Liveness of an extended S3PR

Ding Liu a, ZhiWu Li b,∗, MengChu Zhou c

a School of Electro-Mechanical Engineering, Xidian University, Xi’an 710071, China
b Automation Technology Lab, Institute of Computer Science, Martin Luther University of Halle-Wittenberg, Kurt-Mothes, 06120 Halle, Germany
c Department of Electrical and Computer Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA

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A B S T R A C T

Most existing prevention methods tackle the deadlock issue arising in flexible manufacturing systems modeled with Petri nets by adding monitors and arcs. Instead, this paper presents a new one based on a characteristic structure of WS3PR, an extension of System of Simple Sequential Processes with Resources (S3PR) with weighted arcs. The numerical relationships among weights, and between weights and initial markings are investigated based on simple circuits of resource places, which are the simplest structure of circular wait, rather than siphons. A WS3PR satisfying a proposed restriction is inherently deadlock-free and live by configuring its initial markings. A set of polynomial algorithms are developed to implement the proposed method. Several examples are used to illustrate them.

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1. Introduction

As an important component of Computer Integrated Manufacturing, a Flexible Manufacturing System (FMS) is built with some amount of flexibility that allows it to react in the case of changes of production requirements, whether predicted or unpredicted. It mainly consists of robots, computer-controlled machines, and conveyors, all known as resources of a system. They are dynamically arranged according to varying specifications to meet the demand of high-mix-low-volume production. Several different raw workpieces are concurrently processed in it by various resources. Due to the concurrency and limited quantity of shared resources, one undesirable situation is the deadlock arising in a fully automated system (Zhou & DiCesare, 1993; Li & Zhou, 2009; Wu & Zhou, 2010).

As an effective formalism for modeling and analyzing FMS, Petri nets are used extensively to reveal the relationship between deadlock and resources (Jeng & DiCesare, 1995; Wu, 2009; Xing, Hu, & Chen, 1996; Zhou & Fanti, 2005). The primary causes of deadlock are the deficiency of resources and their improper allocation. Therefore, deadlock can be handled by simply increasing resources, which are unfortunately limited in practice and mean more cost, or by adding some control to coordinate the use of shared resources among different processes. Four necessary conditions of deadlock summarized in Coffman, Elphick, and Shoshani (1971) become the starting point of developing various deadlock control policies. Since the seminal work by Ezpeleta, Colom, and Martínez (1995), various deadlock prevention methods, e.g., Abdallah and ElMaraghy (1998), Barkaoui and Abdallah (1995), Barkaoui, Chaoui, and Zouari (1997), Barkaoui, Couvreur, and Klai (2005), Hu, Zhou, and Li (2009), Huang, Jeng, Xie, and Chung (2001), Huang (2007), Li and Zhou (2004, 2006), Li, Hu, and Wang (2007), Park and Reveliotis (2001), Tricas, García-Vallés, Colom, and Ezpeleta (1998), Uzam and Zhou (2006) and Xing and Hu (2005) are implemented by adding monitors (also called control places) to the original model plant, most of which are based on siphons. System of Simple Sequential Processes with Resources (S3PR) (Ezpeleta et al., 1995) is widely used to model and analyze deadlock problems and other properties of FMS.

Numerous extensions to S3PR, such as L-S3PR (Wang, Li, Jia, & Zhou, 2009), LS3PR (Ezpeleta, García-Vallés, & Colom, 1998), ES3PR (Huang et al., 2001), WS3PR (Tricas & Martínez, 1995), S4R (Abdallah & ElMaraghy, 1998; Hu et al., 2009), S4PR (Tricas, García-Vallés, Colom, & Ezpeleta, 2000), S3PGR2 (Chao, 2007; Park & Reveliotis, 2001), and G-systems (Zouari & Barkaoui, 2003), are subsequently proposed, which can be used to model more general systems. This study deals with WS3PR, a weighted extension of...
A generalized Petri net (structure) is a four-tuple \((P, T, F, W)\) where \(P\) and \(T\) are finite and nonempty sets. \(P\) is the set of places and \(T\) is a set of transitions with \(P \cap T = \emptyset\). \(F \subseteq (P \times T) \cup (T \times P)\) is a flow relation of the net, represented by arcs with arrows from places to transitions or from transitions to places. \(W : (P \times T) \cup (T \times P) \rightarrow N\) assigns a weight to an arc: \(W(x, y) > 0\) if \((x, y) \in F\), and \(W(x, y) = 0\) otherwise, where \(x, y \in P \cup T\). A mapping assigns a weight to an arc: \(W(x, y) > 0\) if \((x, y) \in F\), and \(W(x, y) = 0\) otherwise, where \(x, y \in P \cup T\). A net \(N\) is called an ordinary Petri net.

