SimHPN: A MATLAB toolbox for simulation, analysis and design with hybrid Petri nets

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ABSTRACT

This paper presents a MATLAB embedded package for hybrid Petri nets called SimHPN. It offers a collection of tools devoted to simulation, analysis and synthesis of dynamical systems modeled by hybrid Petri nets. The package supports several server semantics for the firing of both, discrete and continuous, types of transitions. Besides providing different simulation options, SimHPN offers the possibility of computing steady state throughput bounds for continuous nets. For such a class of nets, optimal control and observability algorithms are also implemented. The package is fully integrated in MATLAB which allows the creation of powerful algebraic, statistical and graphical instruments that exploit the routines available in MATLAB.

1. Introduction

Petri nets (PNs) [1,2] is a mathematical formalism for the description of discrete-event systems, that has been successfully used for modeling, analysis and synthesis purposes of such systems. A key feature of a PN is that its structure can capture graphically fundamental primitives in concurrency theory such as parallelism, synchronization, mutual exclusion, etc. The state of a PN system is given by a vector of non-negative integers representing the marking of its places.

As any other formalism for discrete event systems, PNs suffer from the state explosion problem which produces an exponential growth of the size of the state space with respect to the initial marking. One way to avoid the state explosion is to relax the integrality constraint in the firing of transitions and deal with transitions that are fired in real amounts. A transition whose firing amount is allowed to be any real number between zero and its enabling degree is said to be a continuous transition. The firing of a continuous transition can produce a real, not integer, number of tokens in its input and output places. If all transitions of a net are continuous, then the net is said to be continuous. If a non-empty proper subset of transitions is continuous, then the net is said to be hybrid [3].

Different time interpretations can be considered for the firing of continuous transitions. The most popular ones are infinite and finite server semantics which represent a first order approximation of the firing frequency of discrete transitions. For a broad class of Petri nets, infinite server semantics offer a better approximation of the steady-state throughput than finite server semantics [4]. Moreover, finite server semantics can be exactly mimicked by infinite server semantics in discrete transitions simply by adding a self-loop place. A third firing semantics, called product semantics, is also frequently used when dealing with biochemical and population dynamics systems.

In this paper, we present a new MATLAB embedded software called SimHPN that provides support for infinite server and product semantics in both, discrete and continuous, types of transition. A description of a preliminary version of this software can be found in [5,6]. As far as we know, this is the first MATLAB package that enables the analysis and simulation of hybrid
Definition 1. A Hybrid Petri Net (HPN) system is a pair \( \langle \mathcal{N}, m_0 \rangle \), where \( \mathcal{N} = \langle P, T, \text{Pre}, \text{Post} \rangle \) is a net structure, with set of places \( P \), set of transitions \( T \), pre and post incidence matrices \( \text{Pre}, \text{Post} \in \mathbb{R}_{\geq 0}^{|P| \times |T|} \), and \( m_0 \in \mathbb{R}_{\geq 0}^{|P|} \) is the initial marking.

The token load of the place \( p_i \) at marking \( m \) is denoted by \( m_i \), and the preset and postset of a node \( X \in P \cup T \) are denoted by \( X^* \) and \( X^\ast \), respectively. For a given incidence matrix, e.g., \( \text{Pre}, \text{Pre}(p_i, t_j) \) denotes the element of \( \text{Pre} \) in row \( i \) and column \( j \).

In an HPN, the set of transitions \( T \) is partitioned into two sets \( T = T^c \cup T^d \), where \( T^c \) contains the set of continuous transitions and \( T^d \) the set of discrete transitions. In contrast to other works, the set of places \( P \) is not explicitly partitioned, i.e., the marking of a place is a natural or real number depending on the firings of its input and output transitions. Nevertheless, in order to make net models easier to understand, those places whose marking can be a real non-integer number will be depicted as double circles (see \( p_1^c \) in Fig. 3), and the rest of places will be depicted as simple circles (such places will have integer markings; see \( p_1^c \) in Fig. 3). Continuous transitions are graphically depicted as two bars (see \( t_2^d \) in Fig. 3), while discrete transitions are represented as empty bars (see \( t_2^d \) in Fig. 3).

