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A discrete event systems approach to discriminating intermittent from permanent faults

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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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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 Δ_{F^P}, $\Delta_{F^P} = \{F_1^P, F_2^P, \cdots, F_m^P\}$. We define the set of IF labels Δ_{F^I}, the set of CIF labels $\Delta_{F^{IC}}, \Delta_{F^{IC}} = \{F_1^{IC}, F_2^{IC}, \ldots, F_n^{IC}\}$; the set of RIF labels $\Delta_{F^{IR}}, \Delta_{F^{IR}} = \{F_1^{IR}, F_2^{IR}, \ldots F_n^{IR}\}$, $\Delta_{F^I} = \Delta_{F^{IC}} \cup \Delta_{F^{IR}}$. We define the set of current fault labels $\Delta_{F^D}, \Delta_{F^D} = \Delta_{F^P} \cup \Delta_{F^{IC}}$, and the complete set of possible labels $\Delta = \{N\} \cup \Delta_{F^P} \cup \Delta_{F^I}$.

2.2. Regulations of fault evolution

As stated above, since IFs can automatically recover once they have occurred, they usually test well, or NFF during ground test. IFs behavior which is activated and deactivated through f_{iIC} and r_i is shown in Fig. 1.

In Fig. 1, IFs behavior usually follows a square wave pattern. The fault amplitude varies, time between faulty behavior varies, and the duration time of faulty behavior may vary as well. The high parts of the wave caused by f_{iIC} represent points in time with an IF and on-going, and the low parts caused by r_i represent an IF but not currently on-going. Each high-low pattern represents one cycle in the wave. Since fault events are usually unobservable and the behavior of the current IFs and PFs is similar, it may be unclear whether it is intermittent or persistent when a fault first occurs.[25] In general, IFs typically tend to worsen with time, and it eventually becomes substantial enough that it can be detected with conventional test equipment. The regulations of fault evolution are described by labels associated with f_{iP}, f_{iIC} and r_i is shown in Fig. 2.

In Fig. 2, ε denotes empty trace, the notation $(x, \{F_1^D, F_2^{IR}, F_3^{IC}, F_4^P\})$ is assumed to mean that along a trace that leads to state x the events $f_{1D}, f_{2IC}, r_2, f_{3IC}, r_3, f_{4P}$ have occurred, r_2 is the last one to occur among f_{2IC} and r_2, and f_{3IC} is the last one to occur among f_{3IC} and r_3. As well as f_{iIC} leads the system to an intermittent and on-going state, those of r_i return it to intermittent but not currently on-going state, and f_{iP} leads whatever state of the system to a permanent failure state. Next, we define the extended label function ELP(ω) that will be applied to traces and sub-traces in L.

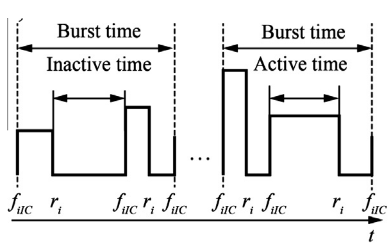

Fig. 1 An example of fault behavior of IFs.

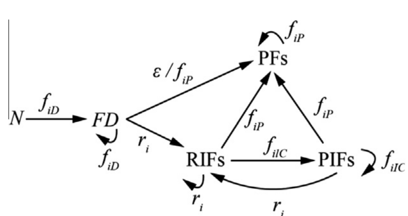

Fig. 2 Regulations of fault evolution through fault and reset events.

