NIST Advanced Manufacturing Series 100-31

Summary Report: Meeting of the ASME Standards Subcommittee on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations Hosted at NIST

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National Institute of Standards and Technology
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Abstract

The National Institute of Standards and Technology (NIST) hosted the *ASME Standards Subcommittee Meeting on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations* on May 22-23, 2019, at the NIST Gaithersburg (Maryland) campus. The purpose of the meeting was to discuss progress and future needs, and to prioritize work activities for standards and guidelines related to advanced monitoring, diagnostic, and prognostic technologies (also identified as Prognostics and Health Management (PHM)) for enhancing manufacturing maintenance and control strategies. This report documents the results of the meeting, including priority topics for standards and guidelines. The next steps in this effort are presented towards the end of this document, including planning for future standards events, subcommittee meetings, and white paper publication of one of the priority topics.

Keywords

Best Practices; Diagnostics; Factory Operations Planning & Control; Guidelines; Manufacturing; Measurement; Monitoring; Process Improvement; Process Measurement & Control; Prognostics; Prognostics and Health Management (PHM); Standardization.

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1 Introduction

1.1 Background

Many manufacturers lack the knowledge to effectively design and implement advanced monitoring, diagnostic, and prognostic (also identified as Prognostics and Health Management (PHM)) technologies to optimize maintenance and control strategies. Overcoming this challenge is more complex as manufacturing has been evolving with a growing number of smart, connected technologies. New fault and failure modes are emerging as advanced technologies are integrated into manufacturing operations and existing processes are reconfigured. Connectivity brings opportunities to gather more information than ever before through more accessible and easier-to-integrate sensors, while analytics offer greater intelligence and awareness. Effectively using PHM can reduce overall unplanned downtime and optimize planned downtime leading to greater asset availability. PHM can help maintain process quality and productivity targets and minimize waste (e.g., excess raw material) to reduce costs and increase profit.

Most manufacturers are familiar with reactive maintenance – repair a component or piece of equipment after an unexpected failure [1-3]. Reactive maintenance is typically the least preferred maintenance strategy since it causes unplanned downtime and usually brings about poor process quality and insufficient productivity. To avoid reactive maintenance, nearly every manufacturer employs a form of preventive maintenance – repair a component or piece of equipment based upon a measurable unit (normally cycle- or time-based) - to keep systems and processes operating within specification. While this strategy is typically perceived as more cost effective than reactive maintenance, it can sometimes lead to unnecessary cost and downtime if maintenance occurs too frequently or can still lead to failures if maintenance is not performed frequently enough. Predictive maintenance, along with condition-based maintenance, are of growing interest, i.e., planning maintenance activities based upon analyzing equipment sensor data to inform system and process performance and health. Proactive maintenance, intelligent maintenance, and autonomous maintenance are emerging predictive strategies that take advantage of smart, connected systems and have tremendous potential for minimizing equipment and process downtime. These different strategies have benefits and challenges, so it can be difficult for a manufacturer to choose which is best – and no single solution solves every maintenance challenge. Selecting the most appropriate balance of maintenance strategies is also compounded in that it can be difficult to estimate the return on investment (ROI) for choosing one strategy over another in maintaining a piece of equipment or process.

A worker in a protective cab on a NIST-developed revolutionary robotic platform strips paint off a U.S. Air Force C-130. The easily maneuverable platform uses computer-controlled cables to 'float' around the aircraft to reduce paint-stripping time per airplane, cut maintenance costs and lessen incidents of operator stress and injury.

Photo Courtesy: NIST/N.E. Wasson Jr./US Technologies

PHM technologies can advance maintenance strategies and corresponding activities so manufacturers can identify and monitor the metrics most critical to operations and process/equipment health; and determine what maintenance needs to be performed and when maintenance should be done to minimize unplanned downtime and cost. The development of standards and guidelines that describe and promote advanced PHM technologies, along with ways of verifying and validating their performance, would highly benefit the manufacturing industry [4-6].

1.2 Workshop Scope and Objectives

The *American Society of Mechanical Engineers (ASME) Standards Subcommittee Meeting on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations (ASME PHM Meeting)* was held on May 22-23, 2019 at the NIST Gaithersburg (Maryland) campus. Appendix A – provides a detailed agenda for the event.

The ASME PHM Meeting brought manufacturing stakeholders together to discuss progress, future needs, and prioritize work activities for standards and guidelines related to advanced monitoring, diagnostic, and prognostic technologies for enhancing manufacturing maintenance and control strategies. Participants (full list provided in Appendix B – Participant List) also provided critical input on producing standards and/or guidelines to support natural language document analysis as well as monitoring, diagnostic, and prognostic technologies at the factory floor level. The meeting was preceded by the *Standards Requirements Workshop for Natural Language Analysis* on May 21, 2019. Information on both workshops is available at the official event website.[1]

During the workshop, Brian A. Weiss and Michael P. Brundage, from NIST, explored specific priority areas and next steps for generating and delivering guidelines to enhance a manufacturer's ability to plan, design, deploy, verify, and validate their maintenance-related capabilities. The first day of the meeting included presentations and discussions on a variety of topics related to PHM standards, including review of previous subcommittee meetings and outcomes, and a proposed strategy for standardized maintenance terminology. Several sessions focused on the PHM priority topic "Determining When and Where PHM should be Integrated in Manufacturing Operations." These sessions covered development of a white paper and initial subcommittee perspectives on generating specific, targeted guidelines for this topic. The second day included a tour of the NIST Prognostics and Health Management for Robot Systems Lab and discussion on the next steps of terminology and guidelines development.

This report summarizes the results of workshop discussions and recommendations for actions going forward. It is not intended to represent the viewpoints of the entire manufacturing community, but to provide a snapshot of the perspectives of the ASME PHM Standards Subcommittee members and experts attending the workshop. Participants were selected based on their manufacturing and maintenance expertise, as well as an interest in contributing to the development of standards and guidelines in this field.

