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Discrete Event Logistics Systems (DELS) simulation modeling incorporating two-step Remaining Useful Life (RUL) estimation

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ABSTRACT

Prognostics and Health Management (PHM) exerts an essential influence on the spare supply process and the maintenance activities. Discrete Event Logistics Systems (DELS) simulation model facilitates a better understanding of the maintenance and logistics/support systems. Previous DELS models treat the RUL estimation as a one shot event. However, the treatment would be rough to coordinate the logistics and maintenance activities, and the estimated RUL result would not be sufficiently reliable. In this paper, we propose the principle and operational technique of two-step RUL estimation for the DELS simulation model. Two-step RUL estimation starts with the component RUL modeling subject to a continuous accumulation of degradation. The component deterioration is modeled using a time-dependent stochastic process, which combines the linear degradation path with a random effect. Besides, the sequential logics of the DELS simulation model incorporating two-step RUL estimation is exploited in the local behavior study. Finally, the proposed technique is testified with a case study via the DELS simulation implementation, showing that the performance using two-step RUL estimation outperforms traditional one-step RUL estimation.

1. Introduction

The logistics and maintenance systems are widely investigated for people to have a better understanding of their internal interactions and external performances. In recent years, Condition Based Maintenance (CBM) is gaining an increasing attention due to its precaution mechanism in maintenance scheduling. CBM is based on collecting observations over time, by assessing system state, to prevent the fault occurrences and to determine the optimal maintenance strategies [1,2]. The heart of CBM is the condition monitoring (CM) process, where signals are continuously monitored using certain types of sensor or other appropriate indicators [3]. Thus, maintenance activities (e.g., repairs or replacements) are performed only ‘when needed’ or just before a fault [4].

Prognostics and Health Management (PHM) is an approach that enables early detection and prediction of an impending fault [5]. The PHM concept derives from the CBM framework, where health condition can be further predicted, and optimal maintenance actions can be arranged for preventing system breakdown and reducing total costs [6,7].

The PHM application reported in the literature is largely toward maintenance scheduling and decision making depending on prognostic and Remaining Useful Life (RUL) estimations [8]. The main goal of PHM is to perform a real-time assessment of equipment conditions to make maintenance decisions, consequently reducing unnecessary maintenance and related costs [9]. By combining fault information and tracking trends of system degradation, the probable fault occurrence time is predicted and the RUL value is subsequently estimated.

With the prognostic function and the estimated RUL, actions are taken during the deterioration, which highly reduces the time to allocate logistic resources and schedule maintenance activities. Do et al. [10] provide an aperiodic inspection policy based on the RUL estimation, in which a new inspection time is adaptively forecast when a prognostic event is activated and performed. Camci [11] exploits the prognostics and RUL information in system maintenance scheduling to dynamically optimize the threshold value at which the maintenance is performed. Other related researches concerning how the prognostic information can be applied in

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maintenance engineering can be found in Rodrigues et al. [12], Huynh et al. [13], Horenbeek and Pintelon [14,15], You and Meng [16], etc.

PHM is said to exert an essential influence on the spare supply process and the maintenance activities [17,18]. Nonetheless, a reliable prognostic mechanism and RUL estimation approach is supposed to be the prerequisite of it. This is also true for the matching logistics and maintenance configurations involving spare preparation, maintenance assignments, and administrative policies. Luna et al. [19] primarily explore the challenges toward maintenance and support systems of PHM implementations by stating in a conceptual level. Carrasco and Cassady [20], Lun et al. [21] respectively conduct researches in the evaluation and comparison a simple system performance under three maintenance policies on the scope of PHM. The researches show that an accurate prognostic result is a necessary part of effective maintenance activity scheduling, without which the PHM incorporation would be meaningless.

Maintenance system modeling and simulation is a good approach to acquire useful information of the logistics and maintenance systems. Previous works have been done on a strategic, operational and tactical level using different modeling methodologies and tools, including agent-based model [22], ALSim Java model [23], Arena model [24], etc. Discrete Event Logistics Systems (DELS) simulation combines the principles of discrete event simulation and focuses on the networks of resources through which material and manpower flow [25–27]. The DELS modeling and simulation methods are well exploited in a variety of aspects; see the literature review proposed by Tako and Robinson [26].