Definition 1. The extended label function ELP(ω):$\Sigma^* \to 2^\Delta$ is defined as follows:[26]

$$\mathrm{ELP}(\omega) = \{N\} \quad \text{if } \forall i : (f_{iD} \notin \omega)$$
$$F_i^D \in \mathrm{ELP}(\omega) \quad \text{if } (f_{iD} \in \omega) \wedge (r_i \notin \omega)$$
$$F_i^P \in \mathrm{ELP}(\omega) \quad \text{if } (f_{iP} \in \omega)$$
$$F_i^{Ic} \in \mathrm{ELP}(\omega) \quad \text{if } \exists s, s' : (\omega = ss') \wedge ([s \in \psi(\Sigma_{f_{iIC}})] \wedge (r_i \in s) \wedge (r_i \notin s'))$$
$$F_i^{IR} \in \mathrm{ELP}(\omega) \quad \text{if } \exists s, s' : (\omega = ss') \wedge ([s \in \psi(\Sigma_{r_i})] \wedge (f_{iIC} \notin s'))$$

We write $\psi(\Sigma_{f_{iIC}})$ to denote the set of all traces of L that end with the fault event f_{iIC}. That is $\psi(\Sigma_{f_{iIC}}) = \{sf_{iIC} \in L\}$. Similarly, we write $\psi(\Sigma_{r_i})$ to denote the set of all traces of L that end with the reset event r_i. That is $\psi(\Sigma_{r_i}) = \{sr_i \in L\}$. Hence, if ELP($\omega$) is $\{N\}$, i.e., "normal", then no event from the set of fault events and the set of reset events have occurred along the trace ω. If ELP(ω) contains the label F_i^D, then f_{iD} has occurred along ω but r_i has not occurred along ω. If ELP(ω) contains the label F_i^P, then f_{iP} has occurred along ω. If ELP(ω) contains the label F_i^{IC}, then both f_{iIC} and r_i have occurred at least one time or possibly multiple times along ω, but the last of the two to have occurred in ω is f_{iIC}. If ELP(ω) contains the label F_i^{IC}, then both f_{iIC} and r_i have occurred at least one time or possibly multiple times along ω, but the last of the two to have occurred in ω is r_i.

In a sum, by integrating the evolution of PFs events and IFs events, the information of labels, the observable events, along with some other condition, we can diagnose the current fault event.

3. Notions of diagnosability

The objective of the diagnosis problem is to detect the occurrence of an unobservable failure in the system, based on the information available from the record of observed events. The diagnosability is used to analyze whether the system is diagnosable or not. It depends on the structure of system and the locations of sensors. The notion of diagnosability proposed in Ref.[2] does not capture all the key issues associated with the diagnosis of IFs. Ref.[19] introduced the notions of diagnosability for IFs. Roughly speaking, a language is said to be diagnosable if it is possible to detect (within bounded delay) occurrences of certain specific unobservable events, namely, the fault event. In order to analyze the diagnosability of systems considered in this paper, we defined the notion of Type-P diagnosability and the notion of Type-I diagnosability.

Definition 2. Type-P diagnosability

A prefix-closed and live language L is said to be Type-P diagnosable with respect to projection P, which "erases" the unobservable events in a trace,[2] if the following holds:

$$[\forall i \in \{0, 1, \ldots, m\}](\exists n_i \in N)[\forall s \in \Psi(\Sigma_{F_i^P})] \cdot \{\forall t \in L/S\}[\|\boldsymbol{t}\| \geq n_i \Rightarrow D_P]$$

where the diagnosability condition D_P is

$$\omega \in \{P_L^{-1} P(s\boldsymbol{t})\} \Rightarrow [F_i^P \in \mathrm{ELP}(\omega)]$$

Type-P diagnosability, where P stands for "PFs", implies that along every continuation $\boldsymbol{t}$ of s one can diagnose the occurrence of a fault of the type F_i^P within bounded delay.