1.3 Participation

The event was attended by 20 external stakeholders and 21 NIST representatives; Appendix B includes a complete list of participants. The targeted audience included members of the manufacturing, monitoring, diagnostic, and prognostic communities, including technology developers, technology integrators, end-users (including both large manufacturers and Small and Medium-sized Manufacturers (SMMs)), researchers (from academia and other organizations), and government entities. All participants have a

[1] Event website: https://www.nist.gov/news-events/events/2019/05/nist-standards-requirements-workshop-natural-language-analysis-and

strong interest in the development of standards and guidelines for PHM; many participated in prior workshops to develop priorities for standards and guidelines for PHM.

2 ASME Subcommittee Meetings Recap

The ASME Standards Subcommittee (Subcommittee) on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations was formed to facilitate the development of standards and guidelines for manufacturers in this important field. The charter for the Subcommittee is shown in Figure 2-1. Exploratory meetings to gauge interest on this topic began in 2017 and continue today through the work of the formal Subcommittee. NOTE – the subcommittee was officially approved by ASME in June 2018.

> *Develop standards and guidelines that advance the design and implementation of monitoring, diagnostic, and prognostic capabilities, along with ways of verifying and validating their performance, to enhance adaptive maintenance and operational control strategies within manufacturing.*

Figure 2-1 Standards Subcommittee Charter

2.1 Role of Standards

Brian A. Weiss from NIST provided an overview of subcommittee activities and the need for standards and guidelines for PHM in manufacturing. There are many benefits to creating standards and guidelines, especially when bringing new technologies into the manufacturing enterprise. Standards become most relevant when key organizations participate in and help to shape standards development. Manufacturing is evolving, becoming more complex and reconfigurable. Robotics is an example of an evolving and often complex technology that is becoming more commonplace in manufacturing environments. Robotic systems can typically work faster and longer than prior technologies and human workers. Equipment is becoming highly connected and autonomous, with more sensors available and data streams being collected. These advances are happening rapidly, sometimes with uncertain impacts on equipment wear and longevity, and maintenance strategies. For example, it is unclear how certain environments impact a robot's degradation when the robot is running at a relatively fast rate. It is challenging to predict where failures will occur with new robotics and other automated systems? It is also not well understood how grippers, parts, fixtures, etc., behave differently in a highly sensed environment?

Data and analysis can help to answer these questions. The enormous amounts of data now available are increasing the complexity of predictive analytics. Companies are developing new and innovative solutions to handle data – but those methods are typically proprietary. Exploring external solutions, as well as participating in standards development, may help organizations to solve some of the larger challenges presented by the evolving manufacturing environment.

2.2 Subcommittee Meeting Recap

Through a series of events, the ASME PHM Standards Subcommittee has made significant strides toward identifying and refining priority topics for PHM standards as well as a path forward for guidelines development [6,7,8,9]. These events have led to the development of a

1. **Workshop** – June 2017 at ASME MSEC (Los Angeles, CA, USA)
2. **Workshop** – Oct 2017 at the PHM Society Conference (St. Petersburg, FL, USA)
3. **Standards Meeting** – May 2018 at the NIST Industry Forum (Gaithersburg, MD, USA)
4. **Approval of the ASME Subcommittee** –Summer 2018
5. **Standards Meeting** – Oct 2018 at TechSolve (Cincinnati, OH, USA)

Figure 2-2 Prior Events Contributing to PHM Standards and Guidelines

white paper as well as action plans on priority topics. The complete list of events that contributed to this progress to date are shown in Figure 2-2.

Prior to the May 22-23 meeting, the most recent meeting was held at the TechSolve campus in Cincinnati, OH, in October of 2018. During that meeting, a small group examined action plans from the prior workshop, with initial focus on Standardized *Terminology for PHM Guideline* and *Guideline to Determine Where and When PHM Capabilities should be Added/Integrated*. Discussions covered near, mid and long-term activities, milestones and key performance targets, infrastructure, stakeholders and roles, and other factors.

Another topic involved reorganizing how the priority topic areas could work and fit together. For example, the MTConnect[2] standard was identified as an area with synergies to other topic areas. This standard is being used frequently in the machining and robotics community, providing a standard language and dictionary for communications, from sensors to operation. NIST participation in the MTConnect standard is already strong. Connections were also found between guideline roadmaps (developed in the scope of this subcommittee) on where to add/integrate PHM and data collection, fusion, and analysis.

The Techsolve-hosted meeting had several positive outcomes. First, a working group was formed to draft a white paper articulating goals, scope, and expected benefits of the *Guideline to Determine Where and When PHM Capabilities should be Added/Integrated* (this guideline is currently in progress). Second, another working group was formed to research existing standards and terminology that may be relevant to

