either fault avoidance (e.g., stress-strength analysis), architectural analysis and dependability allocation (bottom-up methods, such as FMEA, or top-down methods, such as FTA), or estimation of measures for basic events (such as failure rate prediction). Analysis based on either a hardware (bottom-up), functional (top-down), or combination approach should be used to assess high risk items and provide corrective actions (United States Department of Defense, 1980).

Another standard that covers various dependability analyses is SAE ARP4761, an Aerospace Recommended Practice (ARP) that provides guidelines and methods of performing safety assessments for certification of civil aircraft (SAE International, 1996). Methods covered in SAE ARP4761 for safety assessment include FTA, dependence diagram (DD), Markov analysis, FMEA, and common cause analysis.

To support the quantification of dependability, the IEC technical committee 56 (Dependability) developed IEC 61703 to provide the mathematical expressions for reliability, availability, maintainability, and other maintenance terms (International Electrotechnical Commission, 2001). The expressions are grouped into classes for various items: non-repaired items, repaired items with zero time to restoration, and repaired items with non-zero time to restoration. Numerous equations are provided in IEC 61703 for the generic case of an exponentially distributed time to failure.

2.2.2. Bottom-Up Methods

FMEA

FMEA is a formal and systematic approach to identify potential failure modes of a system along with their causes and immediate and final effects on system performance (International Electrotechnical Commission, 2006a) through the usage of information about failure ("What has failed?") and its effects ("What are the consequences?") (SAE International, 2001). It is advantageous to perform FMEA early in the development of a product or process so that failure modes can be eliminated or mitigated as cost effectively as possible. FMEA can be used to identify failures (e.g., hardware, software, human performance) and improve reliability and maintainability via information for the development of diagnostic and maintenance procedures. FMEA has been modified for various purposes; failure modes, effects and criticality analysis (FMECA) is an extension of FMEA that uses a metric called *criticality* to rank the severity of failure modes (International Electrotechnical Commission, 2006a) as well as the probability of each failure mode (SAE International, 2001).

For example, SAE ARP5580 describes the procedure for how to perform FMEA. This procedure includes a basic methodology for the three FMEA classifications related to how the failure modes are postulated: functional FMEA (at the conceptual design level), interface FMEA (before the detailed design of the interconnected subsystems), and detailed FMEA (performed when detailed designs are available) (SAE International, 2001). SAE ARP5580 can be used to assess the reliability of systems with increasing impact when FMEA is performed at increasing levels of detail during development of hardware or software. SAE ARP5580 provides many definitions of key terms (e.g., 'allocation', 'criticality', and 'fault tree') and other items typically included within FMEA. SAE ARP5580 provides ground rules (with an example), numbering conventions for functional FMEA to describe systems according to a hierarchy (subsystems, components, software, etc.) with well-defined inputs and outputs, and examples of severity classifications for military, aerospace, and automobile industries.

DFMEA and PFMEA

Another standard concerning FMEA is SAE J1739, which supports the development of an effective design FMEA (DFMEA) and a FMEA for manufacturing and assembly processes (PFMEA) (SAE International, 2009). Based on references (e.g., SAE ARP5580 and IEC 60812) and input from original equipment manufacturers (OEMs) and their suppliers, SAE J1739 includes current terms, requirements, ranking charts, and worksheets for the identification and mitigation of failure mode risks. Examples are given for a block or boundary diagram (for DFMEA), a process flow diagram (for PFMEA), and design and process FMEA worksheets related to the auto industry. Also, suggestions are given in tabulated form for design and process FMEA severity (S) evaluation criteria as well as those for occurrence (O) and detection (D) evaluation criteria. Even though the risk priority number (RPN) is defined as the product S × O × D, SAE J1739 warns that this number, which ranges from 1 to 1000, should not be used as the sole metric for risk evaluation via thresholding.

