Latent Nestling Method as an Abstraction Method in Colored Petri Nets for Fault Diagnosis in Complex Systems

Método de anidamiento latente como método de abstracción en redes de Petri coloreadas para el diagnóstico de fallos en sistemas complejos

La détection latente comme méthode d'abstraction des Réseaux Petri colorés pour le diagnostique d'erreurs des systèmes complexes

Método de nidificação latente, como método de abstração nas Redes Petri coloridas para o diagnóstico de falhas em sistemas complexos

Leonardo Rodríguez-Urrego*

Mariela Muñoz-Añasco**

Fecha de recepción: 15 de abril de 2015
Fecha de aprobación: 10 de junio de 2015
Pp.97- 124.

* Grupo Ontare, Facultad de Ingeniería, Universidad EAN.
** Grupo de Automática Industrial, Universidad del Cauca.

Abstract

This paper presents the mathematical formalization in Hybrid and Colored Petri Nets applied to the Latent Nestling Method (LNM) as an abstraction method in regard to the Fault Diagnosis, termed: Hybrid Colored Petri Net for Fault Diagnosis (DHCPN). In addition, enhanced synthesis and modeling capability for fault isolation and diagnosis in complex systems is demonstrated. Moreover, this paper shows a practical example of implementation that consists of a liquid storage tank.

Keywords

Discrete event systems, fault diagnosis, hybrid systems, colored Petri nets.

Resumen

Este artículo presenta la formalización matemática de las redes de Petri híbridas y coloreadas para el anidamiento Latente de Fallos (ALf), como método de abstracción respecto al diagnóstico de fallos llamado Redes de Petri Híbridas y Coloreadas para el Diagnóstico de Fallos (RdPHCDF). Además de esto, se demuestra la mayor capacidad de síntesis y modelado en el aislamiento y diagnóstico de fallos en sistemas complejos. Por otra parte, este trabajo presenta un ejemplo práctico de aplicación del método que consiste en un tanque de almacenamiento de líquidos.

Palabras clave

Sistemas de eventos discretos, diagnóstico de fallos, sistemas híbridos, redes de Petri coloreadas.

Résumé

Cet article présente la formalisation mathématique des Réseaux de Petri de type Hybrides et Colorés pour la Détection Latente d'Erreurs (DLE) comme méthode d'abstraction du diagnostique d'erreurs appelé: Réseaux de Petri de type Hybride et Colorés pour le Diagnostique d'Erreurs (RPHC-DE). Nous démontrerons par ailleurs la capacité accrue de synthèse et modelage lors de l'isolement et du diagnostique d'erreurs dans les systèmes complexes. Finalement ce travail présentera un exemple pratique d'application de la méthode utilisant des réservoirs liquides.

Mots clefs

Système d'évènements discrets, diagnostiques d'erreurs, systèmes hybrides, Réseaux de Petri Colorés

Resumo

Este artículo apresenta a formalização matemática das Redes de Petri Híbridas e Coloridas para a Nidificação Latente de Falhas (ALF) como método de abstração respeito ao diagnóstico de falhas chamado: Redes de Petri Híbridas e Coloridas para o Diagnóstico de Falhas (RdPHCDF). Além disto, se demonstra a maior capacidade de síntese e modelado no isolamento e diagnóstico de falhas em sistemas complexos. Por outra parte, este trabalho mostra um exemplo prático de aplicação do método que consiste em um tanque de armazenamento de líquidos.

Palavras-chave:

Sistemas de eventos discretos, diagnósticos de falhas, sistemas híbridos, Redes de Petri Coloridas.

1. Introducción

Nowadays, one of the research areas that has been deeply studied because of security, reliability, viability and economy issues is the fault diagnosis area, which guarantees some behavior states in a system, a machine or in the process of fault detection, isolation and recovery, or even its prevention.

Some techniques for fault diagnosis and detection are applied in different processes such as chemical processes, as well as in systems for the study of renewable energy generation where both control and diagnostic systems have a large number of variables. These systems need new and robust techniques for the diagnosis of these complex systems. These methods, among others, are the techniques for modeling discrete event (SEDs) with Petri Nets (RDPs).

The study of these techniques has increased significantly over time owing to the large number of applications that have been found. The formalism contributed by the PNs in concepts such as concurrency, mutual exclusion, and resource sharing are of special interest and have provided greater capacity and power representation in the resulting models as those carried out by Finite State Machines (FSMs) (Sampath et al., 1996). Additionally, the PNs provide the ability to apply techniques of merging places, which allow reducing the size of the resulting models. This synthesis capacity in the resulting models is further accented with the Colored Petri Nets (CPNs) (Jensen, 1992), designed for the general purpose of being a graphical structure based on PN useful in specifying, designing, and analyzing concurrent systems that contribute to the possibility of applying merging techniques for the representation of different concurrent sub processes that coexist in the same PN graphical structure. The CPNs allow assigning functions in their arcs with linear transformation capacity, which allows great functional variability to the final model. All these characteristics of synchronism and concurrency of the PNs, in addition to the merging techniques of the CPNs, provide the necessary robustness for the implementation of fault diagnosis in any complex system.