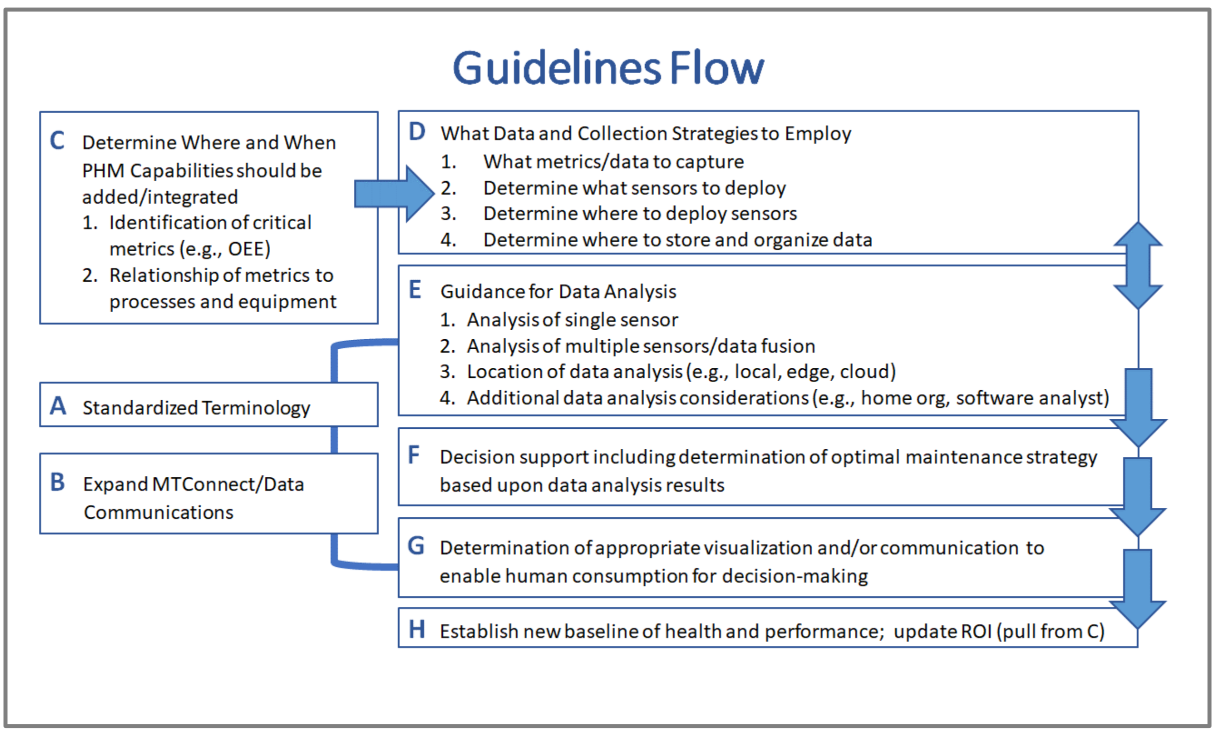

Figure 2-3 Guidelines Flow Diagram for Priority Topics for PHM Standards

[2] https://www.mtconnect.org/

this effort. Third, a guideline 'flow chart' was produced to highlight the relationships between the various priority topic areas (Figure 2-3).

3 Priority Topics Update and Discussion

The objective of this session was to review and update the priority topics and refine the path forward. A summary of the priority topics is shown in Figure 3-1. To better inform both returning and new participants on the ASME PHM Standards Subcommittee activities, the session began with an introduction to these priority topics and how they are defined, followed by a brainstorming session on refinements and new ideas for priorities.

3.1 Select Priority Topics

Using the priority topics and associated flow diagram (see Figure 2-3) as a guide, several ideas were generated for selected priority topics. These ideas include refinements to scope as well as approaches to planning and generating future guidelines for these topics.

A. Standardized Terminology for PHM Guideline (Topic 1) *

B. Expand MT Connect/Data Communications (Topic 6)

C. Guideline to Determine Where and When PHM Capabilities should be Added/Integrated (Priority Topic 2)

D. Guideline to Determine What Health Data to Capture and Collection Strategies to Employ (Priority Topic 3)

E. Guidance for Data Analysis (Combined Priority Topics 4-5, 7)

F. Data-based Decision Support for Optimal Maintenance Strategies (new priority)

G. Visualization and/or Communication to Enable Human Decision-making (new priority under consideration)

H. Guideline for Baseline of Health and Performance and PHM ROI (new priority under consideration; includes portion of Topic C)

I. Natural Language Analysis for Maintenance Documents (new priority under consideration)

*Original priority topic numbers in parenthesis, for reference.

Figure 3-1 Updates on Priority Standards Topics for PHM

Guideline C – Where and When to Integrate PHM. This guideline is important because it is where one would develop and incorporate a maintenance strategy. It is integrally connected with the types of data being collected and analyzed, and the types of required decision support. In addition to the where and when of maintenance, do additional sensors need to be installed, e.g., are more temperature sensors needed to monitor health? Developing the most appropriate maintenance strategy can be an iterative process and is usually coupled with data collection and metrics. This guideline should help to determine in advance, for example, where the major maintenance-related pain points are that could be improved by PHM. While the solution may not be apparent, the point of this guideline is to determine where to start, then to plan and start implementing (see Section 4.0, White Paper). Some approaches and ideas for determining the best maintenance strategy for PHM were raised, including:

- Using system health baseline information – While this is part of Guideline H, Guideline C should include feasibility along with the definition of health, i.e., what is a healthy process? If the system is working at 50% health, then what is the acceptable baseline? The economic feasibility of PHM should also be included here.
- Functional failure analysis – There is a tendency to stick with what has been done historically; this is not always a good approach. It is better to determine what equipment is most critical to the plant and

then apply failure modes and effects analysis (FMEA) (e.g., how can it fail, what are the observable measurable parameters to sense to predict failure, etc.). One approach is to start with the most critical failure modes, one problem at a time, and show value. The question arises of, "who is most competent to conduct the failure analysis – an equipment integrator or manufacturing operator?" Using the robot example, the equipment supplier has the design knowledge, the manufacturer has the local plant knowledge, while the integrator has the functional knowledge about the robot, and all expertise needs to be combined. Ideally, it is always preferred to conduct a cost-effective functional analysis, yet this may not be possible when considering breadth and depth of potential failures.

- Using data to inform strategy – data from manufacturers monitoring/tracking the same equipment in different ways could help inform maintenance strategies. Data from failure events (Guideline D) can also be used to inform Guideline C.
- Automating process versus automating maintenance – if the objective behind integration of new/additional PHM technology is automating your process to achieve improvements, rather than automating maintenance function, a different approach is needed. How important is PHM in your automation scheme? What are the costs and risks of automating, i.e., how does increased automation change the presence of failure and its characteristics? The manufacturing process objective and failure characteristics (of equipment/process failures) will dictate what data to collect; critical failures will tell you where to integrate PHM; and measurable symptoms will tell you what sensors to use. Immeasurable symptoms, or those symptoms that are costly to track, will steer the PHM design to more preventive maintenance strategies. Methods of processing the data so it can be interpreted and analyzed can then be defined. Data collection/analytics might be entirely new to the company, or there could be some legacy experience (and data); an equipment integrator might also be involved in data collection/utilization. Examining the process, itself, might allow the operator to make inferences about failure modes more readily than the equipment vendor. If parts production goals are being met, the failure mode detection might not be as big of a concern. There is other process-oriented data that can inform process performance, in addition to sensors that are attached to equipment (e.g., calculating cycle times of the overall process, sub-processes, etc. and comparing this data to baseline performance).