Definition 3. Type-I diagnosability

A prefix-closed and live language L is said to be Type-I diagnosable with respect to projection P, if the following holds:

$$[\forall i \in \{0,1,\ldots,n\}](\exists n_i \in N)[\forall s \in \psi(\Sigma_{F_i^P})] \cdot \left\{\forall t \in \frac{L}{s}\right\}[\|\boldsymbol{t}\| \geq n_i \Rightarrow D_I]$$

where the diagnosability condition D_I is

$$\exists \|\boldsymbol{t}'\| \leqslant \|\boldsymbol{t}\| : \omega \in \{P_L^{-1}P(st')\} \Rightarrow [F_i^{IC} \in \mathrm{ELP}(\omega)] \vee [F_i^{IR} \in \mathrm{ELP}(\omega)]$$

where $||\boldsymbol{t}'||$ and $||\boldsymbol{t}||$ are the length of trace $\boldsymbol{t}'$ and $\boldsymbol{t}$, respectively. Type-I diagnosability, where I stands for "IFs", implies that along every continuation $\boldsymbol{t}$ of s one can diagnose the occurrence of a fault of the type F_i^{IC} within bounded delay. Therefore, a language L is Type-P or Type-I diagnosable if it is possible to diagnose the fault using the record of observed events within bounded delay. Alternately speaking, diagnosability requires that every fault event leads to observations distinct enough to enable unique diagnosis of the fault within bounded delay.

4. Extended diagnosers

The notion of a diagnoser automaton was originally introduced in Ref.[2]. A diagnoser automaton, or simply diagnoser, serves two purposes: (A) online detection and isolation of PFs by observing the system behavior; and (B) off-line analysis of the diagnosability properties of the system regarding PFs. The latter is based on an examination of the structure of the diagnoser in order to determine the presence or absence of certain types of cycles termed indeterminate cycles. We focus on the latter in this paper, albeit their structure needs to be modified to diagnose both PFs and the dynamics of IFs. It turns out that the diagnoser is still at the core of the approach present in this paper. We construct the extended diagnoser G_d^E to include IFs information in the same way as in Ref.[2].

The diagnoser G_d^E for G is also an automaton:

$$G_d^E = (Q_d, \Sigma_o, \delta_d, q_0) \tag{2}$$

where Q_d, Σ_o, δ_d, q_0 have the usual interpretation. The state space of G_d^E is composed of the states q_d of the diagnoser that are reachable from q_0 under δ_d. Therefore, q_d of G_d^E is of the form:

$$q_d = \{(x_1,l_1),(x_2,l_2),\cdots,(x_n,l_n)\}, x_i \in X_o, \quad l_i \subseteq \Delta \tag{3}$$

where $X_o = \{x_0\} \cup \{x \in X : x \text{ has an observable event into it}\}$.

The diagnoser G_d^E can be thought of as an extended observer, and gives estimates of the current state of the system after the occurrence of every observable event. In addition, it carries information about potential past fault occurrence in the form of labels of fault types. If all state components, which are pairs (x_i, l_i) and are constructed by state and the labels attached to the state, in a state x_i of G_d^E have label F_i^P in common, this means that whenever G_d^E in state x_i, we can ascertain the occurrence of a fault of type F_i^P, even though we may not be certain about what state G is in. We call such states F_i^P -certain. On the other hand, if some state components of x_i of G_d^E contain label F_i^P but others do not, then in state x_i we are uncertain about the occurrence of a fault of type F_i^P. It could have occurred, since the label F_i^P is current, but it need not have, since F_i^P does not appear in all state components. We call such states F_i^P-uncertain. Similarly, we can get concepts F_i^I-certain states and F_i^I-uncertain states.[10] We assumed the system G is normal to start with, hence, we define $q_0 = \{(x_0,\{N\})\}$. The label propagation LP must be extended in order to include IFs recoveries, since the LP in Ref.[2] does not account explicitly for the dynamic behavior of IFs. We define the extended label propagation function $\mathrm{ELP}_d(x, l, s)$ as follows.

