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A novel framework to link Prognostics and Health Management and Product–Service Systems using online simulation

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ABSTRACT

Product–Service Systems (PSS) and Prognostics and Health Management (PHM) have so far been researched individually in different domains and as unrelated research theme. However, to guarantee the availability of the asset, which is a typical demand in some PSS contracts, it is fundamental for PSS providers to be able to properly manage the asset's lifetime variability in order to avoid unscheduled downtimes and contract penalties. This paper describes part of a research project to investigate how PHM can support more effective fulfilment of some PSS contracts. In particular, this paper aims to present a novel framework to link PHM and PSS using online simulation. The paper also presents a prototype of the online simulation model and three experimental cases comparing the outcomes of the online simulation model against those obtained from the traditional simulation model.

1. Introduction

Product–Service System (PSS) has emerged as a new manufacturing strategy whereby manufacturers shift their business model from selling 'only product' to selling 'an integrated of product and services' [1,2]. In PSS, customers are typically no longer buying the product (asset) but instead buying the availability or capability of that asset [3]. In PSS, the Original Equipment Manufacturers (OEMs), typically, do not offer product ownership but an integrated solution combining product and service provision. OEMs are therefore responsible for managing the asset's lifetime, spare parts and maintenance services in order to maximise the asset's performance and to minimise the operational cost [4]. Enabling technologies, such as Prognostics and Health Management (PHM), are often needed to manage the asset's lifetime and to execute the appropriate maintenance activities to avoid catastrophic failures or unscheduled downtimes [5].

Fault diagnosis and fault prognosis functions (typically found in PHM technology) are often integrated in many high value products or assets to open up new service opportunities [6]. Using those technologies, the companies can capture unforeseen performance variations during the asset's lifetime. This is particularly useful in high-tech sectors, e.g. aerospace, military, etc., where operational costs have become a significant source of revenue generation for the PSS providers. Indeed, an effective PHM helps increase the asset's reliability and safety using a concept known as *autonomic logistics* [7]. This concept considers a PHM system as an autonomic response or like a subconscious reflex of human being's nervous systems to react automatically to an unforeseen potential problem.

The Rolls-Royce's TotalCare® is one of the most widely reported cases of the integrated PSS and PHM. The TotalCare® is considered as "*a flexible approach to achieving an engine support service that has the correct fit and scope of services to meet the operator's specific needs*".[1] In this case, not only does Rolls-Royce supply the aero engines, they also use the engine health monitoring to make an advance fault prediction in order to avoid the expensive cost of operational disruption and unnecessary engine repairs [58]. PHM is also reported to be the backbone of the maintenance and logistics management for the Joint Strike Fighters (JSF) [8]. In this case, PHM components aid the logistic policy change of the US Department of Defense (DoD). Another example is the method to perform PSS for the machine tool proposed by Zhu et al. [9]. In the Industrial Product–Service System for CNC machine tool (mt-iPSS), the capability of the machine tool and its attachment are sold as an intangible service. The business core is to provide machining capability rather than product ownership. In this case, the service

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[1] Rolls-Royce website: http://www.rolls-royce.com/civil/services/totalcare/ (last accessed 23.11.10).

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provider, usually, retains the maintenance programme ensuring machine utilisation over a given period of time [10].

Jazouli and Sandborn [11] proposed a new method to determine an unknown system attribute to fulfil a specific availability constraint. They demonstrated that the use of PHM technology to increase the availability of an asset can provide a value beyond failure avoidance and minimisation of cost. Greenough and Grubic [12] investigated the use of Condition-Based Maintenance (CBM) in 'servitisation' contracts. Using the tools they developed, i.e. machine tool health simulation (MATHS) and life-cycle risk evaluation of machine tool health (LIKEMATH), they demonstrated considerable benefits from PHM technology gained by the OEMs in terms of asset's availability and utilisation.

Even though existing literature has revealed substantial benefits offered by PHM technology to support operational decisions, very few of them actually considered the effects of *dynamic behaviour* to the asset's performance in their analysis. The dynamic behaviour concerns operational and environmental disturbances that can influence the expected asset's lifetime and the scheduled performance goals. One characteristic of dynamic behaviour is that it cannot be forecast with some degree of certainty. Under the PSS contract where the ownership of the asset remains within the OEMs, the uncertainty is also transferred from the customers to the OEMs, and consequently there is an ever increasing need for the OEMs to better manage the uncertainty especially in the case of availability contracts [13]. In addition to that, there is a great deal of risk that the contractual targets defined at the PSS design phase cannot be achieved when the assets are severely affected by the dynamic behaviour.