Guideline D – Health Data to Capture and Collection Strategies. To determine what health data to capture, you must first determine how the manufacturing process might degrade, may go offline, etc. This is analogous to a functional failure analysis, i.e., where/when does poor performance become a significant issue (unacceptable part quality, safety, shutdown, etc.). A functional analysis of the system would identify how the equipment degrades to apply sensing technology to analyze data and predict potential issues. In an ideal world, the maintenance strategy could evolve based on intelligence from sensing or other sources (maintenance logs, etc.) and other data. One such guideline would be a top-down approach and include the following:

- A process for the manufacturers to follow to help them identify what health data to capture and what sensors to install to get the needed data.
- Types of information that can help to build a profile/baseline of an efficiently operating plant (e.g., sensor data, historical data, etc.). This data can be used to develop a fusion algorithm (i.e., an algorithm that combines multiple sensor streams into a single data stream to provide a more holistic measurement or metric) or model that describes an ideal plant or process to compare against performance; this model could also be used to predict performance as the plant configuration changes.

- Initial efforts should aim to collect as much data as possible; then step back and evaluate the data to determine, what, if any, data is irrelevant or repetitive.
- Incorporate information-based decision support for optimal maintenance strategies higher up in the workflow (Guideline F); types of metrics to apply, data you need to collect, and how data will be used. Guideline C (where to apply PHM) should be coupled with and inform Guideline D (what data to collect).
- How to correlate data with current maintenance practices and production, and then use that knowledge to improve production and the process.

Guideline H (proposed) – Guideline for Baseline of Health and Performance and PHM ROI. An initial baseline is needed to understand the health and performance of the system, then to determine an appropriate PHM implementation strategy going forward, updating return on investment (ROI) and baseline for PHM as you go along. Economics significantly influences the design and implementation of the overall manufacturing process; the process' performance requirement is critically important to the entire enterprise. This economic influence also heavily dictates the extent of any PHM additions or integrations. Economic feasibility should be included in Guideline C. The recommendation is that recommendations to be outlined in Guideline H be performed sooner in the overall PHM integration workflow (not the workflow of these guideline development activities) rather than later, at the beginning of investments, before early targets for health/performance and PHM ROI are established. Afterwards, the plant operations and maintenance practices should be examined to see if benefits stemming from PHM implementation are being achieved. New process systems and equipment will be coming in periodically, so an early baseline is important to avoid future mistakes. Other parts of Guideline H include how you track the baseline and the benefits.

Guideline I (proposed) – Guideline for Natural Language Analysis for Maintenance Documents. Many manufacturers generate maintenance records to document equipment/process faults, failures, root causes, repairs, etc. as part of their maintenance strategy. Software technologies are emerging to allow manufacturers to more efficiently parse through this human-generated documentation to improve the efficiency of their maintenance practices including performing speedier troubleshooting and capturing greater intelligence to enhance failure prediction. NIST researchers are keenly aware of these emerging technologies and recognize the community's lack of guidance in how to both effectively deploy and evaluate such capabilities. The Nestor Graphical User Interface (GUI)[3] is a free toolkit that NIST has developed to help plant operators annotate their Maintenance Work Order (MWO) data through a process called "tagging." The MWOs are stored as comma-separated variable (.csv) files and the user goes through a tagging process to create an annotated, tagged MWO dataset. Nestor uses natural language processing (NLP) to perform structured data extraction from these MWOs with minimal annotation time-cost. NIST has updated the tool with an improved tutorial, different types of installations, easier to load data, ways to save and share progress. It is relatively user friendly and helps plants to build a generic schema quickly for maintenance [10].

NIST also recently participated in the Model-Based Enterprise Summit, presenting a paper addressing standards needs in MWOs, specifically, MWO data collection and storage, MWO data cleaning and parsing, and MWO data analysis needs. Despite the growing landscape of standards in sensing and related analysis, there is a scarcity of similar standards scoped to MWOs [11].

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[3] https://www.nist.gov/services-resources/software/nestor

3.2 Gaps and Additional Considerations

General ideas for priorities, including missing concepts, were raised and summarized below. Some of the ideas fit within existing priorities, while others could potentially be stand-alone elements.

- ***Natural Language Processing (NLP)*** – NLP can come into play with sensor and data fusion and understanding when equipment fails. It can help in documenting and analyzing failure modes from human-generated equipment and maintenance records.
- ***Prioritizing and documenting failures*** – the monitoring and resolution of failures (either those resulting from the loss of critical functions or expected based upon historical evidence) should be prioritized before data collection, before you determine how to document failure data, and before you decide on the recourse for failures. Sensors can be installed to collect large quantities of data, but if the sensors are not capturing information relevant to the failure or point of failure, the resulting intelligence could be very limited. Currently the operator must manually decide what failure happened, then correlate. Good historical data on failures will improve your ability to predict failures.
- ***Labeling of data*** – the success of failure prediction will be low if failure data is not collected and labeled. It is very important to fuse sensor label and failure label data. Labeling data is challenging for industry because the documentation is largely done by manual means; in a small organization, for example, manual means are the predominant way to label data, yet this is likely to breed inconsistencies. Guidelines should distinguish between a new facility with no data, and established facilities that have some historical data. In new facilities, you are collecting data not just for detecting anomalies but also to help establish a baseline for a healthy approach so you can go back and label data.
- ***Product failures*** – Failures can occur not just in the process/system but can also manifest in parts that fail to meet quality inspections or performance requirements. Part failures often originate from the manufacturing equipment and process, but can also be caused by environmental impacts directly affecting the part such as moisture, temperature, water temperature, etc.
- ***Culture change*** – the success of any new PHM solution needs to account for adoption among workers. Ways to minimize operator and technician resistance (e.g., reluctance to record job descriptions, work orders, etc.) should be addressed using human factors (e.g., human machine interactions) research methods.