In this work, the functionality and advantage of the use of LNM for fault diagnosis using CPNs (García et al., 2008; Rodríguez et al., 2011) in the isolation and diagnosis of faults in complex systems have been presented and compared with other diagnostic techniques, as well as their mathematical formalization in discrete, continuous, and hybrid systems, and an example of its implementation.

2. Latent Nestling Method for Fault Diagnosis

LNM was used according to the procedure that was firstly described (García *et al.*, 2008), with the purpose of nestling faults into every place of the initial PN using a folding technique with CPNs, and using the characteristics of the sensor readings to isolate faults in a specific place or fault verification place (PVf). The principal advantage of this method is that it avoids the combinational explosion that provokes intractable models for diagnosis using PNs. Also, this LNM technique allows integration in the same diagnosis model, the operation of normal dynamics in the system or control; this is achieved through the use of the CPNs in concurrent systems.

These Petri Nets for the diagnostic methodology were termed as Colored Petri Net for Fault Diagnosis (DCPNs). DCPNs are defined as:

$$D = (P, T, Pre, Post, M_0, C, PLNf, TF, PVf), \qquad (1)$$

Where,

P is a finite set of places.
T is a finite set of transitions.
Pre and Post are input and output arc functions, with an additional argument C_k that is the color of the transition firing T_j, thus:

$$Pre(P_i, T_j/C_k), \qquad Post(P_i, T_j/C_k).$$

Nevertheless, these functions can be divided into two subsets, depending on the transition-type behavior, namely, normal transition or fault transition.

$$TF = Tf \cup Tr,$$

Where *Tf* and *Tr* are the fault and recovery transitions, respectively.
Furthermore,

$$Pre = Pre^T \cup Pre^{TF} \qquad Post = Post^T \cup Post^{TF},$$

Where the arc function are the following:

$$Pre^T: PLNf \times T \to \mathrm{N}, Pre^{TF}: PLNf \times Tf \cup PVf \times Tr \to \mathrm{N},$$
$$Post^T: PLNf \times T \to \mathrm{N}, \qquad Post^{TF}: PVf \times Tf \cup PLNf \times Tr \to \mathrm{N}.$$

- M_0 is the initial marking.
- *C* is the color set assigned to different identifiers. $C = N \cup f$ and *N* is the subset of colored tokens representing the normal system behavior.
- $f = \{f_1, f_2, \ldots, f_i\}$ is the subset of colored tokens representing fault set.

- $PLNf \subseteq P$ is the subset of fault latent nestling places.
- $PVf \subset P$ is the subset of fault verification place.
- $TF \subset T$ is the fault transitions subset including colored functions.

Definition 1. A normal transition in a DCPN is enabled if each place $PLNf_k$ in ${}^0T_j$ meets the condition:

$$m(PLNf_k) \geq Pre(PLNf_k, T_j). \qquad (2)$$

The diagnosability of this method is given by the following expression:

$$\vee f_i^q \in f \ni (M(PLNf_k(<\bullet q>,<f_i^q>))) \\ [Tf_k = SROVnev(M(PLNf_k(<\bullet q>,<f_i^q>))) \\ > M(PVf(<f_i^q>)), \qquad (3)$$

Where SROVnev is a vector of sensor output values of not expected reading, and SROVev is the same vector but for the expected values (García *et al.*, 2008).

An example of this methodology is used in the lubrication and cooling system of a wind turbine (Rodríguez *et al.*, 2011).

The newest methodologies (Ru & Hadjicostis, 2009) use PN techniques for fault diagnosis, where the faults are modeled as unobservable transitions and are divided into different types. This approach is interesting, but the LNM employs merging techniques for nestling faulty marks in places of CPN, moreover, the control and diagnosis systems are integrated in only one net, which is useful as an abstraction for the diagnosis in complex systems. Spiteri's methodology (2009), uses CPNs for fault diagnosis and recovery in embedded and control systems. This approach puts the information into a token instead of having many additional places and transitions; therefore, it allows reducing the size of the CPN.

3. Fault Diagnosis in Hybrid Systems

3.1 General Features of Hybrid Systems

A hybrid system is a dynamic system with state variables that contain continuous and discrete values. This representation is general for the dynamic systems from certain level of complexity. The hybrid systems theory has developed many models and techniques for analysis and synthesis, finding diverse applications in many areas. One of these techniques is the hybrid automata which has become a standard model for the hybrid dynamic systems. This technique is finite state automata, which is increased both with a state variable vector and a state continuous equation for each discrete state (Krogh, 2002). However, for the fault detection and diagnosis, this representation has a previously noted problem, this is a combinational explosion. PN and CPN are used to try to solve this problem (Koutsoukos *et al.,* 1998; Genc & Lafortune, 2003; Llano-Zuleta *et al.,* 2007).

However, one issue that needs to be addressed is that processes and control systems nowadays are identified by their hybrid and complex nature, allowing the modeling of many methods in different areas of knowledge for process control and fault diagnosis. About this, numerous studies have been carried out to explain the hybrid process in fault diagnosis using different methodologies (Gertler, 1998; Chen, 1999; Patton & Lopez-Toribio, 1993). Furthermore, some researchers analyzed fault models in Hybrid Petri Nets (David & Hassane, 2005), while others used other approximation differential places to represent continuous places with negative markings in a methodology called Differential Petri Nets (Demongodin

& Koussoulas, 1998). In addition, the machine failure models, both time-dependent failure (TDF) and operation-dependent failure (ODF), were also studied (Balduzzy *et al.*, 2001). The newest methodologies focused on timed event graphs with Hybrid Petri Nets (Hacami *et al.*, 2006), and hybrid approach to supervisory control of DES using PNs in complex systems (Uzam & Wonham, 2006), along with some diagnostic techniques using Petri Nets that were also proposed.

