Automatica 46 (2010) 1008–1018

Contents lists available at ScienceDirect

Automatica

journal homepage: www.elsevier.com/locate/automatica

Liveness of an extended S^3PR ☆

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ARTICLE INFO

Article history:
Received 19 February 2009
Received in revised form
15 July 2009
Accepted 8 March 2010
Available online 21 April 2010

Keywords:
Flexible manufacturing system (FMS)
Petri nets
Deadlock prevention
Polynomial algorithms
Circular wait

ABSTRACT

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 WS^3PR, an extension of System of Simple Sequential Processes with Resources (S^3PR) 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 WS^3PR 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.

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 (S^3PR) (Ezpeleta et al., 1995) is widely used to model and analyze deadlock problems and other properties of FMS.

Numerous extensions to S^3PR, such as L-S^3PR (Wang, Li, Jia, & Zhou, 2009), LS^3PR (Ezpeleta, García-Vallés, & Colom, 1998), ES^3PR (Huang et al., 2001), WS^3PSR (Tricas & Martínez, 1995), S^4R (Abdallah & ElMaraghy, 1998; Hu et al., 2009), S^4PR (Tricas, García-Vallés, Colom, & Ezpeleta, 2000), S^3PGR^2 (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 WS^3PR, a weighted extension of

☆ This work was supported by the National Natural Science Foundation of China under Grant No. 60773001, the National Research Foundation for the Doctoral Program of Higher Education, the Ministry of Education, PR China, under Grant No. 20070701013, "863" High-tech Research and Development Program of China under Contract No. 2008AA04Z109, and the Chang Jiang Scholars Program, Ministry of Education, PR China. The material in this paper was partially presented at the 2nd IFAC Workshop on Dependable Control of Discrete Systems, Bari, Italy, June 10–12, 2009. This paper was recommended for publication in revised form by Associate Editor Bart De Schutter under the direction of Editor Ian R. Petersen.

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0005-1098/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.automatica.2010.03.011

S^{3}PR, which is a subclass of WS^{3}PSR, S^{3}PGR^2, or S^{4}R. Being different from ordinary Petri nets, the role of weights of arcs in determining the liveness of general ones should be carefully considered. Weights of arcs in WS^{3}PR mean an operation's requirement for multiple resources. The token counts in resource places and numerical relationship between markings and weights restrict the allocation of system resources. Hence, the studies of structures including arc weights and dynamic properties should be combined together during the evolution analysis of a WS^{3}PR. Generally, it is believed that deadlocks are caused by lack of system resources or improper resource allocation. In some situations, the proposed method can make a system live by decreasing system resources instead of simply increasing them. A proper resource allocation is practically guaranteed by a proper numerical relationship between initial markings of resource places and arc weights. Compared with most existing deadlock prevention control policies, the new one does not add any monitors and arcs. The control cost of software and hardware can be saved. Meanwhile, the problem of structural complexity can be avoided. The proposed method is based on a characteristic structure of WS^{3}PR. Before any deadlock prevention policy is applied, its structure should be checked to decide whether it is inherently deadlock-free and live under certain initial markings. The relation between weights and initial markings is established by using simple circuits of resource places. Polynomial algorithms are developed to implement the proposed method.

The rest of this paper is organized as follows: Section 2 presents the definitions of WS^{3}PR. Section 3 defines and analyzes the generalized circular wait, circular blocking, and deadlock in WS^{3}PR. Section 4 reveals the relation between liveness and weights and initial markings of resource places, and proposes a deadlock prevention method requiring no additional monitors. Polynomial algorithms are developed and illustrated in Section 5. Finally, Section 6 concludes the paper.

2. Preliminaries

This section focuses on the recursive definitions from S^{2}P to WS^{3}PR. It begins with the definition of generalized Petri nets and a recall of S^{3}PR.

2.1. Basics of Petri nets

A Petri net, as a graphical and mathematical model, consists of places, transitions, and directed arcs. A formal definition is given as follows:

Definition 1. A generalized Petri net (structure) is a four-tuple $N = (P, T, F, W)$ where P and T are finite and nonempty sets. P is a set of places and T is a set of transitions with $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$. $F \subseteq (P \times T) \cup (T \times P)$ is called a flow relation of the net, represented by arcs with arrows from places to transitions or from transitions to places. $W : (P \times T) \cup (T \times P) \rightarrow \mathcal{N}$ is a mapping that assigns a weight to an arc: $W(x, y) > 0$ if $(x, y) \in F$, and $W(x, y) = 0$ otherwise, where $x, y \in P \cup T$ and $\mathcal{N} = \{0, 1, 2, \ldots\}$. If $W(x, y) = 1$, $\forall (x, y) \in F$, the net N is called an ordinary Petri net.

