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A complex network-based importance measure for mechatronics systems

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HIGHLIGHTS

- We develop a Component Network suitable for reliability analysis.
- A meaningful IPR is brought into the identifying of important components.
- Components' importance can be evaluated at any life stage of systems via IPR.
- IPR synthesizes the components' usage reliability and functional dependency.

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ABSTRACT

In view of the negative impact of functional dependency, this paper attempts to provide an alternative importance measure called Improved-PageRank (IPR) for measuring the importance of components in mechatronics systems. IPR is a meaningful extension of the centrality measures in complex network, which considers usage reliability of components and functional dependency between components to increase importance measures usefulness. Our work makes two important contributions. First, this paper integrates the literature of mechatronic architecture and complex networks theory to define component network. Second, based on the notion of component network, a meaningful IPR is brought into the identifying of important components. In addition, the IPR component importance measures, and an algorithm to perform stochastic ordering of components due to the time-varying nature of usage reliability of components and functional dependency between components, are illustrated with a component network of bogie system that consists of 27 components.

1. Introduction

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Mechatronics system can be defined as a set of inter-connected components which work together to complete predetermined mission [1]. Recent decades have witnessed not only the rapid development on the highly integrated system of mechatronics systems, but also the significant progress on the functional dependencies between components [2]. Due to the functional dependencies within complex mechatronics systems, the failure of a component may result in failure of another component, which can be called fault propagation. The fault propagation of mechatronics system can enlarge the negative impact of a component failure. In these situations, it is becoming increasingly important to take functional dependencies into

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account when assessing the importance of components and to concentrate the resources on the small subset of components that are most important to the system.

In reliability theory, importance measures are used as effective tools to evaluate the relative importance of components and identify system weaknesses [3]. Component Importance Measures (CIMs) are component related indices that allow security practitioners to identify how a component's fault affects the overall behavior or performance of the whole technological system and are used to evaluate the relative importance of a component. The typical CIMs include but are not limited to Birnbaum importance measures [4], Fussell–Vesely (FV) importance measures [5] and Criticality importance measures [6]. Detailed descriptions and mathematical expression for importance measures can be found in Ramirez-Marquez [7]. Using the CIMs, security practitioners can estimate or prioritize components in order of their importance value with regard to system reliability and concentrate maintenance resources on the most important components. However, it cannot be ignored that while most of these CIMs have been widely used in System Reliability Analysis (SRA), challenges still remain in regard to the following: CIMs are built on the assumption of the independence of components and none of them has taken into account the impact of functional dependency between components.

Recent advances indicate that complex technological systems, such as mechatronics products, can be virtually represented as hierarchies of networks, where the components of technological products are easily depicted by the nodes of complex networks and the dependencies between linkage components are naturally depicted by the links of complex networks [8–10]. More recently, various Centrality Measures (CMs) have been presented to quantify the importance of an individual in a complex network, including Degree Centrality (DC) [11], Betweenness Centrality (BC) [12,13] and Eigenvector Centrality (EC) [14,15] etc. The issue of centrality has attracted the attention of physicists, who have extended its applications to the realm of technological networks. For example, Simon [16] considered the technological products as decomposable systems where dependencies between its components can never be avoided and in Eckert C [17] view, these dependencies between components determine the structure and function complexity of technological products; Based on the centrality measures of complex network, Lee H [18] measured the relative importance of components by using the Analytic Network Process (ANP) approach and Cheng H [19] developed three conceptions of centrality to measure indirectly or directly change impacts. Pasqual M C [20] introduced a multilayer network model which uses a components centrality to measure its components propagation behavior and a Social Network Analysis (SNA) approach is formulated by Wu D [21] to analyze the socio-technical network generated by Cloud-Based Design and Manufacturing (CBDM) systems. However, CMs mentioned above focus only on the components propagation behavior of complex network and are limited from the point of the reliability analysis [22]. For that reason, it is extremely important to research on the negative impact of these restrictions and proactively overcome them by complementation with elaborate reliability contexts on identifying important components of complex technological systems.

This paper introduces a new class of importance measures, the so-called Improved-PageRank (IPR), which is a meaningful extension of the centrality measures in complex network. Our work makes two important contributions. First, we integrate the literature of mechatronic architecture and graph theory to define component network based on the notion of complex networks. Second, a meaningful PageRank is brought into the identifying of important components for which it could give consideration to usage reliability of components and functional dependency between components. The rest of the paper is structured as follows. Section 2 provides background information about the complex network theory and its centrality measures. In Section 3, the component network method is detailed. The following is presented: how to model the mechatronics system as a complex network and by using reliability theory to extract different network physical properties which are related with measuring the importance of components in mechatronics systems. In Section 4, we embed the PageRank into the importance measurements by introducing a fault propagation damping. Section 5 presents a case study Q4 which models a component network of bogie system that consists of 27 components and discusses the advantages of the functional dependency-usage reliability-driven IPR importance measure over the topological indicators of centrality importance in two aspects. Finally, we present the conclusion of our current research on measuring the importance of components in Section 6.

2. Methodological background

2.1. Complex networks

Currently, complex networks are being studied in many fields of science, such as social sciences, computer sciences, physics, biology and economics etc. The majority of systems in reality can be undoubtedly described by models of complex networks. For examples, Internet is a complex network composed of the web sites [23,24]. The brain is a complex network of neurons [25]. The global economy is a complex network of markets, which are themselves complex networks of interacting consumers and producers [26]. An organization is a complex network of people [27]. Also, an engineering product can be a complex network, in which the components are depicted by nodes and the dependencies between linkage components are depicted by links between the corresponding nodes.

According to the view of Estrada E [28], complex networks are networks with non-trivial topological traits, which means that, the generation pattern of the connections in complex networks is neither purely random nor purely regular. A complex network can, in its simplest form, be represented by a graph, where is the set of nodes and is the set of links