Definition 4. The extended label propagation functions $\mathrm{ELP}_d: X_o \times 2^\Delta \times \Sigma_o^*$. Given $x \in X_o$, $l \in \Delta$, $s \in L_o(G, x)$, ELP_d propagates the label l over s, stating from x_0 and following the dynamics of G. It is defined as follows:

$$\mathrm{ELP}_d(x,l,s) = \{N\} \quad \text{if } (l = \{N\}) \wedge (f_{iD} \notin s)$$

$$F_i^D \in \mathrm{ELP}_d(x,l,s) \quad \text{if } \forall i : (1)(F_i^D \in l) \wedge (r_i \notin s), \text{or } (2)(F_i^P \notin l) \wedge (F_i^I \notin l) \wedge (\Sigma_{f_{iD}} \in s) \wedge (r_i \notin s)$$

$$\forall i \in \{0,1,\cdots,m\} \quad F_i^P \in \mathrm{ELP}_d(x,l,s) \quad \text{if } (F_i^P \in l) \wedge (\Sigma_{f_{iP}i} \in s)$$

$$\forall i \in \{0,1,\cdots,n\} \quad F_i^{IC} \in \mathrm{ELP}_d(x,l,s)$$

$$\text{if } (1)[l = \{N\} \vee l = F_i^D] \wedge \mathrm{ELP}_d(x,l,s) = \{F_i^{IC}\}, \text{or } (2)(F_i^{IR} \in l) \wedge [\mathrm{ELP}_d(x,l,s) = \{F_i^D\} \vee \mathrm{ELP}_d(x,l,s) = \{F_i^{IC}\}], \text{or } (3)(F_i^{IC} \in l) \wedge [\mathrm{ELP}_d(x,l,s) = \{N\} \vee \mathrm{ELP}_d(x,l,s) = \{F_i^D\} \vee \mathrm{ELP}_d(x,l,s) = \{F_i^{IC}\}]$$

$$F_i^{IR} \in \mathrm{ELP}_d(x,l,s)$$

$$\text{if } (1) l = \{N\} \vee \mathrm{ELP}_d(x,l,s) = \{F_i^{IR}\}, \text{or } (2)(F_i^{IR} \in l) \wedge [\mathrm{ELP}_d(x,l,s) = \{N\} \vee \mathrm{ELP}_d(x,l,s) = \{F_i^{IR}\}], \text{or } (3)(F_i^D \in l) \wedge (F_i^{IC} \in l) \wedge \mathrm{ELP}_d(x,l,s) = \{F_i^{IR}\}$$

One can find that Definition 9 is consistent with Definition 1. The formal construction procedure of the diagnoser along with the precise definition of indeterminate cycles can be found in Ref.[17] and are therefore omitted due to space limitations of the paper. To ensure Type-P and Type-I dignosability, the following results are given to provide necessary and sufficient conditions.

Ref.[2] presents the formal construction procedure of the diagnoser, along with necessary and sufficient conditions for diagnosability. These conditions are based on the examination of the indeterminate cycles in the diagnoser. See Ref.[2] for a precise definition of indeterminate cycles. Indeterminate cycles in G_d are cycles of uncertain states that have corresponding cycles in G involving their failed states. It turns out that G is diagnosable if G_d^E does not contain indeterminate cycles for any fault types. Roughly speaking, the occurrence of an indeterminate cycle in the diagnoser means that there exist two traces in L, of arbitrarily along length, where one trace contains a fault event of a certain type and the other trace does not. Clearly, the presence of such a pair of traces in L implies that is L not diagnosable. The construction and computation of the new states of the diagnoser are similar to those of Ref.[2] and therefore omitted. However, a little difference should be pointed out. In contrast to denote the current fault by f_i in Ref.[2], we denote it by f_{iD}. The fault types of f_{iD} can be recognized according to the subsequent observable events. Let us demonstrate the construction procedure for diagnoser using a simple example. Consider the system G shown in Fig. 3. The set of observable events in $\Sigma_o = \{\alpha, \beta, \gamma, \tau\}$, and there are three faults types F_2, F_2 and F_3. F_1 and F_2 are IFs, with the corresponding fault and reset events $\{f_{1IC}, r_1\}$ and $\{f_{2IC}, r_2\}$, respectively. The initial state of G_d^E is $\{1, \{N\}\}$, denoted by $1N$ for the sake of simplicity. Similar compact notation is used in all the figures in this paper.

