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Prognostic and health management for safety barriers in infrastructures: Opportunities and challenges

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ABSTRACT: Different types of safety barriers are deployed in many infrastructures to reduce the occurrences of hazards, and protect people, environment and other assets in case the unexpected events have occurred and the capacity of these barriers against hazards can be weakened by degradations or the failures related to changes over time. It is natural to adapt the approaches of Prognostic and Health Management (PHM) to monitor the conditions and measurable parameters of safety barriers, and predict their future performance by assessing the extent of degradations. This study aims to identify the uniqueness and possible challenges when implementing PHM on safety barriers. Definitions and classifications of safety barriers will be discussed with considering their installation environment in infrastructures, in order to reveal what kind of characteristics of barriers can lead to higher demand on prognosis and heath monitoring. Another objective of this paper is to review the qualitative and quantitative measures for the capacity and performance of safety barriers, and to explore the possible methods and research gaps in the assessments for different PHM strategies, taking account their effects on safety barriers, and effects on the infrastructures being protected by the barriers.

1 INTRODUCTION

Maintenances can be defined as the activities to keep a system in a working order (Do et al. 2015). With the development of sensor technologies, the maintenances for many complex systems involve more and more condition-based and preventive activities to reduce maintenance costs on one hand, and improve their performance on the other hand (Sharma et al. 2017, Liu et al. 2017). Prognostics and Health Management (PHM), including fault detection, diagnostics, prognostics and health management, is a developing approach that enables real-time health assessment of a system and predicts of its future state based on up-to-date information. PHM has been conducted in many applications including manufacturing, aerospace systems, railway, energy, and military industry (Sun et al. 2012, Pecht and Rui 2010).

Safety barriers are installed in many critical systems and infrastructures to prevent hazardous events or mitigate their consequences, such as fire prevention systems and railway signaling systems. Technological safety barriers, such as shutdown valves in process, and airbags on cars, are also called as safety-critical system (Rausand 2014). But these safety barriers can also degrade and fail to accomplish their safety function under the evolving environment (Zio 2016). In case of failures of the barriers, serious accidents or disaster may occur. Many studies have been carried out on the operational and performance analysis of the safety barriers (Innal et al. 2015, Duijm and Goossens 2006, Innal et al. 2015, Rahimi et al. 2011, Cai et al. 2012), and most of them assume that the failures of components in the safety barriers follow the exponential distribution (Guo and Yang 2008, Jin and Rausand 2014, Catelani et al. 2011, Liu and Rausand 2011), meaning that their failure rate keep constant in any time.

According to IEC 61508 (2010) and IEC 61511 (2003), many technological safety barriers consist of three subsystems: sensor(s), logic solver(s) and actuating unit(s). The mechanical actuating units can degrade due to corrosion and wear-out etc, become more vulnerable along with time (Zio 2016), and so that the assumption of exponential distribution of failures is challenged. Based on this concern, a growing attention is given to the predict degradations of safety barriers and offer suitable maintenances in advance to ensure the barrier adequacy. PHM can be a helpful approach in performance prediction and decision-making for maintenances.

The purpose of this paper is to review the techniques of PHM and designing and operational characteristics of safety barriers, so as to explore the research issues when the PHM approach is planned to be implemented for improving the integrity of safety barriers.

The remained of this paper is organized as follows: In section 2, the development and advantages of PHM are introduced; Section 3, includes the review of safety barriers in infrastructure and introduces technological barriers; Section 4 introduces several unmet problems and challenges related to using PHM on safety barriers. A conclusion is given in Section 5.

2 PROGNOSTICS AND HEALTH MANAGEMENT

2.1 *Development of PHM*

PHM is developed based on the concept of Condition-based maintenance (CBM). CBM is an approach to carry out maintenance actions based on the information collected through condition monitoring on systems in contrast to breakdown or time-based preventive maintenance. In order to make a timely decision on maintenance, prognostics is the key technology for CBM (Jardine et al. 2006, Shin and Jun 2015, Bousdekis et al. 2015). From this point, PHM is developed from the concept of CBM. A CBM program consists of three key steps (see Figure 1) (Lee 2004):

1. Data acquisition step;
2. Data processing step;
3. Maintenance decision-making step

Diagnostics and prognostics are two aspects in CBM. Diagnostics deals with fault detection, isolation and identification when it occurs (Jardine et al. 2006). Prognostics, in ISO-13381 (2015), is to estimate the time to failure and risk for one or more existing and future failure modes. The relative placement of detection, diagnostic and prognostic can be explained in Figure 2 (Gouriveau and Medjaher 2011).