For the proposed LNM, it is necessary to include places of continuous or differential character, allowing the analysis of continuous dynamical variable by following the formal definition and approaches of this new methodology integrating the use of continuous places.

3.2 Latent Nestling Method in Hybrid Systems

A DHCPN (Rodríguez Urrego *et al.*, 2015) is defined as:

$$DH = (P, T, Pre, Post, M_0, Co, C, PLNf, TF, PVf, OS, tempo), \quad \textbf{(4)}$$

Where P, T, M_0, TF, PVf, have the same definition as DCPN.

$$Pre = PreT \cup PreTF; \qquad Post = PostT \cup PostTF.$$

Then,

$$PreT : (P \times T) \to \mathbb{Q} \text{ ó } N, \quad PreTF : (P \times Tf \cup PV f \times Tr) \to Q \text{ ó } N,$$
$$PostT : (P \times T) \to Q \text{ ó } N, \quad PostTF : (P \times Tr \cup PV f \times Tf) \to Q \text{ ó } N.$$

Every set of places can be defined as:

$$P = P^D \cup P^{C,} \quad \textbf{(5)}$$

As well as PLNf $\subseteq$ P y PVf $\subset$ P^D.

Thus, N corresponds to the case for all $PLNf_i \in P^D$, and Q corresponds to the case where $PLNf_i \in P^C$. Furthermore, C is the set of colored tokens divided into normal behavior marks "*N*" and representing faults marks "*f*". In addition, the normal behavior marks can be of discrete or continuous subset, as follows:

$$N = N^D \cup N^{C.} \qquad \textbf{(6)}$$

C_0: $P \cup T \rightarrow \{D,C\}$, is a composite function that indicates, for every place of the net, if a latent nestling place is of discrete type (set P^D and T^D) or continuous type (set P^C and T^C).

OS is a set of operating states and fault signatures defined in the paragraph as trajectories of fault verification and fault recovery.

Tempo is a delay function that associates a rational number to each transition that can evolve in time, where: if $f(T_j)=D$, $tempo(T_j)=d_i=$ is a delay associate with the transition T_j, expressed in time units, as presented in the method defined by (García *et al.*, 2008),if $f(T_j)=C$, $tempo(T_j)=\{V(T_j), d_i\}=\{V_j, h\}$, V_j represent the maximum firing speed associated with the transition T_j (David & Hassane, 2005), and h is the firing frequency representing the sampling time.

The delay function *tempo* is implemented for continuous places according to the model characteristics. If the markings and weights of the arcs are not negative values, only be uses the function V_j, representing the maximum firing speed as a constant value according to the degree of *D*-enable. In the opposite case, if the model has markings or negative arcs, be uses the function $\{V_j, h\}$ with a discrete transition associated to a discrete place that is linked to the continuous transition that represents the maximum firing speed. In the last case, the behavior of these places and continuous transitions are represented as such (Demongodin & Koussoulas, 1998).

Definition 2. A normal discrete transition in a DHCPN is enabled if each place $PLNf_k \in P^D$ in $^0T_j^D$ meets the condition:

$$m(PLNf_k) \geq Pre(PLNf_k, T_j^D). \quad (7)$$

Definition 3. A normal continuous transition in a DHCPN is enabled if each place $P_i \in P^C$ in $^0T_j^C$ meets the condition:

$$m(PLNf_k) \geq Pre(PLNf_k, T_j^C), \quad \text{if} \quad PLNf_k \in P^{D,} \quad (8)$$

$$m(PLNf_k) > 0, \quad \text{if} \quad PLNf_k \in PC, \quad (9)$$

$$m(PLNf_k) \in \mathbb{Q} \quad \text{if} \quad PLNf_k \in P^C \quad \text{of differential type.} \quad (10)$$

The initial model is similar to that presented in the classic method; however, it represents differential or continuous places where we could model the continuous behavior of the system variables. The first step is to model the behavior of the process, both as discrete and continuous variables involved in the process; it uses the techniques of modeling temporary hybrid systems (David & Hassane, 2005). The second step is the process of folding into subsystems according to the concurrence of these processes (Jensen, 1992). This folding process is carried out using the CPN techniques, and if the model allows for this process, then it can be implemented directly in the CPNs.

If a fault f_i occurs from an abnormal behavior of a continuously variable *h,* knowing that the continuous place is influenced by a normal behavior mark *q* contained in a $PLNf_k$, the fault is designated as a pair $< f_i^q, S_i >$, where f_i is the fault occurred in the subnet *q*, and S_i is the continuous operating state in which the fault has occurred.

3.2.1 Trajectories of fault verification and fault recovery

These trajectories are defined only by the fault and recovery transitions, adding some restrictions to include the status of the places of normal behavior and the marks of the normal behavior. These restrictions are presented in the condition and enabling degree of transitions and complexity, for the construction of fault transitions in continuous places.

