On-Line Diagnosis of Discrete-Event Systems: A Hierarchical Approach

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***Abstract*—Hierarchy is a remedy way to reduce the demanding complexity of model-based diagnosis. In this paper, an approach to diagnosis of discrete-event systems in a hierarchical way is proposed, inspired by the concept "D-holon" and the concept "Silent Closure" presented in the literatures recently. Each extended silent closure can be seen as a special type of D-holons, called SCL-D-holon. Every hierarchical level is an SCL-D-holon built off line. When on line diagnosing a discrete-event system, only related SCL-D-holons will be called instead of all the SCL-D-holons generally, thus the space complexity is reduced. In comparison to on line creating silent closures, the efficiency is improved as well.**

***Index Terms*—Model-based diagnosis, discrete-event systems, hierarchy, on line.**

I. Introduction

Model-based diagnosis (MBD) is one of the active branches of Artificial Intelligence (AI). Since a formalization of MBD with first-order logic given by Reiter [19], it has been widely studied. Earlier, static systems were studied by researchers, and then researches on dynamic systems have begun since the last decade. Especially, model-based diagnosis of discrete event systems (DESs) has arisen increasing interests, as DESs cover continuous-variable systems which, after quantization, are represented as discrete systems [13] for the purpose of diagnosis at a higher level of abstraction, as well as "discrete by nature" systems.

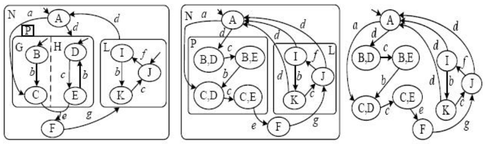
This domain is very active since the seminal work of [22] and [23], which has been the basis not only for subsequent contributions in the control engineering field [6], but also for further research in AI [20]. A number of model-based approaches for diagnosing DESs have been proposed in both fields literatures. And they have been widely applied, particularly in large scale telecommunication networks in [21], [18], and [5], *etc.*, and power transmission networks in [1], [9], [12], and [3], *etc.*

Computational complexity of multiple fault diagnosis is one of the well-known problems in real-world applications of MBD. And hierarchical diagnosis has been advocated as one of the main remedies for this issue (see [17], [4], [7], and [25], *etc.*): firstly, the problem is represented at multiple levels of detail, and then faults are isolated one level at a time, starting at the most abstract possible level and using the results at one higher level to focus reasoning at more detailed levels, so as to reduce the overall computational cost of diagnosis. As to model-based diagnosis of DESs, the hierarchical structure of systems (the network) is considered in [21]. In that hierarchical structure, each branch of the network can be seen as a hierarchical modular component, and a generic model of the system for building a generic diagnoser. Obviously, that approach strongly depends on the special structure of the network. In [26], a formal hierarchical distributed approach based on global consistency is proposed, where each diagnosis in each detailed level can be computed by results of the corresponding abstract level. In addition, there is a hierarchical approach to diagnosis of DESs based on timed automata put forward by [27] and [24], where each higher hierarchical level is a timed automaton. Clearly, that method needs a timed system model, whereas time information might cause complexity. Another hierarchical method of diagnosing DESs is based on the concept "D-holon" presented in [15] and [16], and each higher hierarchy is a D-holon. But how to produce good D-holons by breaking the system model is not given yet. As we know, there are not many more hierarchical methods to diagnosis for DESs.

Diagnosis is usually performed on-line, and there are also some methods to on-line diagnosis, such as the global diagnoser ([22] and [23]), the decentralized diagnoser [18], the monitor based on silent closures ([10] and [11]), *etc.* As each silent closure in the monitor ([10] and [11]) is built on line, the efficiency would not be very good.

In this paper, we present a novel hierarchical approach to diagnosis of DESs, well combining the concept "D-holon" as the basis of hierarchy, and the concept "silent closure" as each hierarchy. All the new silent closures are built off line, and only the relevant D-holons are used when on line diagnosing the system, thus the efficiency will be improved as well.