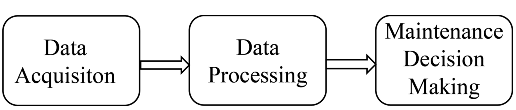

Figure 1. Three steps in CBM.

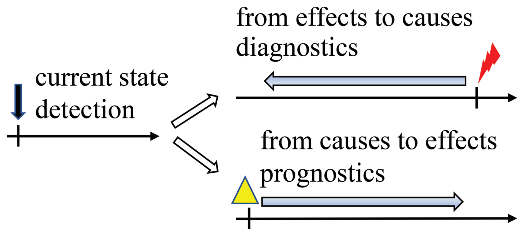

Figure 2. Complementarity of detection diagnostic and prognostic activities (Gouriveau, 2011).

In literature, prognostics is a process of health assessment and prediction, which includes incipient fault/failure detection, performance monitoring, life cracking and predicting residual useful lifetime (RUL) (Hess et al. 2005, Lee et al. 2014);

PHM is the extension of prognostics. According to CALCE (Center for Advanced Life Cycle Engineering) (2012), PHM is the means to predict and protect the integrity of equipment and complex systems, and avoid unanticipated operational problems leading to mission performance deficiencies, degradation, and adverse effects to mission safety.

Sun et al. (2010) regards PHM as a methodology to predict when and where failures will occur and to mitigate risks through evaluating the reliability of a system in its actual life cycle conditions. It is an enabling discipline of solving reliability problem in the process of design, manufacturing, operational and maintenance (Pecht and Jaai 2010). PHM is aiming to all information of an equipment in past, present and future while considering its environmental, operational and usage condition so as to detect its degradation, diagnose fault and predict and manage failures (Zio 2012).

Haddad (Haddad et al. 2012) regards PHM as a discipline that can used for: (i) evaluating the reliability of systems of their life cycle; (ii) determining the possible occurrence of failures and risk reduction; (iii) highlighting the Remanding Useful Lifetime (RUL) estimation. Actually, modern and comprehensive PHM systems take many issues into consideration, such as fault detection, fault isolation, useful life remaining, and performance degradation trending and then provides a broader set of maintenance benefits than any function by itself (Hess et al. 2005).

In this paper, we understand PHM as an approach to carry out dynamic management based on RUL which is predicted by status information collected through actual life cycle conditions, including environmental, operational and usage conditions.

2.2 *PHM architecture*

PHM means a complete process from capturing the data to decision-making (in maintenance,

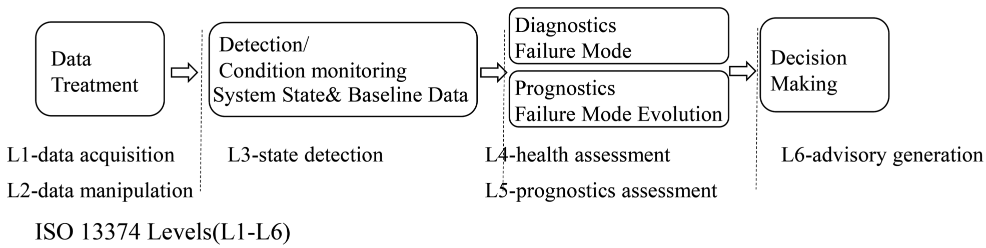

Figure 3. General process of PHM. Correlation with ISO 13374 (Guillén, 2016).

life time control, equipment design, etc.) (Guillén, Crespo, Macchi, & Gómez 2016), which is originally conceived by ISO 13374 and gradually becomes a standard in OSA-CBM (Open System Architecture for Condition Based Maintenance). As shown in Figure 3. The whole process of PHM is based on that of CBM, and can be divided into two parts. The first part (from Level 1/L1 to Level 5/L5) is related to health monitoring and prognostics, and the second part (Level 6/L6) is for health management.

In such a process, PHM attempts to answer several questions, e.g.:

- How is the status of system now? (Performance assessment).
- When will the system fail? (Remaining useful lifetime).
- What will the primary faults that cause system failure?
- Why does the incipient fault occur?

