Fault-diagnosis in discrete event systems: Improvements and new results

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Abstract The malfunction of sensors, actuators, and erroneous actions of human operators can have some disastrous consequences in high risk systems especially if these systems have multiple faults that can lead to undesirable shutdowns and consequently mass reduction. A reduced interpreted Petri net (IPN) diagnoser has been devised only for safe Petri net models with an output function that associates an output vector to each net marking. The main drawback of this approach is that the Petri net model of the system to be monitored should be diagnosable i.e. all faults can be detected that limits its application on a set of diagnosable models. For non diagnosable Petri net model, the conventional diagnoser incidence matrix has columns with null or similar values that fail to detect a single fault. The conventional diagnoser also cannot detect multiple faults even for diagnosable models. This paper introduces a new local diagnoser to overcome such problems. It decomposes the central IPN-diagnoser into a set of local diagnosers that are linked with multi sessions of the process to be monitored. This decomposition should guarantee that the developed local diagnosers have incidence matrices that their columns are different from each other. For null values contained in the incidence matrix of a local diagnoser, this paper proposes a set of rules based on the synchronic composition idea to overcome this problem. This proposed scheme allows multiple faults detection and isolation in quick and accurate manner for all Petri net models. Industrial processes are employed for testing the soundness of the proposed scheme.

1. Introduction

In recent decades, the model based approach has been held for addressing fault detection and isolation (FDI) in discrete event systems (DES) that has been also addressed through distributed approaches for dealing with large and complex systems [1]. A distributed diagnoser was discussed in the work of [2]. Every distributed diagnoser in that work uses the local information or communication among diagnosers for detecting and locating a system fault. Incremental algorithms were presented in [3] to
perform diagnosability analysis for DES. In that work, the authors consider systems whose components evolve by the occurrence of events. The codiagnosability property, any faults occurred in the system must be detected by at least one local diagnoser in a finite number of steps using the local information, was addressed in [4]. Aramburo-Lizarraga et al. [5] proposes a methodology for designing reduced diagnosers and presents an algorithm to split a global model into a set of communicating sub-models for building distributed diagnosers. The diagnosers handle a system sub-model and every diagnoser has a set of communication events for detecting and locating the faults of the corresponding sub-model.

Aramburu-Lizarraga et al. [6] shows how to design low interaction distributed diagnosers reducing the communication among them and proposes a redundant distributed diagnoser scheme composed by a set of independent modules handling among them and proposes a redundant distributed diagnoser scheme composed by a set of independent modules handling different types of diagnosers were presented in [7]. The first one has a set of communication events for detecting and locating faults of the corresponding sub-model. The second diagnoser is a reduced scheme. It uses one place; however the number of tokens could be large. The third diagnoser is a distributed one, were the diagnoser model is distributed over different computers. Adopting the third diagnoser, the problems that appear in centralized versions, are eliminated. Moreover, a redundant diagnoser can be used for increasing the reliability of the distributed diagnosers. An online, distributed, model-based diagnoser can be used for increasing the reliability of the distributed diagnosers. A Petri net structure $G$ is a bipartite digraph represented by the 4-tuple $G = (P,T,I,O)$ where: $P = \{p_1, p_2, \ldots, p_n\}$ and $T = \{t_1, t_2, \ldots, t_m\}$ are finite sets of vertices named places and transitions respectively, $I(\mathcal{O}(p_i) \times T \rightarrow Z^+)$ is a function representing the weighted arcs going from places to transitions (transitions to places); $Z^+$ is the set of nonnegative integers. Pictorially, places are represented by circles, transitions are represented by rectangles, and arcs are depicted as arrows. The symbol $\tau_j(t_i)$ denotes the set of all places $p_i$ such that $I(p_i, t_i) \neq 0$ and $O(p_i, t_i) \neq 0$. Analogously, $\gamma_j(p_i)$ denotes the set of all transitions $t_j$ such that $O(p_i, t_j) \neq 0$. The pre-incidence matrix of $G$ is $C = [c_{ij}]$ where $c_{ij} = I(p_i, t_j)$; the post-incidence matrix of $G$ is $C = [c_{ij}]$, where $C_{ij} = O(p_i, t_j)$ the incidence matrix of $G$ is $C = C^t = C^t$. A marking function $M: P \rightarrow Z^+$ represents a set of tokens (depicted as dots) residing inside each place. The marking of a PN is usually expressed as an $n$-entry vector. An IPN $N = (Q, M_0)$ is an interpreted Petri net structure $Q = (G, \Sigma, \lambda, \phi)$ with an initial marking $M_0$, $P$ is a PN structure, $\Sigma = \{x_1, x_2, \ldots, x_k\}$ is the alphabet of input symbols $x_i; \lambda: T \rightarrow \Sigma \cup \{e\}$ is a labeling function of transitions with the following constraint: $\forall t_x, t_y \in T, j \neq k, if \gamma(t_x) = \gamma(t_y) = I(p_i, t_j) \neq 0$ and both $\lambda(t_x) \neq e, \lambda(t_y) \neq e$, and $\lambda(t_x) \neq \lambda(t_y); e$ represent a system internal event, $\phi: R(Q, M_0) \rightarrow (Z^+)^q$ is an output function, that associates to each marking in $R(Q, M_0)$ a $q$-entry output vector; $q$ is the number of outputs.

