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Diagnosability of fuzzy discrete event systems

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Abstract

In this paper, discrete event systems (DESs) are reformulated as fuzzy discrete event systems (FDESs) and fuzzy discrete event dynamical systems (FDEDSs). These frameworks include fuzzy states, events and IF–THEN rules. In these frameworks, all events occur at the same time with different membership degrees. Fuzzy states and events have been introduced to describe uncertainties that occur often in practical problems, such as fault diagnosis applications. To measure a diagnoser's fault discrimination ability, a fuzzy diagnosability degree is proposed. If the diagnosability of the degree of the system yields one a diagnoser can be implemented to identify all possible fault types related to a system. For any degree less than one, researchers should not devote their time to distinguish all possible fault types correctly. Thus, two different diagnosability definitions FDEDS and FDES are introduced. Due to the specialized fuzzy rule-base embedded in the FDEDS, it is capable of representing a class of non-linear dynamic system. Computationally speaking, the framework of diagnosability of the FDEDS is structurally similar to the framework of diagnosability of a non-linear system. The crisp DES diagnosability has been turned into the term fuzzy diagnosability for the FDES. The newly proposed diagnosability definition allows us to define a degree of diagnosability in a class of non-linear systems. In addition, a simple fuzzy diagnosability checking method is introduced and some numerical examples are provided to illustrate this theoretical development. Finally, the potential applications of the proposed method are discussed.

Keywords: Discrete event systems; Fuzzy discrete event systems; Diagnosability; Fuzzy diagnosability

1. Introduction

Fault detection and diagnosis (FDD) in complex systems is crucial. The main approaches to solve FDD problems include model-based approaches and knowledge-based approaches. The development of the model-based FDD began in the early 1970s. A summary of these approaches and their developments are summarized by Isermann [12]. The knowledge-based FDD is described from analytical and heuristic symptom generation points of view. Some of them are neural networks, adaptive neural networks, neurofuzzy systems and hybrid neurofuzzy systems [4,12].

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The chosen fault diagnosis method is important [33]. It is based on information obtained from the system. If no information is available on the fault-event relation, classification methods (i.e. fuzzy clustering and artificial neural network [29]) can be used. If more information about the event and the fault is available, different methods of reasoning (i.e. probabilistic reasoning, probabilistic reasoning with fuzzy logic and reasoning with artificial intelligence [7]) can be applied. The main benefit of the probabilistic reasoning approach is to provide a treatment for uncertainty, and to reduce the computational effort in assumed independent events. However, probabilistic reasoning approaches are inadequate in many real-world applications, especially in fault diagnosis applications [2,26]. Therefore, it is essential to deal with such applications in a more computationally and structurally efficient way.

Most of the research has focused on DES theory to deal with some uncertain problems in practice [5,24,27]. DES theory is used to model systems that cannot be described by differential or difference equations. However, dynamic models that cannot be easily represented by the ordinary and classical approaches might be modelled by sequences of events recording significant qualitative changes in the state of the system. Although DES theory has been applied in many engineering fields, it is not adequate for other fields. This is especially true when fault diagnosis applications are being considered, in which the state (e.g. a component health status) is uncertain (e.g. degree of fault) and vague even in a deterministic sense [1]. Further, diagnosing a set of faulty components could be too restrictive, since users may want to identify different levels of faults. Usually, the state of the components (i.e. healthy or unhealthy) can be drawn from the measurements from instruments and expert knowledge. Otherwise, the analysis of faulty components using probable schemes cannot be determined accurately. The research on diagnostic problems with fuzziness is important since a state is not usually crisp in these systems. For example, it is vague when the condition of a bearing is considered "good". Furthermore, the transition from one state to another is vague and it is hard to say how exactly the condition of a bearing has changed from "good" to "bad".

To overcome these difficulties, the terms fuzzy state and fuzzy event can be used [8,14]. The fuzzy approach has been applied to automata theory in the early age of fuzzy set theory [17]. Extending the range of logical values $\{0,1\}$ to the interval $[0,1]$ yields fuzzy automata (FA) [1,19,35], which are also called fuzzy finite-state machines [1,23]. They are similar to stochastic automata [18], except that their transition probabilities are replaced by transition correlations, which also may be interpreted as transition possibilities. Fuzzy methods based on fuzzy extensions of the theory of languages and automata exist. The most recent work has a general fuzzy automaton, which degenerates other types of automata, including various popular variants and applications of fuzzy automata under certain restrictions [10,11,15,25,31,34].

A fuzzy automaton is a direct generalization of a non-deterministic automaton [19]. Enriching the definition of FA is a convenient strategy to be embedded in real valued environments. However, existing definitions for FA given in [32] are in the form of a complex fuzzifier. They transform a sequence of inputs to a real value in the range of $[0,1]$ corresponding to the membership degree of that sequence. This view is an extension of the formal language theory. All well-known fuzzy automata assume that the states of fuzzy automaton are mostly discrete elements of a crisp set. A proper state is a crisp element, and fuzziness comes into the automata through the fuzzy transition of crisp elements. The state set is not a fuzzy set. Therefore, bringing such a well-known idea of fuzzy automata closer to more complex fuzziness is essential [32]. Hence, the inputs, outputs and states of an automaton have been taken as fuzzy sets in this paper. These new frameworks are called FDES and FDEDS [3]. They allow us to build each component model separately and combine them by parallel composition. Furthermore, discrete event systems can be dealt with as continuous time systems by the proposed FDEDS. Such representations and calculations are mathematically precise [7].

Recently, FDD problems have been investigated by using FDES and FDEDS theories based on fuzzy rules [16,21]. However, is it possible to discriminate all fault types (i.e. single or multiple) in non-linear dynamical systems by only using these theories? The answer is simple. The FDES or FDEDS theories can only be used to build a diagnoser. Therefore, one needs more than to build a diagnoser. Besides the FDES or FDEDS theories, a new theory such as fuzzy diagnosability is required. By using the fuzzy diagnosability, one can be aware of the maximum fault discrimination capacity of a diagnoser. Thus, researchers should not devote their time to increase a diagnoser's discrimination ability. In literature, the problem of diagnosability of DES [6,22,28,30] has been thoroughly studied in the contexts of centralized [13,30], decentralized and timed systems, modelling systems and its applications [3,26]. However, fuzzy diagnosability has not received enough attention.