A Systems Approach To PHM

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ABSTRACT

The operational objectives of today's complex, software intensive high technology platforms requires taking a systems approach to PHM. A systems approach to PHM includes the complete techno-social system involved in the equipment's operations and maintenance - its full cycle of care. It takes a broad view of health based on wellness and is focused on optimizing the performance of all elements of the system. It provides sustaining value by enabling enterprise wide enhancements in capability. By providing timely and relevant health information for all elements in the equipment cycle of care, a well-designed PHM system can become major facilitator in maximizing the performance and resilience of all elements in the system. This systems approach has major implications for PHM system design, architecture selection, data collection, sensor selection, control system software integration, algorithm development and analytics. PHM systems that encompass the health of the full socio-technical system in which the equipment is developed, operates and supported will maximize the effectiveness of the enterprise.

1. INTRODUCTION

To meet the needs of today's challenging, ever changing and often-unknowable environments, modern high technology systems have become increasingly complex software intensive integrated platforms. These high technology interconnected platforms are expensive to develop, procure, operate and maintain. These systems require enhanced support capabilities to meet their operational goals. While significant progress has been made in making high technology equipment more reliable, maintainable and supportable, it has not been enough. Despite all of these advances, many modern systems fall short of meeting their business objectives.

Advances in diagnostic capability have been pursued for many years but Prognostics and Health Management (PHM) has clearly emerged the winning alternative to the fly-fix-fly and time-based maintenance philosophies of the past. PHM systems monitor the health of the equipment (usually in real-time) and predict its future health so that interventions can be taken to prevent failure and reduce unscheduled maintenance, equipment downtime and secondary damage.

PHM itself is an evolving field. It has progressed from single-issue diagnostic and prognostic capability for troublesome components to health management of major systems. However, many traditional PHM systems have failed to stay current with the ever-changing needs of today's complex platforms. PHM systems that focus only on the physical electromechanical equipment, that take a limited view of health based solely on failure prevention and view value in terms of cost avoidance and cost reduction are often unable to provide the kind of enterprise wide enhancement needed to support today's modern systems.

While the systems themselves are becoming more complex, budget pressures and limited resources are driving the need to keep equipment operating longer with fewer the resources for maintenance and support. The PHM systems needed to support these systems must be value-based, flexible and organic to keep up with these needs.

A new approach to PHM is needed to address these shortfalls. This new approach is based on a broader definition of the system that includes its full cycle of care, a new health model that is focused on optimizing performance of all the system elements and a new value model geared to sustaining continued operational and business improvements.

Advances in descriptive and predictive analytics coupled with the technology from smart connected products provide valuable insights that can be applied to PHM. The internet-of-things (IoT) centers on smart flexible approaches to asset-based management, value added services and collaborative business models. The many-to-many interconnection architectures have applicability that can and should be applied to future PHM system communication networks.

This paper will explore the reasons why a systems engineering approach to PHM that focuses on an inclusive systems model, a broader definition of health based on wellness, and an enterprise wide value model can lead to systems that:

- Contribute to enterprise wide value
- Improve operational efficiency
- Increase in value over the life of the equipment
- Provide a greater return on investment
- Enable real time data driven decisions
- Enhance user experience
- Optimize products and services
- Enable development of more resilient products

2. Background

An illustration of the concepts developed in the paper is taken from a vending machine company's experience in applying the IoT model to their operations. Their experience is not exceptional but it provides a valuable illustration of the concepts further explored in this paper.

Vending machines are not among the typical high technology industries typically discussed at PHM conferences. However, one creative company in this industry was determined to reduce their high machine servicing cost using the IoT model. What they did illustrates the systems, health and value concepts presented in this paper. PHM system developers can directly benefit by incorporating the lessons learned from the example set by this company.