Fault detection and isolation IPN diagnoser models were proposed in [2]. This model consists of a single place, the same number of the system model’s transitions, and a set of weights. The latter is the contents of the incident matrix $C^d$ that is defined as $C^d = B^T \psi \psi^T C^N$, where $B$ is $n \times 1$ vector with internal elements $x$ which can be computed using the exponential base, $b$. That is $h = 2 \max \{\text{abs}(C_{ij})\} + 1$ and $x = b^i$, where, $i$ is an integer numbers, $1, 2, \ldots, n$ for the measurable places, and $h = 0$ for nonmeasurable places. The matrix $\psi$ is $q \times n$ output matrix where, $q$ is the measurable outputs, and $n$ is the number of places. The matrix $C^N$ is $nxm$ matrix that describes the normal process. In this model, the current marking of this place is enough to determine and locate faults occurring within a discrete event system. If an error is detected; $e_q \neq 0$, then a faulty marking was reached. The mechanism used to find out the faulty marking is named fault isolation. The main problem of the use of such model is that its limitation to detect and isolate faults in simple processes with single-input and single-output transitions (diagnosable systems). Let $N = (Q, M_0)$ be an IPN obtained such that it is strongly connected, live, and event detectable then it is diagnosable. Diagnosability means that the diagnoser can be structured. However, event detectable PN-model can be obtained if and only if (iff) the firing of any pair of transitions, $T_1$ and $T_2$ of $(Q, M_0)$, can be distinguished from each others. This is not guaranteed for many complex PN models. Distributed diagnosers were proposed to satisfy the diagnosability and detectability problems, however, they have some problems as mentioned in Section 1. Starting from the central diagnoser, this paper proposes a L-IPN diagnoser that can be detailed in Section 3.
3. The proposed local IPN-based diagnoser with multiple FDI ability

Centralized, reduced, and distributed diagnosers were proposed in [7]. The latter tackles the diagnosability of the two former diagnosers. There is no guarantee in the distributed diagnosers to be event detectable that is the most important property for avoiding the confused problem between two similar values in an incidence matrix of these diagnosers. Also, null values inside the incidence matrix of a local diagnoser may lead to false detection. In this paper, the latter problem can be overcome using the synchronic composition idea that merges transitions according to certain discrete rules. The former property can be summarized as follows.

An IPN \((Q, M_0)\) described by the state Eq. (1) is event-detectable iff the firing of any pair of transition \(t_i, t_j\) of \((Q, M_0)\) can be distinguished from each other by the observation of the sequences of input-output symbols.

\[
M_{k+1} = M_k + C\gamma_k \\
y_k = \phi(M_k)
\]

The following lemma [11] gives a polynomial characterization of event-detectable IPN. It describes the necessary and sufficient conditions of the detectability property.

