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Design of optimal Petri-net controllers for a class of flexible manufacturing systems with key resources

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ABSTRACT

Based on Petri net models, this work aims to address deadlock prevention problem for a class of flexible manufacturing systems (FMSs), which can be modeled by systems of simple sequential processes with resources (S^3PRs). In an S^3PR, a ξ-resource is a resource with unit capacity shared by two or more maximal perfect resource transition circuits (MPRT-circuits) that do not contain each other. For S^3PRs without ξ-resources, the optimal Petri net-based polynomial complexity deadlock avoidance policies are synthesized in the previous work. This work focuses on the design of optimal Petri net controllers for S^3PRs with ξ-resources. First, the concepts of key resources and key transitions are introduced. A key resource is a special ξ-resource. If there is a key transition in an S^3PR, there is a key resource in it, but not vice versa. For S^3PRs with key resources, if there is no key transition in them, optimal Petri net controllers are synthesized; if there exist key transitions in them, it proves that when these nets are maximally permissive controlled (called as first-controlled), key transitions can result in the occurrence of deadlock phenomena (called as secondary-deadlock) in the controlled nets. Second, for S^3PRs with key resources that contain key transitions and satisfy the Key-condition, secondary-deadlocks can be characterized by maximal perfect control transition circuits (MPCT-circuits) that are saturated at some reachable markings of their first-controlled systems. Then, by adding a control place and related arcs to each MPCT-circuit, secondary-deadlocks can be prevented and optimal Petri net controllers are designed for S^3PRs with key resources that satisfy the Key-transition. Thereby, an optimal deadlock control policy for a class of FMSs with key resources is synthesized. Finally, a few examples are provided to demonstrate the presented policy.

1. Introduction

A flexible manufacturing system (FMS) is a computer-controlled manufacturing system that contains multiple concurrent flows of job processes, and often exploits shared resources to reduce the production cost. The introduction of heavy resource sharing can increase flexibility, but can lead to deadlock when two or more jobs keep waiting indefinitely for the other jobs in a production sequence to release resources. Deadlocks can reduce productivity drastically or lead to the entire stagnancy.

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Therefore, to effectively operate an FMS and to make the best use of the shared resources, it is necessary to develop an efficient deadlock control policy to guarantee that deadlocks never happen in FMSs [9,43,44].

The development of efficient deadlock control policies for FMSs has received significant attention for over a decade [1,45]. However, the computation of the optimal or maximally permissive deadlock control policy for a general FMS is NP-hard because it involves the problem of determining the safety of a given resource allocation state or enumerating all deadlock structures in the systems, which is NP-hard.

Petri nets are a powerful, graphical, and mathematical tool for modeling and analyzing FMSs due to their inherent characteristics [10,23,29]. Based on Petri nets, three types of deadlock control approaches are developed for FMSs, i.e., deadlock detection and recovery [14,15], deadlock prevention [8,11,12,13,17,18,20,21,22,24,25,33–37], and deadlock avoidance [30,31,39,41]. The first one uses a monitoring mechanism for detecting the deadlock occurrence and a resolution procedure for appropriately preempting some deadlocked resources. Prevention methods are usually achieved by establishing a static resource allocation policy such that the system can never enter a deadlock state. The last one is online control policies that use feedback information on the current resource allocation status and future process resource requirements, to keep the system away from deadlock states.