The paper is organized as follows. In section II, we briefly review preliminaries of D-holons and Silent closures. In section III, we introduce the concept of SCL-D-holon, and our



(a) HFSM (b) Basic HFSM (c) Flat DES

Fig. 1. An HFSM, its equivalent basic HFSM and its equivalent flat DES.

hierarchical diagnosis approach is given, too. An example is illustrated in section IV. Related comparisons are discussed in section V. Section VI presents the conclusions.

II. Preliminaries of D-holons and Silent closures

In this section, we will first briefly review the concept "D-holon" and the concept "Silent Closure" proposed in [15], [16] and [10], [11], respectively.

A. D-holon

Most of the terminology in this sub-section is adopted from [2]. Consider a hierarchical FSM (**HFSM**) shown in Fig. 1(a), where N, P and L are *super states*, as each of them includes other states; in contrast, B and I are called *basic states*. The states in each super state are called the immediate sub-states or *children* of that super state, and the super state is called the *father* of those states. In Fig. 1(a), for instance, A is an immediate sub-state of N. State L is called an *OR-state* as being in L is equivalent to being in I or J or K, but not in more than one state at any time. In contrast, state P is called an *AND-state* as being in P is equivalent to being in both G and H. The internal transitions of AND-states can be determined by the transition of the synchronous product of their immediate sub-states. For instance, in Fig. 1(b), G and H have been replaced by their synchronous product. Fig. 1(c) shows the equivalent flat model of the HFSM.

A transition path between states is a *basic* one if its source and destination are both basic states, such as the transition-path t =((A), a, (C)) in Fig. 1(a). This transition-path takes the system to the state (C, D). However, D (the initial state of H) is not specified in the destination of t (only (C)). Thus, we call (C, D) the explicit destination of t.

An HFSM with no AND super states is called a **basic HFSM**. In other words, all AND-states are substituted by the synchronous product of their children. In this paper, only basic HFSMs are concerned. Fig. 1(b) shows the equivalent basic HFSM. And the basic states of a basic HFSM are referred to *simple states*. Any HFSM can be transformed to the equivalent basic HFSM [14].

A basic HFSM with a **Father-Child-connected** (FC-connected) forma is that, each transition from a state of a super state takes the system to a state of the super state or to a state in the father or a child of the super state. Also, a basic HFSM which is not FC-connected can be transformed to a basic FC-connected HFSM [14]. Therefore, every transition (x, σ, y) that violates FC-connectivity can be replaced by a sequence of transitions respecting FC-connectivity from x to a dummy state in a common ancestor of x and y, followed by another sequence of transitions to y.

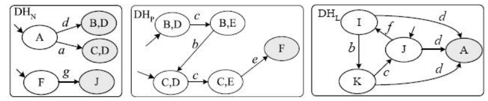


Fig. 2. D-holons of the HFSM in Fig. 1(b), in which external states are shown by gray circles.

A basic HFSM is said to be reachable if every simple state is reachable from the system's initial state x_0. Moreover, we call a basic HFSM H a standard HFSM if H is reachable and FC-connected.

Then, let us review the concept "D-holon". Roughly speaking, a D-holon is a structure, which represents a super state with its internal and external transitions. Intuitively, each D-holon may describe a phase or part of system operation.

Definition 1 [15]: Consider a standard HFSM H. A D-holon DH associated with a super state S in H is defined as a 4-tuple $DH_S := (X^{DH_S}, \Sigma^{DH_S}, \delta^{DH_S}, X_0^{DH_S})$. Here, X^{DH_S} is the state set of DH and is the disjoint union of $X_I^{DH_S}$ and $X_E^{DH_S}$, where $X_I^{DH_S}$ is the internal state set consisting of the immediate simple states of S, (*i.e.*, $X_I^{DH_S} = X_S^{Simple}$), and $X_E^{DH_S}$ is the external state set consisting of the simple states of higher and/or lower level super states which are the target of a transition from a simple state of S. $X_0^{DH_S} \subseteq X_I^{DH_S}$ is the set of initial states consisting of those elements of X_S^{Simple} which are the target of a transition from a state of a higher level or a lower level super state. Σ^{DH_S}, the event set, is the union of the boundary event set $\Sigma_B^{DH_S}$, and the internal event set $\Sigma_I^{DH_S}$. $\Sigma_I^{DH_S}$ consists of the events associated with transitions among internal states and $\Sigma_B^{DH_S}$ includes the events associated with transitions from internal states to external states. δ^{DH_S}: $X_I^{DH_S} \times \Sigma^{DH_S} \rightarrow X^{DH_S}$, the transition function, is the restriction of the transition function of H to $X_I^{DH_S} \times \Sigma^{DH_S}$.

