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ACTIVE FAULT DIAGNOSIS IN AUTOMATED MANUFACTURING SYSTEMS: MODELED USING INTERPRETED PETRI NET

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ABSTRACT:

This paper deals with active diagnosis in Discrete Event System (DES) represented as Interpreted Petri Nets (IPN), which have been used to model an automated manufacturing system (AMS). In addition, a fault diagnosis scheme is implemented through residuals in an AMS controlled by a Mitsubishi PLC, which is monitored by an embedded system capable of measuring the current in the controllers in order to share information to the diagnoser, through the Modbus communication protocol with the purpose of increasing its reliability in the pronouncement.

Key Words: Interpreted Petri Nets, active diagnosis, Factory IO, diagnosability, fault diagnosis.

RESUMEN:

El presente artículo aborda el tema de Diagnóstico Activo en Sistemas de Eventos Discretos (SED) representado como Redes de Petri Interpretadas (RPI), que han sido utilizadas para modelar un Sistema Automatizado de Manufactura (AMS) donde mediante técnicas de control supervisor de Moody se ha impuesto la propiedad de la diagnosticabilidad. Además, se implementa un esquema de diagnóstico de faltas mediante residuos en un AMS controlado por un PLC marca Mitsubishi, que es monitoreado por un sistema embebido capaz de medir la corriente en los actuadores, con el fin de compartir información al diagnosticador mediante el protocolo de comunicación Modbus para incrementar su fiabilidad en el dictamen.

Palabras Clave: Redes de Petri Interpretadas, Diagnóstico Activo, Factory IO, diagnosticabilidad, diagnóstico de faltas.

1. INTRODUCTION

Recently, with technological progress, Automated Manufacturing Systems (AMS) have become more complex, as they are composed of many elements of different nature interacting with each other. According to Paiva [30], faults in these systems are considered inevitable. To analyze the occurrence of these faults, Ramírez [33] defines the property of diagnosability based on Interpreted Petri Nets (IPN), which refers to the possibility of faults being detected in a finite time by means of fault diagnosis schemes. In systems that do not have this property, it is possible to enforce it through active diagnostics.

One of the first works on active diagnosability is by Sampath [38], who defines, characterizes and enforces the diagnosability property by modifying the structure of the model from the point of view of finite automata in a theoretical context. From a practical point of view, the works of Basile [6] and Ran [35] pose the solution of a linear programming problem that obtains the minimum number of sensors to enforce diagnosability, without analyzing the cost-effectiveness of acquiring additional sensors and integrating them into the system controller.

The active diagnosis imposed by Hernández in [16] and [17] proposes two techniques. In his first approach the solution is structural and is obtained by adding extra places in the IPN model to restrict those pairs of transitions where their relative distance is infinite making it finite, this proposal converts the T-semiflows into mono T-semiflows. The second approach consists of a smart regulator circuit, the concept of smart being due to the fact that it only acts when it is in risk zones.

Finally, Prieto [31] proposes a solution based on Moody's supervisory control [27]. The methodology consists of finding a constraint in polynomial time that guarantees that the system is diagnosable; it does not present an assignment rule to enforce diagnosability.

In the context of fault diagnosis schemes in Discrete Event Systems (DES), where practical implementations in Petri nets (PN) are reported, Al-Ajeli [3] and [4] use the Fourier-Motzkin (F-M) elimination method. Faults are modelled as unobservable transitions. In Paiva [30], transitions with the same label are integrated. One of the drawbacks of these works is that they are applied to acyclic models; in a practical context, most of the AMS are concurrent and generally cyclic.

In Moreira [28] and [29], the proposal is to model a fault diagnoser using a deterministic automaton with conditional outputs and transitions. Basile [5] uses residuals for fault diagnosis instead of fault tree, in addition to introducing time limits for the firing of transitions using timed IPN. A disadvantage of employing timers for diagnosis in a real system pertains to constraints in terms of flexibility, i.e., timers are programmed under predefined conditions, if the system conditions change, adjustments to the timers will be necessary. In Kohler's work [25] a fault tree is used for the controller and the plant, both of which modeled with IPN. For monitoring purposes, a predictive sensor and signals from the actuators are utilized.

The present work studies the active diagnosis of permanent faults in an AMS controlled by a Programmable Logic Controller (PLC). AMS is simulated in Factory IO software, physically built, and modeled by IPN. The main objective of this work is defined, characterize and implement an active P-semiflow capable of enforce the diagnosability property while preserving all the T-semiflows of the plant and the full language. Furthermore, to design and build an embedded system that can enhance the accuracy of the fault diagnosis scheme, providing real-time and updated data on the status of the monitored outputs.