FMEA and FMECA

Another standard that gives guidance to produce successful FMEA and FMECA is IEC 60812, which was developed by the IEC technical committee 56 (Dependability) (International Electrotechnical Commission, 2006a). IEC 60812 is a standard that provides steps, terms, criticality measures (potential risk, risk priority number, criticality matrix), failure modes, basic principles, procedures, and examples for FMEA and FMECA. IEC 60812 advises that while FMECA may be a very cost-effective method for assessing failure risks, a probability risk analysis (PRA) is preferable to a FMECA; FMECA should not be the only basis for judging risks, especially since RPNs have deficiencies such as inadequate scaling, as discussed in SAE J1739. Also, FMEA has limitations in that it is difficult and tedious to apply to complex systems with multiple functions (International Electrotechnical Commission, 2006a).

2.2.3. Top-Down Methods

Fault Tree Analysis (FTA)

FTA is a technique that is helpful in overcoming the current limitations of FMEA (SAE International, 2001). FTA is a deductive method used to determine the causes that can lead to the occurrence of a defined outcome, called the 'top event' (International Electrotechnical Commission, 2006b). FTA achieves this goal through use of a fault tree. Construction of the tree is a top-down process that continually approaches the desired lower level of mechanism and mode. The lowest possible level contains the primary (bottom) events, the individual causes of potential failures or faults (International Electrotechnical Commission, 2006b). Thus, FTA identifies potential problems caused by design, operational stresses, and flaws in product manufacturing processes. Hence, fault trees should be developed early during system design and continue throughout the development of a product (International Electrotechnical Commission, 2006b).

To enable the use of fault tree analysis, the IEC technical committee 56 developed IEC 61025, which addresses the two approaches to FTA: a qualitative or logical approach (Method A), used largely in the nuclear industry, and a quantitative or numerical approach (Method B) that results in a quantitative probability of the occurrence of a top event within manufacturing and other industries (International Electrotechnical Commission, 2006b). IEC 61025 describes FTA with its definitions (e.g., 'top event', 'gate', and 'event'), steps (fault tree construction, analysis, reporting, etc.), and fault tree symbols (for static and dynamics gates). IEC 61025 provides the mathematics for reliability of series and parallel (redundant) systems, which uses probabilistic data at the component level from reliability or actual field test data to determine the probability of the occurrence of the 'top event'.

Markov Analysis

Markov analysis is another method to determine the dependability and safety of systems. The IEC technical committee 56 produced IEC 61165, a standard that gives an overview of the Markov technique (International Electrotechnical Commission, 2006c). Markov techniques use state transition diagrams to represent the temporal behavior of a system, which is a connected number of elements, each of which has only one of two states: up or down. The entire system transitions from one state to another as the system elements fail or are restored according to defined rates. IEC 61165 uses symbols from IEC 60050 ('International Electrotechnical Vocabulary') but defines other fundamental terminology (e.g., 'up state' and 'down state'), symbols (circles, rectangles, etc.), and mathematical techniques (e.g., via ordinary differential equations and Laplace transforms). The standard contains examples for the homogeneous Markov technique, in which the state transition rates are assumed to be time-independent (International Electrotechnical Commission, 2006c). IEC 61165 shows that the differences between the expressions for reliability, maintainability, and availability arise from the different state transition diagrams used to create the equations. Maintenance strategies can be modeled with Markov techniques, while other techniques such as fault tree analysis (FTA) and reliability block diagrams (RBDs) do not account for complex maintenance strategies.

Petri Net Analysis

Since their creation in 1962, Petri nets have been used to describe, design, and maintain a wide range of systems and processes in industries including aerospace, banking, manufacturing systems, and nuclear power systems (International Organization for Standardization & International Electrotechnical Commission, 2004). Petri nets are a rigorous method to mathematically describe processes based on basic set theory (Truss, 1998). Furthermore, Petri nets can be used to generate Markov models. In the 1980s, Petri nets were extended to Higher-level Petri nets (HLPNs) to model discrete-event systems. HLPNs were also used to advance the use of Petri nets for complex systems, analogous to the use of high-level programming languages to overcome challenges with assembly languages.

