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A Discussion on Fault detection for a class of Hybrid Petri Nets

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Abstract: This paper is about fault detection for hybrid dynamical systems modeled with Partially Observed Timed Hybrid Petri Nets (POTHPNs). The marking of some continuous places and the firing of some discrete transitions are assumed to be measured on-line. Abrupt faults are considered as unexpected firings of some discrete silent transitions. From the collected measurements, a fault detection approach is proposed that combines residual design based on continuous time observers with a discrete diagnosis method based on the computation of all discrete trajectories that are consistent with the measurements. The method is suitable for the class of hybrid systems that concerns continuous processes driven by discrete controllers.

Keywords: Timed hybrid Petri nets, observers, fault detection, fault diagnosis.

1. INTRODUCTION

The prevention of faults is a critical issue in numerous systems to preserve the safety of both equipment and humans. These issues have been addressed in several studies with fault detection and diagnosis (FDD) methods. The aim of fault detection is to create an alarm each time a fault occurs, and the aim of diagnosis is to isolate the fault within a group of candidates (Blanke *et al.*, 2003).

In the domain of discrete event systems (DESs), fault detection and diagnosis FDD has been often formulated with automata and with Petri nets (PNs), in particular labeled PNs. Various approaches have been proposed; these are based either on the analysis of the PN reachability graph or on the direct properties of the PNs (Cabasino, *et al.*, 2012)(Dotoli, *et al.*, 2009)(Basile, *et al.*, 2009)(Ramírez-Treviño, *et al.*, 2007) (Alcaraz-Mejía, *et al.*, 2003). Other methods have been developed based on partially observed Petri nets (POPNs) (Ru & Hadjiscotis, 2009)(Lefebvre, 2014a; 2014b). The previous methods are based on a model that includes the faulty behaviors (represented with faulty transitions).

In the domain of continuous systems, a large literature also exists for FDD methods (Blanke *et al.*, 2003). Some results have been adapted for timed continuous PNs that relax the integrity constraints of the original discrete nets using fluidification and provide a smart approximation of the discrete behaviors (Silva and Recalde, 2004; Silva *et al.*, 2011). Fluidification and FDD issues represented as linear programming problems have been considered for untimed nets (Seatzu *et al.*, 2009, Mahulea *et al.*, 2012). These works are based on an approach similar to the usual diagnosis of DESs associated to an integer constraint relaxation. For timed continuous Petri nets, some works about observability have been considered. Structural and generic observability have been investigated in (Mahulea *et al.*, 2010). A multi-structure Luenberger observer with a specific structure associated to each timed continuous PNs configuration has been proposed in (Julvez *et al.*, 2008). Then, distinguishability of the configurations (Aguayo-Lara *et al.*, 2012), sensor placement problems (Aguayo-Lara *et al.*, 2011a) and design of single-structure observers (Aguayo-Lara *et al.*, 2011b; 2014) have been considered. These results have been used to detect and isolate abrupt and drift faults in timed continuous Petri nets (Lefebvre and Aguayo-Lara, 2015).

In this work, we consider the problem of fault detection for a class of hybrid Petri nets that represents continuous processes driven by discrete controllers. The discrete part includes the controller and also the fault processes that may be intermittent. The nets are partially observed: the marking of some continuous places and the firing of some discrete transitions are measured on-line. From these measurements, a fault detection approach is proposed. It combines residual design based on observers for the continuous measurements as developed in (Lefebvre and Aguayo-Lara, 2015) with a discrete diagnosis method based on the computation of all discrete trajectories that are consistent with the measurements as developed in (Lefebvre, 2014a; 2014b). The main contribution of the article is to use the continuous residuals to extend the discrete observation sequences by adding an estimation of some silent events.

2. PETRI NETS SYSTEMS: BASIC CONCEPTS

For this work, it is assumed that the reader is somehow familiar with PNs, its continuous and hybrid relaxations s. An interested reader should consult (David & Allah, 1992) for further details.

