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Optimization of reliability centered predictive maintenance scheme for inertial navigation system

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ABSTRACT

The goal of this study is to propose a reliability centered predictive maintenance scheme for a complex structure Inertial Navigation System (INS) with several redundant components. GO Methodology is applied to build the INS reliability analysis model—GO chart. Components Remaining Useful Life (RUL) and system reliability are updated dynamically based on the combination of components lifetime distribution function, stress samples, and the system GO chart. Considering the redundant design in INS, maintenance time is based not only on components RUL, but also (and mainly) on the timing of when system reliability fails to meet the set threshold. The definition of components maintenance priority balances three factors: components importance to system, risk degree, and detection difficulty. Maintenance Priority Number (MPN) is introduced, which may provide quantitative maintenance priority results for all components. A maintenance unit time cost model is built based on components MPN, components RUL predictive model and maintenance intervals for the optimization of maintenance scope. The proposed scheme can be applied to serve as the reference for INS maintenance. Finally, three numerical examples prove the proposed predictive maintenance scheme is feasible and effective.

1. Introduction

Predictive maintenance (PdM) has been introduced in many applications for real-time diagnostics of potential defects and to evaluate the future status of system health [1–4]. Compared with passive maintenance and preventive maintenance (PM), reasonable PdM may effectively optimize maintenance time, improve system availability and reduce life-cycle cost.

PdM scheme formation is a complex system engineering consisting of condition monitoring, historical statistical data, expert knowledge and so on. Incorporating detected/predicted system condition information over time to formulate maintenance schemes has drawn significant attention in recent years [3,4]. For example, Tinga et al. [5] established a physical system failure model with dominant loads as contributors to critical system failure, and evaluated the system fatigue level utilizing dynamic samples of the loads. Michele et al. [6] estimated equipment Remaining Useful Life (RUL) to identify the optimal maintenance time by Particle Filtering. Deloux, through combining statistical process control (SPC) and condition-based maintenance, built a model for a deteriorating system subject to stress and constructed a maintenance policy for such a model [7]. Hsieh et al. [8] proposed a virtual-metrology (VM) based baseline predictive maintenance (BPM) scheme that possesses the capabilities of fault detection and classification (FDC) and PdM. Huynh et al. [9] dealt with the condition-based maintenance of a single-unit system that is subject to competing and dependent failures.

The models mentioned above are merely for single-component systems, or they view systems as monolithic structures and ignore the dependencies among components. However, due to the increasing complexity and variety of systems, more attention is being paid to PdM for multi-component systems [10]. A maintenance scheme for multi-component systems should consider not only the component characteristics independently, but also the components' failure interaction, structural relationships and economic aspects [11]. Nicolai et al. [11] modeled the dependence between components and gave an overview of optimal maintenance policies for multi-component systems. Hu et al. [12] built a DBN-HAZOP model to quantify the hazard and operability analysis of each component and system; this work proposed an opportunistic PdM strategy for global cost optimization. Adriaan et al. [13] introduced a dynamic PdM policy based on prognostic/predictive information while considering different component dependencies for complex multi-component systems under the hypothesis of components in series. Zhang et al. [14] formulated the maintenance problem of multi-component systems considering

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opportunistic maintenance (OM) and environmental influences simultaneously. Moreover, from the perspective of the economic relevance of components, Grouping Maintenance (GM) strategy is increasingly widespread in complex multi-component systems; e.g., Mahmood et al. [15] proposed an optimal age-based GM policy for a multi-unit series system. In this policy, a unit is repaired at the point of failure or preventively maintained at a predetermined age *T*. Bouvard, through inspecting a system at each inspection date and taking the component degradation information into account in the maintenance decision scheme, presented a dynamic GM strategy with a rolling horizon for a commercial vehicle [16]. Van et al. [17] discussed a dynamic GM strategy for multi-component systems in series considering only the components economic dependence among components. Vu et al. [18] presented a dynamic maintenance grouping strategy with both positive (due to setup cost) and negative (due to shutdown cost) economic dependencies for multi-component systems, discussing especially the case of systems with any combination of basic structure (series, parallel or k-out-of n structures).