**Lemma 1.** A live IPN given by \((Q, M_0)\) is event-detectable iff:

1. \(\forall t_i, t_j \in T\) such that \(\lambda(t_i) = \lambda(t_j)\) or \(\lambda(t_i) = \lambda(t_j) = \epsilon\) it holds that \(\phi(C(\cdot, t_i)) \neq \phi(C(\cdot, t_j))\) and
2. \(\forall t_k \in T\) it holds that \(\phi(C(\cdot, t_k)) \neq 0\)

To satisfy the necessary and sufficient conditions (Lemma-1) of the detectability property, this paper develops a L-IPN diagnoser of a central diagnoser shown in Fig. 1 and listed below.

3.1. The conventional IPN-based diagnoser [12]

3.1.1. Inputs

\(M_k, M_0, e_k;\) where: \(M_k\) is the marking vector of the normal process, \(M_0\) is the marking place of the diagnoser, and \(e_k\) is the error between them.

3.1.2 Outputs

The faulty place is \(p^f\), the faulty marking vector is \(M_p\), and the IPN-based diagnoser structure incidence matrix is \(C^d\). The index, \(i = 1, 2, \ldots\), of the incidence matrix \(C^d\) indicates the number of column such that,

**IFC** \((1, i) = e_k\) \(\quad\text{Then}\)

1. \(\forall p \in t_i, M(p) = 0\).
2. \(\forall p \in t_i, M(p) = 0\).
3. \(\forall p^f \in (t_i)^* \cap P^f, M(p^f) = 1\).
4. \(M_f = M_k\).
5. Return \((p, M_f)\).

Unlike, the distributed diagnoser was proposed in [7], the proposed diagnoser partitions the incidence matrix of the central diagnoser into a set of local diagnosers such that:

1. each local diagnoser has different weights,
2. no more than null value is permitted.

These two conditions devised two notable features to the developed diagnoser, one is event detectable, and the other is its ability to detect and isolate multiple faults in a process. The proposed diagnoser of any central diagnoser is shown in Fig. 2.

As shown in Fig. 2, the proposed L-IPN diagnoser is structured from a set of local diagnosers that are linked with multi sessions of the process to be monitored. The main idea of the developed diagnoser depends on decomposition of the incidence matrix of the central diagnoser into sub-modules such that the sufficient and necessary conditions (Lemma-1) of the detectability property of each local diagnoser are satisfied. These local diagnosers intercommunicate with each other with a single place linked with all diagnosers. The intercommunicator overcomes the redundancy problem resulted from using several computers (CPU) [7]. This is because the proposed distributed diagnoser is developed and implemented on one logic unit instead of several CPUs.

The proposed distributed local IPN-based diagnoser can be summarized as follows. Let us consider the central IPN model described in the conventional algorithm described above, \((Q, M_0)\), such that a module \(\mu_i = (G_i, \Sigma_i, \lambda_i, \Phi_i, M_0)\) is the \(i^{th}\) local IPN of the central model. In this local module, the inputs can be described as follows: \(M_i, M_0, e_i;\) where, \(M_i\) is the marking vector of the normal submodule, \(M_0\) is the marking place of the local diagnoser, and \(e_i\) is the error between them. The \(O(t_k)\) is the output place of the \(k^{th}\) transition that represent a fault. The L-IPN based diagnoser is summarized below.

3.2. The proposed L-IPN based diagnoser

3.2.1. Constants

The \(C^d\) is the incidence matrix of the \(i^{th}\) local IPN diagnoser that is defined as \(C^d_i = B_i^\dagger \psi_i^\dagger C^\dagger i\), where \(B_i\) is \(n \times 1\) vector with
internal elements \( x \) which can be computed using the exponential base, \( b_i \). That is \( b_i = 2\text{MAX}\{\text{abs}(C_{d})\} + 1 \) and \( x = (b_i)^n \), where, \( n \) is an integer numbers, 1, 2, \ldots, for the measurable places, and \( b_i = 0 \) for non measurable places.

\[
i = \text{index of the column of } C^d \text{ such that:} \\
\text{IF } C^d(1,i) < 0 \text{ & } e_k < 0 \text{ Then} \\
The \text{synchronic composition is applied} \\
\text{ELSE-IF } C^d(1,i) = e_k, \\
\text{Multi faults or a fault can be detected} \\
\text{ELSE} \\
\text{Do Nothing; Normal conditions} \\
\text{END}
\]

The synchronic composition idea shown in the proposed algorithm can be briefly summarized as follows: Generating the linear logic of the PN-model, proofs the reachability marking in a Petri net [13]. This paper borrows this idea and generates a set of discrete linear logic as follows.

\[ i; \quad (A \text{ set of conditions is satisfied}) \Rightarrow (A \text{ set of consequents can be inferred}). \]

The mapping may be understood as each transition corresponds to a simple rule, composite conjunctive rule or a disjunctive branch of a composite disjunctive rule; each place corresponds to a proposition (antecedent or consequent).