The primary contribution of this article is twofold: first, active diagnosis and, second, fault diagnosis schemes. In the context of active diagnosis, an aspect that has not been previously explored, Hernández [17], Hu [19], [20] and [21], and Cong [11] have not considered preserving structural properties. In contrast to these approaches, the present research proposes a methodology that fully preserves T-semiflows, a property that the other approaches limited. On the other hand, in fault diagnosis by means of residues, the contribution of this work lies in the design and assembly of an embedded system capable of monitoring the state of the outputs of a PLC. This system is able to be gathered information with the diagnoser via Modbus protocol. Basile's proposal [5] where the diagnoser lacks certainty regarding the receipt of the signal sent by the PLC to the actuator, this work ensures the diagnoser obtains reliable information concerning the state of the outputs.

2. METHODS

For the development of this work, a digital AMS and its physical twin were built to validate the obtained results. The AMS model was constructed using IPN, which are distinguished by their capacity to model DES in an efficient manner. Then, the diagnosability property was revised under the Ramírez approach [33]. Subsequently, the concept of active P-semiflow was defined, characterized and implemented. Finally, an embedded system was developed to monitor outputs in real time, thereby enhancing the accuracy of the diagnosis by means of residuals. In the following, some important theoretical concepts are defined.

2.1 Interpreted Petri Nets

The IPN subclass is defined in Ramirez [33]. Its main use is to represent input symbols in transitions and output symbols for places.

Definition 1. A Petri net (PN) is a bipartite graph expressed by a 4-tuple $G = (P, T, I, O)$ where $P = \{p_1, p_2, \dots, p_n\}$ is a finite set of places, $T = \{t_1, t_2, \dots, t_o\}$ is a finite set of transitions. $I: P \times T \to Z \geq 0$ is a function representing the weight of an arc connecting places to transitions, $O: P \times T \to Z \geq 0$ is a function representing the weight of an arc connecting transitions to places. $Z \geq 0$ represents the non-negative integers. Where $P \times T$ represents the cartesian product of $P \times T$ (set of the pairs (p, t) where $p \in P$ and $t \in T$).

Definition 2. An Interpreted Petri Net (IPN) is a sextuple $Q = (G, M_0, \Sigma_I, \Sigma_o, \lambda, \varphi)$ where (G, M_0) is a PN. $\Sigma_I\ y\ \Sigma_o$ is the input and output alphabet respectively, while $\lambda: T \to 2^{\Sigma_I}$ is the function for labelling inputs to transitions and $\varphi: T \to 2^{\Sigma_o}$ is the function for labelling places.

Definition 3. A siphon is a subset of places $S = \{P_1, \dots, P_S\} \subseteq P$ of a PN such that $\bullet S \subset S \bullet$, the notation $\bullet S$ and $S \bullet$ indicate the incoming and outgoing transitions, respectively, of the places forming the siphon S.

Definition 4. Let(Q, M_0) be a PN. The vectors X_i such that, $CX_i = 0, X_i \geq 0$ are known as T-semiflows. The support of a T-semiflow X_i , denoted $\langle X_i \rangle$, is the set of transitions $T_i = \{t_j | X_i(j) > 0\}$.

Definition 5. Let(Q, M_0) be a PN. The vectors Y_i such that, $Y_i C = 0, Y_i \geq 0$ are known as P-semiflows.

Definition 6. The relative distance $D_R(t_j, t_k)$, between any pair of transitions $t_j, t_k \in T$, is the maximum number that t_k can be fired without firing t_j when the mark is retained at the places $\bullet t_j$. The maximum relative distance $D_H(t_j, t_k)$, between any pair of transitions $t_j, t_k \in T$ is $D_H(t_j, t_k) = \max\{D_R(t_j, t_k), D_R(t_k, t_j)\}$.

2.2 Diagnosability

The following proposition was defined by Ramírez [33] for IPN. Where T^F are fault transitions, T^R regular transitions and p_i^N are places of normal behaviour.

Proposition 1. Let (Q, M_0) be a IPN modelled under Ramírez approach [33]. Let $X = \{X_1, \dots, X_\tau\}$ be the set of minimal T-semiflows of (Q, M_0). Let S be any minimum siphon of the IPN, where $p_i^N \in S(p_i^N)^\bullet \cap T^F \neq \emptyset, |\{p_i^N\}| = 1$ and $\lambda((p_i^N)^\bullet \cap T^R) \neq \varepsilon$. If $\forall X_r \in X \| X_r \|$ share transitions with S, then the IPN (Q, M_0) is diagnosable.