2.3 *PHM methodologies*

To answer the above questions, prognostics is currently carried out in different ways, namely with model-based, data-driven and hybrid prognostics (Brahimi et al. 2016).

The model-based approaches are based on a good knowledge of the physics of system and the available failure modes. Analysts can construct mathematical models with the above knowledge, and analyze those systems whose field operational and failure data is not enough (Lee et al. 2014, Luo et al. 2003). However, for many complex systems, one of limitations of the model-based approaches is the difficulty to create deliberate models representing the multiple physical processes (Pecht 2008). Moreover, it is very difficult to adopt the models built for some specific applications to the others, even though the systems are very similar.

The data-driven approaches are based on statistics and machine-learning techniques (Gu et al. 2007). In data-driven the remaining useful life would be predicted by fitting the monitoring data of developing fault to the degradation mechanism before it reaches the predetermined threshold level (e.g., see (Medjaher et al. 2012)). These methods are relatively simple to deploy due to the necessary of an analytical model of behavior and failure of the system.

The hybrid approaches are proposed in consideration of the pros and cons of the previous two groups (Lee 2004), in which prognostics results are claimed to be more reliable. The hybrid approaches have been used for the RUL prediction and maintenance of systems, such as (Kumar et al. 2008, García et al. 2010, Skima et al. 2015, Zhang et al. 2009).

PHM has been conducted in many areas, such as the infrastructures, aerospace industry, and in this paper we focus on the approach for safety barriers.

3 SAFETY BARRIERS

3.1 *Safety barriers and classification*

Safety barriers, or simply barriers are the equipment and features that are installed to protect people, the environment and other assets against harm should features or deviations occur in the most-designed system (Rausand 2013). Safety barriers are always related with a certain safety functions, which are defined by Sklet (2006) as the functions planned to prevent, control, or mitigate undesired events or accidents.

Figure 4 is a Bowtie diagram widely used in the field of risk analysis, where we can identify the two different roles of safety barriers. A hazardous event can occur due to some causes, so that some barriers can be located on the left side of the diagram (the causes side), to reduce the probability of the hazardous event. This kind of barriers are called as proactive barriers or prevention barriers, such as antilock braking system, electronic stability control system in automobiles. On the right side, some barriers are located on the right side (the consequences side), in case of the occurrence of a hazardous event, for reducing its effects or failure

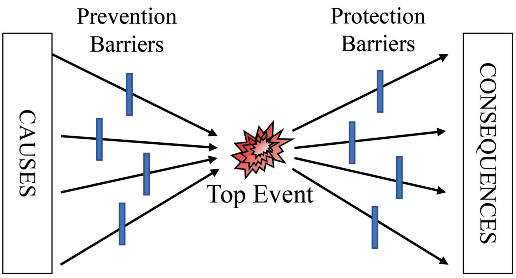

Figure 4. Bowtie diagram for a Top Event with prevention and protection barriers.

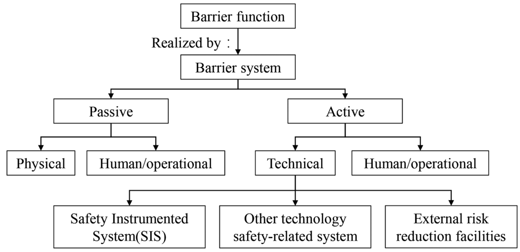

Figure 5. Classification of safety barriers (adopted from Sklet, 2006).

escalation, and they are regarded as reactive barriers, or protection barriers, e.g. seat belts, airbag systems (Hollnagel 2004, Rausand 2013, Groot 2016).

This classification is based on the objectives or functions of barriers. In addition, considering the operational modes of barriers, Rausand (2013) has distinguished safety barriers as passive and active barriers. An active barrier is dependent on some energy sources and a sequence of detection-diagnosis-action to perform its function, such as an airbag, Meanwhile, a passive system is not required to take an action and just by the presence of their elements to achieve its function (e.g. a seat belt).

Safety barriers also can be divided into on-line and off-line barriers. The on-line barriers operate continuously or so often, and on the contrary, the off-line ones are only used intermittently or infrequently. In practices, most protective barriers are off-line ones (Rausand & Arnljot 2004).