In this paper, we assume that for any D-holon DH, the boundary events are observable. Therefore, a D-holon can describe a specific phase of operation. And the boundary transitions represent change of the phase of operation.

We can see that an HFSM can be completely defined by its D-holons and its initial state. Fig. 2 shows the D-holons associated with the super states in Fig. 1(b). After the whole system model is broken into several D-holons, we can design a diagnoser for each of them. The basic idea of diagnosing the system is that, when we obtain an observation, only the relevant diagnosers of D-holons instead of the whole diagnoser of the system will be used, and the local diagnostic results will be gathered to produce the whole diagnostic results. Therefore, space complexity is reduced. The more detailed approach to design the diagnoser for each D-holon can be referred to [15] and [16], we omit it here.

Though the method can reduce space complexity, there are no good specialized methods to get a good hierarchy, given a real DES. And the following concept "silent closure" ([10] and [11]) can be seen as a special way of producing a good hierarchy of a system.

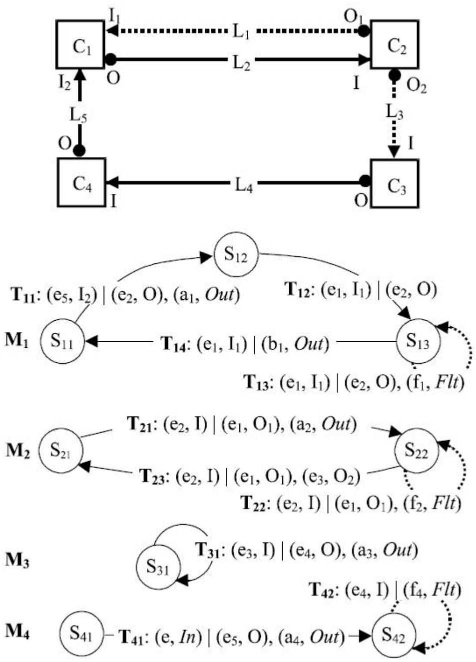


Fig. 3. A system Ψ and its components' models.

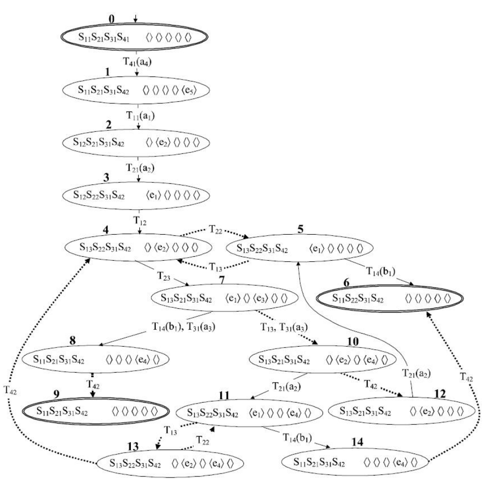


Fig. 4. The universal space $Usp(\Psi, \Psi_0)$.