4 Priority Topic A. Standards and Terminology Research and Guidelines Development

4.1 Overview of Terminology Research

NIST has been developing the terminology to enable guidelines for maintenance practices and implementation of advanced PHM techniques [12]. A key part of this effort is determining the terminology that is most common, as well as articulating appropriate definitions for those words.

To develop terminology, Michael Brundage and Brian Weiss, both from NIST, are leading an effort to search maintenance documents to identify the currently defined maintenance related terms and their corresponding definitions. A preliminary list of major terms has been developed (examples in Figure 4-1). The larger list of terms that have been identified and classified into priority levels were presented for review at the workshop (see Appendix C).

Table 4-1 Examples of Maintenance Terminology and Characteristics

Terminology	Acronym	Priority
condition-based maintenance	CBM	1
condition-based maintenance plus	CBM+	1
corrective maintenance	CM	1
performance life remaining	PLR	1
predictive maintenance	PdM	1
preventive maintenance	PM	1
reactive maintenance	RM	1
reliability centered maintenance	RCM	1
remaining useful life	RUL	1
time-based maintenance	TBM	1
assembly line		2
asset		2
component		2
engine health management		2
enterprise		2
equipment		2
failure modes and effects analysis	FMEA	2
fault detection and isolation	FDI	2
fault tree		2

Terms were compiled by searching through a large number and wide variety of existing standards, guidelines, organizational documents, and reports. These included reviewing content published by the International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM), Society of Automotive Engineers International (SAE) and International Electrotechnical Commission (IEC). Search results yielded summaries, titles, outlines, and other metadata, across multiple topics including manufacturing, railway engineering, oil and gas, engineering, and aerospace.[4] Besides identifying key terms from existing documents, this ASME Subcommittee is seeking stakeholder input on new terms that should be identified to enable guidelines development.

The NIST effort includes determining the types of terms, and how best to define them or update the existing definition so it is more applicable. One way to establish importance is the frequency of words used in maintenance-related standards and documents. A first step is compiling all the terms and frequency of terms from standards documents; the second step is working with stakeholders to determine what's most relevant and what, if anything, is missing. As more guidelines take shape, new words will be identified, defined, and added. Many common terms are shared by other industries where maintenance is critical and where guidelines have been established (e.g., nuclear, aerospace, etc.), so terminology is not restricted to manufacturing although that is the domain of focus.

[4] ISO 14224 provides a comprehensive basis for the collection of reliability and maintenance (RM) data in a standard format for equipment in oil and gas facilities.

The process is to define each term, reference the applicable standards/best practice, then gain group consensus/approval. If both existing ASME standards and other organizations have good definitions, the prevailing thought is to use those definitions already documented by ASME. A number of terms were identified from both the white paper (see Section 5.) and other sources and will be incorporated in the terminology document being developed by NIST (Appendix C).

4.2 Stakeholder Perspectives on Terminology

Several perspectives and ideas were considered on how to improve, refine, and prioritize the terminology for maintenance terms. These are summarized below.

General Suggestions

- Health monitoring of a machine is not done directly but indirectly through monitoring of certain parameters. Health could be a derived quantity that is made possible through fusion of sensed data, historical data, and other data (as available) using processing capabilities such as AI or Machine Learning (ML). Example – temperature and pressure are measured, but the health of a machine or robot is a derived term. An alternative view is that health applies to the overall process, while condition applies to equipment, where the two measures of health are unique. As guidelines are being written, those best practices that are also common should be considered.

Challenges

- Multiple definitions exist for some terms (e.g., condition-based, predictive versus reactive, etc.); terms need to have a single, uniform and common definition.
- Many standards were not created with data in mind, especially considering the large volumes of data that are currently available. There is a need to understand how to apply these standards given new paradigms in data and need for future integration of data.
- Establishing a single terminology is a problem.

5 Priority Topic B: When and Where to Integrate PHM in Manufacturing Operations

5.1 White Paper Scope

A white paper (to be published), “Determining When and Where PHM Should be Integrated into Manufacturing Operations,” has been developed to highlight the rationale and key considerations behind the initiative to develop guidelines for the priority topic of When and Where to Integrate PHM in Manufacturing Operations. The paper was produced by the ASME Subcommittee on Monitoring, Diagnostics, and Prognostics for Advanced Manufacturing. The overall objective of this specific guideline is to inform the manufacturing community as to when and where PHM technology could be integrated within a factory. The white paper indicates that guidelines will include recommended best practices for:

1) Identifying areas for improving operational efficiencies through enhanced maintenance practices,
2) Defining operational use cases linked to desired cost benefits and operational improvements,
3) Including safety and environmental factors,
4) Establishing baseline of current maintenance practices and health-ready capability levels,
5) Implementing cost-effective equipment asset condition management strategies, and

6) Measuring progress on improving operational efficiencies via PHM.

The white paper provides a rationale for this priority topic, an approach for determining equipment and manufacturing failure points (assessing both equipment and process health), and a discussion for advancing maintenance strategies within an enterprise. Several recommendations were elicited on the format and approach of the white paper. These recommendations are summarized below.