The vending company's machines were being serviced by company technicians who, because they had no way of knowing product usage, would bring a full complement of product to each machine on a scheduled basis to service them. Only when the servicers opened the machine did they learn which products were needed and in what quantity. Sometimes the machines needed only a few items. At other times the machines were out of stock on popular items – a condition representing a missed sales opportunity for those items. Occasionally, the servicers would discover that a machine was broken and required reactive maintenance. The servicers manually recorded product replenishment information and cash collected. While these records provided some financial information they provided little insight into customer buying behavior or usage patterns.

The vending machine company reached out to an IoT provider with a request for help. Their challenge was to reduce their servicing costs and they believed an IoT approach could help them.

Good analytics starts with questions. With the IoT provider they deconstructed their problem into the following series of questions:

> Where and when should we send our servicers and what stock should they bring?
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> How can we be sure the cash collected from the machine reflects the actual cash collected by the machines?
>
> How can we know when an out-of-stock situation occurs so that we can respond sooner?
>
> How can we know when a machine breaks down?

To answer these questions the IoT and vending machine team developed the following solution. They added a few sensors to the machine and connected the machines to the cloud via a wireless cellular network. They put analytics in the cloud to process the sensor data. The sensors were simple and inexpensive. They counted product quantity, usage and cash received. They monitored the machine internal temperature (a proxy for machine health) and its external temperature (a proxy for the local environment). They developed analytic algorithms to provide clear answers to their questions and put the analytics on a cloud so they could serve many machines and provide the needed flexibility to enable the system to evolve.

The analytics enabled them to service the machines intelligently so they could provide the machines with the products they needed when they needed them – significantly reducing the cost of servicing the machines.

This would have been a success story on its own but it is not the end of the story. The benefits spread across the enterprise. The finance department used the data on cash collected and product usage to detect and prevent fraud. The company found that initially they were able to respond faster to out of stock situations and machine breakdowns. They later learned they could proactively avoid out of stock situations and machine breakdowns using the same sensor set coupled with new predictive analytics. Marketing gained additional insight into customer buying patterns and used the information to improve product mix and placement. Inventory management used predictive analytics to prepare for predictable events (holidays) and weather conditions. The system continued to grow and learn as various entities across the enterprise continued to discover new uses for the data to support their operations.

This company's experience is not exceptional but it provides a valuable microcosm of lessons learned that can be applied to the high technology products typically discussed at PHM conferences. They started by asking questions involving issues that had the most significant impact on their business. They wanted to understand how they could improve the health of their business. They did this by taking a comprehensive view of their system. They did not focus on the equipment alone but they included the environment and the people and organizations involved in their enterprise. Their value perspective was focused on the business improvements that could be achieved with data from connected products. They were not simply focused on operational cost reduction. While operational cost reduction was initially a key consideration, they looked beyond that to see how the new capability could create value across their organization so they could optimize all elements of their business.

This company leveraged advances in low cost sensor technology, data storage, bandwidth and wireless networks with cloud based descriptive and predictive analytics. They connected their products to their operations and services. They gained visibility into product usage and environments. They became proactive to developing issues and improved the effectiveness of several diverse departments in the company. Information on product usage became a key factor in differentiating their product in the marketplace and enabled their design team to develop more customized and resilient products.

This company looked at health as a measure of wellness and looked at value based on enabling business improvements across their enterprise. They took a system perspective that included the full socio-technical environment. These approaches are directly applicable and even more urgently needed for PHM systems for complex high tech systems where the stakes are even higher.

3. HEALTH

The existential focus of health management is health. When prognosis is involved it encompasses both current health and expected future health.

Health, in a PHM context, is generally thought of in terms of its loss - such as a failure or degraded level of performance. A failure is often defined as the loss of an ability to function normally or the inability to accomplish an intended purpose. Health in the PHM context is generally considered as a loss of capability at the physical equipment level.