A marking M of N is a mapping from P to $\mathcal{N}$. $M(p)$ denotes the number of tokens in place p. A place p is marked by a marking M if $M(p) > 0$. It is insufficiently marked with respect to a transition $t \in p^\bullet$ at M if $M(p) < W(p, t)$. Note that $x^\bullet = \{y \in P \cup T | (x, y) \in F\}$ is a post-set of x. Pre-set of x is ${}^\bullet x = \{y \in P \cup T | (y, x) \in F\}$. The pre-set and post-set of a set of nodes can be also defined. For example, given $P_0 \subset P$, ${}^\bullet P_0 = \bigcup_{p \in P_0} {}^\bullet p$ and $x \in P \cup T$, ${}^{\bullet\bullet} x = \bigcup_{y \in {}^\bullet x} {}^\bullet y$. 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 $\forall p \in S, \forall t \in p^\bullet$, $M(p) < W(p, t)$. (N, M_0) is called a net system or marked net and M_0 is called an initial marking of N.

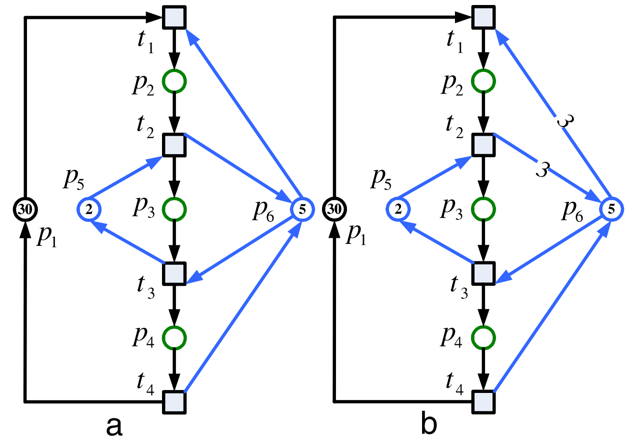

Fig. 1. (a) An S^{2}PR (S^{3}PR) net model and (b) a WS^{2}PR (WS^{3}PR) net model.

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 $P = \{p_1 - p_6\}$, $T = \{t_1 - t_4\}$, $F = \{(p_1, t_1), (t_1, p_2), (p_2, t_2), (t_2, p_3), (p_3, t_3), (t_3, p_4), (p_4, t_4), (t_4, p_1), (t_3, p_5), (p_5, t_2), (t_2, p_6), (p_6, t_3), (t_4, p_6), (p_6, t_1)\}$, and each arc's weight is one. Its initial marking is $M_0 = (\,30 \quad 0 \quad 0 \quad 0 \quad 2 \quad 5\,)^T$, often written as $M_0 = 30p_1 + 2p_5 + 5p_6$ to save space.

Definition 2. Let (N_1, M_1) and (N_2, M_2) be two generalized nets with $N_1 = (P_1, T_1, F_1, W_1)$ and $N_2 = (P_2, T_2, F_2, W_2)$, where $P_1 \cap P_2 = P_C \neq \emptyset$ and $T_1 \cap T_2 = \emptyset$. (N, M) with $N = (P, T, F, W)$ is said to be the composition of (N_1, M_1) and (N_2, M_2), denoted by $N_1 \circ N_2$, via the set of shared places P_C if (1) $P = P_1 \cup P_2$, $T = T_1 \cup T_2$, $F = F_1 \cup F_2$, and $W = W_1 \cup W_2$; and (2) $\forall p \in P_1 \setminus P_C$, $M(p) = M_1(p)$; $\forall p \in P_2 \setminus P_C$, $M(p) = M_2(p)$; and $\forall p \in P_C$, $M(p) = \max\{M_1(p), M_2(p)\}$.

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^{2}P) is an ordinary Petri net $N = (P_A \cup P_0, T, F)$ where (1) $P_A \neq \emptyset$ is called a set of operation or activity places; (2) $P_0 = \{p_0\}$ with $p_0 \notin P_A$ 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 part path.

If $t \in p_0^\bullet$ ($t \in {}^\bullet p_0$), t is called a source (sink) transition. A length of a path from t to 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 part paths 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^{2}PR) is an ordinary Petri net $N = (P_A \cup P_0 \cup P_R, T, F)$ such that

(1) The subnet generated by $X = P_A \cup P_0 \cup T$ is an S^{2}P;