Definition 3. A fault or recovery transition in a DHCPN is enabled for discrete places if each place $PLNf_k^D$ or *PVf* in ^0TF_j meets the condition:

For *Tf*,

$$m(PLNf_k) \geq Pre(PLNf_k, Tf_j). \quad \textbf{(11)}$$

For *Tr*,

$$[m(PVf) \geq Pre(PVf, Tr_j)] \wedge [m(PLNf_k) \geq Pre(PLNf_k, Tr_j)]. \quad \textbf{(12)}$$

The existence of continuous variables within the hybrid model implies the possibility to perform an analysis to obtain new diagnoses on these same variables. The main idea is to use a technique based on quantitative models (i.e., residue generation and subsequent evaluation).

The idea of this new approach to diagnosis in hybrid systems is to obtain a series of residues of the form $r(t) = y(t) - \hat{y}(t)$ in every continuous place, where $\hat{y}(t)$ is the variable represented by the continuous place and *y(t)* is the variable measured by the system or process in real time. The residue is obtained directly in the continuous place, while the residual evaluation is realized in each fault and recovery transition using the knowledge of experts for defining signature faults and isolating fault occurrences in the place *PVf*. Every one of these residues *(ri(k))* is evaluated with respect to the threshold i, according to previous or heuristic knowledge.

To define a systematic approach of this LNM for Hybrid Systems, it is necessary to raise some new conditions to the continuous analysis termed as Operating States (*OS*), and Fault Signatures (*Sf*). This new approach will depend both on the analyzed system and the continuous places with influence by themselves.

3.2.2 States of hybrid operation

Owing to the continuous nature of the hybrid models, it is important to analyze continuous places that influence themselves according to the system to be treated. This influence in continuous places is an important factor in an effect known as coupling faults, which involves erroneous readings of faults owing the propagation of these faults (García *et al.*, 2002). This factor has been used to analyze the residues of continuous places in a more systematic way, and achieve more effective fault isolation.

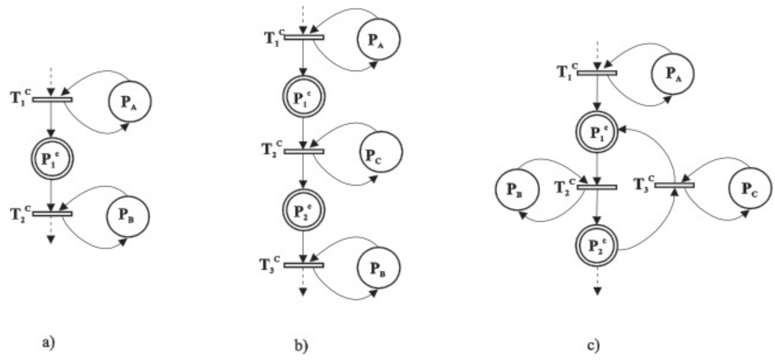
For every hybrid system that exists, three types of influences occur according to the continuous places behavior (Figure 1): a) continuous isolated places, b) continuous places cascade influence, and c) continuous places cyclic influence.

A hybrid model has a set of operating states for the failure and recovery as well:

$$OS=OS_f \cup OS_{r,} \qquad \textbf{(13)}$$

Where OS_f are the fault operating states and OS_r the recovery operating states.

Figure 1. Continuous influence type according to the hydrid model.



Source. By the authors.

3.2.2.1 Continuous isolated places

These models usually have only one continuous place in the hybrid model with a single vector of operating states; however, depending on the model, several continuous places not influenced by themselves may exist, indicating a vector of operating states for each continuous place. In the expression, $OS_f=(os_l,...,os_k)$, l and k subscripts correspond to the places P_l^c and P_k^c, respectively, and $|OS_f|$, in this case, indicates the number of P^c isolates in the model. Every os_i is a vector that contains many operating states as signature faults for every continuous place P_i^c; thus, $os_i=(Sf_1(k),..., Sf_m(k))$. The OS_r set has the same definition as that of OS_f, with the vector os_i, in this case, containing the recovery signature faults.

3.2.2.2 Continuous places mutually influenced

A. Cascade influence

These models of continuous places are influenced one-to-one; however, the information flow is transferred in an open loop, signifying that the behavior of a continuous place P_i^c directly influences the behavior of the continuous place P^c_{i+1}, successively, but does not influence the immediately preceding P^c_{i-1}.

B. Cyclic influence

These models are characterized by flow behavior in closed or feedback manner, indicating that there is a mutual influence in every continuous place according to the control of the discrete places. Both, continuous places cascade influence and continuous places cyclic influence exist in the same manner as a single fault transition, Tf_i, for every continuous isolated places, which defines a number of *Pre* arcs for this Tf_i as:

$$\Pr e^{Tf_i} = \sum_{j=x}^{n} (P_j^c \times Tf_i) \quad (14)$$

Where, x is the initial continuous place influenced and n is the last continuous place influenced.

C. Mixed influence

This model may have mixed operation structures, such as isolates, cascades, or cyclic. To determine the operating states of the continuous places mutually influenced with greater ease, it is necessary to develop a table called "table of continuous places influenced." This table will have the number of operating states of the model, and obtains the fault signatures according to the discrete places that influence each continuous place.