A marking \(M\) of \(N\) is a mapping from \(P \rightarrow N\), denoted \(M(p)\). The number of tokens in place \(p\) is \(M(p)\). A place \(p\) is marked by a marking \(M\) if \(M(p) > 0\). It is insufficiently marked with respect to a transition \(t \in P^*\) if \(M(p) < W(p, t)\). Note that \(P^* = \{y \in P \cup T | (x, y) \in F\}\) is a set of tokens. Pre-set of \(x\) is \(x^- = \{y \in P \cup T | (y, x) \in E\}\). The pre-set and post-set of a set of nodes can be defined. For example, \(p_0 \subseteq P\), \(p^* = \{p_0\}^*\). A subnet \(S \subseteq P\) is marked by \(M\) if at least one place in \(S\) is marked by \(M\). The sum of tokens in all places in \(S\) is denoted by \(M(S)\), i.e., \(M(S) = \sum_{p \in S} M(p)\). S is said to be empty at \(M\) if \(M(S) = 0\). S is insufficiently marked at \(M\) if \(\forall p \in S, Vt \in T, M(p) < W(p, t)\). \((N, M_0)\) is called a net system or marked net and \(M_0\) is called an initial marking of \(N\).

For a Petri net modeling an FMS, an initial marking represents the numbers of different raw workpieces that are to be concurrently processed in the system, and the quantity (and/or capacities) of every type of resources, such as machining centers and robots. For example, the ordinary Petri net model shown in Fig. 1(a) is with \(P = \{p_1, p_2\}, T = \{t_1, t_2\}, F = \{(p_1, t_1), (t_1, p_2), (t_2, p_2), (t_2, p_3), (t_3, p_4), (t_4, p_4), (t_1, p_5), (t_5, p_5), (t_5, p_6), (t_6, p_6), (t_6, p_7)\}\), and each arc’s weight is one. Its initial marking is \(M_0 = (30, 0, 0, 0, 2, 5)\), often written as \(M_0 = 30p_1 + 2p_2 + 5p_6\) to save space.

Definition 2. Let \((N_1, M_1)\) and \((N_2, M_2)\) be two generalized nets with \(N_1 = (P_1, T_1, W_1)\) and \(N_2 = (P_2, T_2, W_2)\), denoted by \(N_1 \circ N_2\) via the set of shared places \(P_c\). If \((1) P = P_1 \cup P_2, T = T_1 \cup T_2, F = F_1 \cup F_2, W = W_1 \cup W_2;\) and \((2) \forall y \in P_1 \setminus P_c, M(p) = M_1(p) = M_2(p) = 0;\) and \(\forall y \in P_2 \setminus P_c, M(p) = M_2(p)\). This concept of net composition is employed by the recursive definitions of \(S^3\)PR and \(WS^3\)PR next.

2.2. \(S^3\)PR and \(WS^3\)PR

In this subsection, the definitions of both \(S^3\)PR and \(WS^3\)PR are introduced to make this paper self-contained.

Definition 3. A simple sequential process (\(S^3\)P) is an ordinary Petri net \(N = (P_0 \cup P_0, T, F)\) where \((1) P_0 \neq \emptyset\) is called a set of operation or activity places; \((2) P_0 = \{p_0\}\) with \(p_0 \notin P_0\) is called the idle process place; \((3) N\) is a strongly connected state machine; and \((4)\) every directed circuit of \(N\) contains \(p_0\) called a path part.

If \(t \in P^*_o \neq \emptyset\), \(t\) is called a source (sink) transition. A length of a path from \(t\) to \(t\) of sink transition \(t_{sink}\) is defined as the number of downstream places from \(t\) to \(t_{sink}\). For example, in Fig. 1 the length of a path from \(t_3\) to \(t_4\) is 1. The concept of path plays an important role in showing the relationship between the structures of circular waits and deadlocks.

Definition 4. A simple sequential process with resources (\(S^3\)PR) is an ordinary Petri net \(N = (P_0 \cup P_0 \cup P_0, T, F)\) such that:

1. The subnet generated by \(X = P_0 \cup P_0 \cup T\) is an \(S^2\)P.

Fig. 1. (a) An \(S^3\)PR (\(S^3\)PR) net model and (b) a \(WS^3\)PR (\(WS^3\)PR) net model.
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