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A discrete event systems approach to discriminating intermittent from permanent faults

Deng Guanqian, Qiu Jing *, Liu Guanjun, Lyu Kehong

*Laboratory of Science and Technology on Integrated Logistics Support, College of Mechatronics and Automation,
National University of Defense Technology, Changsha 410073, China*

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Abstract Almost all work on model-based diagnosis (MBD) potentially presumes faults are persistent and does not take intermittent faults (IFs) into account. Therefore, it is common for diagnosis systems to misjudge IFs as permanent faults (PFs), which are the major cause of the problems of false alarms, cannot duplication and no fault found in aircraft avionics. To address this problem, a new fault model which includes PFs and IFs is presented based on discrete event systems (DESs). Thereafter, an approach is given to discriminate between PFs and IFs by diagnosing the current fault. In this paper, the regulations of (PFs and IFs) fault evolution through fault and reset events along the traces of system are studied, and then label propagation function is modified to account for PFs and the dynamic behavior of IFs and diagnosability of PFs and IFs are defined. Finally, illustrative examples are presented to demonstrate the proposed approach, and the analysis results show the fault types can be discriminated within bounded delay if the system is diagnosable.

1. Introduction

Fault diagnosis is a crucial and challenging task in the automatic control of large complex systems.[1,2] However, diagnosis systems such as built-in test equipments (BITE) have not performed as efficiently as expected. The primary contributor to its inefficiency is misjudging intermittent faults (IFs) as permanent faults (PFs), which is the major cause of the problems of false alarms (FAs), cannot duplication (CND) and no fault found (NFF). It has negatively impacted maintenance costs and mission readiness.[3–7] When a fault is detected, and is assumed permanent (without analyzing whether it is or not), two steps are usually carried out: (A) locating the fault; and (B) correcting the fault. Correction is accomplished by repairing the fault or by replacing the faulty module with a fault-free one. It is common for modules to be replaced as faulty but later usually proved to be IFs.[8] IFs are defined as failures that can automatically recover once they have occurred. It may be activated or deactivated by some external disturbance, such

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* Corresponding author. Tel.: +86 731 84573305.
E-mail addresses: guanqiandeng@163.com (G. Deng), qiujing@nudt.edu.cn (J. Qiu).

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as high G loading, vibration, thermal extremes, or some combination of stress. Therefore, if the disturbance ends then the failure will disappear. Instead PFs, once they appear, do not disappear.[9] IFs are known to be the great majority of causes of errors. Even in an optimal environment, these faults can occur 10–30 times as often as the PFs.[8,10] Furthermore, due to technology scaling, lower supply voltage and increased clock frequency, this problem will become more severe and prominent.[9,11]

From the viewpoint of repair, it is urgent and critical to discriminate IFs from PFs when a fault occurs. If the current fault is diagnosed to be an IF, the right fault treatment actions can be taken timely. In the way, a lot of maintenance cost can be saved by avoiding unnecessary shutdown and repair.[5,6] This is the topic of this paper. We will use the term "diagnosis" to designate this specific problem: deciding whether the current fault is a PF or IF.

A considerable amount of research has been devoted to fault diagnosis.[1,2,4,5,12–20] Among these methodologies, discrete event systems (DESs) approaches, on which this paper focuses, have been recognized as a promising framework due to the significance of event-driven models in large and complex systems, the well developed theory that allows systematic construction of a diagnostic system, and the computational efficiency that enables online diagnosis for large systems.[1,2] Nevertheless, almost all work on model-based diagnosis (MBD) potentially presumes faults are persistent and does not take IFs into account.[21,22] The time-varying failures such as transient failures are considered in Ref.[23] and the diagnosis of temporal misbehavior which is based on Markov-processes is present. However, the failure probability is difficult to obtain. In recent years, IFs diagnosis has attracted more and more attention. Ref.[19] extends the approach in Ref.[2] to diagnose IFs. IFs diagnosis based on DESs in industrial processes is studied in Ref.[16]. Refs.[14,15] present a state-based modeling of faults (and implicitly their resets) and focuses on the diagnosis of the number of occurrences of faults. In order to assess IFs probabilities, Refs.[21,22] present an overall framework. Exactly computing the probabilities of IFs can be found in Refs.[12,13]. Ref.[17] presents an approach to diagnose IFs dynamics. However, these approaches usually potentially presume that the faults to be diagnosed are IFs, namely, assume the fault types are known a priori (even if not explicitly stated). This assumption is not necessarily true, which is not required in this paper. Since fault events are usually unobservable and it is difficult to recognize the fault types of the current fault (within bounded delay). To the best of our knowledge, this problem has not been addressed so far within the context of DESs.