3.2.3 Fault signatures

These fault signatures represent the faults in the place *PVf* isolated in a recurrent manner according to the residual behavior, like using the threshold for every operating state. For example:

$$Sf_n(k) = \begin{cases} < f_i, s_n > if \rightarrow r_i(k) > \\ < f_i f_k, s_n > if \rightarrow r_i(k) < \\ \vdots \\ < f_m, s_n > \cdots \end{cases} \quad (15)$$

Owing to the possibility of including faults from the continuous dynamics, the set $SROV_{nev}(M(k))$ may include a fault signature $Sf_n(k)$ in a case of single continuous place, or an os_i fault signature vector in a mutually influenced place, according to the faults obtained by the residues, dynamic behavior of the continuous place P_i^c, and place of latent nestling faults, *PLNf*, that influence this continuous dynamic.

3.2.4 Diagnosability of the model

The diagnosability concept can be explained based on the second paragraph, but the fault signatures for each operating state of the continuous places analyzed, P_i^c, must be included. Likewise, it is necessary to satisfy the condition that at least one fault signature, $Sf_n(k) \subseteq os_i$ must exist for each continuous place P_i^c.

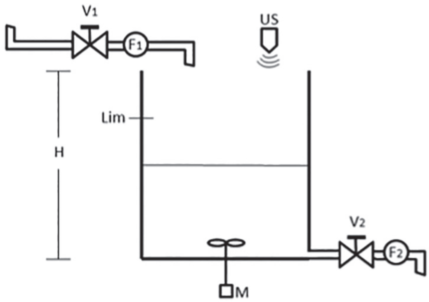
$$\forall \; PLNf_i^c \in \; P^c \, \exists \; Sf_n(k) \subseteq \; os_i . \qquad \textbf{(16)}$$

4. Illustrative Example

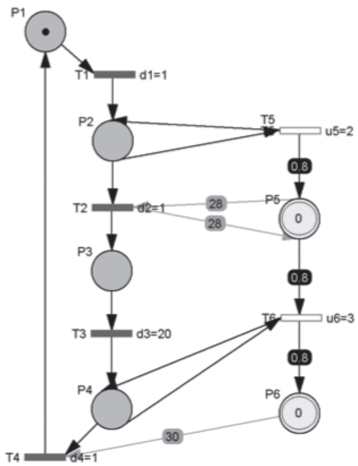
The example system consists of a liquid storage tank. With the following components: a storage system or tank, three actuators (two pass valves, one mixer), three sensors (two flow binary, one level - ultrasound). Figure 2a shows physical structure of the system.

Figure 2.

a) Example of hybrid system



b) Hybrid model using Sirphyco tool



Source. By the authors.

The process starts giving the order to open valve V_1 for filling tank with a flow ratio of 2v.u/t.u (volume units by time unit). When the ultrasonic sensor reaches the value lim=30, the mixer M is energized; t1=20 seconds after and valve V1 is closed not to deposit more product. Lastly, it deactivates the mixer and opens valve V2 with a flow ratio of 3v.u/t.u to empty the tank. Both input and output flows are a fixed ratio, which indicate that the function of filling and emptying are linear. In the real model $K\sqrt{h(t)}$ is used as an outflow; but in the previous simulation, the flow ratio is indicated above. The process runs on a cyclical mode. The hybrid model using the Sirphyco software is shown in Figure 2b (David, 2005).

To analyze the behavior of the discrete dynamic system, four reachable markings in the normal behavior should be obtained. Thus:

M_0= initial condition, valve V_1 closed state.
M_1= the valve V_1 is ordered to open.
M_2= the valve V_1 is ordered to close, and the mixer is activated.
M_3= the valve V_2 is ordered to open, and the mixer is deactivated.
The markings of the initial vector can be expressed in the following form: $*M_0= (M_0, M_1, M_2, M_3.)$.

The dynamic analysis of the continuous system is given by a simple differential equation.

$$\frac{dh(t)}{dt} = \frac{1}{A}(q_1(t) - q_2(t)) \quad , \qquad (17)$$

Where A is the tank area, $\frac{dh(t)}{dt}$ the height variation, and q_1, q_2 the input and output flow for the valves V_1 and V_2 respectively. To define the faults, the knowledge of experts is used for the proposed system.

In this case, the faults are the following: stuck valves, leakage in the tank and sensor faults. Classifying these faults in identifiers using colored marks:

f_1= stuck open valve, V_1 fault. f_4= stuck close valve, V_2 fault.

f_2= stuck close valve, V_1 fault. f_5= leakage in the tank fault.

f_3= stuck open valve, V_2 fault. f_6= level sensor fault.

The readings of the discrete behavior sensor are:

$$srov_{11}(M_k)=\{F_1,NF_1\}, \qquad srov_{12}(M_k)=\{F_2,NF_2\}.$$

Using the level sensor as a measured discrete:

$$srov_2(M_k)=\{L,NL\},$$

Where: *L*= There is a fluid level, *NL*= empty tank.
Table 1 shows the faults according to the sensors readings and the discrete markings.