**Type 1**: A Simple Production Rule

\[ t_k; p_i \Rightarrow p_j \]

**Type 2**: A Composite Conjunctive Rule

\[ t_k; p_i \otimes p_j \Rightarrow p_l \]

**Type 3**: A Composite Conjunctive Rule

\[ t_k; p_i \Rightarrow p_l \otimes p_m \]

**Type 4**: A Composite Conjunctive Rule

\[ t_k; p_i \otimes p_j \Rightarrow p_l \otimes p_m \]

where, \( p_i, p_k, p_l, p_m \) are the \( i \text{th}, j \text{th}, k \text{th}, \text{and } s \text{th places and the } t_k \text{ is the } k \text{th transition. Based on the synchronic composition idea, the faulty places and transitions can be described as depicted in Fig. 3.} \]

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**Figure 2** The proposed L-IPN diagnoser.

**Figure 3** The faulty places and transitions.

Applying the above discrete linear logic when zero detected in the incidence matrix of the local diagnoser, distinguishes the actual fault from the false detection. The two notable points of the above proposed algorithm is that it satisfies the detectability property (Lemma-1), and solves the null value detection. Unlike the previous published diagnosers, the proposed diagnoser detects and isolates multiple faults if they happen at any concurrent sections of the process to be modeled as will be shown in simulation results.

**4. Industrial productivity processes**

The industrial productivity process (IPP) [14] is employed to test the soundness of the proposed L-IPN diagnoser. It comprises three pump stations (IPP-1, 2 and 3) to pump oil from this plant to different locations [12]. The pumps IPP-1 and IPP-2 are steam pumps with pump speed control, while pump IPP-3 is a motor driven pump with fixed speed. This paper will be looking at one unit of this station named flow control valves (FCV) for testing the proposed diagnoser.
The operation of the FCV unit can be described as follows. The normal process conditions consist of the shuttle line pressure PC1025 device that its reading is greater than the set point of 550 psig. The pressure override loop PC1358OV is in auto mode. The master flow controller FCV1358 is in automatic control. The FCV unit control valves HC1358/1359/1360 are in auto mode with control output provided by the master flow controller. This process depends on the flow reading transmitters.

If the Shuttle Line B (SLB) line master flow controller FC1358 deviation between the process variable and the setpoint (PV-SP) greater than +25%, the rupture detection logic that places the FCV unit in DDC mode to close the HC1358/1359/1360 control valves is activated. To restore from rupture detection, the operator has to change the HC1358/1359/1360 mode to manual or auto mode for normal operation of the shuttle line. The SLA master controller and pressure override action is similar to the SLB FC1358 controller. The pressure override loop PC1358OV activates the pressure valves if the difference between the SP and its PV is very low. In this case, the higher level in the TFU-2 tanks. The possible faults in the rundown line and the tanks. As long as steady state operation exists, the pumps operate reliably. However, if the stabilizer trip affects the rundown line flow and pressure, the override loop PC1358OV activates the pressure valves if the pressure controller PC1358 deviation between the process variable and the set point (PV-SP) greater than +25%, the rupture detection logic that places the FCV unit in DDC mode to close the HC1358/1359/1360 control valves is activated.