2.3 Supervisory Control

Supervisory control is a fundamental theory of DES control proposed by Ramadge [32]. The problem of supervisory control is to modify the open-loop behavior of a DES so that it is within a desirable range. In Moody's supervisory control [27] this is done by adding an extra place to the network, the objective of the controller is to restrict the markings of the plant μ_P, refer to equation (1).

$$L\mu_p \leq b \tag{1}$$

Where μ_P is the marking of the plant, b a scalar, $L \in \mathbb{Z}^{n_c \times n}$, $\mathbb{Z}$ is a set of integers, n is the number of plant places, m the number of transitions and n_c is the number of constraints of the type of equation (1). The solution of the problem uses the slack variables, as shown in equation (2), where $\mu_c \in \mathbb{Z}^{n_c}$ is the integer vector representing the marking of the control places, the subscript p represents the plant and the subscript c represents the controller.

$$L\mu_P + \mu_c = b \tag{2}$$

On the other hand, the matrix C_c contains arcs connecting control places to plant transitions. The incidence matrix $C \in \mathbb{Z}^{(n+n_c)\times m}$ of the closed loop is given by equation (3).

$$C = \begin{bmatrix} C_p \\ C_c \end{bmatrix} \tag{3}$$

The vector of markings $\mu \in \mathbb{Z}^{n+n_c}$ and the initial marking μ_0, refer to equation (4).

$$\mu = \begin{bmatrix} \mu_p \\ \mu_c \end{bmatrix}; \mu_0 = \begin{bmatrix} \mu_{p0} \\ \mu_{c0} \end{bmatrix} \tag{4}$$

Equation (2) is of the form of a P-semiflow, which can be substituted by equation (5) and (6). Where $I \in \mathbb{Z}^{n_c+n_c}$ is the identity matrix with the coefficients of the loosely defined variables set as one.

$$X^T C = [L \quad I] \begin{bmatrix} C_p \\ C_c \end{bmatrix} = 0 \tag{5}$$

$$LC_P + C_c = 0 \tag{6}$$

3. ACTIVE DIAGNOSIS PROPOSAL

This section describes the methodology and implementation of active diagnostics in a real and digital AMS.

3.1. Physical model and digital system in Factory IO software

Figure 1 shows the isometric and top view of the digital twin built in Factory IO software. The operation consists of sorting boxes according to their size: small, medium and large. The process begins with the activation of the start button (BA), which generates a random size box in the box generator on conveyor belt 1 (B1). The box then to the sensor zone for small (SI1), medium (SI2) and large (SI3) boxes. If the box is small, it will travel along the whole of B1, and at the end of B1, there is a sensor SF_{B1} that, when activated, restarts the cycle. For the medium box, when it is positioned in front of piston 2 (P2), band 1 stops and P2 is activated. The box then moves to the conveyor belt zone (B3) and, upon reaching the end sensor on belt 3 (SF_{B3}), the cycle is restarted. Finally, when the large box, when positioned in front of piston 1 (P1), it extends after belt B1 stops. It then moves to conveyor belt zone 2 (B2) where the cycle restarts after the end sensor SF_{B2} on belt 2 is activated.

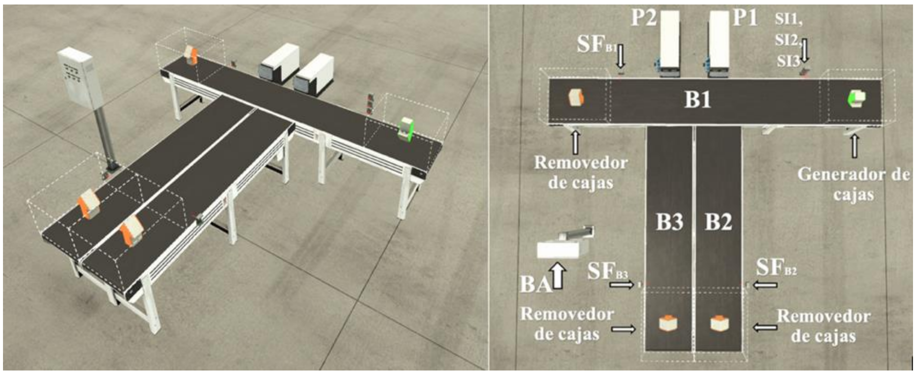

Figure 1. Digital system in Factory IO, isometric view and top view.

Figure 2 shows the top view of the physical AMS, elements P1 and P2 are electric pistons, while elements B1, B2, and B3 correspond to the conveyor belts. Sensors SI1, SI2, SI3 are responsible for detecting the size of the boxes. Additionally, sensors SF_{B1}, SF_{B2} and SF_{B3} are the sensors at the end of the conveyor belts.