B. Silent closure

In [1], a discrete-event system Ψ is a network of *components* connected to one another through *links*. Formally, each component communicative automaton can be described as a 6-tuple ($\mathbb{S}$, $\mathbb{E}_{in}$, $\mathbb{I}$, $\mathbb{E}_{out}$, $\mathbb{O}$, $\mathbb{T}$), where $\mathbb{S}$ is the set of *states*, $\mathbb{E}_{in}$ the set of *input events*, $\mathbb{I}$ the set of *input terminals*, $\mathbb{E}_{out}$ the set of *output events*, $\mathbb{O}$ the set of *output terminals*, and $\mathbb{T}$ the (nondeterministic) *transition function*. Moreover, components are implicitly equipped with three *virtual terminals*, the *standard input* (*In*) for events coming from the external world, the *standard output* (*Out*) for events directed toward the external world, called *messages*, and the *fault terminal* (*Flt*) for modeling faulty transitions. The *state* of a link is the queue of events generated on it and not yet consumed. Initially, Ψ is in a *quiescent* state Ψ_0, wherein all links are empty. On the occurrence of an event from the external world, Ψ becomes reacting, thereby doing a series of *system transitions*, called a *history* of Ψ. A system transition is a set of component transitions, which may generate a set of observable events (message). A component is *faulty* if it makes a faulty transition. Roughly, the set of faulty components encompassed by a history is a *diagnosis* for Ψ. More details can be seen in literatures ([1], [9], [10], and [11], *etc.*).

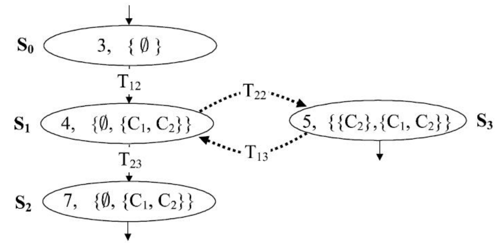


Fig. 5. A silent closure.

Given an initial state Ψ_0, Ψ evolves consistently with both its topology and the behavioral model. The resulting automaton is called *universal space*, $Usp(\Psi, \Psi_0)$. For example, a system Ψ and its universal space $Usp(\Psi, \Psi_0)$ with the initial state Ψ_0 are shown in Fig. 3 and Fig. 4, respectively.

Based on the universal space of the system, we will review the concept of "Silent Closure" in the following.

Definition 2 ([10] and [11]): Let ψ_0 be a node of the universal space $Usp(\Psi, \Psi_0)$. The *silent closure*, $Scl(\psi_0)$ = ($\mathbf{S}$, $\mathbf{E}$, $\mathbf{T}$, S_0, $\mathbf{S}_{out}$), is an automaton defined as follows. Each state $S \in \mathbf{S}$ is a pair (ψ, $\mathcal{D}$) where ψ is a state of $Usp(\Psi, \Psi_0)$ and $\mathcal{D}$ a set of diagnoses δ such that a path $\psi_0 \rightsquigarrow \psi$ in $Usp(\Psi, \Psi_0)$ implies δ, the *diagnostic attribute*. $\mathbf{E}$ is the set of transitions of Ψ. $\mathbf{T}$: $\mathbf{S} \times \mathbf{E} \mapsto \mathbf{S}$ is the transition function such that (ψ, $\mathcal{D}$) $\xrightarrow{\tau}$ (ψ', $\mathcal{D}$') $\in \mathbf{T}$ iff τ is a *silent* transition (the transition label is not obervable) of Ψ and $\psi \xrightarrow{\tau} \psi$' is a transition in $Usp(\Psi, \Psi_0)$. S_0 = (ψ_0, $\mathcal{D}_0$) is the *root*. $\mathbf{S}_{out} \subseteq \mathbf{S}$ is the *leaving set*, defined as follows. S = (ψ, $\mathcal{D}$) $\in \mathbf{S}_{out}$ iff $\psi \xrightarrow{\tau} \psi$' is an observable transition in $Usp(\Psi, \Psi_0)$.

For example, a silent closure of the system Ψ is shown in Fig. 5. The automaton is isomorphic to the subpart of $Usp(\Psi, \Psi_0)$ involving nodes 3, 4, 5 and 7.