Based on the information collected above about the IPP-3, the recipe of the FCV unit is depicted in Table 2. The methodology described in [15] is employed in this paper to develop the PN-model of the FCV unit as depicted in Fig. 4 using the Petri net tool-based MATLAB version 7. The developed model can be verified using the PN-tool is MATLAB version 7. The marking vector is $M = \{P_{F1}, P_{F2}, \ldots, P_{F20}\}^T$, and the input or firing vector is $q = \{t_{F1}, t_{F2}, \ldots, t_{F16}\}^T$. Let us starting from firing $t_{F1}$; $q = \{10000000000000000000000000000000\}^T$, and the initial marking $M_0 = \{10000000000000000000000000000001\}^T$. The new state after firing the transition $t_{F1}$ is; $M_1 = \{01000000000000000000000000000001\}^T$.

According to the recipe shown in Fig. 4, the new states are put PC1358OV, FC1358, HC1358/1359/1360 in auto mode ($P_{F2}$). Firing the transition $t_{F2}$; $q = \{01000000000000000000000000000000\}^T$ leads to the new state, $M_2 = \{00011000000000000000000000000001\}^T$. This means the reading of the shuttle line low pressure and flow are available, ($P_{F3}$), and ($P_{F4}$) respectively. If the low pressure set point is 550 psig, the closer to this value the more probably to activate the flow controller PC-1358 OV and ignore the flow request, i.e. this firing sequence is carried out via $t_{F11}$ to $T_{F15}$. On the hand, far from this value (550 Psig) the more probably to activate the flow controller and ignore the pressure effect, i.e. this firing sequence is carried out via $t_{F12}$ to $T_{F20}$. It is clear that the developed Petri net module of the FCV unit is safe, satisfy the sufficient test of the validation method (each place has one or zero token), and identical to the given recipe shown in Table 2. The following section describes the methodology to execute the proposed L-IPN diagnoser algorithm-1 using the FCV module of the IPP.

### 5. Simulation results

The central IPN-Based reduced diagnoser described in Section 3 is firstly employed to monitor the FCV process. Its incidence matrix is $C^d = \{1 11 -3 -9 27 81 0 00 -27 -81 243 729 -243 -729 0 0\}$. It is clear that the transitions $\{t_5, t_6, t_8, t_9\}$ are similar and null values. The initial marking vector is $M_0 = \{1 0 0 1\}^T$. At firing $t_1$, the firing marking vector becomes $M_0 = \{0 1 0 1\}^T$, the error $e_k = 0$. This error matches the transitions $\{t_5, t_6, t_8, t_9\}$ and the diagnoser detects these transitions as fault transitions, although $e_k = 0$ means that no fault should be detected. This is compound problem that

<table>
<thead>
<tr>
<th>Fault #1</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fault #2</td>
<td>PC1358OV, FC1358, HC1358/1359/1360 valves do not in auto mode</td>
</tr>
<tr>
<td>Fault #3</td>
<td>The reading of the shuttle line low pressure set point is not correct</td>
</tr>
<tr>
<td>Fault #4</td>
<td>The reading of the shuttle line flow set point is not correct</td>
</tr>
<tr>
<td>Fault #5</td>
<td>The reading the pressure transmitter, PC1025 (PV1) is not ready</td>
</tr>
<tr>
<td>Fault #6</td>
<td>The reading of flow transmitter (FT) (PV2) is not ready</td>
</tr>
<tr>
<td>Fault #7</td>
<td>Pressure problem</td>
</tr>
<tr>
<td>Fault #8</td>
<td>Flow problem</td>
</tr>
</tbody>
</table>
Table 2 The FCV basic recipe.