To aid the use of HLPNs and facilitate the development of Petri net software tools, the ISO/IEC 15909-1 standard was developed by SC 7 (‘Software and system engineering’) of JTC 1 (‘Information technology’), a Joint Technical Committee (JTC) composed of ISO and IEC members (International Organization for Standardization & International Electrotechnical Commission, 2004). ISO/IEC 15909-1 defines a mathematical semantic model, an abstract mathematical syntax for annotations, and a graphical notation for High-level Petri nets (International Organization for Standardization & International Electrotechnical Commission, 2004). ISO/IEC 15909-1 defines terms (such as ‘arc’, ‘multiset’, ‘Petri net’, ‘token’, ‘transition’, etc.) and mathematical conventions needed for High-level Petri nets and provides the formal concepts of marking, enabling, and transition rules needed for HLPN graphs (HLPNGs) that represent complex processes within manufacturing and other industries. ISO/IEC 15909-2 defines the transfer format, the Petri Net Markup Language (PNML), to support the exchange of HLPNs (International Organization for Standardization & International Electrotechnical Commission, 2011).

2.3. Measurement Techniques

Dependability analysis, whether top-down or bottom-up or some combination thereof, is used to identify the failure modes of the system and help manufacturers to determine which risks should be mitigated or eliminated. If a failure mode must exist, being unavoidable for system operation, then the failure mode may be monitored or predicted via diagnostics and prognostics with sensors and established measurement and analysis techniques. The system designer must be aware of the various measurement techniques and their preferred uses based on the accepted experience of others.

Several standards contain explicit guidelines on the use of measurement techniques for PHM. This section summarizes those particular standards indicated under the ‘Measurement techniques’ category within Table 3. However, due to the detailed nature and variety of measurement techniques, this section covers only the standards that are relatively general in scope and application for manufacturing.

For example, Annex B of ISO 17359 contains nine tables of guidance for measurement techniques for various systems, including generators, fans, engines, and pumps (International Organization for Standardization, 2011). The tables relate the possible faults for each system to the associated measureable symptoms. For example, ISO 17359 reveals that the bearing unbalance of an electric motor affects the vibration directly, but only impacts the other detectable symptoms tangentially. Such tables are essential for understanding the basic physical consequences of system faults to aid in the selection and positioning of sensors. Similarly, Annex D of ISO 13379-1 relates measurement techniques and numerous diagnostic models in tabular form (International Organization for Standardization, 2012b). The combination of the information from ISO 17359 and ISO 13379-1 helps both novices and experts in PHM to determine the measurement types and associated diagnostic techniques for a given system fault. For example, a bearing unbalance could be detected via vibration monitoring (according to ISO 17359) and analyzed via a subsequent data-driven statistical method (according to ISO 13379-1).

2.4. Diagnostics and Prognostics

Diagnostics is the determination of the current condition of a component or system, and prognostics is the predictive ability of future performance degradation and expected failures (SAE International, 2008). The following subsections summarize those particular standards indicated under the ‘Diagnostics and Prognostics’ category within Table 3. The number of standards dedicated to diagnostics and prognostics is fairly small, offering a significant opportunity for standards development.

2.4.1. Diagnostics

One recently-published standard aids the diagnostics of general PHM processes; ISO 13379-1 was created to aid the condition monitoring of industrial machines including turbines, compressors, pumps, generators, electrical motors, blowers, gearboxes, and fans (International Organization for Standardization, 2012b). ISO 13379-1, which was prepared under SC 5 (Condition monitoring and diagnostics of machines) of ISO/TC 108 (Mechanical vibration, shock and condition monitoring), outlines the nine generic steps for diagnostics, composed of the union of FMEA or FMECA, as outlined in IEC 60812, and failure mode symptoms analysis (FMSA) methodology outlined in ISO 13379-1. FMSA is essentially a modification of a FMECA process that focuses on the selection of the most appropriate detection and monitoring techniques and strategies. The process results in a monitoring priority number (MPN) for each failure mode. The MPN is the product of four numbers representing the confidence (each rated from 1 to 5) of detection, severity, diagnosis, and prognosis for the given failure mode. The highest MPN value indicates the most suitable technique for detection, diagnostics, and prognostics of the associated failure mode (International Organization for Standardization, 2012b).

ISO 13379-1 also compares the strengths and weaknesses of data-driven diagnostic approaches (e.g., neural network, logistic regression, and support vector machine) and knowledge-based diagnostic approaches (e.g., causal tree and first principles). The last step in the diagnostic process is a formal diagnostic report, such as the example given in Annex E of ISO 13379-1, which includes information about the event, its diagnosis, symptoms, failure modes, and recommendations for corrective action and fault avoidance.