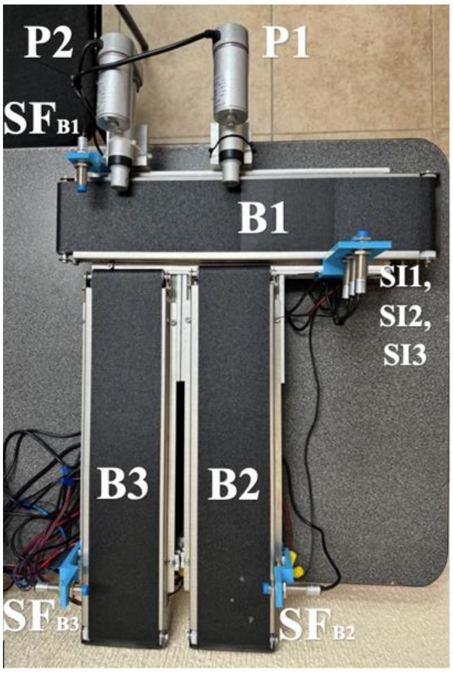

Figure 2. Top view of the physical model.

3.2. Physical system or digital system model in Interpreted Petri Nets

This section shows the IPN model of the AMS under Guevara's approach [14]. Table 1 provides an overview of the system's components, the variables that participate in the dynamics and the range for each variable.

Table 1. Elements of the system.

Name in Model	Description	Variable	Range
BA	Start button	State	<activated (A1), deactivated(D1)>
Sensor Size (SI_1, SI_2 y SI_3)	Inductive Sensor 1 Inductive Sensor 2 Inductive Sensor 3	State	<activated size 1 (AT1), activated size 2 (AT2), activated size 3 (AT3), deactivated(D2)>.
SF_{B1}	Inductive Sensor 4	State	<activated(A3), deactivated (D3)>
SF_{B2}	Inductive Sensor 5	State	<activated(A4), deactivated (D4)>
SF_{B3}	Inductive Sensor 6	State	<activated(A5), deactivated (D5)>
B1	Conveyor belt	State	<on (E1), off (Ap8)>
B2	Conveyor belt	State	<on (E2), off (Ap9)>
B3	Conveyor belt	State	<on (E3), off (Ap10)>
P1	Electric piston	Position	<extended (Ex1), retracted(R1)>
P2	Electric piston	Position	<extended (Ex2), retracted(R2)>

Figure 3 based on Table 1, presents the model of each system element in IPN. Each range is described by a place P and its description is abbreviated in the "Range" column of Table 1. The synchronic composition is identified by the "X" labels, which relate the firing of two or more transitions at the same instant of time. Finally, the permissive composition is those that relate transitions to places, which are identified by the letter "Y", these labels correspond to events that are cause-effect.

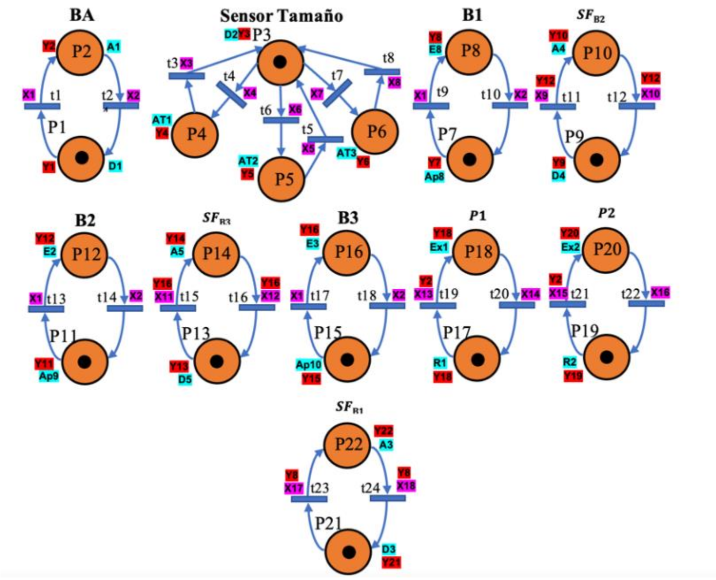

Figure 3. Isolated IPN models.

Figure 4 shows the complete model with permanent faults; it shows the permissive composition in red color Y_n , which relates places to transitions. Those elements that are related must have an arc linking the place to the transition and the transition to the place, or a bidirectional arc can be used. For example, the transition t_{16} with the place P_{16} in figure 3. On the other hand, the synchronic composition, pink color X_n , happens when two events occur at the same instant of time, this makes the transitions merge into a single transition. For example, the transitions t_1 and t_9 which are both labelled X_1 in Figure 3.