In Fig. 3, it is difficult to recognize the types of the current fault at the first time on States 4, 7 and 11; we denote it by f_{1D}, f_{2D} and f_{3D} respectively. The effect of ELP_d manifests itself when State 8 is first reached after observed trace $\alpha\beta$, yielding the label F_1^{IC} due to the r_1 transition between States 5 and 6, therefore, the fault event f_{1D} is f_{1IC}. We can recognize the fault event f_{2D} is f_{2IC} similarly. The State 12 keeps persistent after observed trace $\lambda\tau$, according to the assumption made in Section 2, the fault event f_{3D} thus is thought to be f_{3P}. As the system settles in the cycle 5-6-7-8-9-10-5, the diagnoser will alternate between the states $\{(2, \{N\}), (5, \{F_1^{IC} F_2^{IR}\}), (12, \{F_3^D\})\}$ and $\{(3, \{N\}), (8, \{F_1^{IR} F_2^{IC}\})\}$.

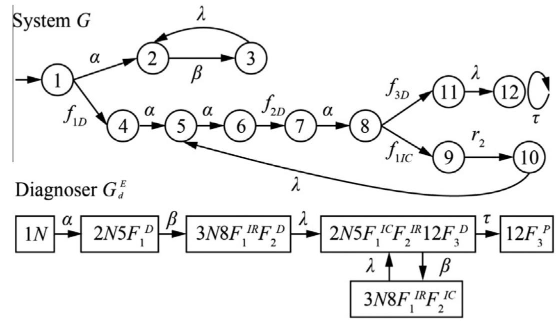

Fig. 3 Construction of extended diagnose.

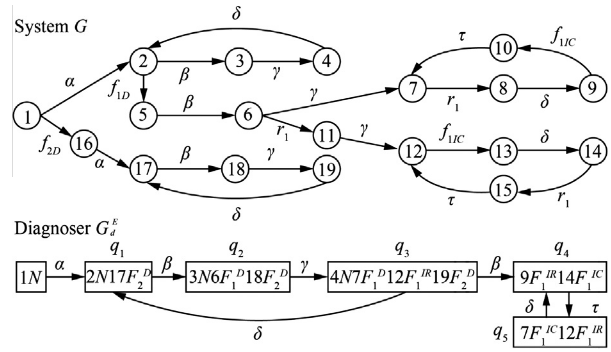

Fig. 4 Example of a system that is neither Type-P nor Type-I diagnosable.

5. Illustrative examples

This approach can be applicable to systems that fall naturally in the class of DESs; moreover, for the purpose of diagnosis, continuous variable dynamic systems can often be viewed as DESs at a higher level of abstraction. This approach does not require detailed in-depth modeling of the system to be diagnosed. The states of the discrete-event model reflect the normal and the failed status of the system components while the failure events form part of the event set. The problem is to detect the occurrence of these events. In this regard, we use several illustrative examples to demonstrate the proposed approach in this section. For simplicity, we assume that the system is normal to start with, the observable set in $\sum_O = \{\alpha, \beta, \lambda, \tau, \rho\}$.

In Fig. 4, there are two fault events in States 5, 16, respectively. The set of States 2, 4 and 17, 19 both form a cycle, the set of States 7, 9 and 12, 14 both form a cycle too, States $q_1 - q_3$ and q_4, q_5, form a F_i^P-indeterminate and F_i^I-indeterminate cycle respectively in G_d^E. Given the results quoted in the preceding section, we conclude that the system is neither Type-P diagnosable nor Type-I diagnosable.