2.4.2. Prognostics

Other standards provide guidance for prognostics, because there is currently no precise procedure or standard methodology. Fault prognostics require prior knowledge of the probable failure modes, the anticipated future activities of the machine, and the relationships between failure modes and operating conditions (International Organization for Standardization, 2004).

To facilitate the development of prognostics within general PHM processes, ISO 13381-1 outlines general guidelines, approaches, and concepts for prognostics (International Organization for Standardization, 2004). Terms such as prognosis (an estimation of time to failure and associated risk), confidence level, root cause, and estimated time to failure (ETTF) are defined in ISO 13381-1. The standard also outlines the four basic phases of prognosis: pre-processing, existing failure mode prognosis, future failure mode prognosis, and post-action prognosis. ISO 13381-1 states that the trip set point used for thresholding to prevent damage or failure is a parameter value, normally determined from standards, manufacturers' guidelines, and experience. Other thresholds, such as alert and alarm limits, are set at values below the trip set point to initiate maintenance. Once a fault has been detected based on a failure mode behavior model (FMECA, FTA, etc.), the estimated time to failure (ETTF) needs to be determined by expert opinion and/or empirical methods (International Organization for Standardization, 2004).

2.5. Data Management

Monitoring the condition of machines is not an easy task because the integration of various PHM software is typically not 'plug-and-play' (International Organization for Standardization, 2003). This section summarizes several standards that guide the management of PHM data and, hence, the integration of various PHM software via the transfer of standardized data formats.

ISO 13374-1 provides the basic requirements for open software specifications to facilitate the transfer of data among various condition monitoring software, regardless of platform or hardware protocols (International Organization for Standardization, 2003). ISO 13374-1 establishes the general guidelines, including the requirement of an 'open machine condition monitoring information schema architecture as an underlying framework' (International Organization for Standardization, 2003). Vendor-independent extensible markup language (XML) schema and protocols can be used for the network exchange of PHM information. In accordance with ISO 13374, the Machinery Information Management Open Systems Alliance (MIMOSA) published a conceptual schema called the Common Relational Information Schema (CRIS) in XML schema and other formats. The CRIS has been used in the condition monitoring industry to integrate information from many systems (MIMOSA, 2006).

ISO 13374-2 provides details of the methodology and requirements for data processing within condition monitoring and diagnostics (CM&D) systems. ISO 13374-2 describes all the data objects, types, relationships, etc. required for a CM&D information architecture (International Organization for Standardization, 2007). ISO 13374-2 provides an informative annex about the unified modeling language (UML), XML, and Middleware services. Finally, MIMOSA publishes an open CM&D information specification known as the MIMOSA Open Systems Architecture for Enterprise Application Integration (OSA-EAI™), which is compliant with the requirements outlined in ISO 13374-1 and ISO 13374-2 and free for download (MIMOSA, 2013). MIMOSA also publishes an open CM&D specification known as the MIMOSA Open Systems Architecture for Condition Based Maintenance (OSA-CBM™), which is based on OSA-EAI™, enabling integration of systems from various suppliers (International Organization for Standardization, 2007).

ISO 18435-1 gives an overview of the elements and rules of an integration modeling method to describe a manufacturing application's requirements for integration of an automation application with other applications, e.g., diagnostics, prognostics, capability assessment, and maintenance applications with production and control applications (International Organization for Standardization, 2009). The method is based upon the Application Domain Integration Diagram (ADID), which facilitates the transfer of information among domains of the manufacturing process. The domains include the processing blocks of ISO 13374, such as the Data Monitoring block or the State Detection block. ISO 18435-1 defines terms (e.g., 'integration' and 'interaction') and provides examples of exchanged information among domains.

ISO 18435-2 defines the application interaction matrix element (AIME) and application domain matrix element (ADME) structures and relationships, including the steps to construct an ADME for support by a set of AIMEs (International Organization for Standardization, 2012a). An AIME represents a set of capabilities provided by a set of manufacturing resources of an application. An ADME is a means to model the information exchanges between applications, being constructed from interoperability profiles referenced in AIMEs. ISO 18435-2 outlines the XML schema for the headers and bodies that comprise AIMEs and ADMEs. AIME bodies consist of context and conveyance sections, and ADME bodies consist of context, conveyance, and content sections. ISO 18435-2 also contains formal definitions of the ADME/AIME schemas in informative annexes (International Organization for Standardization, 2012a).