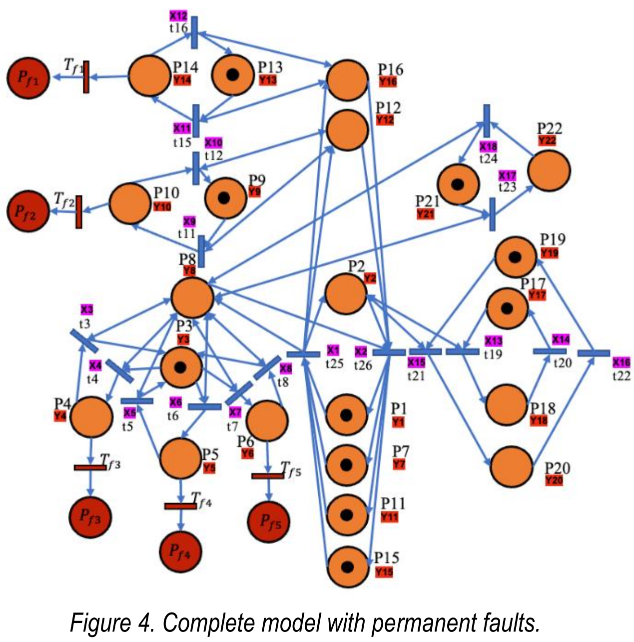

Figure 4. Complete model with permanent faults.

3.3. Diagnosability analysis

Figure 4 shows the permanent faultsT_{f1}, T_{f2}, T_{f3}, T_{f4} and T_{f5} , which correspond to faults in the sensors. For instance, T_{f1} indicates that inductive sensor 6 (SF_{B3}) has a fault.

In practice, the vector M_k will represent the number of marks assigned to each place p_n, with $M_k = [p_1 \ldots p_{22}]$. According to Ramirez's characterization [33], all faults are non-diagnosable because the T-semiflows $\langle X_a \rangle$ are not related via transitions to the siphons (W_b). In a practical context T-semiflows related to sensor activation will not represent the system as non-diagnostic, therefore, T-semiflows related to sensors when another sensor fails will not be considered as T-semiflow of interest, as the activation or non-activation of a sensor will not affect the actual manufacturing system. For example, the fault T_{f1} is non-diagnosable because the T-semiflows $\langle X_1 \rangle = \{t_3, t_4\}$, $\langle X_2 \rangle = \{t_5, t_6\}$, $\langle X_3 \rangle = \{t_7, t_8\}$, $\langle X_4 \rangle = \{t_{11}, t_{12}\}$, $\langle X_5 \rangle = \{t_{20}, t_{22}, t_{25}, t_{26}\}$ and $\langle X_6 \rangle = \{t_{23}, t_{24}\}$ are not related via transitions to the subnetwork induced by the siphon $W_1 = \{p_{13}, p_{14}, p_{f1}\}$, if fault T_{f1} is fired, the T-semiflows X_1, X_2, X_3, X_4, X_5 and X_6 can be fired infinitely. As mentioned before, the T-semiflows related to the sensors will not be considered, therefore only the T-semiflowX_5 will be considered. Such T-semiflow causes the fault T_{f1} to be non-diagnosable, because this work approaches the problem from a real context

3.4. Enforcing Active Diagnosis

Moody's supervisory control [27] consists of a behavioral constraint based on the number of marks. For example, $M(P_1) + M(P_{12}) \geq 1$ indicates that the number of marks from P_1 added to the number of marks from P_{12} must be greater than or equal to 1.

The objective of this paper is to compute a P-semiflow with a monitor place over the risk places. The goal is to ensure that the T-semiflows that make the system non-diagnosable because they tend to shoot to infinity become finite. This P-semiflow will be referred to as the active P-semiflow and is defined below.

Definition 7. Let (Q, M_0) be a IPN and $t_i \in T_f$. The set of risk places of t_i are $P_{R_i} = \{p_k | p_k \in \bullet\, t_i\}$. The T-semiflows of interest that are fired infinitely after the fault t_i occurred are defined as $\langle X_{int} \rangle = \{\langle X_i \rangle | D_H(t_j, t_k) = \infty, t_j, t_k \in \langle X_i \rangle\}$. Places of interest are defined as follows: $P_{int} = \left\{p_i \in P \middle| \left|\bullet\, p_i \in \langle x_{int_\rho} \rangle\right| = 1 \wedge \left|p_i \bullet \in \langle x_{int_\rho} \rangle\right| = 1\right\}$. The active P-semiflow that makes the fault diagnosable is defined as $\langle Y_{Act} \rangle = \left\{p_{int_1}, \ldots, p_{int_{|X_{int}|}}, P_R\right\}$, only one place P_{int} must be chosen for each element of $\langle X_{int} \rangle$ that meet the definition of place of interest, even if two or more places meet the definition. Finally, the relationships via transitions with the IPN are calculated according to Moody's supervisory control approach where: $M(p_{int_1}) + \cdots + M\left(p_{int_{|X_{int}|}}\right) + M(P_R) \geq 0$.