In the literature about multi-component systems, most maintenance policies describe component degradation in terms of failure rate or hazard rate. Maintenance actions are triggered when a system condition breaks one or more prescribed thresholds. Finally, the problem usually becomes how to optimize these thresholds or other parameters to minimize costs (e.g., maintenance internals, maintenance scope). However, during the actual operation of a system, many factors will reduce the credibility of a maintenance scheme that has been optimized, such as characteristic change of varying components, task switching or variability of external environment. It is very necessary to adjust maintenance actions dynamically according data such as on-line operating information and external environment factors. This concept has been widely accepted for single-component system maintenance [4,5,9], but few applications of it exist for multi-component systems [14]. Moreover, most methods of describing system parameters (e.g., system reliability) are one-sided; this is because most studies for complex multi-component systems rely only on the assumption of simple structure dependencies between components, such as in series [13,14,17], in parallel [18], in parallel-series [19]. Things like redundant designs and bridge connections within complex systems are not taken into account. Hence, there are problems with theoretical methods used to create applications meant to analyze complex multi-component systems that have strong structural dependencies; these problems are especially apparent in the presence of many redundant components.

Inertial Navigation System (INS) represents a complex electro-mechanical system with failure results depending not only on a logical combination of components, but also on a component failure sequence and the previous state of system. Work environment of INS as applied in the military setting, for example, is extremely harsh. Traditional static maintenance conducted at regular intervals may occasionally omit vital maintenance work while conversely, maintenance intervals may also be overly conservative for the system's key unit, leading to unnecessary maintenance attention [5]. Besides, INS features redundant design to meet a high demand for reliability, thus addressing the component failure-to-system reliability issue. Maintenance scheme should be adapted to take into account these interactions between components in order to find a system-wide optimal maintenance policy. Design and optimization of the PdM scheme for INS should consider the following aspects: (i) accurate prediction of components RUL considering environmental influence; (ii) dynamic evaluation of system reliability; and (iii) maintenance cost-effectiveness.

GO Methodology is an effective technique for system reliability analysis. It has been applied successfully in many applications; namely, in the analysis of nuclear power, equipment performance and the power distribution system[20,21]. GO Methodology provides the ability to translate a system flow chart or system principle diagram into a GO chart (the equivalent of system reliability model) directly. As long as system principle diagram provided, it is easily done by GO Methodology to evaluate the reliability of complex

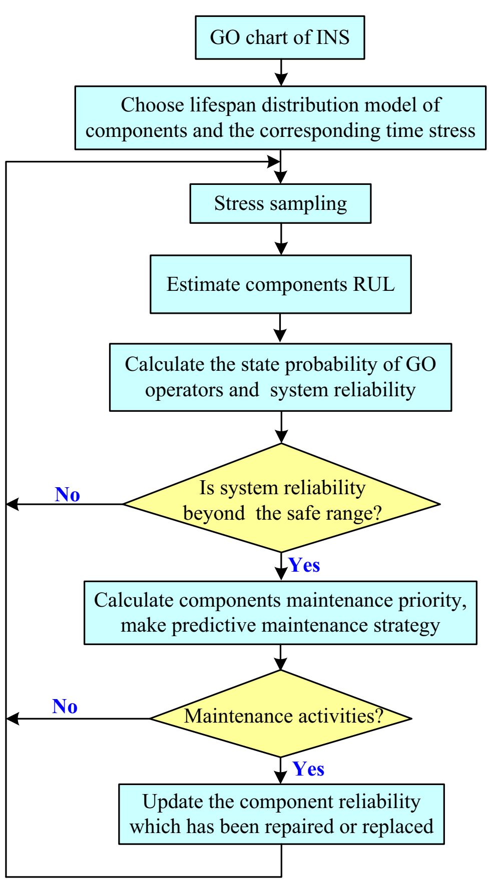

Fig. 1. The making process of reliability centered PdM for INS.

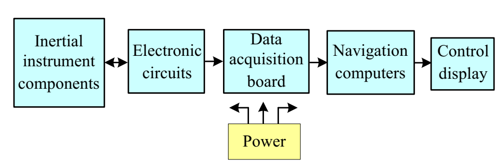

Fig. 2. Simplified logical block diagram of sample SINS.

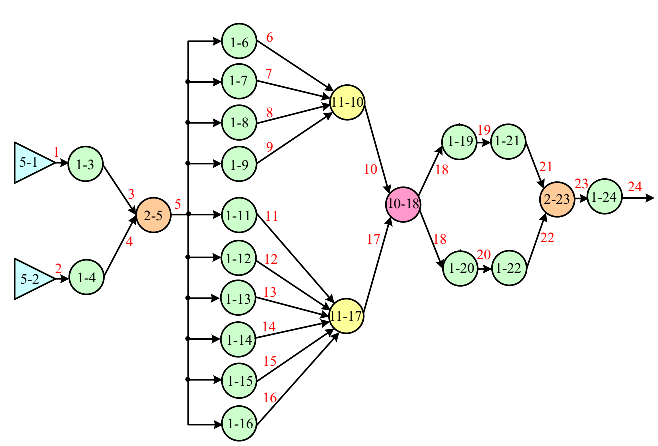

Fig. 3. GO chart of sample SINS.