Generally, effective design of a complex system is a challenging task, simply because the system designers usually do not have early visibility of the system performance. For this reason, simulation modelling has traditionally been used to aid the validation of the systems (or sub-systems) design in order to improve the overall system performance [14]. Simulation modelling can be intuitive and visually appealing to use to support decision making [15], and in this instance, simulation modelling can also be considered as a tool to support PSS design. As pointed out by Phumbua and Tjahjono [16], however, simulation modelling tools are usually employed only during the *design phase* of PSS. Furthermore, in traditional discrete-event simulation models, an asset's downtime uncertainty is only represented by random variability [17]. During the execution of the PSS, which is typically in the form of contractual agreement, various unpredicted events, such as machine overload due to extreme weather conditions and improper use, can affect the asset's expected lifetime. The impact from these unpredictable events, unfortunately, cannot be properly modelled with random variability and Mean Time Between Failure (MTBF) information alone. Any maintenance activities that do not consider modifications in the operational environment lead to many unexpected system and component failures [18].

As there is no direct coupling between the simulation model and the actual systems, the model usually runs from an initial or empty state. As the model reaches the steady state, experimentation can progress and various what-if scenarios can be performed. Nonetheless, it is very common that this state does not necessarily correspond to the state which the actual system is currently at, and it is challenging to bring the model to this initial state. One way to address those issues is by coupling the simulation model with the actual system in an *online* mode. Online simulation, or real-time simulation as it is also known, uses some kind of feedback mechanism to couple the model and the actual system. It adopts similar principles used in real-time control systems where the simulation model is applied as a feedback loop. One distinct feature of the online simulation is that the parameters obtained from the actual system become a set of current state parameters of that system which in turn will be used to initialise the simulation model. This feature consequently enables the simulation model to be used not only during the design phase of PSS but more importantly can be extended to the *operational phase* where the simulation model can now be used as a *day-to-day operational tool*.

The main aim of this paper is to propose a novel framework to link PHM and PSS technologies using online simulation. The paper is organised into six sections. Section 2 presents a brief literature review of the research domain. Section 3 presents the proposed framework and the detailed explanation on its modules. Section 4 presents the framework implementation. Section 5 describes the three case studies and their respective experimental results. Finally, Section 6 lists the concluding remarks and future work.

2. Literature review

2.1. Prognostics and Health Management

Prognostics and Health Management (PHM) is considered as key to improved safety and reliability of components through an intelligent and autonomous detection, and isolation of fault to estimate the Remaining Useful Life (RUL) of such component with the aim to reduce the operational and support cost [19]. This enabling technology shows the potential to address reliability problems that have been manifested due to the complexities in design, manufacturing, environmental and operational use conditions and maintenance [20]. Manufacturers have been often driven to embrace a PHM programme in order to improve their product performance, improving availability, improving maintenance efficiency and effectiveness and differentiating from their competitor's products [21]. In other words, the main goal of a PHM technology is to provide the most up-to-date health status of the assets in order to support proactive actions to improve the system's performance.

The PHM programme, typically incorporates data acquisition, data processing, diagnostic and prognostic disciplines. During the data acquisition, sensor technology captures one or more performance conditions (e.g. temperature, vibration, shock, pressure, etc.) of the critical component. Complex systems often require several parameters to be monitored in the whole asset's lifetime to provide the information entailed by PHM programme [22]. A pre-processing stage is also needed to clean and to filter the data for further data analysis. In the next stage, the filtered data must be transformed and manipulated. Numerous models, algorithms and tools for data analysis (time domain analysis, frequency domain analysis, time-frequency domain analysis, etc.) exist in the current literature. Afterwards, a fault diagnosis technique determines the condition of the system or the critical component based on processed data. The fault diagnosis procedure is a method for detecting, isolating and identifying a failure condition of a system, while its critical components are operating even though they are in a degradation mode [23]. Statistical, Artificial Intelligence and Model-based approaches are the most common methods for fault diagnostic purposes [24].

Based on fault diagnosis analysis, the fault prognosis technique estimates the RUL. The RUL information can be used to plan, in advance, the entailed maintenance activities [37]. The accuracy of its estimation depends on what prognostic technique was employed. Prognostic techniques can be grouped into physics-based, trend-based evolutionary and experience-based [25,26]. According to Vachtsevanos et al. [27], physics-based models remain the most accurate but expensive as they provide a straightforward method to calculate the damage of the critical component based on operating conditions and to assess the cumulative effects in terms of component life usage. In addition,