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Monitor design with multiple self-loops for maximally permissive supervisors

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ABSTRACT

In this paper, we improve the previous work by considering that a control place can have multiple self-loops. Then, two integer linear programming problems (ILPPs) are formulated. Based on the first ILPP, an iterative deadlock control policy is developed, where a control place is computed at each iteration to implement as many marking/transition separation instances (MTSIs) as possible. The second ILPP can find a set of control places to implement all MTSIs and the objective function is used to minimize the number of control places. It is a non-iterative deadlock control strategy since we need to solve the ILPP only once. Both ILPPs can make all legal markings reachable in the controlled system, i.e., the obtained supervisor is behaviorally optimal. Finally, we provide examples to illustrate the proposed approaches.

1. Introduction

Petri nets [42] are an effective tool to model and control flexible manufacturing systems (FMSs) [56]. Petri nets have compact structures and can be represented in the form of matrixes. Thus, they can be simply analyzed by linear algebras. Deadlocks [16] are a constant issue in FMSs [9,14,17,31,33,34,36–38,40] due to the competition for limited shared resources. The last two decades have shown that Petri nets are widely used in the deadlock control of FMSs, which leads to abundant results [3–5,12,13,15,19,20,23,24,27–30,32,39,58,59,61,63–67,69].

In the framework of Petri nets, a deadlock prevention approach usually finds a supervisor for a system to be controlled, which consists of control places and the arcs connecting them to transitions that belong to the system. The supervisor is computed off-line and once a deadlock control policy is established and enforced, no deadlocks can occur anymore. Based on Petri nets, the performance of a deadlock control policy is always evaluated by three criteria: behavioral permissiveness, structural complexity, and computational complexity. Behavioral permissiveness is measured by the number of legal states kept in the controlled system. In the case that all legal states of a system to be controlled are reachable, the corresponding supervisor is said to be maximally permissive (or optimal). The structural complexity is defined in terms of the number of control places and arcs in a Petri net supervisor. A simplification of the supervisory structure can reduce the costs of hardware and software at implementation stage. An efficient computation indicates that the supervisor can be obtained in a reasonable time. In this work, we mainly focus on the optimization of the first two criteria.

Behavioral optimality plays an important role in the development of deadlock control of Petri nets. A representative work is the theory of regions proposed by Ghaffari et al. [25] and Uzam [52], which can definitely find a maximally permissive Petri net supervisor if it exists. The approach first generates the reachability graph of a net model. Then, the set of marking/transition separation instances (MTSIs) is derived. An MTSI is a pair of a marking M and a transition t, denoted as (M,t), where M is a legal marking and once t fires at M, it yields an illegal marking. For deadlock control purposes, Ghaffari et al. [25] develop an iterative approach where at each iteration, an MTSI (M,t) is singled out and a linear programming model is designed to find a control place to implement (M,t) by preventing t from firing at M. Meanwhile, all legal

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markings are ensured to be reachable. The process carries out until all MTSIs are implemented. Then, a set of control places is obtained, which can make the controlled system live with all legal markings. That is to say, the obtained supervisor is behaviorally optimal. However, the approach does not consider the structural complexity since it always leads to a supervisor with too many control places.

Another representative study based on the reachability graph analysis is presented by Uzam and Zhou [53,54]. They classify a reachability graph into two parts: a live zone (LZ) and a deadlock zone (DZ), where the LZ contains all legal markings and the DZ contains all illegal markings. Then, the set of first-met bad markings (FBMs) is computed, where an FBM is an illegal marking that can be directly reached by firing a transition at a legal marking. That is to say, an FBM is within the DZ and represents the very first entry from the LZ to the DZ. Uzam and Zhou also develop an iterative approach to prevent deadlocks in a net model. An FBM is forbidden by using a place invariant (PI) based control place synthesis method [62]. Once all FBMs are forbidden, the controlled system is live. This approach is easy to use since it does not require to compute control places by solving linear programming problems. However, it cannot guarantee the behavioral optimality of the obtained supervisor. Motivated by Uzam and Zhou's work [54], the work in [6] develops a maximally permissive deadlock control method such that a control place is computed by solving an integer linear programming problem (ILPP) while an FBM is prohibited but no legal markings are forbidden. The process cannot terminate until all FBMs are forbidden. Then, we can obtain a supervisor with all legal markings reachable in the resulting controlled net model. Meanwhile, a marking reduction approach is proposed to reduce the number of markings that need to be considered. Thus, the number of constraints in the ILPP can be reduced. In [7,8], ILPPs are proposed to design optimal supervisors with the minimal number of control places. The work [7,8] can successfully handle the behavioral permissiveness and structural complexity problems but suffers from the computational complexity due to the existence of too many constraints in the ILPPs.