The DELS modeling and simulation technology provides a practical approach to the analysis of the characteristics and regularities of logistic and support activities with the PHM incorporation [28]. Iwata and Mavris [29] integrate the PHM factors in maintenance and logistics design of aerospace vehicles using the Simulation in Python (SimPy) package. Zhiyu et al. [30] makes the availability analysis by modeling the material flows and illustrating the maintenance decision-making under the CBM/PHM policy in a discrete event logistics system. Julka et al. [31] present a comprehensive roadmap to investigate the optimal performance of the consolidated operational PHM information supported aerospace spare components logistics. The all-round aspects such as spare component delivery time, pool stock distributions are carefully optimized in comparisons to afford the maximum utility of the material supply chain.

PHM has been implemented using approaches that are either model-based or data-driven. The model-based approaches make the lifetime prediction by proceeding with the physics-of-failure (PoF) modeling, while the data-driven techniques portray statistical characteristics of the monitoring data to estimate RUL [32,33]. No matter which approach is utilized, the fault prediction is based on the extent of the deterioration, and the accuracy of RUL estimation would vary over time.

A major concern is the model fidelity of the DELS simulation model incorporating PHM concept [34]. Previous works treat the RUL estimation as a one shot event and only a simple RUL result is generated with a static probability distribution, as is the case in [19]. However, perceptual intuition tells us that the fidelity of RUL results would vary with the time point of executing estimation. This is also demonstrated in [35,36], showing that the treatment to estimate only once might not be promising.

Under such circumstances, we propose the concept and technique of two-step RUL estimation for the DELS simulation model. Two-step RUL estimation includes first-step and second-step RUL estimation, where the former is executed earlier and the latter later. The first-step RUL estimation is associated with the primary logistics and maintenance events activities, while the second-step RUL estimation calibrates the fault occurrence time information to better coordinate the logistics and maintenance events. Compared with conventional one-step RUL estimation, the two-step RUL estimation modeling method can better reflect the real practical prognosis process.

The rest of this paper is organized as follows. Section 2 introduces the two-step RUL estimation concept with an overview of the research. Section 3 presents the degradation fault model and the corresponding two-step RUL estimation techniques, and verifies the method by using engineering data sets. Section 4 analyzes the simulation sequential logics of the two-step RUL estimation in the DELS simulation model. Section 5 makes an implementation study of DELS simulation incorporating two-step RUL estimation in a flight setting. The performance analysis and comparative study is also done in this section. Finally, Section 6 concludes the whole paper.

2. Two-step RUL estimation

In this section, we first introduce the one-step RUL estimation used in DELS modeling, and then present the two-step RUL estimation concept. The overview of the research is also outlined in this section.

2.1. One-step RUL estimation in DELS models

DELS follows the discrete event simulation principles where the events (or the time points corresponding to the events) are the most important factor to drive the simulation. With the RUL knowledge, one can arrange the spare allocations ahead of a real fault, which largely reduces the logistic delays [37]. The spare supply and maintenance activities are brought forward, earlier than a real functional fault that would cause the whole system to halt. At the same time, component replacement can be performed proactively in light of an anticipated fault, as opposed to reactively performed upon a real fault [38]. Compared with the situations where we need to passively waiting for the fault occurrences, now we have more dominance over the unforeseen fault occurrences.

As a simple assumption, one-step RUL estimation refers to the situation where the prognostic action is executed only once before the real fault, and the one-shot RUL information is incorporated in the event-based model. Fig. 1 depicts the basic profile in one-step RUL estimation [31]. The major parameters defining the one-step RUL estimation profile are listed below.

- Estimated RUL (T_{RUL}): The RUL estimated by the PHM unit.
- Predicted time of fault (t_{pf}): The predicted fault occurrence time.
- Time to trigger prediction (t_{tp}): The time when the PHM unit begins to make predictions and reports the estimated RUL. It is generally assumed that only when the degradation of the system has reached to a certain level (threshold) will the prediction be triggered.
- Time of latest expected delivery (t_{td}): The time by which the corresponding spare component have been sent and transported to the designated place.
- Spare delivery preparation time (T_0): Duration between the time when the prognostics fulfillment has to be triggered and the latest point of time at which a replacement component should be delivered (i.e. how early before the deadline must the logistics support process be completed).
- Spare delivery duration (T_{SD}): Duration between t_{pf} and the latest point of time at which a spare starts to be delivered. If a spare is transported to the designated place within T_{SD}, then the maintenance activities can be started. However, if a spare fails to arrive within T_{SD}, one has to wait until its arrival before starting the maintenance activities.