Based on the concept of "silent closure", a monitor relevant to a system Ψ with initial state Ψ_0 is a graph: $Mtr(\Psi, \Psi_0)$ = ($\mathbb{N}$, $\mathbb{L}$, $\mathbb{E}$, $\boldsymbol{N}_0$), where $\mathbb{N}$ is the set of nodes, $\mathbb{L}$ the set of labels, $\mathbb{E}$ the set of edges, and $\boldsymbol{N}_0$ the initial node. Each node $N \in \mathbb{N}$ is an automaton N = ($\mathbf{S}$, $\mathbf{E}$, $\mathbf{T}$, S_0, $\mathbf{S}_{out}$) = $Scl(S_0)$, where $S_0 \in Usp(\Psi, \Psi_0)$. Let $\mathbb{S}_{out} = \bigcup_{N \in \mathbb{N}} \mathbf{S}_{out}(N)$, $\mathbb{S}_0 = \bigcup_{N \in \mathbb{N}} \{S_0(N)\}$, and $\mathbf{M}$ and $\mathbf{F}$ be the domain of system messages and of faulty components in $Usp(\Psi, \Psi_0)$, respectively. Each edge $E \in \mathbb{E}$ is marked by a label in $\mathbb{S} \times \mathbf{M} \times 2^{\mathbf{F}} \times \mathbb{S}$. An edge $N \xrightarrow{(S,\mu,\mathcal{F},S')}$ N', (where S = (ψ, $\mathcal{D}$) and S' = (ψ', $\mathcal{D}$') are internal nodes of N and N', respectively) is such that:

(1) S' = $S_0(N')$; (2) $\psi \xrightarrow{\tau} \psi$' is a transition in $Usp(\Psi, \Psi_0)$; (3) μ is the set of messages generated by τ; (4) $\mathcal{F}$ is the set of faulty components relevant to τ.

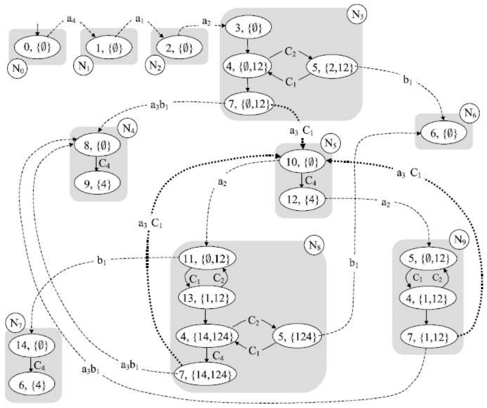


Fig. 6. Monitor $Mtr(\Psi, \Psi_0)$.

The initial node N_0 is such that $S_0(N_0) = (\Psi_0, \mathcal{D}_0)$.

The monitor of the system Ψ with its initial state Ψ_0 is shown in Fig. 6. Diagnoses are expressed by a list of the indexes of the relevant faulty components. Plain arrows denote the (necessarily silent) transitions between internal states. Identifiers of transitions are omitted. If an internal transition is faulty, it is marked by the relevant set of faulty components. All the internal nodes are qualified with the only relevant local diagnostic attribute. Edges of the monitor are depicted by either dashed or dotted arrows, the latter involving faulty components. Each edge is labeled by the pair (μ, $\mathcal{F}$), that is, a system message and a set of faulty components. When empty, $\mathcal{F}$ is omitted, as is in all dashed arrows.

The basic idea of the monitor to on line diagnose a DES is that, when we get an observation, then from all the leaving transitions of current possible silent closures, we find next silent closures by matching the obtained observation with the labeled observation on the corresponding transitions. Therefore, we can get the local diagnoses of the new silent closures. And then, we will get the current global diagnostic results by the whole transition path from the initial state. The more detailed algorithm can be referred to [10] and [11], we omit it here.

III. Hierarchical diagnosis by SCL-D-holons

Though the monitor of a system mainly composed by silent closures, can be used for on line monitoring the system and give the diagnostic results, its efficiency would be affected by the factor: all the silent closures are created on line not off line.

In order to overcome the shortcomings of the two approaches mentioned above, we combine the two concepts and give a new concept SCL-D-holon, based on which we will give a novel approach to on line diagnose DESs hierarchically as follows.

