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An information transfer based novel framework for fault root cause tracing of complex electromechanical systems in the processing industry

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ABSTRACT

As one of the most important approaches for analyzing the mechanism of fault pervasion, fault root cause tracing is a powerful and useful tool for detecting the fundamental causes of faults so as to prevent any further propagation and amplification. Focused on the problems arising from the lack of systematic and comprehensive integration, an information transfer-based novel data-driven framework for fault root cause tracing of complex electromechanical systems in the processing industry was proposed, taking into consideration the experience and qualitative analysis of conventional fault root cause tracing methods. Firstly, an improved symbolic transfer entropy method was presented to construct a directed-weighted information model for a specific complex electromechanical system based on the information flow. Secondly, considering the feedback mechanisms in the complex electromechanical systems, a method for determining the threshold values of weights was developed to explore the disciplines of fault propagation. Lastly, an iterative method was introduced to identify the fault development process. The fault root cause was traced by analyzing the changes in information transfer between the nodes along with the fault propagation pathway. An actual fault root cause tracing application of a complex electromechanical system is used to verify the effectiveness of the proposed framework. A unique fault root cause is obtained regardless of the choice of the initial variable. Thus, the proposed framework can be flexibly and effectively used in fault root cause tracing for complex electromechanical systems in the processing industry, and formulate the foundation of system vulnerability analysis and condition prediction, as well as other engineering applications.

1. Introduction

Production systems in the processing industry are typical complex electromechanical systems [1,2]. Functional equipment items in such systems are coupled and operate in conjunction with each other. The failure of any one of these internal components may lead to the fault of the whole item, and may also propagate and affect to other items due to coupling. Even worse, the running condition of the whole system will be abnormal and inconsistent if no intervention is undertaken. Thus, the fast identification of the root cause of faults in complex electromechanical systems in the processing industry is

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necessary for effective maintenance, and can help the enterprise to take immediate and corrective measures to prevent any major accident due to fault propagation.

Fault root cause tracing technology originates from fault diagnosis methods. It focuses on analyzing the relationships between the condition changes of different components from the system's perspective and focuses on the propagation and development of the root events or causes. It tries to trace the root causes of faults based on exceptional system conditions. Thus, there are three major issues that need to be addressed: (i) What are the relationships of condition changes among various components? (ii) What is the fault propagation process? (iii) How to identify the root event or essential reasons of the fault?

In recent years, several methods for fault root cause tracing have been proposed. Among these methods, due to its ability to characterize the relationships between different system conditions and carrying amount of information, the signed graph method, which has first appeared in a mathematical paper in 1953 [3,4], has proven to be suitable for identifying the root node of abnormal conditions and has been rediscovered many times due to its natural emergence in many unrelated areas [5–8]. Iri et al. [9,10] introduced the definition of the signed directed graph (SDG) in the chemical field, and the depth-first search strategy was applied to implement a basic search for incomplete samples. Multi-level SDG was proposed by Umeda [11] to characterize the causality over time and to analyze the dynamic process. The drawbacks of complexity and high occupancy rate of the computation source limit its application. Unlike the previous methods that have limitations in tracing the root cause based on SDG, Kramer et al. [12] proposed the rules for an expert system based on forward analysis of SDGs, and applied these rules to online fault diagnosis of the plant. However, this approach cannot avoid the problem of rule explosion. Chang et al. [13] presented a method to simplify the SDG model by deleting the non-potential root nodes based on the system's conditions and fault propagation pathways. Huang et al. [14,15] proposed a fault root cause tracing method integrated with SDG and a fault graph based on the relationships between multiple-factors. There is no doubt that the derivation of knowledge base rules based on SDGs is an important topic in the field of fault root cause tracing. However, these rules come from superficial expert knowledge, and are usually unable to reveal the deep disciplines of faults and achieve the requirements of completeness.

The most commonly used method for detailed event analysis and risk assessment is failure mode and effects' analysis (FMEA) [16,17]. Since its appearance, FMEA has become a powerful tool used extensively for the safety and reliability analysis of systems, products, processes, and services in many industries [18–22]. When also aimed at the prioritization of potential failure modes, FMEA is referred to as failure mode, effects and criticality analysis (FMECA) [23]. According to the ISO 9000 and ISO/TS 16949 standards, the best classified analysis for prevention of failures during the production process is process failure mode and effect analysis (PFMEA) [24]. As a top-down deductive method that aims to compute the probabilities of occurrence of the top event as a function of the probabilities of occurrence of basic events, fault tree analysis (FTA) is the easiest and most used technique in dependability assessment [25]. In the literature, hybridized fault trees have been successfully used in some work to assess reliability, availability, and safety of complex systems [25–28]. FTA and FMEA have advantages of describing the fault root cause and fault propagation pathway. However, because of the complexity of electromechanical systems in the processing industry, it is difficult to model the physical systems based on the fault disciplines, which limits their application in actual scenes.

Therefore, new approaches to deal with complexity are not only welcome but needed. Production systems in the processing industry are essentially joined with the discrete electromechanical equipment resulting in the formation of a coupled, highly corrective, distributed, and complex electromechanical system, which can transmit power, energy, and control information. The transformation of information is an expression of fault, and fault propagation can be described as information transfer. Based on this rationale, the fault propagation pathway and root cause can be obtained without any prior knowledge of the physical structure of system if the information transfer model of the electromechanical system is known. In this paper, an information transfer-based novel framework is proposed to trace the fault root cause in a complex electromechanical system in the processing industry. The symbolic transfer entropy method is improved to analyze the direction and strength of information transfer, which is the foundation for information modeling. The binary search method is applied to determine the slow changing phase of faults. Then, the tracing process is performed from an arbitrary initial point along with the bidirectional information transfer in the information model by comparing the changes of information transfer between different variables.

The structure of the rest of this paper is as follows. Section 2 starts with a brief presentation of information flow, transfer entropy and symbolic transfer entropy. A symbolic transfer entropy-based new approach is proposed in Section 3. The general framework and the detailed steps for fault root cause tracing are presented in Section 4. Section 5 investigates the effectiveness of the proposed framework for fault root cause tracing, while the paper is concluded in Section 6.

2. Preliminaries

We begin this section by providing a brief introduction to information theory and information measures. Then, the concept of transfer entropy and its extensions are introduced by analyzing the characteristics of information entropy, joint entropy, conditional entropy, mutual information and other quantities.