<table>
<thead>
<tr>
<th>P</th>
<th>Description</th>
<th>T</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{F1}$</td>
<td>PC13580V, FC1358, HC1358/1359/1360 not in auto</td>
<td>$T_{F1}$</td>
<td>Put PC13580V, FC1358, HC1358/1359/1360 to auto</td>
</tr>
<tr>
<td>$P_{F2}$</td>
<td>PC13580V, FC1358, HC1358/1359/1360 in auto</td>
<td>$T_{F2}$</td>
<td>Read the Shuttle line low pressure and the flow set points</td>
</tr>
<tr>
<td>$P_{F3}$</td>
<td>The reading of the Shuttle line low pressure set point</td>
<td>$T_{F3}$</td>
<td>Set the Shuttle line low pressure set point (SP1) to 550 PSI</td>
</tr>
<tr>
<td>$P_{F4}$</td>
<td>The reading of the Shuttle line flow set point</td>
<td>$T_{F4}$</td>
<td>Set the Shuttle line flow set point (SP2) to 100%</td>
</tr>
<tr>
<td>$P_{F5}$</td>
<td>The pressure set point (SP1) is 550 PSI</td>
<td>$T_{F5}$</td>
<td>Read the value of PC1025 (PV1)</td>
</tr>
<tr>
<td>$P_{F6}$</td>
<td>The flow set point (SP2) is 100%</td>
<td>$T_{F6}$</td>
<td>Read the value of FT (PV2)</td>
</tr>
<tr>
<td>$P_{F7}$</td>
<td>The reading of the value of the pressure transmitter, PC1025 (PV1)</td>
<td>$T_{F7}$</td>
<td>Intermediate transition</td>
</tr>
<tr>
<td>$P_{F8}$</td>
<td>The reading of the value of flow transmitter (FT) (PV2)</td>
<td>$T_{F8}$</td>
<td>Intermediate transition</td>
</tr>
<tr>
<td>$P_{F9}$</td>
<td>Intermediate place</td>
<td>$T_{F9}$</td>
<td>Calculate the difference (PV1 – SP1 = X1)</td>
</tr>
<tr>
<td>$P_{F10}$</td>
<td>Intermediate place</td>
<td>$T_{F10}$</td>
<td>Calculate the difference (PV2 – SP2 = X2)</td>
</tr>
<tr>
<td>$P_{F11}$</td>
<td>The value x1 is</td>
<td>$T_{F11}$</td>
<td>If x2 high and x1 low</td>
</tr>
<tr>
<td>$P_{F12}$</td>
<td>The value x2 is</td>
<td>$T_{F12}$</td>
<td>If x2 low and x1 high</td>
</tr>
<tr>
<td>$P_{F13}$</td>
<td>Activating the FC-1358 OV controller (pressure problem indicator)</td>
<td>$T_{F13}$</td>
<td>Start to close the valves HC1358/1359/1360</td>
</tr>
<tr>
<td>$P_{F14}$</td>
<td>Activating the FC-1358 controller (flow problem-indicator)</td>
<td>$T_{F14}$</td>
<td>Manipulate HC1358/1359/1360 to keep the flow to the set point</td>
</tr>
<tr>
<td>$P_{F15}$</td>
<td>The current state of the HC1358/1359/1360 valves</td>
<td>$T_{F15}$</td>
<td>Go back to read PV1 every 10 min. ($T_{FV5}$)</td>
</tr>
<tr>
<td>$P_{F16}$</td>
<td>The current state of the HC1358/1359/1360 valves</td>
<td>$T_{F16}$</td>
<td>Go back to read PV1 every 10 min. ($T_{FV6}$)</td>
</tr>
<tr>
<td>$P_{F17}$</td>
<td>The new state of the HC1358/1359/1360 valves (pressure problem)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{F18}$</td>
<td>The new state of the HC1358/1359/1360 valves (Flow problem)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{F19}$</td>
<td>Go back to read the PV1 (TF5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{F20}$</td>
<td>Go back to read the PV2 (TF6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The incidence matrix has similar values and null values. Another problem is noticed, the central diagnoser cannot detect the multiple faults – if any – in the two parallel processes of the FCV module. To solve these complex problems this paper uses the proposed L-IPN based diagnoser that can be summarized in three steps as follows.

- Decomposition the incidence matrix into sub modules such that each module should have different values and apply the proposed local diagnoser described in Section 3.
- If the incidence matrix of the decomposed module has null value, the synchronic composition idea described in Section 3 is applied.
- The local diagnoser is safely applied to detect and isolate multiple faults unlike the central diagnosers.

To perform the above three steps do the following. The FCV Petri net central model is composed into five local diagnosers $C^d = \{C_1^d, C_2^d, \ldots, C_5^d\}$ where $C_i^d$ is the $i$th local model and $L$ is the number of them, $L = 5$. The 3rd local model as an example of the local diagnoser can be described as follows.