An approach to health management based only on failure prevention does not recognize the greater value that can be achieved when the health system is designed to get the most capability out of the equipment given its current circumstances and condition. Most operational equipment is not failed, but it is also not operating at its best either. In a manufacturing environment at Ford Motor Company, Edie, Kekedjian and Jalluri (2014) found that 98% of the equipment it was monitoring was not failed, but was not completely healthy either. Economic interventions can often be taken to address equipment that is not operating at its best. This is particularly true when the degraded equipment is impacting the larger system operation. Oskin (2014) recently discussed that monitoring Key Performance Indicators (KPIs) in real time could be used to enhance manufacturing system performance. Rather than focus on failure detection or impending failure prediction, measurements of various key performance indicators are taken in real time to keep factory operations at their best. Resources are applied not just to fix and prevent “failures” but to obtain the best performance possible for the system at all times. Health information is used at all levels to improve system performance – not simply to avoid failure.

The medical field defines health very broadly. The medical field views health as a system property - a property of the whole organic system. The World Health Organization (1948) views health as not merely the absence of disease or an infirmity, but as a state of complete physical, mental and social well being. In this context the health practitioner’s goal is not simply to help patients when they are ill or becoming ill, but to keep their patients well enabling them to perform at their best throughout their life.

The definition of health management systems in the medical field complements this broad definition of health. The World Health Organization (2010) defines a well functioning health system in the medical context as one that can respond in a balanced way to a population’s needs and expectations by improving the health of individuals and groups. It defends the population against threats to health, protects the population against the financial consequences of ill health and makes it possible for collaboration among people participating in decisions affecting their health and the health system itself. Porter and Teisberg (2006) argue that a well-functioning, value-based health system should be built around improving value to all participants in the health care network.

Applying this medical health model to equipment health implies that PHM systems should not merely be limited to detecting and isolating actual and impending faults in specific items of equipment, but it should have a goal of improving the performance all of the elements in the health care network. The goal should be to optimize the performance of all elements in the system. This more holistic approach to health care has major implications for the development of PHM systems. With this perspective on health care systems, the PHM systems would include the physical system along with its operations, support and management. It would integrate health management over the full cycle of care from equipment development, to monitoring, to fault prevention, diagnosing, predicting, repairing, restoring and improving. It would include both the equipment and the support environment in which it operates.

A well functioning health system should be capable of responding in a balanced way to the needs of individual equipment users and the overall asset base by:

- Providing visibility into the health status of the equipment and asset base to users at all levels
- Enabling the projection of future health status for alternative operating scenarios and environments
- Providing information needed to improve the health status of the equipment and asset base
- Providing information needed to improve the maintenance support environment
- Enabling innovation and specialization across the operational and support environments
- Supporting maintenance decisions
- Supporting logistics decisions
- Identifying new and emerging issues
- Responding to changes in usage, environment and configuration
- Supporting financial projections
- Supporting logistics and repair facility planning and coordination
- Making it possible for all users to participate in decisions affecting health
- Enabling evidence-based decisions for operations, maintenance and product resiliency improvements
- Integrating with existing business systems such as engineering, logistics, sourcing, quality, finance, analytics and others.

Achieving these goals requires the adoption of an integrated systems approach to PHM where all participants in the value chain (equipment providers or OEMs, maintenance providers, repair facilities, sourcing organizations, logistics agencies and regulators) can redefine their strategies, operating practices and organizational structures to unlock sustaining improvement in value delivered. Measuring and reporting of results at each level enabled by the PHM system is critical to reforming the entire system.

Measuring outcomes for every piece of equipment, for every service provider, and for every condition over the full cycle of health is critical for improving first time yield. Knowing the actual capability of each equipment item and subsystem and the capability of each provider in the equipment health cycle enables optimal use of resources and encourages resources to go to the best performers.

When PHM systems are focused only on the electromechanical equipment and view health and value based on a loss reduction models they often fail to live up to the needs of the platforms they are designed to serve. PHM systems that include the full cycle of care and are designed to provide enterprise wide business enhancement correct that problem.