- Safety and environmental factors, as well as other benefits and operational improvements, should be added to (2) above.
- Guidance should include a generally-accepted definition of Overall Equipment Effectiveness (OEE); there are currently multiple definitions, interpretations, and calculations for OEE. Generally, OEE is a measure of a manufacturing operation's performance relative to its full potential during a typical run (percentage of manufacturing time the operation is truly productive). A simple OEE calculation is the ratio of Fully Productive Time to Planned Production Time; a preferred calculation is based on Availability, Performance, and Quality. ISO Standard 22400[5] presents commonly-accepted OEE calculations including specific timing calculations.
- Measuring the quality of the product is important to OEE and should be included. Process and equipment effectiveness and product quality are related. When determining where to integrate PHM, you will look at the process, from a relatively high-level, first to see if it [the process] is meeting the necessary quality requirements. However, the process should also be viewed at lower levels to directly see if sub-processes are meeting their respective quality targets. Process evaluation and identifying failures can't be done without instrumenting the equipment. It's also desirable to specify the equipment performance targets needed to achieve product quality. In the end, the process dictates what equipment should be used, but equipment health directly correlates to overall process health and product quality.
- Raw materials, supply chain, external factors could be incorporated into the guidelines where these elements are considered during the PHM design and inclusion process. Materials, scheduling and operational aspects are all important to the manufacturing process.
- Asset condition management (ACM), an important component of predictive maintenance, should be integrated into this guideline. ACM refers to the capability of assessing the current and future state of health of a manufacturing system and integrating that knowledge with enterprise applications to meet the demand of production operations. Some of the benefits of ACM include early warnings of potential failures, the ability for continuous remote monitoring, reduction in unplanned downtime and maintenance costs, ongoing reliability and risk reduction, and reduced inspection required for challenging locations (e.g., remote, confined, high altitude, etc.). ACM allows for a system to monitor and report on its own health. Considerations for incorporating ACM include:
    - ACM of an asset is readily defined, e.g., the asset reports on a set of performance metrics agreed upon by stakeholders.
    - Goals for asset management are uniquely specified for those that need to be aware of ACM (e.g., schedulers may require different ACM intelligence as compared to maintenance technicians).
    - ACM capability levels could be adapted from aerospace and automotive, 6 levels starting at zero (nothing in place) to Level 5 (sophisticated systems talking to each other). A chart is

[5] https://www.iso.org/standard/54497.html

available which could be included in the guidelines. Being able to 'grade' performance is related consideration.
- Include in general guidelines ways to assess how well the system is doing at different levels and compare with different users of the same equipment. This would help to assess how well problems are being diagnosed.

5.2 Outline for Guidelines for Where and When to Integrate PHM

A scope and basic outline for proposed guidelines for this priority topic were developed by some of the committee members; the results are outlined below. The results are intended to be a preliminary view on how the guidelines might be developed. Additional input will be gathered from stakeholders throughout the development process and in conjunction with generation of the related white paper.

5.2.1 Guideline Scope

The proposed guidelines for this topic are intended to assist manufacturers in making decisions about when and where to integrate Prognostics and Health Management (PHM) technologies and capabilities within their facilities. Guidelines will aid in answering key questions, such as where implementation of PHM can improve productivity and costs or help solve chronic maintenance problems. A process is envisioned that a manufacturer can follow to identify equipment/system health challenges and where PHM can help (e.g., where to add a sensor). Guidelines should be written so that the user can select which steps, if not all, are most critical to their efforts and follow only those that are warranted. The high-level headings of the outline are shown below.

5.2.2 Proposed Outline for Guideline

1. **Information Gathering to Establish a Baseline**: Define all the physical assets and how they work together to yield the overall manufacturing process and specific sub-processes.
2. **Identification of 'Pain Points':**[6] Identify asset or process health degradations that impact quality, productivity, scrap, cost of maintenance, and other health factors.
3. **Current Monitoring Capabilities:** Understand current capabilities for monitoring asset and process health.
4. **Potential for Deployment of PHM:** Determine best places (i.e., that will produce a return on investment) to deploy and integrate new PHM or improve existing PHM.
5. **Business Case:** Determine your business case for improving or implementing PHM.
6. **Appendices**

5.2.3 Additional Recommendations for Drafting Guideline

Additional recommendations for this guideline include how to define health-ready equipment and components; guidance for creating maintenance strategies, and PHM metrics.

- *Defining a health ready-component*. A health-ready asset would have robust information associated with it, e.g., remaining useful life projections, a PHM Readiness Level, etc. A definition for health-ready component could include:

[6] Suggestion was made to use different wording, not 'pain point', phrasing TBD but should be recognizable.

- Monitors itself and reports on itself, or supplier provides design information to do so.
- Incorporates intelligent sensors, i.e., sensors with data acquisition and data manipulation functions.
- Comes from supplier equipped with descriptive data to provide a coherent picture of the overall health status of the asset; could include, for example, access to data tags, component-level health data, etc.

- *Automatic Data Collection (ADC) Implementation Metrics*: Applied properly, ADC can enhance the effectiveness of maintenance operations. ADC today relies on bar codes, touch memory, magnetic stripe cards, radio frequency communication, voice recognition, etc. to collect performance and other data. Guidelines could be provided for effective ways to use ADC to track adoption and performance of the new PHM process, as well as the savings being realized and readiness levels (e.g., are you moving to level 2?). Hardware and software vendors have recently started realizing the potential of ADC for maintenance management.
- *Maintenance Strategies* – In some plants, emphasis may be just on routine scheduled maintenance rather than a maintenance strategy which incorporates a full spectrum of PHM tools. While the plant might not experience a lot of shutdowns, they could be doing scheduled maintenance too frequently. A guideline section could be included that talks about overall maintenance strategies that can improve condition and assessment.

6 Next Steps

This two-day standards subcommittee meeting was extremely productive and maintains the strong, forward momentum of the group. Numerous next steps have been identified and are actively being realized. Those interested participating in the subcommittee should contact ASME Staff Engineer Donnie Alonzo at AlonzoD@asme.org.