A part of the central FCV Petri net model shown in Fig. 3 is described with a set of normal places $\{P_{FV4}, P_{FV6}, P_{FV8}, P_{FV10}, P_{FV12}, P_{FV20}\}$, a set of faulty places $\{P_{FV2}, P_{FV23}\}$, a set of normal transitions $\{T_{FV4}, T_{FV6}, T_{FV8}, T_{FV10}\}$, and a set of faulty transition $\{T_{FV12}, T_{FV21}\}$. The incidence matrix the 3rd local diagnoser of this part is $C_3^{d} = [\begin{array}{c} -1 \ 3 \ 0 \ -3 \end{array}]$. The local IPN-based diagnoser proposed in Section 3 is used in this case with ease. Notice that although the incidence matrix has different values, its third value is zero. This means the local diagnoser cannot distinguish between the faulty transition and the normal condition; $e_k = 0$. This problem is tackled using the synchronic composition idea described in Section 3 by testing the pre and post condition of that transition similar to the faulty places and transitions depicted in Fig. 3. Also, based on the local diagnoser features that are event detectable and null value investigation, it is easy to detect faults in different locations of the process to be monitored. This is because the local modules depend on the local information of a part of the process. Let us consider the 3rd L-IPN based diagnoser that monitors the third part of the FCV unit. Where, the incidence matrix of the normal second session of the FCV Petri net module is.

The initial marking vector is $M_0 = [1 \ 0 \ 0 \ 0 \ 0 \ 1]^T$. Using the input vector $q = [1 \ 0 \ 0 \ 0 \ 0 \ 1]^T$ where $q \in Q$ and $Q$ is the total input vector, and the faulty input vector $v = [0 \ 0 \ 0]^T$, leads to no faults. At $q = [0 \ 1 \ 0 \ 0 \ 0 \ 1]^T$, $v = [0 \ 0 \ 0]^T$, there is no fault. At $q = [0 \ 0 \ 0 \ 1 \ 0 \ 0]^T$, and the faulty input vector $v = [0 \ 0 \ 0]^T$, leads also to no fault. At $q = [0 \ 0 \ 0 \ 0 \ 1 \ 0]^T$, and the faulty input vector $v = [0 \ 1 \ 0]^T$, leads fault at transition #4 that is equivalent to transition #10 in the whole Petri net model of the FCV unit. This fault means that the reading of the value of flow transmitter (FT) (PV2) is not correct or the transmitter is faulty.
Finally, the multiple faults can be detected using the proposed L-PIN based diagnoser as follows. Firing $t_1$, with the normal input $q = [1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]_T$, and the faulty input $v = [0]_T$, leads to firing the local diagnoser $\#1$ and in this case no fault is detected. Firing $t_2$, with the normal input $q = [0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0]_T$, and the faulty input $v = [0]_T$, leads to firing the local diagnoser $\#1$ and in this case no fault is detected. Firing $t_3, t_4$ respectively with the normal input $q = [0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0]_T$, and the faulty input $v_1 = [1 0]_T$ and $v_2 = [1 0]_T$, leads to firing the local diagnoser $\#2$ and $\#3$ simultaneously. In this case the proposed diagnoser detected and isolated two faults in the two different sessions of the FCV process. These two faults mean that the reading of the Shuttle line low pressure and flow set points are not correct. On the other words, the two transmitters, pressure and flow, that are located in different branches are faulty. This obtained great result encourages the authors who usually avoid extending their work to discuss and solve multiple fault detection.

6. Conclusions

This paper introduced a new local IPN-based (L-IPN) diagnoser for detecting and isolating multiple faults in complex discrete event systems. The proposed diagnoser decomposes the central IPN-diagnoser into a set of local diagnosers that are linked with multiple sessions of the process to be monitored. These local diagnosers have incidence matrices that their columns are different from each other unlike the central diagnosers. For null values contained in a local diagnoser, this paper borrowed the synchronic composition idea to overcome this problem. The developed scheme allows multiple faults detection and isolation in quick and accurate manner. The main features of the proposed L-IPN diagnoser are its ability to satisfy the detectability conditions and detect multiple faults simultaneously. The latter big feature of the proposed local diagnoser helps the researchers to address the multiple faults detection and isolation problem in depth. Industrial FCV unit is employed for testing the soundness of the proposed scheme and good results have been obtained.

References