This work focuses on deadlock prevention methods. Petri net-based deadlock prevention techniques can be classified into reachability graph analysis [2–7,26–28] and structural analysis [16]. The reachability graph analysis method is an important and fundamental approach for verification and qualitative analysis of the Petri net models. Further, it provides complete and detailed information about the dynamic behavior of Petri nets because it requires all state place enumeration. On the contrary, the structural analysis method is marking-independent and only depends on the place-transition relationship of underlying net by the flow relation. The underlying static structure has a potential to provide important information about the dynamic behavior of the system. The latter is utilized to design deadlock control policy in this work. A number of such methods characterize deadlocks in terms of deadlock structures of Petri nets, such as siphons [8,12,15,17,19,25,32,38] and resource transition circuits [11,24,39,40]. Both are structural objects related to the liveness of Petri net models and can be used to characterize and prevent deadlocks. Siphon-based methods for avoiding deadlocks are to add a new control place and related arcs for each unmarked siphon such that it is always marked in the controlled systems. Ezpeleta et al. [8] describe an FMS using a special class of Petri nets named by systems of simple sequential processes with resources (S^3PRs). They prove that a marked S^3PR net is live if and only if each minimal siphon has at least one token at each reachable marking from the initial markings. By adding a control place and related arcs to each unmarked strict minimal siphon (SMS), the liveness of the controlled system can be guaranteed in [8]. Huang et al. [12] propose another prevention policy for S^3PRs without complete computation of siphons. This policy is an iterative approach and consists of two main stages. The first stage is known as siphon control, and the second stage is known as augmented siphon control. Li and Zhou [17] pioneer in the concept of elementary siphons. They then make other siphons controlled by controlling their elementary ones. Liu et al. [25] present the concept of controllable siphon basis to design a suboptimal Petri net controller with small size.

Xing et al. [39,40] utilize resource transition circuits (RT-circuits) to characterize deadlock states in S^3PRs. An RT-circuit is a circuit that only contains resource places and transitions. A deadlock state occurs when a maximal perfect RT-circuit (MPRT-circuit) is saturated, i.e., all tokens in its resource places go to their related operation ones, at a reachable marking. A ξ-resource is a one-unit resource shared by two or more MPRT-circuits that do not contain each other. For a marked S^3PR without ξ-resources, by adding a control place and related arcs to each saturated MPRT-circuit, Xing et al. [39] derive an optimal Petri-net-based polynomial complexity deadlock avoidance policy. For a marked S^3PR with ξ-resources, by reducing all ξ-resources and applying the design of an optimal deadlock avoidance policy for S^3PRs without ξ-resources to the reduced one, a suboptimal deadlock avoidance policy is established, and its computation is of polynomial complexity. If adding to each MPRT-circuit a control place and related arcs, the structural complexity of Petri net controllers is exponential because the number of MPRT-circuits in S^3PRs grows exponentially with the net size. To synthesize a small size controller, Liu et al. [24] propose the concept of transition covers. A transition cover is a set of MPRT-circuits, and the transition set of its MPRT-circuits can cover the set of transitions of all MPRT-circuits. Based on the concept of MPRT-circuits, Han et al. [11] propose a two-stage deadlock prevention policy for S^3PRs with crucial resources. In [42], You et al. design a live Petri net controller for α-S^3PRs with ξ-resources.

Enlightened by the work in [11] and [39], the concepts of key resources and key transitions are introduced. Key resources are a special type of ξ-resources, and the input resources of key transitions are key resources. When each MPRT-circuit in FMSs with key resources is maximally permissive controlled, the existence of key transitions can damage the liveness of these controlled systems (called as first-controlled systems). That is, there still exist deadlock markings in the first controlled systems, and these deadlocks are defined as secondary-deadlock. The Key-condition is proposed, and for the S^3PRs with key resources that satisfy such condition, secondary-deadlocks can be characterized by maximal perfect control transition circuits (MPCT-circuits) that are saturated at some reachable marking of the first controlled systems. Finally, by adding a control place and related arcs to each MPCT-circuit, secondary-deadlock can be prevented, and an optimal deadlock control policy for the S^3PRs with key resources satisfying the Key-transition is synthesized.

The rest of the paper is organized as follows. Section 2 reviews preliminaries used throughout this paper. The concepts of key resources and key transitions are introduced in Section 3. Based on them, maximal perfect control transition circuits are utilized to characterize secondary-deadlock. Meanwhile, an optimal deadlock control policy is developed for a class of S^3PRs with key resources in Section 3. Two examples are utilized to illustrate the deadlock control policy in Section 4. Finally, Section 5 concludes this paper.