4. SYSTEM

Since health is a system property and health systems are designed to maintain and support the health of the system, the PHM system should be inclusive of all elements in the equipment cycle of care.

PHM systems that are focused only at the electromechanical equipment level severely limits PHM system effectiveness. Focusing on the physical equipment alone does not address the impact of the integrated system environment, the software interactions, information integration, the people, organizations training and leadership or equipment usage and environmental factors.

4.1 Integrated System Environment

The PHM systems should be defined to include all elements in the equipment cycle of care, including the complete social and technical environment. It should acquire, integrate and share information to enhance the value for all participants in the enterprise.

Many traditional PHM systems do not address the complex interactions found in high-technology software intensive systems. Complex operations, high dynamic loads and cascading effects from other systems create anomalies in sub-systems that can be far removed from the original source of the anomaly. Similarly, software interactions and information fusion from disparate systems must be addressed. PHM must be framed in an integrated system environment.

PHM developers often assume that a support system is well defined and deterministic. They assume that PHM support systems are deterministic - similar to software routines and control systems with well-defined inputs, outputs and processes. PHM is anything but. PHM systems are highly complex and dynamic. Operational and support environments involve complex interactions among the people, organizations and services. Due to situations that are contingent, vague, ill defined or involve varied, distorted and conflicting patterns, these interactions cannot be scripted in advance. Optimal PHM systems are not fully human or fully autonomous, but hybrids where machine intelligence augments human decision-making.

A comprehensive PHM system model is needed for modern high tech systems. The system must include the full socio-technical environment – including hardware and software as well as all of the operational support and management elements needed to support the operational system. A comprehensive PHM system will accommodate the ever-increasing equipment complexity and integration, changes in usage, environments, equipment and failure modes. A comprehensive PHM system must support human decision-making and collaboration.

4.2 Software and System Interactions

Traditional PHM systems based on simple cause and effect models often do not address the complex software driven interactions so important in complex operational systems. In a discussion of safety in complex systems Levison (2005) reported that accidents in complex systems are often due to unforeseen interactions among components, including the effects of software, rather than individual component failures. Ignoring software driven interactions can result in serious shortfalls in the health management system.

4.3 Information Integration

When a PHM system definition is limited to a specific electromechanical item, that item is often unable to utilize information from other elements in the larger system or information external to the system - even when that additional information could aid in health assessment. Similarly, information from fundamentally different data sources may not be available to other sub-systems where it could aid in those systems' PHM performance. Occasionally, when the external information is available, it may not be sufficiently coded, defined or synchronized to be useful to other sub-systems. External information, such as the weather and weather forecasts or future usage planning information is also often available but inaccessible to equipment centric PHM systems, even when use of that information could assist with health assessment and health prognosis.

4.4 People, Organization, Training and Leadership

Traditional PHM systems are often developed as isolated, single issue systems that do not effectively communicate with the many other elements in the cycle of care. These systems often fail to consider the social nature of the operating and support environment in which they reside. This includes the organizations, training and leadership essential to the health of those systems. People, organizations and service providers (such as OEMs, maintenance and repair shops and logistics providers) are often not considered in the PHM system design. Furthermore, assumptions about the people, organizations and service providers that rely on the PHM information may not reflect their actual performance or needs.

Actionable intelligence requires getting the appropriate information to individuals in various roles in multiple organizations. Different people, organizations and service providers require different information from a PHM system to do their work effectively.

Many traditional PHM systems have a single user assumption. They provide a single output of health and failure prediction assuming that it can meet the needs of all users. These systems often fail to recognize the diverse needs of people and organizations that use health information or the variety of different ways the information is used. PHM systems must also address differences in user experience and levels of training.

