Supporting group maintenance through prognostics-enhanced dynamic dependability prediction

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ABSTRACT

Condition-based maintenance strategies adapt maintenance planning through the integration of online condition monitoring of assets. The accuracy and cost-effectiveness of these strategies can be improved by integrating prognostics predictions and grouping maintenance actions respectively. In complex industrial systems, however, effective condition-based maintenance is intricate. Such systems are comprised of repairable assets which can fail in different ways, with various effects, and typically governed by dynamics which include time-dependent and conditional events. In this context, system reliability prediction is complex and effective maintenance planning is virtually impossible prior to system deployment and hard even in the case of condition-based maintenance. Addressing these issues, this paper presents an online system maintenance method that takes into account the system dynamics. The method employs an online predictive diagnosis algorithm to distinguish between critical and non-critical assets. A prognostics-updated method for predicting the system health is then employed to yield well-informed, more accurate, condition-based suggestions for the maintenance of critical assets and for the group-based reactive repair of non-critical assets. The cost-effectiveness of the approach is discussed in a case study from the power industry.

1. Introduction

The main goal of maintenance is to achieve desirable system dependability whilst minimising cost [1]. Dependability is a term that encompasses a range of attributes which include safety, reliability, availability, and maintainability [2]. Some industries are moving away from traditional time-based or reactive maintenance regimes towards condition-based maintenance (CBM), where intervention is scheduled when monitoring data indicates asset deterioration [1].

CBM applications have explored different areas for cost-effective maintenance planning such as grouping maintenance strategies or updating maintenance models with prognostics information. Grouping maintenance actions together can reduce downtime and personnel costs through considering functionally or spatially related assets within the system [3–12]. Prognostics and health management (PHM) is an integral aspect of CBM which focuses on system degradation management with the following main groups of activities [13]:

- Anomaly detection: monitoring and detection of abnormal conditions in the system operation.
- Diagnostics: if an anomaly is detected, diagnose the cause of the fault.
- Prognostics: predict the likely future degradation of the asset and estimate its remaining useful life.
- Operation and maintenance planning: mitigate the effects of failure and reduce unnecessary planned maintenance.

PHM techniques have emerged as promising solutions for cost-effective asset management and maintenance planning [14–16]. Namely, the connection between prognostics and maintenance enables updating maintenance plans with up-to-date remaining useful life (RUL) estimations [16–18].

The RUL denotes the time distance from the current prediction time, \( t_p \), to the end of the useful life (or failure time) of the system denoted \( EOL \):

\[
RUL = EOL - t_p \quad \text{if} \quad EOL > t_p
\]

Given that remaining time after \( t_p \) is random, uncertainty representation mechanisms are needed to model RUL [19,20]. Fig. 1 shows the RUL prediction concept, where \( \mathcal{Y} = \{Y_1, ..., Y_p\} \) denotes gathered

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Depending on the specific prognostics prediction method, the format of the RUL prediction results will be different [19,16]:

- deterministic RUL values (e.g. calculated employing neural networks [22]);
- RUL values with confidence intervals $RUL \pm CI$ (e.g. estimated with hidden Markov models [23]);
- probability density function (PDF) of the RUL (e.g. derived using particle filters [14,24]).

So as to use prognostics results within CBM planning, one possibility is to parametrize prognostics prediction results [25]. For deterministic prediction results, the RUL value can be used directly assuming a constant degradation rate and confidence bounds can be used to estimate maximum and minimum boundary values [26]. As for the PDF of the RUL, the PDF can be parametrized through regression methods (e.g., Weibull regression [27,28]), or alternatively mean, maximum and minimum RUL values can be calculated [25].

Despite these advances, cost-effective CBM planning is far from trivial in complex industrial systems. Such systems are comprised of many potentially repairable assets, which can fail in different ways and with various effects. The operation of assets and the system is typically governed by dynamics which include time-dependent and conditional events and they cause complexities in the system reliability prediction and maintenance planning [29]. The use of combinatorial failure models (fault trees, reliability block diagrams) to model the failure logic of complex systems has disadvantages for maintenance planning. For instance, in a fault-tolerant system, the criticality of assets can change substantially over time [30]: in a system with two parallel redundant channels, when one fails the criticality of assets within the single remaining channel increases. Combinatorial failure models have limited ability to represent these situations. Therefore, system maintenance strategies based combinatorial failure models may also mis-calculate dependability and maintenance costs.

Several dynamic dependability techniques have emerged to enable a more accurate analysis of dynamic scenarios that include state changes and sequencing of failures [31]. The application of these techniques for CBM planning would enable a more accurate health assessment of the system operation and the system is typically governed by dynamics which include time-dependent and conditional events and they cause complexities in the system reliability prediction and maintenance planning [29]. The use of combinatorial failure models (fault trees, reliability block diagrams) to model the failure logic of complex systems has disadvantages for maintenance planning. For instance, in a fault-tolerant system, the criticality of assets can change substantially over time [30]: in a system with two parallel redundant channels, when one fails the criticality of assets within the single remaining channel increases. Combinatorial failure models have limited ability to represent these situations. Therefore, system maintenance strategies based combinatorial failure models may also mis-calculate dependability and maintenance costs.

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