3. CURRENT STANDARDS DEVELOPMENT

New standards and revisions to existing standards related to PHM are currently under development, as seen in Table 2. This section summarizes the scopes of these standards.

Table 2. PHM-related standards under development.

Organization	Committee/ Subcommittee	Standard	1st Edition / Revision?	Overview	Dependability analysis	Diagnostics and Prognostics	Data management
SAE Int.	G-11r	ARP6204	1st Edition	X			
SAE Int.	HM-1	ARP6268	1st Edition	X			
SAE Int.	HM-1	ARP6407	1st Edition	X			
SAE Int.	HM-1	ARP6883	1st Edition	X			
IEEE	RS	P1856	1st Edition	X			
ISO/IEC	JTC 1/SC 7	ISO/IEC 15909-2	1st Edition		X		
ISO	TC 108/SC 5	ISO 13379-2	1st Edition			X	
ISO	TC 108/SC 5	ISO 13381-1	Revision			X	
ISO	TC 108/SC 5	ISO 18129	1st Edition			X	
ISO	TC 184/SC 5	ISO 22400-1	1st Edition			X	
ISO	TC 184/SC 5	ISO 22400-2	1st Edition			X	
ISO	TC 184/SC 5	ISO 18435-3	1st Edition				X
SAE Int.	HM-1	ARP6290	1st Edition				X

3.1. Overview

Currently, SAE International is developing SAE ARP6204, a standard for "Condition Based Maintenance (CBM) Recommended Practices," under the G-11r Reliability Committee. The scope of the document is to outline a path for an organization to implement a CBM approach to maintenance, including practices regarding both CBM design and field equipment support (SAE International, 2013). The G-11r Reliability Committee has benchmarked the CBM framework and performance specifications and is developing a formal application specification (Zhou, Bo & Wei, 2013).

Other SAE International standards are under development in the HM-1 Integrated Vehicle Health Management (IVHM) Committee. Guidance is lacking for the systems engineering aspects of IVHM design; SAE ARP6407 will help to fill this gap by providing technology-independent guidance for the design of IVHM systems (SAE International, 2014a). Furthermore, SAE ARP6883 will provide guidelines for writing IVHM requirements for aerospace systems, and SAE ARP6268 will help improve coordination and communication between manufacturers and suppliers.

Another broad standard under development is IEEE P1856 - "Standard Framework for Prognostics and Health Management of Electronic Systems" (IEEE Standards Association, 2013). In 2012, the IEEE Standards Board approved the new standard development project to produce IEEE P1856, which is sponsored by the Reliability Society (IEEE-RS) (IEEE Reliability Society, 2014). The working group meets regularly to prepare a draft for ballot in 2014 (IEEE Reliability Society, 2014). Even though this standard is being developed by IEEE, the intent is for it to have broad applicability in mechanical structures, civil structures, nuclear technology, and aeronautics (The Center for Advanced Life Cycle Engineering (CALCE), 2013).

3.2. Dependability Analysis

The first edition of ISO/IEC 15909-3 is under development by ISO/IEC JTC 1/SC 7 to aid the use of High-level Petri nets (International Organization for Standardization & International Electrotechnical Commission, 2014). ISO/IEC 15909-3, expected to be the last part of the ISO/IEC 15909 series, will address the techniques for modularity and extensions of High-level Petri nets for dependability analysis of PHM systems.

3.3. Diagnostics and Prognostics

ISO 13379-2 ('Data-driven applications') will aid the condition monitoring of industrial machines via diagnostics and is currently in the committee draft stage within ISO/TC 108/SC 5. Also, ISO 13381-1 is now at the committee draft stage while being updated to advance prognostics within PHM systems. Furthermore, within the same subcommittee, a new standard, ISO 18129, is in the draft international stage to address 'approaches for performance diagnosis' (International Organization for Standardization, 2014).