Definition 3: Given a universal space of the system Ψ with the initial state Ψ_0, and a silent closure $N = Scl(\psi_0)$ = (**S**, **E**, **T**, S_0, $\mathbf{S}_{out}$) (all the parameters are defined the same way as in Definition 2), then an SCL-D-holon SCL-DH-N associated with N can be defined as a 4-tuple SCL-D-holon := (X^N, Σ^N, δ^N, X_0^N). Here, X^N is the state set of SCL-DH-N and is the disjoint union of X_I^N and X_E^N, where X_I^N is the internal state set of the silent closure N, (*i.e.*, X_I^N = **S**), and X_E^N is the external state set consisting of the *root* states of other silent closures, each of which is the target of a transition from a state of $\mathbf{S}_{out}$. $X_0^N \subseteq X_I^N$ (*i.e.*, $X_0^N = S_0$) is the set of initial states consisting of those elements of X^N, each of which is the target of a transition from a state of other silent closures. Σ^N, the event set, is the union of the boundary event set Σ_B^N, and the internal event set Σ_I^N. Σ_I^N consists of the events associated with transitions among internal states (*i.e.*, Σ_I^N = **E**) and Σ_B^N includes the events associated with transitions from internal states to external states (*i.e.*, the observable messages). δ^N: $X_I^N \times \Sigma^N \rightarrow X^N$, *i.e.*, the transitions from internal states to internal states (*i.e.*, **T**) and the other transitions from the states of $\mathbf{S}_{out}$ to external states.

Intuitively, an SCL-D-holon is an automaton, composed by a silent closure and all its leaving transitions from it and the corresponding root states of the destination silent closures. An example to describe SCL-D-holons of a system will appear in Fig. 7 in the next section.

From the definition of SCL-D-holon, we can see that the universal space of a discrete-event system with its initial state is just like an HFSM, including a lot of super states, and each super state is a silent closure. In addition, each SCL-D-holon of a silent closure contains the local diagnosis information, as there is corresponding diagnosis information in each silent closure. In this regard, each SCL-D-holon can be seen as a special local diagnoser as well.

According to the concept SCL-D-holon, each SCL-D-holon can be also seen as a hierarchy in the hierarchical system model, therefore, we can give an approach to hierarchically diagnose a DES as follows:

(1) Off-line creat all SCL-D-holons for all silent closures of the system. In other words, for each silent closure, we extend it with all the reachable internal target states in other silent closures. These internal target states are also the corresponding roots of the target silent closures.

(2) Initializie the state of the system, and then call the initial SCL-D-holons. Only the initial SCL-D-holons are used this time.

(3) When a new observation is obtained, we monitor a DES with only relevant SCL-D-holons, each of whose root states is equivalent to some of the reachable external states by the new observation from the current SCL-D-holon.

From this approach, on the one hand, the silent closures can be seen as a good way to break the system model to many sub-models, *i.e.*, D-holons. On the other hand, all the SCL-D-holons have been built off line, therefore the efficiency of on line diagnosing the system is improved. The related diagnosis information is included in each SCL-D-holon, therefore, the current global diagnostic results can be also obtained efficiently as well.

In the next section, we will give an example to describe all the SCL-D-holons of a system, and the concrete computational procedure of the hierarchical approach in detail.

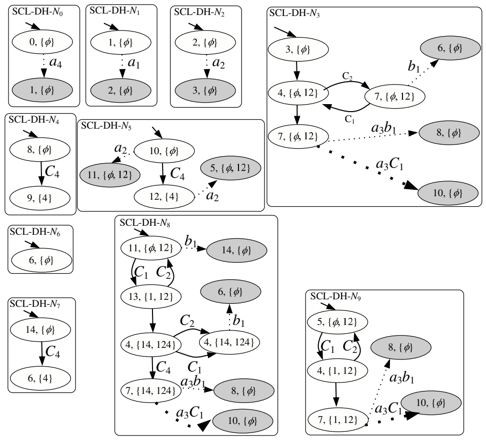


Fig. 7. SCL-D-holons of the system Ψ (components are identified by corresponding indexes in each state), external states are shown by gray circles.

IV. Example

Example: Consider the system Ψ with the initial state Ψ_0 ([10]) shown in Fig.3 and its corresponding universal space shown in Fig. 4.