All the above studies based on Petri nets are in the framework of pure net models. However, there exist some Petri net models that cannot be optimally controlled by pure net supervisors [68]. Self-loops are a classical non-pure Petri net structure. A self-loop contains two arcs (p,t) and (t,p) connecting a place p and a transition t. Self-loops are used in several papers [18,42,48,54,55,57] for structural reductions, systems synthesis, system modeling, etc. In the previous work [11], self-loops are used to design maximally permissive supervisors to handle deadlock problems in FMSs. Similar to the theory of regions [25,52], we prevent deadlocks by implementing all MTSIs of a net to be controlled. For an MTSI (M,t), we assume that there is a self-loop associated with t in a control place. Then, an ILPP is formulated to design the control place. The constraints in the ILPP can ensure that t is disabled at M and no legal marking is forbidden. Meanwhile, no arcs in the LZ of the net model are removed by the self-loop in the control place. The objective function is used to maximize the number of t-critical MTSIs implemented by the control place, where a t-critical MTSI is the one with t as its paired transition. Experimental results in [11] show that Petri net supervisors with self-loops can optimally control the net models that cannot be optimally controlled by a pure net supervisor. Thus, Petri nets with self-loops are more powerful than pure nets in modeling and controlling FMSs.

In this paper, we aim to reduce the structural complexity of the previous work [11]. Instead of one self-loop in one control place, we allow multiple self-loops in a control place. We assume that a control place has a self-loop for each critical transition. A transition t is said to be critical if there exist MTSIs such that t is the paired transition. Then, we propose an ILPP to compute the control place that can implement as many MTSIs as possible. Thus, the obtained supervisor is structurally simple. We also proposed another ILPP to obtain all control places at a time. The constraints are designed to ensure that each MTSI is implemented by at least one control place and the objective function can minimize the number of control places. As a result, all control places can be obtained by solving only one ILPP and the obtained supervisor is structurally minimal in the sense of the number of control places. A drawback of the proposed methods is that they may fail to find a solution if the proposed ILPP for a given net model has no solution. In summary, we reach the following contributions in this work:

(1) In the case that a control place can have multiple self-loops, an ILPP is developed to design an optimal control place with a self-loop for each critical transition. The constraints in the ILPP are used to make all legal markings reachable in the controlled system and the objective function can ensure that the computed control place implements as many MTSIs as possible. Based on the proposed ILPP, an iterative deadlock prevention policy is developed, where a control place is designed at each iteration and the process carries out until all MTSIs are implemented. Hence, we can obtain an optimal supervisor with a small number of control places.
(2) In order to minimize the number of control places in the obtained supervisor, we formulate an ILPP to design a set of control places with self-loops and its objective function is used to select the minimal number of control places. As a result, we can obtain an optimal supervisor with the minimal number of control places. The proposed ILPP can lead to a non-iterative deadlock control policy since it can find all control places to implement all MTSIs by solving only one ILPP.
(3) The proposed approaches are applicable to all FMS-oriented classes of Petri net models in the literature, including PPN [1,26,60], S^3PR [2], ES^3PR [49], S^4PR [50], S^*PR [22], S^2LSPR [44], S^3PGR^2 [45], and S^3PMR [28].

The rest of this paper is organized as follows. Section 2 briefly recalls some basics of Petri nets. In Section 3, we propose two ILPPs to design optimal supervisors with compact structures and an illustrative example is presented to show the applications of the proposed methods in detail. Some examples from the literature are provided in Section 4 to show the control performance of the proposed methods. Finally, we conclude the paper in Section 5.

2. Preliminaries

This section only recalls the basics of Petri nets. More details can be found in [6,7,11,42].

A Petri net [42] is a four-tuple $N=(P,T,F,W)$ where P is a set of places and T is a set of transitions with $P \cap T = \varnothing$, and $F \subseteq (P \times T) \cup (T \times P)$ is a flow relation of the net. $W : (P \times T) \cup (T \times P) \rightarrow \mathbb{N}$ assigns a weight to an arc: $W(x,y) > 0$ if $(x,y) \in F$, and $W(x,y) = 0$, otherwise, where $x,y \in P \cup T$ and $\mathbb{N}$ is the set of non-negative integers. ${}^\bullet x = \{y \in P \cup T \mid (y,x) \in F\}$ is the preset of x and $x^\bullet = \{y \in P \cup T \mid (x,y) \in F\}$ the postset of x. A marking is a mapping $M : P \rightarrow \mathbb{N}$ where $M(p)$ denotes the number of tokens in place p. A net is pure (self-loop free) if $\forall (x,y) \in (P \times T) \cup (T \times P)$, $W(x,y) > 0$ implies $W(y,x) = 0$. The incidence matrix $[N]$ of a net N is a $|P| \times |T|$ integer matrix with $[N](p,t) = W(t,p) - W(p,t)$. A transition $t \in T$ is enabled at marking M, denoted as $M[t\rangle$, if $\forall p \in {}^\bullet t$, $M(p) \geq W(p,t)$. Once a transition t is enabled at M and fires, it yields a new marking M', denoted as $M[t\rangle M'$, where $M'(p) = M(p) - W(p,t) + W(t,p)$. The set of reachable markings of net (N,M_0) is denoted by $R(N,M_0)$ and its reachability graph is denoted as $G(N,M_0)$. A transition $t \in T$ is live at M_0 if