The ISO 22400 series of standards are also being developed by ISO/TC 184/SC 5 to guide the creation, computation, measurement, utilization, and maturation of key performance indicators (KPIs) within the manufacturing operations management (MOM) domain (International Organization for Standardization, 2013). KPIs are the most useful measures for monitoring and evaluating the performance of a production-oriented enterprise to help industries meet their performance targets in an intelligent manner (International Organization for Standardization, 2013). Because KPIs are serviced by effective PHM systems, standards related to KPIs could easily influence the diagnostic and prognostic aspects of PHM systems. NIST personnel are active in the development of the ISO 22400 standard series.

3.4. Data Management

SAE ARP6290, under development in the HM-1 Committee, will provide guidance for the creation of optimum architectures for IVHM that are in line with the organization's business goals and objectives. SAE ARP6290 will incorporate suggestions from ISO 13374 into specific guidelines for IVHM architecture development (SAE International, 2014b).

Future improvements to ATA MSG-3 (Air Transport Association of America, 2013), used for developing maintenance plans for aircraft, engines, and systems, will involve an existing data format specification known as ATA SPEC2000, a comprehensive set of e-Business specifications, products, and services that help to overcome the supply chain challenges in the aircraft industry (Air Transport Association of America, 2012). ATA SPEC2000 helps aircraft manufacturers with information exchange in order to have statistically significant data for optimizing and developing maintenance programs.

4. CONCLUSIONS

The National Institute of Standards and Technology conducted a survey of PHM-related standards to determine the industries and needs addressed by such standards, the extent of these standards, and any similarities as well as potential gaps among the documents. This effort revealed that standards exist that are related to all aspects of the development of prognostics and health management systems: general overview, dependability analysis, measurement techniques, diagnostic analysis, prognostic analysis, data management, performance metrics, and personnel training. Some standards were focused on providing guidance for specific applications, yet still broad enough for general application across industries. Other standards were more focused on a specific product or process within a target industry.

Based on the lessons learned from the PHM-related standards, recommendations can be made for the development of future PHM standards:

- The 'overview' standards cover numerous domains yet could be updated and harmonized by the respective organizations to provide better consolidation among the separate standards, providing for a more generally approved PHM process across disciplines.
- The 'dependability analysis' standards could be extended by combining the KPI standards under development with a dependability method to provide a bridge of guidance between design and business decisions for manufacturing systems and systems of systems.
- The 'diagnostics and prognostics' standards are lacking, due in part to the difficult nature of reliable diagnostics and prognostics techniques across various industries. However, the existing standards are still valuable for industry. Collaborations among PHM experts are recommended for the generation of new standards for diagnostics and prognostics that fill high-priority gaps for manufacturing systems. Priorities will be established at an upcoming industry workshop held at NIST in November 2014.
- The 'data management' standards appear to be thorough and consistent among each other, providing generic structures for PHM data and control flow. Extension to a 'digital factory' could be reported in future editions of these standards.

Consequently, NIST is exploring the development of methods and supporting standards for PHM of manufacturing systems and systems of systems.

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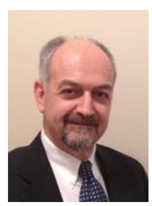
BIOGRAPHIES

Dr. Gregory W. Vogl is a Mechanical Engineer at the National Institute of Standards and Technology (NIST) located in Gaithersburg, Maryland. He received his B.S. (2000), M.S. (2003), and Ph.D. (2006) degrees in Engineering Mechanics from Virginia Tech, Virginia, USA. Currently, Greg is a member of the *Prognostics and Health Management for Smart Manufacturing Systems* (PHM4SMS) project, which seeks to develop a methodology, protocols, and reference datasets to enable robust real-time diagnostics and prognostics for smart manufacturing systems. Previously, he designed, fabricated, and experimented on microelectromechanical systems as a National Research Council Postdoctoral Researcher at NIST. He then joined the Production Systems Group, in which he worked on machine tool metrology and standards development. His interests include machine tool spindle health, diagnostic and prognostic methods, nonlinear dynamics, engineering mechanics, and metrology.