First, we build all the SCL-D-holons off line for each silent closure of the monitor but not build the whole monitor itself. For example, the SCL-D-holons SCL-DH-N_0, SCL-DH-N_1, ..., SCL-DH-N_9, for the corresponding silent closures are shown in Fig.7.

In the following, as in [10] and [11], we would like to compute, for each system message μ, the so-called *snapshot diagnostic set* Δ^s, the set of candidate diagnoses implied by the occurrence of μ, disregarding the whole set of candidate diagnoses relevant to the sequence of messages generated before μ. In contrast, we call the set of candidate diagnoses that accounts for the whole evolution of the system the *historic diagnostic set* Δ^h.

Let SCL-DH-N be an SCL-D-holon. The *local diagnostic set* Δ^l(SCL-D-N) of SCL-D-N is the union of all the diagnoses associated with the internal states of SCL-D-N. In order to determine the diagnostic pair (Δ^s, Δ^h) at each newly generated system message during monitoring, we need to combine sets of diagnoses appropriately. The *diagnostic join* of two sets of diagnoses Δ_1 and Δ_2 is defined as follows:

$\Delta_1 \bowtie \Delta_2 = \{\delta | \delta = \delta_1 \cup \delta_2, \delta_1 \in \Delta_1, \delta_2 \in \Delta_2\}$.

Consider the evolution of Ψ with initial state Ψ_0 relevant to the sequence of system messages $<\{a_4\}$, $\{a_1\}$, $\{a_2\}$, $\{a_3\}$, $\{a_2\}$, $\{a_3\}>$, the same as in [10] and [11]. Initially, the SCL-DH-N_0 is used, and the initial diagnostic set is $\Delta_0(\Psi)$ = $\{\phi\}$. After the occurrence of $\{a_4\}$, as the external state (1, $\{\phi\}$)(components are identified by relevant indexes) in SCL-DH-N_0 is the root of the silent closure N_1, the SCL-DH-N_1 will be called, and the local diagnosis is still $\{\phi\}$. Similarly, after the occurrence of $\{a_1\}$, as the external state (2, $\{\phi\}$) is the root of the silent closure N_2, the SCL-DH-N_2 will be called, and the local diagnosis is still $\{\phi\}$. After the occurrence of the third system message, $\{a_2\}$, as the destination external state (3, $\{\phi\}$) is the root of the silent closure N_3, the SCL-DH-N_3 will be called. Thus, both the snapshot and the historic diagnostic sets correspond to the local diagnostic set of SCL-DH-N_3, namely Δ_3^s = Δ_3^h = Δ^l(SCL-DH-N_3) = {ϕ, {2}, {1, 2}}. The occurrence of $\{a_3\}$ moves the monitoring state to the external state (10, $\{\phi\}$), the root of SCL-DH-N_5 by means of a faulty transition marked by "a_3C_1". Thus, Δ_4^s = Δ^l(SCL-DH-N_5) $\bowtie$ {{1}}= {{1}, {1, 4}}. Whereas, the *historic* diagnostic set is generated by composing the *snapshot* diagnostic set with the diagnostic attribute relevant to the node of the leaving set of SCL-DH-N_3, that is, Δ_4^h = {{1}, {1, 4}} $\bowtie$ {ϕ, {1, 2}} = {{1}, {1, 4}, {1, 2}, {1, 2, 4}}. The occurrence of $\{a_2\}$ produces a nondeterministic pattern, as SCL-DH-N_5 involves two leaving edges marked by a_2, one to SCL-DH-N_8 and the other to SCL-DH-N_9. We have to consider both possibilities in the transition to the new monitoring state, *i.e.*, includeing both SCL-DH-N_8 and SCL-DH-N_9. Since either edge are not marked by any faulty component, the snapshot diagnostic set corresponds to the union of the local diagnostic sets relevant to nodes SCL-DH-N_8 and SCL-DH-N_9, namely Δ_5^s = $\Delta^l(N_8)$ $\cup$ $\Delta^l(N_9)$ = {ϕ, {1}, {1, 2}, {1, 4}, {1, 2, 4}}. In order to compute Δ_5^h, we have to make two joins, corresponding to the two edges leaving SCL-DH-N_5 and marked by a_2, and then merge the results. However, this requires a previous *relocation* of the diagnostic attributes of nodes in SCL-DH-N_5 in order to keep the historic diagnostic information up to date. The relocation ρ(10) of the diagnostic attribute of the root of SCL-DH-N_5 is computed as follows: ρ(10) = {ϕ} $\bowtie$ {{1}} $\bowtie$ {ϕ, {1, 2}} = {{1}, {1, 2}}, where {ϕ, {1, 2}} is the (relocated) diagnostic attribute of the leaving node of SCL-DH-N_3. Similarly, ρ(12) = {{4}} $\bowtie$ {{1}} $\bowtie$ {ϕ, {1, 2}} = {{1, 4}, {1, 2, 4}}. Then, Δ_5^h = ($\Delta^l(N_8)$ $\bowtie$ ρ(10)) $\cup$ ($\Delta^l(N_9)$ $\bowtie$ ρ(12)) = {{1}, {1, 2}, {1, 4}, {1, 2, 4}}. Finally, the occurrence of $\{a_3\}$ matches two edges, one form SCL-DH-N_8 to SCL-DH-N_5 and the other from SCL-DH-N_9 to SCL-DH-N_5, both being marked by the faulty component C_1. Therefore, Δ_6^s is determined by composing the local diagnostic set of SCL-DH-N_5 with C_1, namely Δ_6^s = Δ^l(SCL-DH-N_5) $\bowtie$ {{1}} = {{1}, {1, 4}}. As above, to determine Δ_6^h, we need to relocate the diagnostic attributes relevant to the leaving states in SCL-DH-N_8 and SCL-DH-N_9, that is, ρ(7) = {{1, 4}, {1, 2, 4}} $\bowtie$ ρ(10) = {{1, 4}, {1, 2, 4}}. Incidentally, the relocation leaves the diagnostic attribute unchanged. Similarly, ρ(7') = {{1}, {1, 2}} $\bowtie$ ρ(12) = {{1, 4}, {1, 2, 4}}. Therefore, Δ_6^h = (Δ_6^s $\bowtie$ ρ(7)) $\cup$ (Δ_6^s $\bowtie$ ρ(7')) = {{1, 4}, {1, 2, 4}}.