- Teleconferences – the subcommittee's leadership continues to hold monthly teleconferences. These meetings highlight what work has been recently completed, what work is actively being addressed, and any challenges that the entire group needs to discuss.
- Face-to-face meeting – the subcommittee's next face-to-face meeting is scheduled for November 21st and 22nd, 2019 in St. Louis, Missouri, USA. The meeting will be hosted by The Boeing Company. An agenda is actively being created and is expected to include updates and working sessions on the terminology document and the Guideline to Determine Where and When PHM should be Integrated in Manufacturing Operations. Those wishing to participate should contact Donnie Alonzo.
- White paper finalization – since the ASME PHM standards meeting in May, the subcommittee has finalized the draft white paper including the incorporation of the meeting participant comments. The white paper is now being reviewed by ASME's publication department and, upon review, will be published and made freely available.
- Standards Terminology – NIST's Michael Brundage and Brian A. Weiss are actively developing tools enabling them to search through existing standards to determine both relevant standards and terminology that could be referenced in this current effort. To date, the search tools have been used in several preliminary searches where Dr. Brundage and Dr. Weiss are still analyzing the findings. These findings, coupled with ongoing feedback from the overall subcommittee on what terms are the most appropriate for inclusion and update, will be coupled with new terminology for use within this effort.

- Guideline to Determine Where and When PHM should be Integrated into Manufacturing Operations – led by subcommittee members, Al Salour and Luis Hernandez, a small working group is actively leading the development of these guidelines. This document is being built upon the soon-to-be-published white paper along with feedback captured in this workshop.
- Subcommittee Expansion – Increasing the membership of this subcommittee will directly increase the number of contributors to the afore-mentioned guidelines. In addition to securing further industry involvement, getting more universities together and involved might be useful to build scope, data and long-term relationships and skills that will support these efforts.

Appendix A – Agenda

ASME/NIST Standards Subcommittee Meeting on Advanced Monitoring, Diagnostics, and Prognostics for Manufacturing Operations

Wednesday May 22, 2019

1. Coffee/Breakfast (7:45 AM – 8:30 AM)
2. Call to Order / Welcome (8:30 AM – 8:35 AM) – Donnie Alonzo / Brian Weiss
3. Introductions and Record of Attendance (8:35 AM – 8:45 AM) – Donnie Alonzo
4. Recap of Prior Meeting @ TechSolve (8:45 AM – 9:00 AM) – Brian Weiss / Donnie Alonzo
5. Proposed Priority Topic Areas and Guidelines 'Flow' Review (9:00 PM – 10:30 PM) – All

OUTPUT: Update priority topic areas; confirm next steps on "Determining When and Where PHM Should be Integrated in Manufacturing Operations" and "Standardized Terminology for Availability and Maintenance of Manufacturing Operations" topic; and discuss proposed additions to guidelines 'flow' and immediate work items.

6. Break (10:30 AM – 10:45 AM)
7. Review of Standards and Terminology Research (10:45 AM – 11:30 AM) – Brian Weiss / Michael Brundage

OUTPUT: Understand status of NIST efforts to identify existing standards that are relevant to manufacturing PHM and the corresponding defined terms that can be leveraged in this subcommittee.

8. Lunch (11:30 AM – 12:45 PM) – NIST Cafeteria
9. Review & Finalize White Paper (12:45 PM – 2:00 PM) – Mark Walker / Luis Hernandez / Al Salour / Radu Pavel

OUTPUT: Achieve broad agreement on overall content of white paper "Determining When and Where PHM Should be Integrated in Manufacturing Operations" where the next step would be to submit it for publication.

10. Guidelines Development – "Determining When and Where PHM Should be Integrated in Manufacturing Operations" (2:00 PM – 3:30 PM) – All

OUTPUT: Finalize Working Group (WG) membership, assign a document sponsor (lead). Generation of a draft outline of the guidelines document with this scope including estimated time frames to complete each section and who will be responsible (the document sponsor) for leading the work in the overall document/sections.

11. Break (3:30 PM – 3:45 PM) – All
12. Daily Wrap-up (3:45 PM – 4:30 PM) – All

OUTPUT: Summarize the day's activities to ensure that everyone's priorities are captured whether they are acknowledged in existing priority topic areas or documented in emerging priority topic areas.

Thursday, May 23, 2019

1. Coffee / Breakfast (7:45 – 8:30 AM)
2. Morning Introduction (8:30 AM – 8:45 AM) – Michael Brundage / Donnie Alonzo
3. Tour of the Prognostics and Health Management for Robot Systems Lab (8:45 AM – 10:15 AM, including walking time to/from the lab) - ALL
4. Break (10:15 AM – 10:30 AM)
5. Guidelines Development – "Standardized Terminology for Availability and Maintenance of Manufacturing Operations" (10:30 AM – 12:30 PM) – All

OUTPUT: Generation of a draft outline of the guidelines document with this scope including estimated time frames to complete each section and who will be responsible for leading the work in the overall document/sections.

6. Lunch (12:30 AM – 1:30 PM) – NIST Cafeteria
7. Outstanding Discussion Items/Next Steps (1:30 PM – 3:00 PM)
    a. Future teleconferences and face-to-face meetings
    b. SC advertising opportunities – additional industries/personnel to target for participation

Appendix B – Participant List

Donnie Alonzo, American Society of Mechanical Engineers (ASME)
Shelly Bagchi, National Institute of Standards and Technology
Hasan Bank, Craftnetics Inc.
Ning Bi, ITAMCO
Michael Brundage, National Institute of Standards and Technology
Qing 'Cindy' Chang, University of Virginia
Terril Falls, Institute for Systems Engineering Research, Mississippi State University
John Fanneron, The BP Group
Sara Fuller, Center for Advanced Vehicular Systems Extension, Mississippi State University
Jose Luis Hernandez, Global Strategic Solutions LLC
Michael Hoffman, National Institute of Standards and Technology
Xiaohui 'Mark' Hu, GE Digital
Xiaoning Jin, Northeastern University
Sarah Lukens, GE Digital
Saideep Nannapaneni, Wichita State University
Madhusudanan Navinchandran, National Institute of Standards and Technology
Radu Pavel, TechSolve, Inc.
Joan Pellegrino, Energetics
Guixiu 'Helen' Qiao, National Institute of Standards and Technology
Al Salour, The Boeing Company
Vijay 'Srini' Srinivasan, National Institute of Standards and Technology
Douglas Thomas, National Institute of Standards and Technology
Mark Walker, D2K Technologies LLC
James Waltner, Lockheed Martin
Brian Weiss, National Institute of Standards and Technology
Dazhong Wu, University of Central Florida
Guoxian Xiao, General Motors Company