To address the problem mentioned above, in this paper, an approach based on DESs is given to diagnose the current fault without the assumption of knowing its types a priori. It is an effective and novel way to discriminate between PFs and IFs when a fault occurs. The rest of the paper is organized as follows.

In Section 2, an extended fault model which includes both PFs and IFs is given. Two new notions of diagnosability are defined in Section 3. In Section 4, the construct of the diagnoser which is built from system model is presented. Illustrative examples are carried out to demonstrate the proposed approach in Section 5. Finally, we give a conclusion and some future work in the last section.

2. Modeling of system and faults

2.1. System model

We assume that the reader is familiar with automata theory and regular languages. The system to be diagnosed is modeled as an automaton.[2]

$$G = (X, \Sigma, \delta, x_0) \tag{1}$$

where X is the state space, Σ the set of events, δ the partial transition function, and x_0 the initial state of the system. Model G accounts for the normal and failed behavior of the system which is described by the prefix-closed language $L(G)$ generated by G. We denote $L(G)$ by L. L is a subset of Σ^*, where Σ^* denotes the Kleene closure of the set Σ, and L is assumed to be live. Some of the events in Σ are observable, while the rest are unobservable. Thus, Σ is partitioned as $\Sigma = \Sigma_{\mathrm{o}} \cup \Sigma_{\mathrm{uo}}$, where Σ_{o} represents the set of observable events and Σ_{uo} represents the set of unobservable events. See Ref.[2] for a methodology on how to construct the system model from models of system components and sensor readings.

The faults are typically partitioned as PFs, IFs and transient faults (TFs) according to their duration. IFs and TFs are time-varying faults. TFs are temporary external faults which are mainly generated by environmental conditions, like cosmic radiation and electromagnetic interferences.[9,11] Since it cannot be traced to a defect in a particular part of the system and, normally, their adverse effects rapidly disappear and do not occur too frequently. Therefore, TFs are ignored in this paper; TFs diagnosis can be found in Ref.[24].

The fault model presented in Refs.[2,19] is either geared towards the diagnosis of PFs or the diagnosis of IFs. We thus extend the fault model to include both PFs and IFs in the context of diagnosing the current fault. Since IF behavior often occurs intermittently, with fault event followed by corresponding "reset" event for this fault, followed by new occurrences of fault event, and so forth, it includes the current IF (CIF) and the reset IF (RIF).[18] When a CIF occurs, it looks like a PF. In this regard, we denote the current fault event by f_{iD}, it means there is a trace of s that ends with f_{iD}, where D stands for "to be diagnosed", we denote the CIF event and RIF event by f_{iIC} and r_i respectively. Therefore, f_{iD} is either PF event f_{iP} or f_{iIC}. Since the effect of the set of fault events on the system is the same, we are only concerned about whether f_{iD} is from the set of PFs or the set of IFs. Therefore, the set of fault events Σ_{f} is partitioned into the set of PF events $\Sigma_{\mathrm{f}_{iP}}$ and the set of IF events $\Sigma_{\mathrm{f}_{iI}}$. $\Sigma_{\mathrm{f}_{iP}}$ is assumed to be composed of m different $f_{iP}, \Sigma_{f_{iP}} = \{f_{1P}, f_{2P}, \cdots, f_{mP}\}$. $\Sigma_{f_{iI}}$ is composed of the set of f_{iIC} $\Sigma_{f_{iIC}}$ and the set of r_i Σ_{r_i}, $\Sigma_{f_{iI}} = \{\Sigma_{f_{iIC}} \cup \Sigma_{r_i}\}$. $\Sigma_{f_{iI}}$ is assumed to be composed of n different f_{iIC} and r_i, $\Sigma_{f_{iIC}} = \{f_{1IC}, f_{2IC}, \cdots, f_{nIC}\}$, $\Sigma_{r_i} = \{r_1, r_2, \cdots, r_n\}$. Each f_{iIC} has its corresponding r_i, where r_i cannot happen until f_{iIC} occurs at least once. This assumption points out the fact that IFs can automatically recover once they have occurred. Without loss of generality, we also assume that $\Sigma_{\mathrm{f}} = f_{iP} \cup f_{iIC} \subseteq \Sigma_{\mathrm{uo}}$. Our main concern in this paper is to diagnose f_{iD} within bounded delay.

In order to study the regulations of fault evolution, we introduce four new notions of labels to identify special changes in the status of system as in Ref.[2]. We define the set of PF labels $\Delta_{F^P}, \Delta_{F^P} = \{F_1^P, F_2^P, \cdots, F_m^P\}$. We define