CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

DOI: 10.3303/CET1333066

Advances in PHM Application Frameworks: Processing Methods, Prognosis Models, Decision Making

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Competitiveness in high technological sectors such as industrial processes, utility networks, railway, renewable energy, aircraft, etc., is continuously demanding innovations –with new and more restrictive requirements, specially, reliability requirements- and operation and maintenance costs reduction (prevention, appraisal and failure costs). In this context, both maintenance strategies and maintenance methodologies improvements are needed in order to adapt them to such a new technological complex scenario. Within this challenge there is a big opportunity as well: all these advances or innovations include information and communication technologies (ICT), allowing the development of concept PHM (Prognosis Health Management) as the key for achieving efficient maintenance and lowering life-cycle costs. This paper outlines the main topics that are included in an integrated view of PHM application framework, from the signal monitoring and diagnostic techniques to prognosis, toward the generation of "business value". Then, describes the importance of the "detection function" in the emerging challenges of designing efficient PHM frameworks. Finally, an integrated view that relates PHM with e-maintence strategies is proposed.

1. Introduction

Now it's really possible to take advantage of the capabilities of the ITCs for improving systems operation and maintenance, and, consequently, get more reliable systems with less cost while assets life cycle is extended. Among other capabilities, a most accurate description of the degradation processes is now available. How deep can we characterize the system states? Is it possible to take maintenance decision based on objective knowledge about these current and future states? PHM goes lot further than other maintenance management tools to answering these questions. PHM has emerged as one of the key enablers for achieving efficient system-level maintenance and lowering life-cycle costs. (Ly et al. 2009)
The actual technological context is characterized by: a great number of sensor systems available, more communication capability, more reliability of ITCs applications, higher computation level, detection techniques maturity, (...) In these terms, Belini et al. (2008) argues, referring to electrical machines, that the advent of condition monitoring has revolutionized the maintenance of systems. The electrical machines study is a "case of use" reference. Not only for its specific interest but also because electrical machines are presented in most of industrial systems and other (aircrafts, railways or renewables energies), where PHM based improvements could give higher impact. A brief summarize of sectors where this concept is starting to implement with hopeful results is showed in Table 1.
On the other hand, the implementation medium costs have been decreasing continuously during last years. More precisely, the ratio performance/cost has been growing, both terms, qualitative and quantitative. Also the success of standards and flexible information systems has to be considered as advantage, in two different senses: by interrelation between different system (software, operational systems, measurement equipment, communication system) and providing the elimination of the premature obsolescent of the systems and software. Flexibility is a key factor for the adoption standards as MIMOSA (Machinery Information Management Open System Alliance)-IEEE1232, and it can facilitate the integration of asset management information providing a freedom to choose from a broader selection of software

Please cite this article as: Guillen A., Gomez J., Crespo A., Guerrero Bolanos A., Sola A., Barbera L., 2013, Advances in phm application frameworks: processing methods, prognosis models, decision making, Chemical Engineering Transactions, 33, 391-396
DOI: 10.3303/CET1333066

applications, and save money by reducing integration and software maintenance costs (Muller et al 2008). High cost and low flexibility of the information systems had been important entry barriers for the industrial application.

Table 1: PHM application sectors references

Sector	Technologic Item	References
Aeronautics	1. Electro-mechanical, electronic, navigatio system	Vatchevanos et al 2006,
Aerospace	IVHM technology development	Dai et al. 2009
Utility Network	Smart grid-Generation Distributed system, Comunication	Gomez & Crespo 2012
Electric Store	Batteries	Miao et al 2012
Electric Machines	Electric Motors, Converter,	Belini et al 2008
Renewables Energy	Off shore wind farm	Gacia et al 2012
Nuclear	Nuclear System	Zio & Maio 2010
Micro-electronic	Electronic component: digital electr., power supplies, pcb	Pecth & Rubyca, 2010

This field, maintenance engineering based on ITC capabilities, combines a large number of scientific and technological disciplines, which provide their own approaches to the common goal of trying to improve knowledge of degradation systems processes and their control. Also, the level of knowledge required by each area is very high, so that highly specialized engineers and technicians are needed. It implies, in most cases, high costs with no warranties of good results at the short term. The principal conclusion is that general frameworks and strategic view are needed to harness all their potential capabilities. The paper is organized as follows. In Section II, a review of most of the topics and terms is presented, distinguishing into functions and types of maintenance. The Section III discusses the need for a comprehensive approach that permits to link the new PHM capabilities with the different levels of management through the use of e-maintence strategies. Finally the conclusions are given in Section IV.