Appendix C – Maintenance Terminology

Table C-1. Proposed Maintenance Terminology and Priority Levels

LEVEL 1	
3.1.1. Maintenance*	**3.1.3. Prognostics**
3.1.2. Diagnostics	**3.1.4. Monitoring**
LEVEL 2	
3.3.1. Abnormal situation management	**3.3.26. Health Monitoring (HM)**
3.3.2. Advanced Manufacturing	**3.3.27. Health**
3.3.3. Advisory Generation	**3.3.28. Health Assessment (HA)**
3.3.4. Anomaly, Abnormal Condition	**3.3.29. Health-Ready Capability**
3.3.5. Anomaly Detection (AD)	**3.3.30. Healthy-Ready Asset**
3.3.6. Asset Condition Management (ACM)	**3.3.31. Inspection**
3.3.7. Asset Condition Monitoring	**3.3.32. Knowledge-based (KB)**
3.3.8. Asset Performance Management (APM)	**3.3.33. Knowledge-based System(s) (KBS)**
3.3.9. Assessment	**3.3.34. Model**
3.3.10. Availability	**3.3.35. Model-based Reasoning**
3.3.11. Condition	**3.3.36. Operational Use Case**
3.3.12. Condition-based (CB)	**3.3.37. Overall Equipment Effectiveness (OEE)**
3.3.13. Condition Indicator (CI)	**3.3.38. Process**
3.3.14. Condition Monitoring (CM)	**3.3.39. Productivity**
3.3.15. Critical Failure Mode (CFM)	**3.3.40. Prognostics Assessment**
3.3.16. Data Acquisition	**3.3.41. Prognostics and Health Management**
3.3.17. Data Manipulation	**3.3.42. Quality**
3.3.18. Degradation	**3.3.43. Reliability Centered Maintenance (RCM)**
3.3.19. Equipment	**3.3.44. Remaining Useful Life (RUL)**
3.3.20. Expert System	**3.3.45. Sensor**
3.3.21. Failure	**3.3.46. Sensor Fusion**
3.3.22. Failure Indicator (FI)	**3.3.47. State**
3.3.23. Failure Mode (FM)	**3.3.48. State Detection**
3.3.24. Failure modes and effects analysis (FMEA)	**3.3.49. System**
3.3.25. Fault	**3.3.50. Usage**
LEVEL 3	
3.4.1. Abnormal Situation Management	**3.4.9. Predictive Maintenance (PdM)**
3.4.2 Alarm	**3.4.10. Preventive Maintenance (PM)**
3.4.3. Condition-based Maintenance (CBM)	**3.4.11. Reactive Maintenance (RM)**
3.4.4. Condition-based Maintenance Plus (CBM+)	**3.4.12. Reliability**
3.4.5. Corrective Maintenance (CM)	**3.4.13. Resilience**
3.4.6. Human Factor(s)	**3.4.14. Risk**
3.4.7. Performance Life Remaining (PLR)	**3.4.15. Time-based Maintenance (TBM)**
3.4.8. Performance Load/Loading	
LEVEL 4	
3.5.1. Assembly	**3.5.11. Flexibility**
3.5.2. Assembly line	**3.5.12. Health indicator (HI)**
3.5.3. Asset Criticality	**3.5.13. Health reporting code (HRC)**
3.5.4. Component	**3.5.14. Health-ready component**
3.5.5. Engine health management	**3.5.15. Integrated systems health management (ISHM)**
3.5.6. Enterprise	**3.5.16. Integrated vehicle health management (IVHM)**
3.5.7. Fault detection and isolation (FDI)	**3.5.17. Maintenance, Repair & Overhaul (MRO)**
3.5.8. Fault Isolation (FI)	**3.5.18. Root cause analysis (RCA)**
3.5.9. Fault tree (FT)	**3.5.19. System health management**
3.5.10. Feature	**3.5.20. Vehicle health management (VHM)**
	3.5.21. Workcell

Table C-1. Proposed Maintenance Terminology and Priority Levels

LEVEL 5	
3.6.1. Control	**3.6.9. Mean Time to Repair (MTTR)**
3.6.2. Data center infrastructure management (DCIM)	**3.6.10. Medium/Heavy-Duty E/E Systems Diagnosis**
3.6.3. Digital control system (DCS)	**3.6.11. Operator**
3.6.4. Digital twin	**3.6.12. Proactive alert identifiers (PAI)**
3.6.5. Electrical/Electronic Systems Diagnostic	**3.6.13. Probabilistic reliability assessment (PRA)**
3.6.6. Machine	**3.6.14. Robustness**
3.6.7. Machine Control	**3.6.15. Supervisory control/data acquisition systems (SCADA)**
3.6.8. Mean Time Before Failure (MTBF)	**3.6.16. Technician**

*Maintenance Definition(s): As defined by Subcommittee (SC); as defined by existing standards

Appendix D – References

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Appendix E – Acronyms

ACM	Asset Condition Management
ADC	Automatic Data Collection
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CBM	Condition-based Maintenance
CBM+	Condition-based Maintenance plus
CM	Corrective Maintenance
COTS	Commercial-off-the-shelf
FDI	Fault Detection and Isolation
FMEA	Failure Modes and Effects Analysis
IEC	International Electrotechnical Commission
ISO	International Organization of Standardization
ISA	The International Society of Automation
IEC	International Electrotechnical Commission
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
NIST	National Institute of Standards and Technology
NLP	Natural Language Processing
PdM	Predictive Maintenance
PHM	Prognostics and Health Management
PLR	Performance Life Remaining
PM	Preventive Maintenance
RCM	Reliability Centered Maintenance
RM	Reactive Maintenance
ROI	Return on investment
RUL	Remaining Useful Life
SAE	Society of Automotive Engineers
SDO	Standards Development Organization
SME	Small and Medium-sized Enterprise
SMM	Small and Medium-sized Manufacturer
TBM	Time-based Maintenance