Our approach has a much similar computational procedure as the monitor, however, we build all the SCL-D-holons off line firstly, and during the monitoring, only the related SCL-D-holons will be directly called and not be created on line.

V. Comparison

There have been many approaches to diagnosis of DESs since the method of "global diagnoser" proposed by Sampath et al. ([22] and [23]). However, the global diagnoser depends on the global system model, which is exponential to the number of system components, thus it is impractical to application generally.

In order to overcome the space complexity, the approach of "decentralized diagnoser" based on a decentralized system model is proposed in [18], which can also be used to on line diagnose DESs. In contrast, [1], [8], and [9] mainly concern *a posterior* diagnosis of DESs, based on a distributed system model. However, the efficiency of decentralized/distributed methods greatly depends on the merging strategy.

In [10] and [11], an approach to on line diagnose DESs based on silent closures is presented, where a monitor is built on line. As every silent closure is created on line, the efficiency is affected. Moreover, in comparison to that approach, our method is more scalable generally, as only related SCL-D-holons are called.

The concept "D-holon" proposed in [15] and [16] can be seen as a hierarchy of a system model, but how to produce a good hierarchy has not given. In contrast, each silent closure in our hierarchical approach can be seen as a special hierarchy easily to be built.

VI. Conclusion

In this paper, an approach to hierarchical diagnosis of discrete-event systems is proposed, combining the concept of "D-holon" and the concept "silent closure". It is easy to create the hierarchy of the system based on silent closures of the system model HFSM. Assume all possible SCL-D-holons have been stored in a database (off line created), when we process a specialized observation sequence, only the related ones will be called, thus the space complexity is reduced. Of course, when the database is empty, we have to firstly construct the related SCL-D-holons gradually, which need some more time. However, when most of the related SCL-D-holons have been found in the database, the efficiency will be improved heavily.

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