Dr. Brian A. Weiss has a B.S. in Mechanical Engineering (2000), Professional Masters in Engineering (2003), and Ph.D. in Mechanical Engineering (2012) from the University of Maryland, College Park, Maryland, USA. He is currently the Associate Program Manager of the *Smart Manufacturing Operations Planning and Control* program and the Project Leader of the *Prognostics and Health Management for Smart Manufacturing Systems* project within the Engineering Laboratory (EL) at the National Institute of Standards and Technology (NIST). Prior to his leadership roles in the SMOPAC program and the PHM4SMS project, he spent 15 years conducting performance assessments across numerous military and first response technologies including autonomous unmanned ground vehicles; tactical applications operating on Android devices; advanced soldier sensor technologies; free-form, two-way, speech-to-speech translation devices for tactical use; urban search and rescue robots; and bomb disposal robots. His efforts have earned him numerous awards including a Department of Commerce Gold Medal (2013), Silver Medal (2011), Bronze Medals (2004 & 2008), and the Jacob Rabinow Applied Research Award (2006).



Dr. Alkan Donmez is currently the Group Leader of the Production Systems Group as well as the Program Manager for the *Measurement Science for Additive Manufacturing* program in the NIST Engineering Laboratory. He has been with NIST for more than 25 years conducting and supervising research in advanced manufacturing sciences, including machine tool performance modeling and metrology, machining process metrology, as well as the recent efforts in metal-based additive manufacturing (AM). He has actively participated in national and international standard committees, developing machine tool performance testing standards, for more than 20 years. He has published more than 70 technical papers and reports in the area of machine tool metrology and manufacturing sciences. He has received various awards for his technical contributions, including R&D100, Applied Research Award of NIST, and Department of Commerce Silver and Bronze Medals.

APPENDIX

Table 3. Standards related to PHM for manufacturing.

Organization	Committee/ Subcommittee	Standard	Year Issued	Title	Overview	Cost and Dependability analyses	Measurement techniques	Diagnostics and Prognostics	Data management	Training	Applications
ATA	MSG	ATA MSG-3	2013	MSG-3: Operator/Manufacturer Scheduled Maintenance Development, Volume 1 – Fixed Wing Aircraft	X						X
IEC	56	IEC 61703	2001	Mathematical expressions for reliability, availability, maintainability and maintenance support terms	X						
ISO	TC 108/SC 5	ISO 13372	2012	Condition monitoring and diagnostics of machines – Vocabulary	X						
ISO	TC 108/SC 5	ISO 17359	2011	Condition monitoring and diagnostics of machines − General guidelines	X		X				
SAE	E-32	ARP1587B	2007	Aircraft Gas Turbine Engine Health Management System Guide	X						X
US Army	Aviation Engineering	ADS-79D-HDBK	2013	Aeronautical Design Standard Handbook for Condition Based Maintenance Systems for US Army Aircraft	X		X	X			X
IEC	56	IEC 60300-3-1	2003	Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology		X					
IEC	56	IEC 60300-3-3	2004	Dependability management – Part 3-3: Application guide – Life cycle costing		X					
IEC	56	IEC 60812	2006	Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)		X					
IEC	56	IEC 61025	2006	Fault tree analysis (FTA)		X					
IEC	56	IEC 61165	2006	Application of Markov techniques		X					
SAE	AQPIC	J1739	2009	Potential Failure Mode and Effects Analysis in Design (Design FMEA), Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA)		X					
SAE	HM-1	ARP6275	2014	Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System		X					
SAE	G-11r	ARP5580	2001	Recommended Failure Modes and Effects Analysis (FMEA) Practices for Non-Automobile Applications		X					
SAE	S-18	ARP4761	1996	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment		X					X
ISO/IEC	JTC 1/SC 7	ISO/IEC 15909-1	2004	Software and system engineering − High-level Petri nets − Part 1: Concepts, definitions and graphical notation		X					
ISO/IEC	JTC 1/SC 7	ISO/IEC 15909-2	2011	Software and system engineering − High-level Petri nets − Part 2: Transfer format		X					
ISO	TC 108/SC 2	ISO 13373-1	2002	Condition monitoring and diagnostics of machines − Vibration condition monitoring − Part 1: General procedures			X				
ISO	TC 108/SC 2	ISO 13373-2	2005	Condition monitoring and diagnostics of machines − Vibration condition monitoring − Part 2: Processing, analysis and presentation of vibration data			X				
ISO	TC 108/SC 5	ISO 18434-1	2008	Condition monitoring and diagnostics of machines – Thermography – Part 1: General procedures			X				
ISO	TC 108/SC 5	ISO 20958	2013	Condition monitoring and diagnostics of machine systems – Electrical signature analysis of three-phase induction motors			X				
ISO	TC 108/SC 5	ISO 22096	2007	Condition monitoring and diagnostics of machines – Acoustic emission			X				
ISO	TC 108/SC 5	ISO 29821-1	2011	Condition monitoring and diagnostics of machines – Ultrasound – Part 1: General guidelines			X				
ISO	TC 108/SC 5	ISO 13379-1	2012	Condition monitoring and diagnostics of machines − Data interpretation and diagnostics techniques − Part 1: General guidelines				X			
ISO	TC 108/SC 5	ISO 13381-1	2004	Condition monitoring and diagnostics of machines − Prognostics − Part 1: General guidelines				X			