2. Main terms and topics related with PHM applications and its development.

There are several topics in the literature that help engineers and technician to use and take advantage of the capabilities of ITC for improving systems operation and maintenance and, consequently get more reliable systems with less cost while assets life cycle is extended. After a literature review, the first conclusion is that the main terms are accepted and widely used by the scientific community. However in many cases different shades are introduced with the aim of emphasize relevant aspects of the approaches or methodologies been studied. In associated with CBM and PHM topics, among others as IVHM or ISHM, recent advances have prompted the development of new and innovative algorithms for fault, or incipient failure, diagnosis and failure prognosis aimed at improving the performance of critical systems. For a comprehensive view of PHM two different approaches are exposed in this section: 1) PHM functions and capabilities and 2) PHM relation with other tools or types of maintenance is relay.

2.1 How to Know and follow system states. PHM functions: Monitoring, Detection, Diagnosis and Prognosis

A great deal of technology has been developed that could make degradation visible. Definitions of these terms vary upon applications. In the definitions below a disaggregated view of "detection", "diagnosis", and "prognostic" is presented, in order to highlight that everyone has specific weight and requirements. In some way they could be understood as PHM functions or even capabilities.

<u>Monitoring:</u> This function can range from the data acquisition to its preprocess in order to obtain measures of the key parameters for diagnostics and prognostic. The definition of these parameters (what parameters, and how operate them) is defining in the detection function, as we explain below. Monitoring is based on measure physical changes on equipment conditions, their operations and operation environment (Gomez an Crespo, 2011). As a function, it is limit to the observation of a current system state. It is distinguished between On-line Monitoring (remote and real-time instantaneous feedback of condition) and Off-line (data being collected at regular time intervals using measurement systems that are not integrated with the equipment). What technologies are available, measureless magnitudes, technical features and other characteristic are analyzed by Cheng and Petch (2010)

Detection: This term is included by most authors in the diagnosis function, but should be studied separately because the complex issues involved in it (feature extraction, condition indicators, fault isolation, fault detection), whose resolution requires the combined use of high specialization techniques and mathematical methods. There is a need for a better understanding of different factors involved in the degradation of equipment and products. Detection may include define anomalies and recognize that a monitored parameter has departed its normal operating envelope or passed a threshold. Analytical techniques such as FMEA, virtual simulations, and knowledge from maintenance records and experts can help identify the proper parameters for in situ monitoring. Understanding the physical processes and system behavior can help in choosing the techniques for diagnosis and prognosis (Petch and Jaai, 2010). Also detection would have a direct relation with alarm management (Kalgren, 2006).

Diagnostics: Diagnostics refers to the process of determining the current state of a system (Rosunally et al.2011). This function has a very high relevance, with a great difficulty level, when systems have no history data, sensors or even no maintenance strategy before the analysis. In these cases the methodology and tools used in order to determinate the current state requiring a specific approach. Jardine et al. (2006) introduced de idea of "pattern recognition" when they define machine fault diagnostics as a procedure of mapping the information obtained in the measurement space and/or features in the feature space to machine faults in the fault space. This mapping process is called as pattern recognition.

Prognostics: Refers to the process of predicting the future state (of reliability) based on current and historic conditions, or estimating the remaining useful life (RUL) of components or systems (Ly et. al 2009, Rosunally et al. 2011). Prognostic function would have to include dynamic adaptation, i.e., after diagnosis, the system continues working and also is possible that any maintenance decision has been taken. So, prognostic would have to be a dynamic process that would give new predictions along the time. This approach is included in the trend to automatization of the productive processes, where the automatic maintenance control has a crucial role. Lee et al. (2006) define Intelligent Prognostics as a systematic approach that can continuously track health degradation and extrapolating temporal behavior of health indicators to predict risks of unacceptable behavior over time as well as pinpointing exactly which components of a machine are likely to fail.

2.2 Maintenance tools and types: CM, CBM, PHM

Based on the capability presented before, along last decades different topics have being developed in the literature. PHM, CBM, and condition monitoring are broad concepts that are using referring to the predictive maintenance. In many cases the boundary between them is not clear being used interchangeably. This paper presents a brief description of these concepts and how they have been used in the literature for then (section III) propose an ordered structure, in order to take better advantage of the capabilities aligning the whole process towards general management objectives.

CM: condition monitoring: this term refers to a monitoring system that can diagnose the condition of equipment in order to determine the types of faults and their severity while it is under normal operating conditions (Belini et al. 2008) CM is the root element of condition maintenance. The condition of a system is quantified by parameters that are continuously monitored and are system or application specific. CM is the concept that is closer to a technological approach. Here advances from other disciplines are using and, in this sense, is the gateway between technological researches and maintenance applies.