To enforce the diagnosability property on the system, a constraint is set that creates dependence between the support of the T-semiflow $X_{int} = \langle X_2 \rangle = \{t_{20}, t_{22}, t_{25}, t_{26}\}$ with the transitions of the net induced by the siphon $W_1 = \{p_{13}, p_{14}, p_{f1}\}$. Given that the risk place is $P_R = \{p_{14}\}$ and the places $P_{int} = \{p_{17}, p_{18}, p_{19}, p_{20}\}$, it is essential to note that only one place per induced net of the T-semiflows must be chosen, based on the set, a constraint is established with all places forming the active P-semiflow $\langle Y_{Act} \rangle = \{p_{14}, p_{18}, p_{20}\}$. Equation (7) shows the constraint that enforces diagnosability property. In equation (8) the slack variable is added to solve the problem, this equation contains the new monitor place P_x.

$$M(P_{14}) + M(P_{18}) + M(P_{20}) \geq 0 \tag{7}$$

$$M(P_{14}) + M(P_{18}) + M(P_{20}) + M(P_x) = 0 \tag{8}$$

Equation (9) shows the left annihilator of the incidence matrix which, according to the methodology, the new place forms a P-semiflow. The result of equation (10) and (11) shows the structural solution for the constraint posed in equation (1).

$$Y^T \cdot \begin{bmatrix} C_p \\ C_C \end{bmatrix} = 0 \tag{9}$$

$$Y^T = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 0\ 1\ 0\ 1\ 0\ 0\ 1] \tag{10}$$

$$\begin{bmatrix} C \\ P_x \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \\ x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 & x_{10} & x_{11} & x_{12} & x_{13} & x_{14} & x_{15} & x_{16} & x_{17} & x_{18} \end{bmatrix} \tag{11}$$

The initial marking (μ_{px}) of the place P_x is defined by equation (12), where b is the value to which the constraint is equal, L is the vector Y^T without considering the place P_x and μ_{P_0} the initial marking of the plant without considering the place P_x. The result of equation (13) shows that the initial marking is 0.

$$\mu_{px} = b - L\mu_{P_0} \tag{12}$$

$$\mu_{px} = 0 - [0\;0\;0\;0\;0\;0\;0\;0\;0\;0\;0\;0\;0\;1\;0\;0\;0\;1\;0\;1\;0\;0\,] \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} = 0 - 0 = 0 \tag{13}$$

As it shown in Figure 5, the monitor place P_x exhibits a relationship with IPN model of the system. This is obtained by equation (11), where these are: $x_1 = x_2 = x_3 = x_4 = x_5 = x_6 = x_7 = x_8 = x_9 = x_{10} = x_{17} = x_{18} = 0$ means that the transitions are not associated with the new place. Conversely, when $x_{12} = x_{14} = x_{16} = 1$ transitions take a mark away from the new place P_x , as illustrated by the arcs from the place P_x to the transitions x_{12}, x_{14} and x_{16}. Finally, $x_{11} = x_{13} = x_{15} = -1$, will give a mark to the new place P_x as seen in the arcs from the transitions x_{11}, x_{13} and x_{15} to the place P_x.