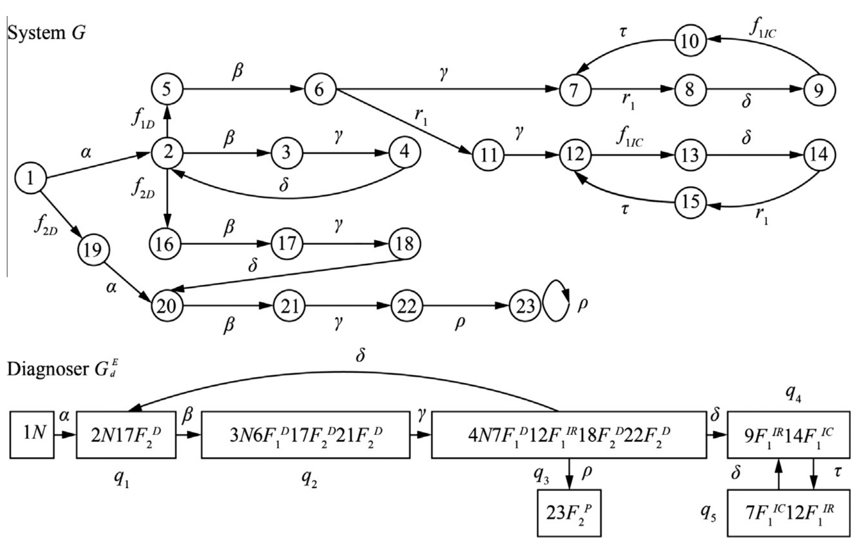

Fig. 5 Example of a system that is Type-P but not Type-I diagnosable.

In the system of Fig. 5, the set of States 7, 9 and 12, 14 forms a cycle, respectively, and States q_4 and q_5 form a F_i^I-indeterminate cycle in G_d^E. States $q_1 - q_3$ form a cycle in G_d^E and are not F_i^P-certain. However, there are no cycles involving states that carry the label F_i^P in the cycle in G_d^E, namely, States 17 and 18, 20–23. Therefore, there is no F_i^P-indeterminate cycle and the system is Type-P diagnosable but not Type-I diagnosable.

We now provide an example of a system which is Type-I diagnosable. In Fig. 6, the set of States 2, 4 and 19, 21 both form a cycle, States q_4 and q_5 form a F_i^P-indeterminate cycle respectively in G_d^E. However, there are no F_i^I-indeterminate cycles in G_d^E. Therefore, the system is Type-I diagnosable but not Type-P diagnosable.

We now give an example of a system which is Type-P and Type-I diagnosable. In Fig. 7, there are no F_i^P (F_i^I)-indeterminate cycles in G_d^E, therefore, the system L is Type-P diagnosable and Type-I diagnosable. Moreover, we can diagnose f_{1D} is f_{1IC} when the trace $\alpha\beta\gamma\tau\rho$ is observed; according to the assumption made in Section 2, we can also diagnose f_{2D} is f_{2P} when the trace $\alpha\beta\gamma\delta\rho\tau$ is observed.

6. Conclusions and future work

IFs are expected to become especially problematic and pose a great challenge to fault diagnosis. With scaling of semiconductor devices, this problem will become more severe and prominent. Misjudging IFs as PFs has plagued the diagnosis system since the use of diagnosis technology. In this paper we have addressed the problem of fault discrimination (discriminating between PFs and IFs) for FAs mitigation purpose. In particular, a novel approach based on DESs is given to discriminate between PFs and IFs without the assumption of knowing its types a priori. For the examples we considered, we find that it is able to discriminate the fault types within bounded delay if the system is diagnosable.

Recently, some significance work has developed to the diagnosis problem. A related approach is proposed by Ref.[27], where the notion of supervision pattern is introduced. It is general enough to express and solve in a unified way a broad class of diagnosis problem, e.g., diagnosing PFs, multiple faults, and some problem of IFs. However, the approach remains to be explored in the context of fault discrimination, since they do not account