CBM: Condition Based Maintenance: CBM could be presented as a maintenance decision making strategy where the decision to perform maintenance is reached by CM results of the system and/or its components. The decision making in CBM focuses on predictive maintenance. In many cases CBM is identify with predictive maintenance directly. CBM methods and practices have continued to improve over recent decades. The main idea of CBM is to utilize the product degradation information extracted and identified from on-line sensing techniques to minimize the system downtime by balancing the risk of failure and achievable profits (Lee et al. 2006)

PHM: Prognosis Health Management: is the process of determining the current state of a system in terms of reliability and prediction of its future state. Generally it combines sensing and interpretation of environmental, operational, and performance-related parameters to assess the health of a product and predict remaining useful life. Zio and Di Maio 2010, relate the prognostics with challenging tasks in Reliability, Availability, Maintainability and Safety (RAMS) and fix the primary goal of a prognostic system to indicate whether the structure, system or component of interest can perform its function throughout its lifetime with reasonable assurance and, in case it cannot, to estimate the Remaining Useful Life (RUL), i.e. the lifetime remaining before it can no longer perform its function

2.3 Prognostics approaches

Most of the authors distinguish three basic groups in current prognosis approaches: model-based prognostics, data-driven prognostics, and hybrid prognostics (Lee et al. 2006, Petch and Jaai 2010).The model-based approaches takes into account the physical processes and interactions between components in the system. Use mathematical representations to incorporate a physical understanding of the system, and include both system modeling and physics-of-failure (PoF) modeling. Prognosis of remaining useful life (RUL) is carried out based on knowledge of the processes causing degradation and leading to failure of the system. The data-driven approaches use statistical pattern recognition and machine-learning to detect changes in parameter data, thereby enabling diagnostic and prognostic measures to be calculated. are based on the assumption that the statistical characteristics of the system data remain relatively unchanged until a fault occurs in the system. Anomalies and trends or patterns are detected in data collected by in situ monitoring to determine the state of health of the system and the time to failure. Fusion or hybrid prognostic methodologies combine the strengths of the model-based and data-driven approaches, in order to estimate RUL under both operating and non-operating life cycle conditions, detect anomalous behavior or intermittent faults, identify precursors to failure for effective maintenance planning, and identify the potential processes causing system failure and the nature and extent of the fault for effective maintenance strategies

Comparing the practical application of both main approach, model-based and data-driven, Zio and Di Maio (2010) describes that when the cost/benefit ratio of using physics-based degradation evolution models is not favorable but sufficient data (possibly simulated) are available for constructing a map of the damage space, data-driven techniques may be more apt to the prognostics task. Furthermore, recent advances in sensor technology and refined simulation capabilities enable us to continuously monitor the health of operating components and manage the related large amount of reference data. This could be the trend from now to the future taking to account that the general use of this technology will make itself more reliable and more accessible by the costs reduction.

3. An integrated view of PHM within e-maintenace strategies.

As we have mentioned PHM is view by the different authors as the key factor to definitely promoted a qualitative jump toward intelligent maintenance. Lee et. al, (2006) give to PHM and e-maintence a fundamental role in maintenance development. They claim that continuous knowledge into present and future health of machines and their components, enable the move to e-maintenance based on intelligent prognostics (PHM) where maintenance actions are synchronized with the overall operation of the system as well as with the necessary maintenance resources and spare parts. Ly et. al. (2009) explain how to develop solutions for CBM/PHM effectively and efficiently, it will take a tremendous effort to coordinate all levels of managements from engineers to the top corporate level (maintenance managers, project officers, program managers,…). The entire enterprise must be coordinated in order to make PHM/CBM effective over the lifecycle operation of any system from the design, manufacturing, operational and logistical domains. The Return On Investment (ROI) is another highlight by these authors.

It possible to conclude that there are two general challenges in this development process: the coordination between corporate levels (alignment of technology with the business model) and the design of methodologies and frameworks to support its implementation (usually complex scenarios). It would let the development of the PHM potential. PHM systems have yet to be discovered or developed (Sheppard et al, 2008). In fact, arguably, PHM technology is still very much in its infancy, and its development is linked to e-maintenace strategies (Muller et al. 2008)

3.1 e-maintence and PHM

The e-maintenance approach is the conceptual support for integration of various corporate resource management solutions with the PHM system for maintenance planning. Essentially provides a framework for assisting in maintenance decision making with the aid of information and communication technologies (Gomez and Crespo 2011). Muller et al. 2008 defines e-maintenance as: “Maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (i.e. ICT, Web-based, tether-free, wireless, infotronics technologies) but also, e-maintenance activities (operations or processes) such as e-monitoring, e-diagnosis, e-prognosis, etc.”. Terms like proactive decision, e-diagnosis or e-prognosis include in this definition show the weight of PHM into e-maintenance concept.