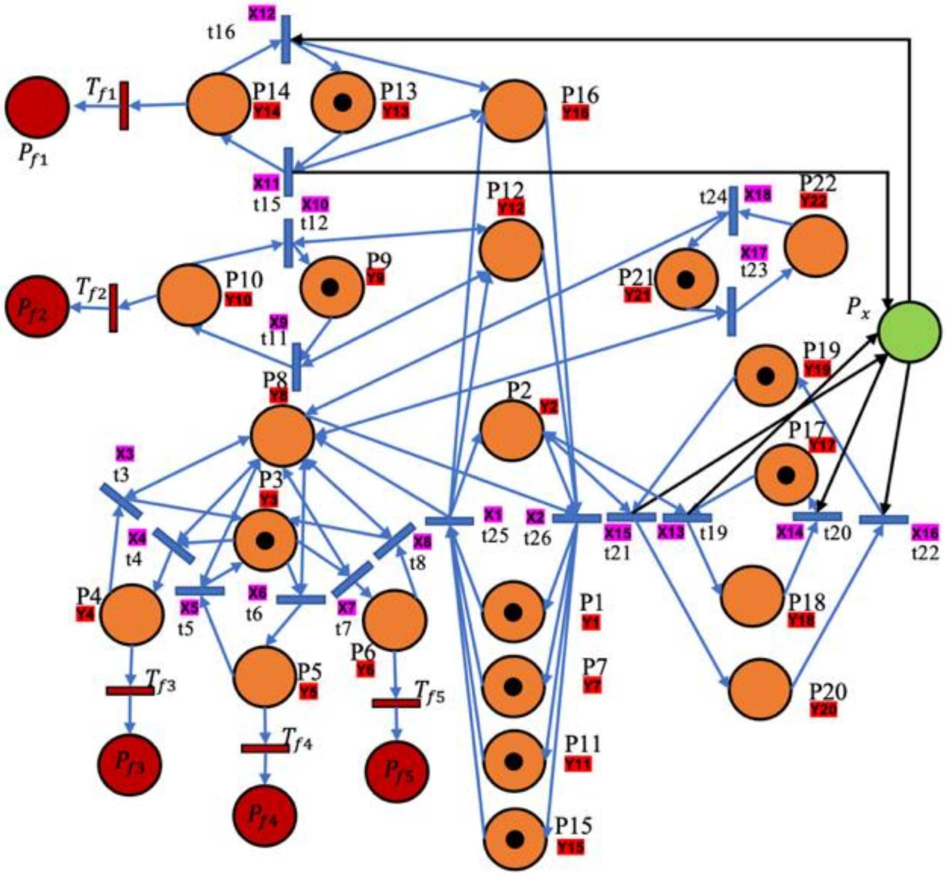

Figure 5. Active diagnosis using active P-semiflow.

4. ACTIVE DIAGNOSIS IMPLEMENTATION

One of the multiple faults that made the system non-diagnosable was T_{f1}. After integrating the new monitor place P_x , the fault T_{f1} becomes diagnosable. If fault T_{f1} is fired, the mark is removed from P_{14} and placed at P_{f1}. This marking prevents the firing of any other transition since the monitor place P_x does not allow the transitions of the pistons $P_1\{t_{17}, t_{18}\}$ and $P_2\{t_{19}, t_{20}\}$ to fire infinitely, for such reason, the fault will be diagnosed in a finite number of steps. In contrast to that shown by Hernandez [17] the present proposal preserves in its entirety the T-semiflows of the IPN model.

4.1. Diagnoser scheme

According to Ramírez [33], the occurrence of faults in a system can be detected in a finite number of steps (or events). To validate the results obtained, an AMS was designed and built (see figure 3).

The diagnosis scheme uses Basile's proposal [5], which is based on the monitoring of system inputs and outputs. It is assumed that the PLC submits a vector v_k to the diagnoser, see equation (14).

$$v_k = \begin{bmatrix} l_{I,k} \\ l_{O,k} \\ t_{s_k} \end{bmatrix} \quad (14)$$

Where $l_{I,k}$ represents all the input elements connected to the PLC and $l_{O,k}$ are the output actuators, finally, t_{s_k} is a time stamp, i.e. the data update time. Basile [5] proposes two types of residuals, those with missing behavior, see equation (15) and (16), and those with unidentified behavior, see equation (17) and (18).

$$Res_1(m_k, v_k,\ v_{k+1}) = Events_{obs}(v_k,\ v_{k+1}) \setminus Events^{\cup}_{exp}(m_k) \quad (15)$$

$$Res_2(m_k, v_k,\ v_{k+1}) = Events_{obs}(v_k,\ v_{k+1}) \setminus Events^{\cap}_{exp}(m_k) \quad (16)$$

$$Res_3(m_k, v_k,\ v_{k+1}) = Events^{\cap}_{exp}(m_k) \setminus Events_{obs}(v_k,\ v_{k+1}) \quad (17)$$

$$Res_4(m_k, v_k,\ v_{k+1}) = Events^{\cup}_{exp}(m_k) \setminus Events_{obs}(v_k,\ v_{k+1}) \quad (18)$$

In a practical context, the PLC identifies the activation of an input through its peripherals, i.e., an element of the set $l_{O,k}$. The primary challenge lies in the outputs, set $l_{O,k}$. In AMS, the PLC submits a signal to activate an actuator, but there is no direct confirmation that the actuator has been activated. This can result in critical failures, including incomplete movements, which in turn impact operator safety, product quality and process efficiency. This paper proposes an embedded system that actively checks the actuator response, thus ensuring that faults are detected in time.

As illustrated in Figure 6, the designed embedded system is equipped with non-invasive current sensors capable of confirming the activation of the output elements. This is achieved through four AC/DC doughnut-type and four AC hook-type current sensors. The sensors transmit the information to the microcontroller, which in turn processes it and shares it with the Mitsubishi PLC via Modbus.