Sklet (2006), on the other hand, considers who are carrying out safety functions, and classifies barriers as the physical, technical, and human/operational barriers. Combining with the categorization based on the operational modes, we can obtain Figure 5. In the figure, technical barriers are always active. They are further divided into three groups: Safety Instrumented System (SIS), meaning that a technical barrier which involves the electric, electronic, and programmable electronic (E/E/PE) technologies, other technology safety-related systems and External risk reduction facilities. In the rest of this paper, we focus on technical barriers.

3.2 *Technological barriers*

A technological barrier, involving E/E/PE technologies and some mechanical items, generally consists of three subsystems: input element subsystem (e.g., sensors, transmitters), logic solver subsystem (e.g., programmable logic controllers [PLC]) and finial element subsystem (e.g., safety valves, circuit breakers). The main parts are illustrated in Figure 6.

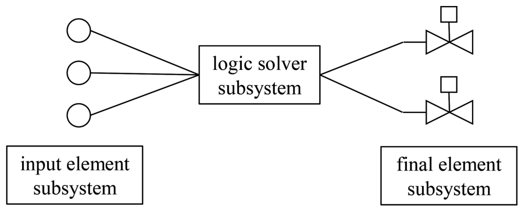

Figure 6. Main parts of a technological barrier.

The system protected by a technological barrier is called the Equipment Under Control (EUC). A safety-instrumented function (SIF) is a function that has been designed to protect the EUC against a specific demand. To enhance the reliability of a barrier, redundancy is often implemented in the system configuration.

4 DEVELOPMENT A PHM FOR SAFETY BARRIERS

We can introduce the PHM to safety barriers, with the purpose to assess the degree of deviation or degradation of barriers, and then plan maintenances in advances, so as to improve their availability and bring safety to EUC.

4.1 *Main functions of PHM on barriers*

Compared to the existing diagnostics of barriers, PHM is expected to predict failures from incipient failures or deviations in components. The main functions and potential benefits of the PHM on barriers can include:

- Advance warning of failures—Prognostics in PHM can evaluate the degradations of barriers, so as to detect incipient deviations. It is possible for maintenance staffs with prognostic results regarding the operational conditions to take actions on a barrier before a failure really occurs.

- Optimized maintenances—With prognostics, maintenance staffs also can estimate the remaining life of a component, especially a mechanical one, in a barrier, and then develop a maintenance, repair or replacement plan. Compared with scheduled maintenances, these condition-based and predictive maintenances eliminate unnecessary activities, and keep the barrier effective.
- Logistic support and cost reduction—Ideal prognostics tell the maintenance staffs when and where failures will occur, and thus they can identify and fix the failed components easily. PHM can reduce lead time and therefore increase the available time of safety barriers. Moreover, the "just-in-time" maintenances based on prognostics decrease the unnecessary costs of scheduled inspections and interruptions.

4.2 *Challenges of PHM on barriers*

Although PHM has been proved in many applications, we may meet challenges when we implement PHM on the technological safety barriers, due to the following design and operational characteristics of barriers:

4.2.1 *Operational modes of barriers*

Current PHM is always used for systems continuously running, while safety barriers have several operational modes in stead:

- Low-demand mode: where the safety function is only performed on demand, and where the frequency of demands is relatively low;
- High-demand mode: where the mechanism is same as low-demand, but the frequency of demands is relatively high;
- Continuous mode: where the safety function is a part of normal operation.

In the latest version of IEC 61508 (2010), the borderline between low-demand and high-demand is once per year in terms of demand frequency.

For those technologies barriers with demanding operational modes, they are usually in a dormant state and transit to an active state in case that demands come. The degradation mechanisms in different states are varied. Not many studies have been conducted so far on degradation prediction with state transitions. We need new approaches of parameters to predict the future performance of a barrier in response to demands during the durations of demands.

4.2.2 *Structures of barriers*

Redundancy structures are often used in barriers to improve availability and to enhance safety, e.g., two shutdown valves are installed in parallel to stop flow when the downstream pressure is too high. When one of them cannot activate, the process is still safe if the other works. Such kind of structures is called as 1-out-of-2 configuration. For a system with N channels, if at least K of the N channels need to be functional to ensure that the system is functional, the system has a K-out-of-N (Koo$N$) configuration.

Many barriers can be adaptive, meaning that they can change their configurations to perform safety functions when some expected occur. For example, a 2oo3 barrier can automatically transit to a 2oo2 configuration when one of the three channels fail. The challenge for PHM is to predict the effects of degradations in one channel on the entire barrier system with complex configuration and adaptivity, as well on the EUC.