Health information is required to make decisions impacting operations, maintenance and management. Each participant has unique information needs and decision-making responsibilities. For example, an operator needs to know if the equipment is working or not and, if not, what they can do to restore its functionality. Operators, when they encounter problems beyond their ability to fix, inform their maintenance staff that the operation has been compromised and needs repair. The maintenance staff then requires additional information to troubleshoot the problem and assemble the tools, materials and instructions needed to conduct the repairs. Management, at multiple levels, requires additional information on the anomaly so they can assess the impact on the larger operational goals. They must evaluate their options for mitigating the adverse impacts caused by the problem.

Wheeler (2013) explained that during complex negotiations people "act in real time on often incomplete and ambiguous information even when the stakes are high." The same is true for PHM. People will make tough decisions based on the information provided by the PHM system. Sometimes that information is incomplete but people need to understand what it says and have sufficient confidence in the information provided to make their decisions.

When PHM systems are developed without input from its users, the developers make decisions about what they think the individuals involved with operations and maintenance need to know. The actual individuals using the system may see things differently. For example, the decision on whether to provide a forecast could be based on best case, worse case or most likely case. The use of the information is highly dependent on circumstances that often cannot be determined in advance.

PHM is a revolutionary system developed to support the needs of complex products and systems. In his book on the revolution in military affairs, Boot 2006) explained that a technology revolution requires far more than revolutionary technology. “It also requires revolutions in organizations, doctrine, training and personnel.” The revolution in support concept needed for modern systems must include the people, organizations, training and leadership at all levels in the enterprise. The PHM system must recognize that people and organizations at different levels in an organization ask different questions about the current and expected future health. The PHM system should connect with all the elements in the business enterprise, especially the traditional ILS functions that interact with equipment information in various ways.

4.5 Usage and Environment

The PHM system should actively monitor and report on the actual usage of the equipment and the environment in which the equipment operates. Deviation from specification usage and environment must be continually monitored, so that the effects of any change on the equipment performance can be evaluated quickly. Usage and exposure that exceeds the equipment design limits is problematic but even prolonged exposure to harsh environments or abusive usage within design limits can cause premature failure and aging.

4.6 Validation and Verification

It is often difficult to validate and verify PHM systems particularly early in their design phase. PHM systems are designed to monitor the causes of failures and to detect actual failures. The initial fault library is typically based on the results of a FMECA or similar reliability analysis. The physics-based causes of failures (corrosion, overstress, etc.) and the causal warrant linking the failure cause to the failure effect are often still unknown and unproven during development. Failures and failure causes can be simulated and tested on the bench, but system performance in the real world remains unknowable until real failure conditions occur in the actual techno-social environment in which the equipment operates.

4.7 Prognosis

When PHM is based on simple physical models without including the system elements, failure progression estimation can be problematic. Prognosis models typically follow assumed trends or reasoning logic that may not reflect real world conditions. An effective PHM prognosis algorithm should include all relevant information from the system environment to quantify failure progression. This is needed to inform the decision makers of the true situation so that they can make evidence based decisions and take the necessary remedial actions.

5. VALUE

A well functioning health system should be centered on creating value for all participants in the value chain. In the IoT model, the value of interconnected products lies in the operational and business improvements possible when the health system information is incorporated into the business operational system.

Modern high tech systems are highly reliable and downtime is minimal. Failures rarely occur, but when they do they are of great concern. However, it is often difficult to justify adding costly sensors, enclosures and software to prevent failures when the conditions they are designed to prevent are believed to be rare and unexpected. Historical failure conditions experienced in previous designs are generally mitigated in upgraded or new design.

Traditional PHM systems are often justified based on a cost-benefit analysis focusing primarily on cost avoidance and cost reduction. The cost savings is typically based on maintenance cost avoidance, downtime reduction and secondary damage avoidance. It is difficult to justify funding for PHM systems to offset the effects of failures that the equipment designers hoped to have mitigated by design. These value models often exclude user inconvenience, customer impact and business impact caused by a loss of system capability. Rarely do they consider the loss of capability due to operating sub-optimally for long periods of time.