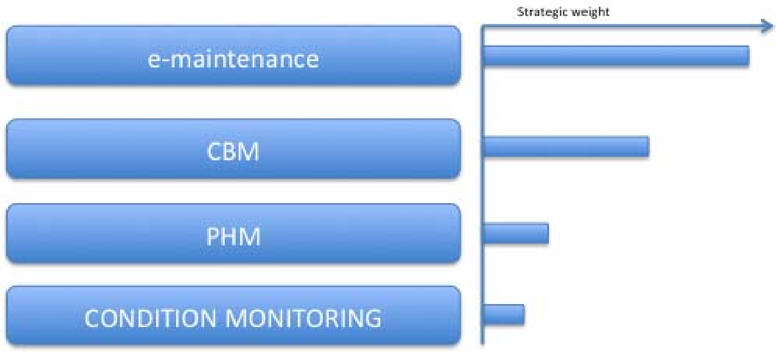

Figure 1.- Hierarchical relation of maintenance topics from strategic point of view.

In the previous section types of maintenance or maintenance approach, PHM included, have been listed. The scheme in Figure 1 try to organize all this topics taking to account the point of view presented before. In this approach, e-maintenance is the most strategic level because bring together the results of the rest of maintenance tools and function as gateway with the management system. PHM is rely on CM, giving a smart knowledge of the systems state. CBM, in this scheme, has a wider use than in traditional approaches and provide a maintenance planning based on PHM results which includes

3.2 Open standards and frameworks .

As we have exposed before the PHM results will be later incorporated into a maintenance decision support system and with e-maintenance strategic connected with other e-manufacturing and e-business system. Muller et al. 2008 argues in this sense, even claiming that maintenance is a key element of e-enterprise. Standards and frameworks are being development according to the complexity of the concerned systems (an enterprise) and the heterogeneity of the existing models, this modelling activity has become a very complex one. The Machinery Information Management Open Systems Alliance (MIMOSA) has adopted the development and support of the Open System Architecture Condition Based Management (OSA-CBM) , showed in Figure 2, standard that purports to provide a standard architecture for CBM and PHM systems (Sheppard et al. 2008) (Ly et al. 2009)

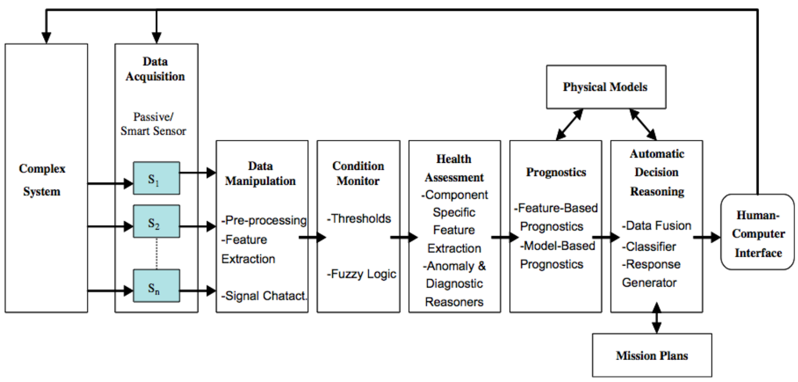

Figure 2: seven functional layers of OSA-CBM architecture, Muller et al. 2008

OSA-CBM is the most accepted reference. From this some authors have constructed simpler application frameworks. As an example here we present (Figure 3) the Petch and Jaay (2010) general proposal of hybrid prognostic methodologies that has being successfully implemented on electronics system (printed circuit card assembly subjective to temperature cycling conditions), and the adaptation of this framework making by Rosunally et. al (2011) who introduce it as a decision making support in the maintenance of an iron structure. Also include the use of Bayesian network models as a fusion approach to obtain more accurate remaining life predictions.

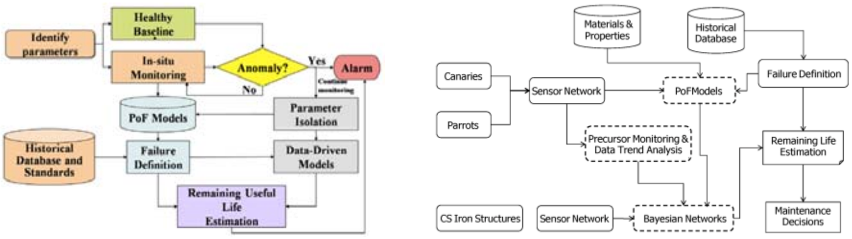

Figure 3: Framework proposed by Petch & Jaay 2010 and adaptation of Rosunally et al. 2011

4. Conclusions

PHM, in combination with e-maintence as strategical support, appears as the concept whose development can provide greater capabilities for the ongoing modernization of maintenance engineering. However, general frameworks and strategies are needed to harness all its potential capabilities. In this paper functions, capabilities and types of maintenance, PHM included, have been listed. The role of the detection function has been analyzed separately from prognostics and diagnostic. Then a proposal of scheme for hierarchical integration of the different approach, from condition monitoring to e-maintenace, has been presented, for helping to introduce corporate levels coordination and also to design of methodologies and frameworks to support PHM systems application.

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