Table 1. Fault behavior according to the discrete sensor readings

F_1	F_2	L	M_0	M_1	M_2	M_3
0	0	0	$SROV_{ev}$	f_2	f_6	f_4f_6
0	0	1	f_6	f_6f_2	$SROV_{ev}$	f_4
0	1	0	f_3f_6	$f_2f_3f_6$	f_3f_6	f_6
0	1	1	f_3	f_2f_3	f_3	$SROV_{ev}$
1	0	0	f_1f_6	f_6	f_1f_6	$f_1f_4f_6$
1	0	1	f_1	$SROV_{ev}$	f_1	f_1f_4
1	1	0	$f_1f_3f_6$	f_3f_6	$f_1f_3f_6$	f_1f_6
1	1	1	f_1f_3	f_3	f_1f_3	f_1

Source. By the authors.

In continuous case analysis, the continuous variables that influence the process should be considered. Likewise, the discrete sensors that influence the continuous place should be taken into account. For this case, there is a single continuous place of isolation-type, implying that there is a single operating state, as well as a series of fault signatures for each discrete place that influence the behavior of the continuous place $S=osf_5$. The operating state osf_5 corresponds to the vector that contains the number of operating states of the continuous place P_5^c. The places that influence the behavior of the continuous place are $PLNf_2$, $PLNf_3$, and *PLNf4*; where the vector osf_5 is define as follows:

$$osf_5=(Sf_2(k),Sf_3(k),Sf_4(k)).$$

Owing to the presence of the continuous-type sensor for the measured height, a comparison between the measured height *h* and the estimated height *h'* is possible. Using the equation 17,

Case 1: first operating state. Filling the tank:

$$h'=\frac{1}{A}\int q_1(t)\cdot dt \qquad (18)$$

Where r_1 is the residue obtained as follows:

$$r_1=h-h'$$

$$Sf_2(k)=\begin{Bmatrix}\langle f_5,S_2\rangle if \rightarrow r_1>\square_{11}=0.3\\ \langle f_6,S_2\rangle if \rightarrow r_1<\square_{12}=-1\end{Bmatrix} \qquad Sr_2(k)=\begin{Bmatrix}\langle f_5,S_2\rangle if \rightarrow r_1>\square_{41}=0.15\\ \langle f_6,S_2\rangle if \rightarrow r_1<\square_{42}=-0.5\end{Bmatrix}$$

Case 2: second operating state. Resting state, where the height is a constant and r_2 is the residue obtained as follows:

$$r_2=h-h'$$

$$Sf_3(k)=\begin{Bmatrix}\langle f_5,S_3\rangle if \rightarrow r_2>\square_{21}=0.1\\ \langle f_6,S_3\rangle if \rightarrow r_2<\square_{22}=-0.5\end{Bmatrix} \qquad Sr_3(k)=\begin{Bmatrix}\langle f_5,S_3\rangle if \rightarrow r_2>\square_{51}=0.08\\ \langle f_6,S_3\rangle if \rightarrow r_2<\square_{52}=-0.4\end{Bmatrix}$$

Case 3: third operating state. Emptying the tank:

$$h'=\frac{1}{A}\int q_2(t)\cdot dt \qquad (19)$$

Where r_3 is the residue obtained as follows:
$r_3 = h - h'$

$$Sf_4(k) = \begin{cases} \langle f_5, S_4 \rangle if \rightarrow r_3 > \square_{31} = 1 \\ \langle f_6, S_4 \rangle if \rightarrow r_3 < \square_{32} = -0.4 \end{cases} \quad Sr_4(k) = \begin{cases} \langle f_5, S_4 \rangle if \rightarrow r_3 > \square_{61} = 0.8 \\ \langle f_6, S_4 \rangle if \rightarrow r_3 < \square_{62} = -0.3 \end{cases}$$

The thresholds set $\tau = (\tau_{11}, \ldots, \tau_{32})$ is given by the knowledge of the experts. These thresholds are analyzed according to different factors such as: hysteresis, disturbances, noise, as well as the sensor resolution and sensitivity.

In the same way that there are fault operating states for each continuous place, there are also recovery operating states. In these recovery states, the τ values change owing to the sensor hysteresis.

For example, if $r_1 = 0.4$ when the tank is filling, the isolate and recovery of fault f_5 are given by the expression:

The fault isolation of f_5 is produced if the marking meets the condition:

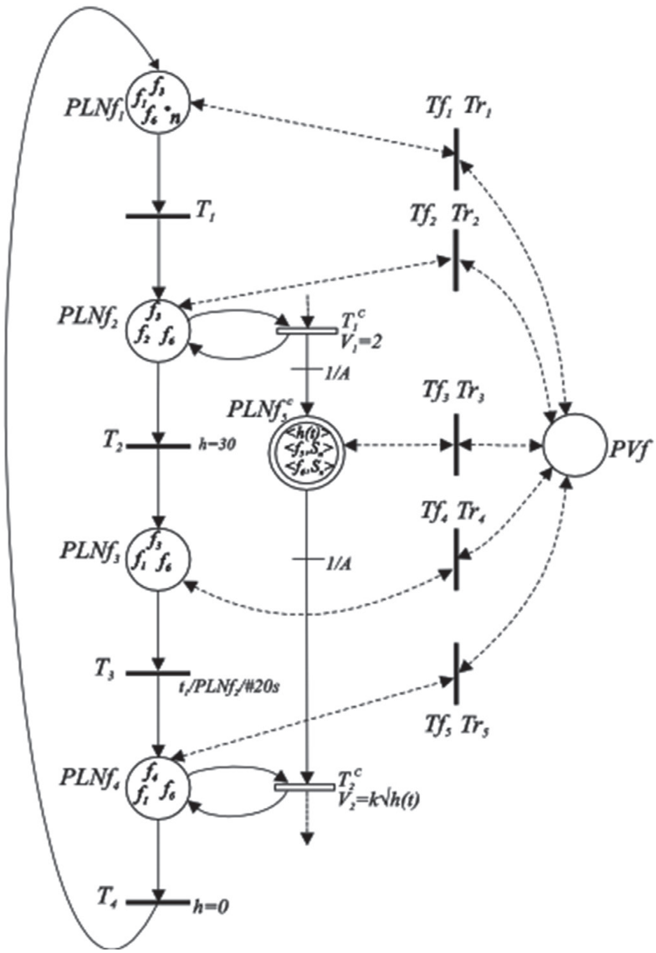
$$\begin{gathered} (M(PLNf_2(<\bullet n>)) \wedge M(P_5^c(<h>, \langle f_5, S_2 \rangle))) \\ [Tf_3 / r_1 > 0.3\ (M(PLNf_2(<\bullet n>)) \wedge M(P_5^c(<h>, \langle f_5, S_2 \rangle))) \\ > M(PVf(\langle f_5, S_2 \rangle)). \end{gathered}$$

The fault recovery of f_5 is produced if the marking meets the condition:

$$\begin{gathered} M(PVf(\langle f_5, S_2 \rangle)) \\ [Tr_3 / r_1 < 0.15\ (M'(PLNf_2(<\bullet n>)) \wedge M'(P_5^c(<h>) \wedge M(PVf(\langle f_5, S_2 \rangle))) \\ > M(P_5^c(<h>, \langle f_5, S_2 \rangle)) \end{gathered}$$

In Figure 3, the final model for the tank example is shown.

Figure 3. DHCPN model (example of filling tank).



Source. By the authors.

The results obtained from the final model of DHCPN are shown in Figure 3. The diagnosis system is able to detect and isolate faults of individual type f_1, f_2, f_3, f_4, f_6, and simultaneous type f_1f_6, f_1f_3, f_1f_4, $f_1f_3f_6$, $f_1f_4f_6$, f_2f_3, $f_2f_3f_6$, f_4f_6, f_6f_2, as well as the faults of process type $\langle f_5,S_2\rangle$, $\langle f_6,S_2\rangle$, $\langle f_5,S_3\rangle$, $\langle f_6,S_3\rangle$, $\langle f_5,S_4\rangle$, $\langle f_6,S_4\rangle$.

5. Conclusion

The method based on CPNs shows that the reduction and simplicity of the system models are discrete, continuous, or hybrid, giving them characteristics of readability, implementability, and treatability, irrespective of the number of sensors to be treated or the number of faults to be diagnosed. These features are impossible to obtain with other methodologies, such as MEFs. Likewise, the LNM focused on continuous and hybrid systems presents an excellent and clear solution to fulfill the objectives of diagnosis and isolation of any fault type that may arise in the system. This solution is owing to the use of CPNs as an abstraction method because these nets allow nestling the faults both in the Latent Nestling Place (fault allocation) and in the Fault Verification Place (Isolation) (Rodríguez *et al.*, 2012)

The hybrid nestling technique shows the need to analyze the residues with the information of the discrete state in normal behavior for characterizing the type of fault, its location, and subsequent isolation.

Operating states and the influence tables of continuous places offer an overview of the system's behavior by sharing the information that is a continuous variable to treat in the model. The operating states and fault signatures provide the possibility of locating fault transitions, and thus, analyze fault coupling to avoid false warnings in the verification place. Further experimental investigations are needed to estimate different methods for nestling faults in the latent nestling places, for example, structural analysis (Staroswiecki, 2007). According to recent studies (Ghazel *et al.*, 2009), it is necessary to take the State Observer for DES with Timed Petri Nets in the LNM into account, in order to exploit temporal constraints and thus, ensure the best evaluation of the system state.

6. References

Balduzzy, F., Giua, A., & Seatzu, C. (2001). Modeling Manufacturing Systems with First-Order Hybrid Petri Nets. *International Journal of Production Research, Special Issue on Modeling, Specification and Analysis of Manufacturing Systems, 39* (2).

Chen, J. & Patton, R.J. (1999). *Robust model-based fault diagnosis for dynamic systems.* Boston, MA: Kluwer Academic Publishers.

David, R. & Hassane, A. (2005). *Discrete, Continuous, and Hybrid Petri Nets.* Berlin: Springer-Verlag.

Demongodin, I. & Koussoulas, N.T. (1998). Differential Petri nets: Representing Continuous Systems. *IEEE transactions on Automatic Control* , 43(4), 573-579. IEEE.

García, E., Morant, F., Blasco, R., Correcher, A., & Quiles, E. (2002). Centralized Modular Diagnosis and the Phenomenon of Coupling. *WODES02: Workshop On Discrete Event Systems* (pp. 161-168). Zaragoza: IEEE.