Two enabled transitions \( t_i \) and \( t_j \) are in conflict when they cannot occur at the same time. For this, it is necessary that \( \ast t_i \cap \ast t_j \neq \emptyset \), and in that case it is said that \( t_i \) and \( t_j \) are in structural conflict relation. Right and left non negative annulars of the token flow matrix \( \mathcal{C} \) are called \( T \)- and \( P \)-semiflows, respectively. A semiflow \( \mathcal{V} \) is minimal when its support, \( \| \mathcal{V} \| = \{ i \mid \mathcal{V}(i) \neq 0 \} \), is not a proper superset of the support of any other semiflow, and the greatest common divisor of its elements is one. If there exists \( \mathcal{Y} > 0 \) such that \( \mathcal{Y} \cdot \mathcal{C} = 0 \), the net is said to be conservative, and if there exists \( \alpha > 0 \) satisfying \( \mathcal{C} \cdot \alpha = 0 \), the net is said to be consistent. As it will be seen, the basic tasks that \( \text{SimHPN} \) can perform on untimed hybrid Petri nets are related to the computation of minimal \( T \)- and \( P \)-semiflows.

The enabling degree of a transition \( t_j \in T \) is:

\[
\text{enab}(t_j, m) = \begin{cases} 
\min_{p_i \in \ast t_j} \left( \frac{m_i}{\text{Pre}(p_i, t_j)} \right) & \text{if } t_j \in T^d \\
\min_{p_i \in \ast t_j} \left( \frac{m_i}{\text{Pre}(p_i, t_j)} \right) & \text{if } t_j \in T^c.
\end{cases}
\]

Transition \( t_j \in T \) is enabled at \( m \) iff \( \text{enab}(t_j, m) > 0 \). An enabled transition \( t_j \in T \) can fire in any amount \( \alpha \) such that \( 0 \leq \alpha \leq \text{enab}(t_j, m) \) and \( \alpha \in \mathbb{N} \) if \( t_j \in T^d \) and \( \alpha \in \mathbb{R} \) if \( t_j \in T^c \). Such a firing leads to a new marking \( m' = m + \alpha \cdot \mathcal{C}(\cdot, t_j) \), where \( \mathcal{C} = \text{Post} - \text{Pre} \) is the token-flow matrix and \( \mathcal{C}(\cdot, t_j) \) is its \( j \) column. If \( m \) is reachable from \( m_0 \) through a finite sequence \( \sigma \), the state (or fundamental) equation, \( m = m_0 + \mathcal{C} \cdot \sigma \), is satisfied, where \( \sigma \in \mathbb{R}_{\geq 0}^{|T|} \) is the firing count vector. According to this firing rule the class of nets defined in Definition 1 is equivalent to the class of nets defined in [3,9].

2.2. Timed hybrid Petri net systems

Different time interpretations can be associated to the firing of transitions. Once an interpretation is chosen, the state equation can be used to show the dependency of the marking on time, i.e., \( m(\tau) = m_0 + \mathcal{C} \cdot \sigma(\tau) \). The term \( \sigma(\tau) \) is the firing count vector at time \( \tau \). Depending on the chosen time interpretation, the firing count vector \( \sigma(\tau) \) of a transition \( t_j \in T^c \) is differentiable with respect to time, and its derivative \( \dot{\sigma}(\tau) = \mathcal{J}(\tau) \) represents the continuous flow of \( t_j \). As for the timing of discrete transitions, several definitions exist for the flow of continuous transitions. \( \text{SimHPN} \) accounts for infinite server and product server semantics in both continuous and discrete transitions, and additionally, discrete transitions are also allow to have deterministic delays.

Definition 2. A Timed Hybrid Petri Net (THPN) system is a tuple \( \langle \mathcal{N}, m_0, \tau, \lambda \rangle \) where \( \langle \mathcal{N}, m_0 \rangle \) is a HPN, \( \tau : T \rightarrow \{id, pd, dd, ic, pc\} \) establishes the time semantics of transitions and \( \lambda : T \rightarrow \mathbb{R}_{\geq 0} \) associates a real parameter to each transition related to its semantics.
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