Porter and Happelmann (2014) argued that the IoT value model is based on a more positive value model where the real value of interconnected products is the enterprise wide enhancements made possible by knowing and improving the condition and usage of all elements in the system.

The cost of the PHM system should be justified based on a value model based on enterprise wide enhancement made possible by the system. Once the basic infrastructure is designed and built, additional costs can be allocated to enhance functionality as funds are allocated and circumstances allow. New analytics can be developed for previously unforeseen uses of the data. Additionally, analytic software can be refined and re-purposed for other applications.

6. PHM SYSTEM DESIGN

The basic design principle of PHM implied by this paper is to start with the questions that the business needs to have answered. Then identify the information needed by the various participants in the system to make value-based evidence driven decision. Continue the PHM system design using a broad definition of the social and technical of the system, including the full cycle of care in which the system resides.

The basic system architecture and network infrastructure can flow from this. It can be designed and built during development, but the system should be allowed to grow organically to meet the needs of multiple participants in the cycle of care. Developers should plan for new and advanced descriptive and predictive analytics to meet the ever-evolving business needs.

Product designers can use the information from the PHM system to improve the product design. They can make the products more customer focused and more resilient. Financial managers can make evidence based budget decisions and projections based on real data and accurate forecasts. The maintenance shops can forecast upcoming demand for their services and resources and the logistics managers can forecast future parts demands.

6.1 PHM System Design Guidelines

The following guidelines summarize the recommended steps a PHM system designer should consider in developing a PHM solution based on the recommendations presented in this paper.

- Identify the questions with the most significant enterprise wide impact that the PHM system seeks to answer. Typically this involves assessing the present and future health of the equipment and service providers and assessing the performance and usage of all system elements.
- Identify the complete socio-technical system in which the equipment is operated, maintained and supported. Include all potential interactions (hardware and software) with other systems. Include components beyond the equipment's physical boundaries that may impact the equipment. Include all elements in the full cycle of care. This should include elements of fault prevention, diagnostics, maintenance, repair and reuse.
- Identify the needs of the people and organizations across the enterprise involved in operations, maintenance and support of the equipment.
- Actively monitor the operating environment, product usage and failure modes. These are variables. Do not assume the equipment will be operated in accordance with the original equipment specifications.
- Select a PHM system architecture and network to maximize flexibility, learning and adaptation.
- Minimize on-equipment algorithms to only those needed for real time responses, such as operations and safety.
- Sensors are the prime source of basic information. Select them based on their value to the overall system.
- Exercise caution in leveraging or repurposing existing sensors, software and enclosures. They may not be suitable for PHM and may limit flexibility in the future.
- Maximize off-equipment (cloud based) PHM functionality to allow for growth and adaptation and enable data mining and analytics.
- In operation, provide timely and relevant health information to all participants in the value chain. Gather feedback - both good and bad.
- Utilize the results of the PHM system to make enterprise wide enhancements in all elements of the equipment cycle of care. Monitor progress and value created.
- Continue to improve the capability and performance of the product and the enterprise to establish a sustainable competitive advantage for your organization.

7. CONCLUSION

In their HBR paper on smart connected products, Porter and Happelmann (2014) claim that "smart, connected products offer exponentially expanding opportunities for new functionality, far greater reliability, much higher product utilization, and capabilities that cut across and transcend traditional product boundaries." PHM can leverage the IoT example and take PHM for high technology system to the level of support needed for today's modern equipment.

When properly developed and executed, the PHM system becomes a platform to build out an enterprise-based system with far reaching benefit to all participants in the value chain. A systems approach to PHM addresses the health of individual items, assets, operations and service providers. It is based on a broad definition of health based on wellness and a value model that is based on enterprise wide improvements.

By providing timely and relevant information for all elements in the equipment cycle of care a well designed, the PHM system becomes a major facilitator in maximizing the performance and resilience of all elements in the business.

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BIOGRAPHY

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