García, E., Rodríguez, L., Morant, F., Correcher, A., & Quiles, E. (2008). Fault Diagnosis with Coloured Petri Nets Using Latent Nestling Method. *Proceedings of ISIE08.* Cambridge: IEEE.

García, E., Rodríguez, L., Morant, F., & Correcher, A. & Quiles, E. (2008). Latent Nestling Method: A new fault diagnosis methodology for complex systems IECON08. *The 34th Annual Conference of the IEEE Industrial Electronics Society.* Orlando: IEEE.

Genc, S. & Lafortune, S. (2003). Distributed diagnosis of discrete-event systems using Petri nets. *Proceedings of the International Conference of Application and Theory of Petri Nets* (pp. 316-336). Eindhoven.

Gertler, J. (1998). *Fault Detection and Diagnosis in Engineering Systems.* New York, NY: Marcel Dekker.

Ghazel, M., Toguyéni, A., & Pascal, Y. (2009). State Observer for DES Under Partial Observation with Time Petri Nets. *Discrete Event Dynamic Systems , 19* (2), 137-165. Hingham, MA: Kluwer Academic.

Hacami, S., Boimond, J. L., & Lahave, S. (2006). Modeling and Control of Hybrid Timed Event Graphs with Multipliers Using (Min, +) Algebra. *Discrete Event Dynamic Systems, 16* (2), 241-256. Hingham, MA: Kluwer Academic.

Isermann, R. (1997). Supervision, fault-detection and fault-diagnosis methods - an introduction. *Control Engineering Practice ,* 5(5), 639-652.

Jensen, K. (1992). *Coloured Petri Nets 1: Basic Concepts, Analysis Methods and Practical Use.* Berlin, Germany: Springer-Verlag.

Koutsoukos, X., He, K., Lemmon, M., & Antsaklis, P. (1998). Timed Petri nets in hybrid systems: Stability and supervisory control. *Discrete Event Dynamic Systems*. 8(2), 137-173. Hingham, MA: Kluwer Academic.

Krogh, B. (2002). Recent advances in discrete analysis and control of hybrid systems. *WODES02: Proceedings of the Sixth International Workshop on Discrete Event Systems* (pp. 311-314). Washington: IEEE.

Llano, L., Zapata, G., & Ovalle, D. (2007). Hybrid system based on fuzzy inference and colored petri nets to identify electrical fault events in real time. *CERMA07: Fourth Congress of*

Electronics, Robotics and Automotive Mechanics (pp. 400-405). Los Alamitos, CA: IEEE.

Patton, R. J., Lopez-Toribio, C. J., & Uppal, F.J. (1993). Artificial intelligence approaches to fault diagnosis for dynamic systems. *International Journal of Applied Mathematics and Computer Science , 9* (3), 471-518.

Rodríguez, L., García, E., Morant, F., Correcher, A., & Quiles, E. (2008). Application of Latent Nestling Method using Coloured Petri Nets for the Fault Diagnosis in the Wind Turbine Subsets. *Proceedings of the International Conference on Emerging Technologies and Factory Automation, ETFA›08* (pp. 767-773). Hamburg: IEEE.

Rodríguez, L., García, E., Morant, F., Correcher, A., & Quiles, E. (2011). Hybrid Latent Nesting Method: A fault Diagnosis case study in the wind turbine subsets. *IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (pp. 566-571). Budapest: IEEE.

Rodríguez, L., García, E., Morant, F., Correcher, A., & Quiles, E. (2011). Coloured and Hybrid Petri Nets applied to Fault Diagnosis based on Latent Nesting Method. *IEEE/SDEMPED International Symposium on Diagnostics for Electircal Machines, Power Electronics & Drives.* Bologna: IEEE.

Rodríguez, L., García, E., Morant, F., Correcher, A., & Quiles, E. (2012). Hybrid Analysis in the Latent Nestling Method Applied to Fault Diagnosis. *IEEE Transactions on Automation Science and Engineering, 10* (2), 415-430.

Rodríguez, L., García, E., Quiles, E., Correcher, A., Morant, F., & Pizá, R. (2015). Diagnosis of Intermittent Faults in IGBTs using the Latent Nestling Method with Hybrid Coloured Petri Nets. *Petri Nets: Theory and Applications* (pp. 1-21).

Ru, Y. & Hadjicostis, C. N. (2009). Fault Diagnosis in Discrete Event Systems Modeled by Partially Observed Petri Nets. *Discrete Event Dynamic Systems,* 19(4), 551-575.

Sampath, M., Sengupta, R., Lafortune, S., Sinnamohideen, K. & Teneketzis, D. C. (1996). Failure diagnosis using discrete-event models. *IEEE Transactions on Control Systems Technology,* 4(2), 105-124.

Spiteri, A. (2009). A Compact Colored Petri Net Model for Fault Diagnosis and Recovery in Embedded and Control Systems. *International Journal of Computers, 3*.

Staroswiecki, M. (2007). A structural view of fault-tolerant estimation. J*ournal of Systems and Control Engineering*, 221(6), 905-914.

Uzam, M., & Wonham, W. A. (2006). Hybrid approach to supervisory control of discrete event systems coupling RW supervisors to Petri nets. *The International Journal of Advanced Manufacturing Technology , 28(7-8)*, 747-760.