2.1 Hybrid Timed Petri nets

Hybrid Petri nets (HPNs) have been developed to model and study a large class of hybrid dynamical systems (HDSs) (Silva and Recalde, 2004). A HPN structure is defined as $G = \langle \boldsymbol{P}, \boldsymbol{T}, W_{PR}, W_{PO} \rangle$. $\boldsymbol{P}$ is a set of n_d discrete places p_i, $i = 1,...,n_d$ and n_c

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continuous places p_i, $i = n_d+1,..., n_d+n_c$: $\boldsymbol{P} = \boldsymbol{P_d} \cup \boldsymbol{P_c}$ such that $n = |\boldsymbol{P}| = n_d + n_c$. Similarly, $\boldsymbol{T}$ is a set of q_d discrete transitions $t_j, j = 1,...,q_d$ and q_c continuous ones $t_j, j = q_d+1,..., q_d+q_c$: $\boldsymbol{T} = \boldsymbol{T_d} \cup \boldsymbol{T_c}$ such that $q = |\boldsymbol{T}| = q_d + q_c$. $W_{PO} \in (\mathbf{R}^+)^{n\times q}$ and $W_{PR} \in (\mathbf{R}^+)^{n\times q}$ are the post and pre incidence matrices ($\mathbf{R}^+$ is the set of non-negative real numbers) that define the structure of the net and $W = W_{PO} - W_{PR}$ is the incidence matrix that is written as (1):

$$W = \begin{pmatrix} W^{dd} & W^{dc} \\ W^{cd} & W^{cc} \end{pmatrix} \tag{1}$$

where the sub-matrices of W have proper dimensions to refer respectively to the discrete and continuous transitions and places. A continuous transition t_j may have as input or output both continuous or discrete places subject to the following condition: $\forall\ (p_i;\ t_j) \in \boldsymbol{P_d} \times \boldsymbol{T_c}$, $W^{dc}{}_{PR}(p_i;\ t_j) = W^{dc}{}_{PO}(p_i;\ t_j)$ which implies $W^{dc}(p_i;\ t_j) = 0$. This property ensures that the firing of a continuous transition does not alter the marking of the discrete places, whatever the evolution of the net is. A discrete transition t_j has only discrete places as input or output: $\forall\ (p_i;\ t_j) \in \boldsymbol{P_c} \times \boldsymbol{T_d}$, $W^{cd}{}_{PR}(p_i;\ t_j) = W^{cd}{}_{PO}(p_i;\ t_j) = 0$. Thus $W^{cd}{}_{PR} = W^{cd}{}_{PO} = 0$. To conclude the class of HPNs, considered in this article, corresponds to continuous processes (modeled by the continuous part of the HPNs) driven by discrete event systems (modeled by the discrete part of the HPNs). In addition the considered PN structures are assumed to be k-bounded.

$M(\tau) = ((M_d(\tau))^T,\ (M_c(\tau))^T)^T$ refers to the marking of the HPN at date τ where $M_d(\tau) \in (\mathbf{Z}^+)^{nd}$ is the discrete marking vector ($\mathbf{Z}^+$ is the set of non-negative integer numbers) and $M_c(\tau) \in (\mathbf{R}^+)^{nc}$ is the continuous marking vector. $M_I = M(0)$ is the initial marking at date $\tau = 0$. The firing count vector of discrete and continuous transitions at date τ is given by $X(\tau) = ((X_d(\tau))^T,\ (X_c(\tau))^T)^T$ such that $X_d(\tau) \in (\mathbf{Z}^+)^{qd}$ and $X_c(\tau) \in (\mathbf{R}^+)^{qc}$. The enabling degree $enab_j(\tau,M)$ is given by (2) for a discrete transition $t_j \in \boldsymbol{T_d}$ and by (3) for a continuous transition $t_j \in \boldsymbol{T_c}$:

$$enab_j(\tau,M) = \min\{\lfloor m_i(\tau)/W^{PR}(p_i;\ t_j)\rfloor \text{ for all } p_i \in {}^\circ t_j\},\ t_j \in \boldsymbol{T_d} \tag{2}$$

$$enab_j(\tau,M) = \min\{m_i(\tau)/W^{PR}(p_i;\ t_j) \text{ for all } p_i \in {}^\circ t_j\},\ t_j \in \boldsymbol{T_c} \tag{3}$$

where ${}^\circ t_j$ stands for the preset of t_j and $\lfloor\ .\ \rfloor$ stands for the integer part of (.).

Timed HPNs (THPNs) are HPNs where temporal constraints have been added. A THPN system is defined as <G, M_I, D_{min}, X_{max}>. On one hand, $D_{min} = (d_{min\ j}) \in (\mathbf{R}^+)^{qd}$ is the vector of the minimal firing delays of the discrete transitions and immediate transitions are transitions with null firing delays: $d_{min\ j} = 0$. Before firing a discrete transition t_j, tokens are reserved in the preset of t_j during a duration $d_j \geq d_{min\ j}$. On the other hand, $X_{max} = \mathrm{diag}(x_{max\ j}) \in (\mathbf{R}^+)^{qc \times qc}$ is the matrix of the firing rates of the continuous transitions. The firing of each continuous transition t_j is a flow with a rate $x_j(\tau)$ at date τ that does not exceed $x_{max\ j}$. The time semantic is infinite server for the continuous transitions, thus $x_j(\tau) = x_{max\ j}.enab_j(\tau,M)$ and the firing of the discrete transitions occurs as soon as the temporal constraints are satisfied. Conflicts may occurs that are solved according to arbitrary policy that is not considered here. As long as the continuous places are not connected with the discrete transitions there is no additional constraints to consider.