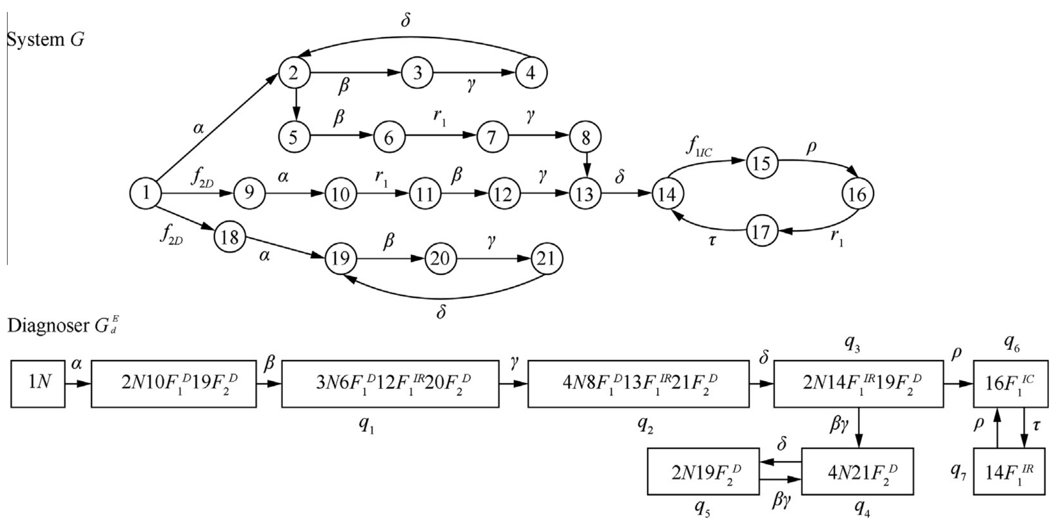

Fig. 6 Example of a system that is nor Type-P but Type-I diagnosable.

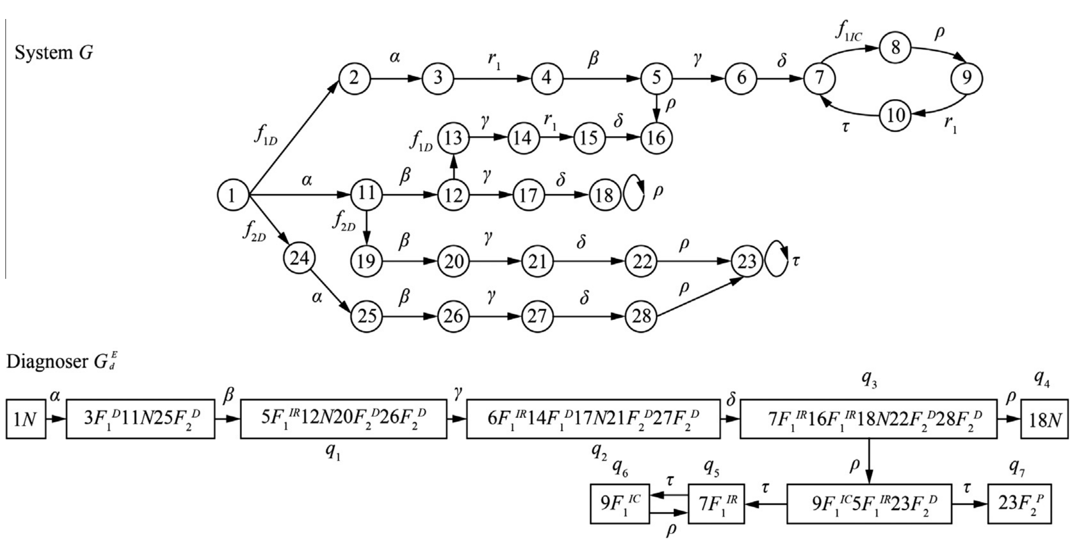

Fig. 7 Example of a Type-P and Type-I diagnosable system.

explicitly for PFs and dynamic behavior of IFs in the same fault model. We hope to investigate the problem of fault discrimination with that approach in future work. It should be noted that the approach proposed in this paper requires the construction of the global model of the system, which is almost invariably impossible for complex DESs (owing to the explosion of the state space). Ref.[28] has described a context-sensitive diagnosis approach; the interpretation of the system behavior is based on the abstraction hierarchy, where different diagnosis rules and different subsystems are defined in the hierarchy. It is a powerful approach and enhances the expressive power of diagnosis of complex DESs. It is a topic worthy of further research.

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