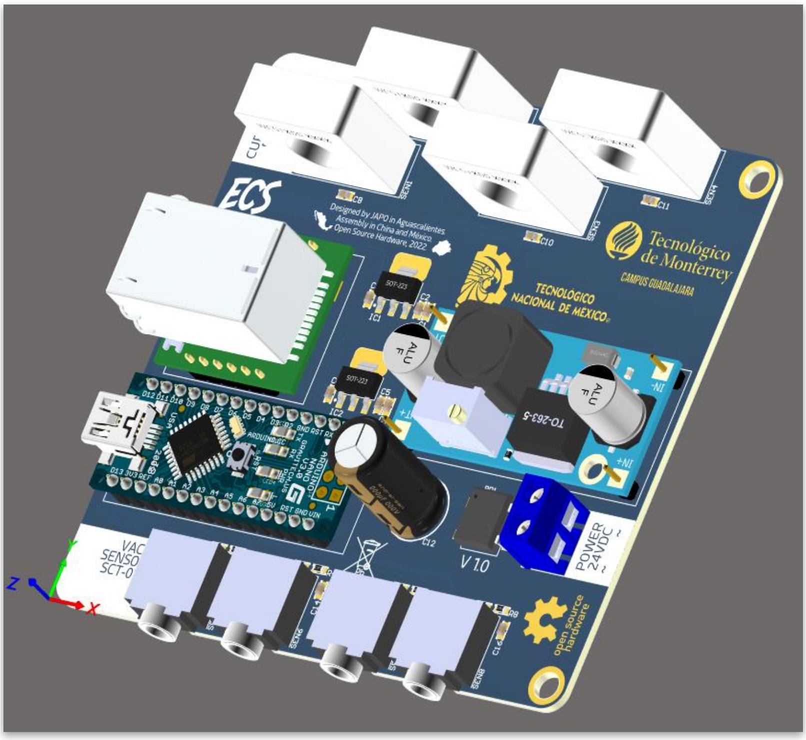

Figure 6. Embedded current measurement system.

Figure 7 illustrates the architecture designed for fault diagnosis applied to the AMS. The diagnoser processes the vector v_k and identifying the presence of any fault. This configuration enables the diagnoser to access precise output information. The non-invasive proposal eliminates the need for modifications to electrical wiring or adding extra peripherals to the PLC, as the information exchange is facilitated via the Modbus protocol.

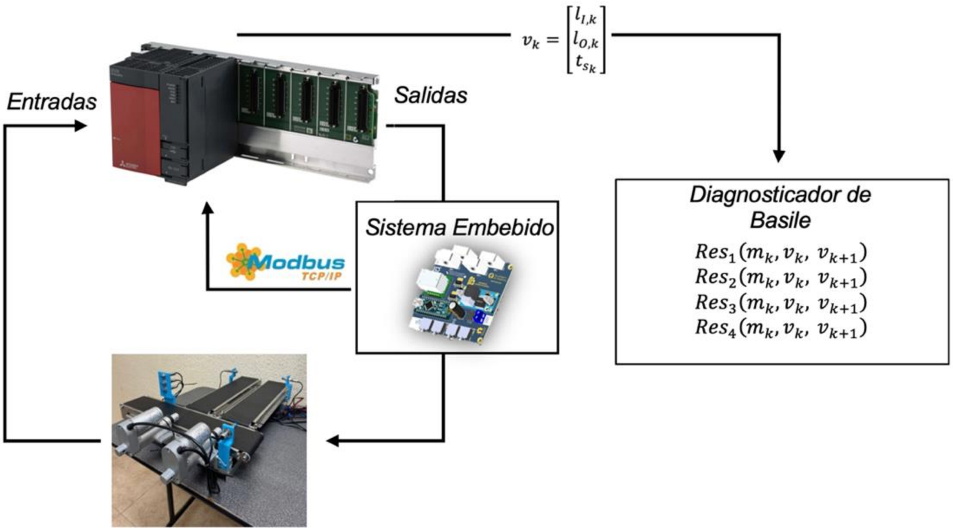

Figure 7. Architecture of the diagnoser.

5. CONCLUSIONS AND FUTURE WORK

The implementation of the active P-semiflow on IPN to guarantee the diagnosability property represents a significant advance from a theory-practice perspective in DES focused on AMS. Previous methodologies restricted the plant language to a single T-semiflow, but the present proposal preserves the totality of T-semiflows, ensuring the diagnosability property in those systems that do not possess it. The developed active P-semiflow proposal establishes dependencies between T-semiflows and non-diagnosable faults. This contribution provides a solid foundation for the development of less restrictive active fault diagnosis methods. Future work will investigate the applicability of active P-semiflow in more complex systems, such as those with a larger number of elements, which pose challenges for system modeling and the analysis of diagnosability properties. It has not yet been determined whether the active P-semiflow can impose the diagnosability property on more than one fault simultaneously.

Regarding respect to the implementation of the embedded system in the fault diagnosis schemes of Basile's method [5], it was possible to enhance the accuracy of the verdict by providing direct and real-time information about the state of the outputs. Additionally, the dependency of assumptions on outputs is reduced, which represents a significant contribution to the implementation of diagnostic schemes in AMS. Future research will explore the optimization of the embedded system, focusing on aspects such as increasing the number of peripherals and the processing speed of the microcontroller for more complex and diversified environments. This will enable the revision of its performance in real conditions.

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