Switches occur in the continuous part of the THPNs according to the function "min(.)" in the expression of the enabling degree (3). Let us denote the critical place(s) for continuous transition t_j at time τ as the place(s) p_i such that i correspond(s) to the value(s) of the index k for which the quantity of tokens $m_k(\tau)\ /\ w^{PR}{}_{kj}$ is minimal for all continuous places $p_k \in {}^\circ t_j$. The continuous reachable space is partitioned into K_c regions (i.e. polyhedral sets in marking space) with $K_c \leq \Pi\{|\boldsymbol{P_c} \cap {}^\circ t_j|,\ j = 1,...,q_c\}$: These regions are characterized by constraint matrices $A_h \in (\mathbf{R}^+)^{qc \times n}$, $h = 1,\ldots,K_c$ $A_h = (a^h{}_{ij})$, where $a^h{}_{ji} = 1/w^{PR}{}_{ij}$ if p_i is the unique critical place of transition t_j anywhere in the interior of region h and $a^h{}_{ji} = 0$ otherwise (Lefebvre, 2012).

Finally, τ_k, $k \geq 0$ are the dates when discrete firings occur or when the continuous marking switches from one region to another and $\tau_0 = 0$. For simplicity, let us denote A_k as the region of the continuous marking in interval $[\tau_k,\ \tau_{k+1}[$ and $X_d(\tau_k)$ as the discrete firing count vector at date τ_k. If τ_k corresponds to a region switch due to the continuous places, then $X_d(\tau_k) = 0$ and if τ_k corresponds to a discrete firing that does not lead to any region switch, then $A_k = A_{k\text{-}1}$. Thus the dynamics of the THPN are defined with equation (4):

$$M_d(\tau_k) = M_d(\tau_{k-1}) + W^{dd}.X_d(\tau_k),\ k > 0$$

$$dM_c(\tau)\ /\ d\tau = W^{cc}.X_{max}.A_k.(M_d(\tau_k))^T\ (M_c(\tau))^T)^T,\ \tau \in [\tau_k,\ \tau_{k+1}[\tag{4}$$

2.2 Partially observed timed hybrid Petri nets

POTHPNs are THPNs for which its behavior is partially known, i.e. it is not known the entire state of the Continuous part of the system nor the whole set of events occurring on its Discrete part. The measurements can be obtained from a set of sensors that capture the occurrence of some discrete events, which are associated to discrete transitions. When an event occurs, then a label can be obtained with a sensor function L. Also, partial information can be obtained from continuous part of the system with the measurement of the marking of a subset of continuous places, that is represented with a marking sensor matrix H. Formally, a POTHPN system is defined as <G, M_I, D_{min}, X_{max}, L, H >, where L and H define the sensor configuration as follows: $L : \boldsymbol{T} \rightarrow \boldsymbol{E} \cup \{\varepsilon\}$ is a labeling function that assigns a label to each discrete transition where $\boldsymbol{E} = \{e_1,...,e_p\}$ is the set of p labels that are assigned to observable discrete transitions and $\boldsymbol{\varepsilon}$ is the null label that is assigned to the silent ones. The labeling function is extended to firing sequences and, the concatenation of labels obviously satisfies: $\varepsilon.\varepsilon = \varepsilon$ and $\varepsilon.e_k = e_k$. Consequently a partial measurement of any timed discrete firing sequence $\sigma = (t_{j1},\ \tau_1)\ \ldots\ (t_{jk},\ \tau_k)\ \ldots\ (t_{jK},\ \tau_K)$ is obtained on the form of a timed observation sequence $\sigma_O = L(\sigma) = (e_{p1},\ \tau_1)\ \ldots\ (e_{pk'},\ \tau_{k'})\ \ldots\ (e_{pK'},\ \tau_{K'})$ where silent transitions have been removed and $e_{pk'}$ is the label of the k'^{th} measured event at date $\tau_{k'}$. A partial measurement of the continuous part of the system is also considered. For this purpose, $\boldsymbol{P_O}$ is defined as the set of measured continuous places and the marking sensor matrix $H \in (\mathbf{R})^{r \times nc}$ defines the projection of the continuous part of the marking vector M_c over a subset of r places which marking is measured on-line. If a place p_i is measured, then matrix H has