SAE	E-32	AIR5871	2008	Prognostics for Gas Turbine Engines				X			X
ISO	TC 184/SC 4	ISO 15531-1	2004	Industrial automation systems and integration – Industrial manufacturing management data – Part 1: General overview					X		
ISO	TC 184/SC 4	ISO 15531-42	2005	Industrial automation systems and integration – Industrial manufacturing management data – Part 42: Time Model					X		
ISO	TC 184/SC 4	ISO 15531-43	2006	Industrial automation systems and integration – Industrial manufacturing management data – Part 43: Manufacturing flow management data: Data model for flow monitoring and manufacturing data exchange					X		
ISO	TC 184/SC 4	ISO 15531-44	2010	Industrial automation systems and integration – Industrial manufacturing management data – Part 44: Information modelling for shop floor data acquisition					X		
ISO	TC 184/SC 4	ISO 15926-1	2004	Industrial automation systems and integration − Integration of life-cycle data for process plants including oil and gas production facilities − Part 1: Overview and fundamental principles					X		
ISO	TC 184/SC 4	ISO 15926-2	2003	Industrial automation systems and integration − Integration of life-cycle data for process plants including oil and gas production facilities − Part 2: Data model					X		
ISO	TC 108/SC 5	ISO 13374-1	2003	Condition monitoring and diagnostics of machines − Data processing, communication and presentation − Part 1: General guidelines					X		
ISO	TC 108/SC 5	ISO 13374-2	2007	Condition monitoring and diagnostics of machines − Data processing, communication and presentation − Part 2: Data processing					X		
ISO	TC 108/SC 5	ISO 13374-3	2012	Condition monitoring and diagnostics of machines − Data processing, communication and presentation − Part 3: Communication					X		
ISO	TC 184/SC 5	ISO 18435-1	2009	Industrial automation systems and integration – Diagnostics, capability assessment and maintenance applications integration – Part 1: Overview and general requirements					X		
ISO	TC 184/SC 5	ISO 18435-2	2012	Industrial automation systems and integration − Diagnostics, capability assessment and maintenance applications integration − Part 2: Descriptions and definitions of application domain matrix elements					X		
ISO	TC 108/SC 5	ISO 18436-1	2012	Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 1: Requirements for assessment bodies and the assessment process						X	
ISO	TC 108/SC 5	ISO 18436-2	2003	Condition monitoring and diagnostics of machines – Requirements for training and certification of personnel – Part 2: Vibration condition monitoring and diagnostics						X	
ISO	TC 108/SC 5	ISO 18436-3	2012	Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 3: Requirements for training bodies and the training process						X	
ISO	TC 108/SC 5	ISO 18436-4	2008	Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 4: Field lubricant analysis						X	
ISO	TC 108/SC 5	ISO 18436-5	2012	Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 5: Lubricant laboratory technician/analyst						X	
ISO	TC 108/SC 5	ISO 18436-6	2008	Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 6: Acoustic emission						X	
ISO	TC 108/SC 5	ISO 18436-7	2008	Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 7: Thermography						X	
ISO	TC 108/SC 5	ISO 18436-8	2013	Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 8: Ultrasound						X	
SAE	S-18	ARP4754A	2010	Guidelines for Development of Civil Aircraft and Systems							X