4.2.3 *Failure modes and tests of barriers*

Failures of technological barriers can be classified as dangerous (D) failure and safe (S) failure. D failure refer to a failure that has the potential to put the barrier in a hazardous or fail-to-function state, while S failure does not leave the barrier in fail-to-function state (Rausand 2014), e.g. a valve shuts down unnecessarily.

The integrity of a technological barrier is highly related with tests, especially for those running in the low-demand mode. Regular proof tests are conducted on technological barriers (e.g. once per year), to reveal failures and then initiate maintenance activities if necessary. Many modern safety barriers have installed automatic self-testing modules, which has a diagnostic function and detects some failures. The D failures that can be found in diagnostic tests are called as dangerous detected (DD) failures, such as signal loss, signal out of range and final element in wrong position (Rausand 2014). The D failures that are not detected are called dangerous undetected (DU) failures. DU failures are only revealed in proof tests with regular intervals.

A research challenge of PHM is therefore to find suitable approaches to link the incipient failures or deviations with those D failures of interest in integrity of barriers. Most data-driven PHM approaches depend on the historical/training data to predict the trends of failure, but in those published data sources for technological barriers, such as Offshore Reliability Data (OREDA) and Process Equipment Reliability Data, we cannot find any clues. For model-based PHM approaches, no guidance is given to deal with those DU failures.

Another challenge is from the failure occurring in the redundancy structures. Common cause failures (CCFs) are the main contributor of the unavailability of redundant safety barriers (Hauge et al. 2015). CCFs are the failures of multiple components simultaneously or with a short time interval due to a shared root cause or a common cause. It is valuable to identify those deviations that can lead to CCFs and predict their potential influences in PHM.

4.2.4 *Measures of technological barriers*

IEC 61508 (2010) suggests the average probability of failure on demand (PFD) as a measure for technological barrier of low-demand, and the probability of failure per hour (PFH) as the measure for technological barrier of high-demand. And then, for different results of PFD and PFH, safety barriers can be located at different integrity levels (SILs), from the loose SIL 1 to the strictest SIL 4. These measures are widely used, and they are calculated always on the basis of some basic assumptions (Jin and Rausand 2014, Wang and Rausand 2014, Rausand 2014), including: (1) each failure is assumed to occur at a constant rate (i.e. exponential distributed failures); and (2) the channels in a redundant structures are identical and independent.

We release these assumptions when implementing PHM, and so weaken the theoretical foundations of measure calculations, since we have realized that deteriorations in mechanical components of a technological barrier is unavoidable. However, to evaluate the effectiveness of a PHM program, we still need to utilize the widely accepted measures, and build a relationship between SILs and effects of PHM.

4.2.5 *Cost-benefit analysis of PHM*

Safety and availability are dominator in the assessment of safety barriers. But for PHM, the return-on-investment (ROI) needs to be considered (Saxena et al. 2008, Wang and Pecht 2011), especially for the fact where other test and diagnostics are also employed on safety barriers.

The main work for ROI analysis or cost-benefit analysis is to quantify the costs and benefits of PHM (Scanff et al. 2007). The costs of a PHM program can includes: the cost of acquisition and installation for data, such as sensors and microprocessors, the cost of re-design of host product, which can be a big investment (Sun et al. 2012). The benefit is more complex including the decrease of proof tests and maintenances. It is challenging on how we choose the indicators to calculate the ROI of a PHM program. Moreover, we also need to determine the best PHM program for a specific technological barrier.

5 CONCLUSIONS

In this paper, a short review of PHM is presented. PHM enables estimating the RUL of the in-service equipment which can provide timely decision for maintenance. Due to the vital role of technological barriers and the advantages of PHM, an idea for developing a PHM system for SIS is presented. Compared with mechanical systems, technological barriers have their own characteristics which propose new challenges.

Therefore, we propose several research topics to be addressed in future, specifically in a PhD project:

- New approaches for predicting degradations of a component with state transitions;
- Mechanism of incorporating redundancy structures and varied configurations in degradation modeling and analysis;
- Models to link the effectiveness of PHM with the measures for safety barriers;
- Methods to optimize PHM and other maintenance activities under the constraints of SIL requirements by safety barriers.

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