Deadlock Avoidance of Flexible Manufacturing Systems by Colored Resource-Oriented Petri Nets With Novel Colored Capacity

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Deadlock Avoidance of Flexible Manufacturing Systems by Colored Resource-Oriented Petri Nets With Novel Colored Capacity*

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Abstract. A variety of colored resource-oriented Petri nets (CROPN)-based control method to realize control policies in flexible manufacturing systems (FMS) are to add control places to the original net, which makes the net being complex. This paper proposes a novel concept in colored resource-oriented Petri nets (CROPN) called colored capacity. Firstly, the foraml definition of colored capacity in a CROPN is given. Based on this concept, the new execution rule of the transitions is proposed. Then, a method is developed such that the colored capacity for places is determined. By colored capacity, all given control policies are realized without adding control places, thus making the net simple. Finally, an FMS example is used to illustrate the proposed method.

Keywords: Deadlock avoidance· discrete event systems· flexibility manufacturing systems· Petri nets· colored resource-oriented Petri net.

1 Introduction

Flexible manufacturing systems (FMS) have been widely used in industrial fields [1]-[7]. However, since a large number of jobs have to share same resource in an FMS, deadlocks may arise, which leads to serious consequences. To deal with deadlock issue in FMSs, many control policies based on Petri net models have been established.

In these control policies, a deadlock avoidance strategy to prevent the FMS modeled by Petri nets from being deadlock is to add some constraints to the targeted FMS such that the system is deadlock-free. The work in [9] proposes a colored resource-oriented Petri net (CROPN) model to analyze the deadlock problem in FMS. The CROPN is considered to be more powerful than other Petri nets such as the resource place-based Petri nets[5].

The work in [5] establishes the deadlock-free operations in CROPN. However, to use the deadlock avoidance policy proposed in [5], we need to add control places to the original net, which makes the net being complex.

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In this paper, a novel CROPN concept called colored capacity is proposed. We define the colored capacity of the place, which represents the biggest number of tokens with the same color that the place can retain simultaneously. It is shown that a place in CROPN may have different colored capacity corresponding to different color. Based on the concept of colored capacity, the new transitions firing rule for CROPN is presented. Then, after we obtain all deadlock and impending deadlock markings by using the method proposed in [5], a method is presented to determine the colored capacity for each place in CROPN by simple calculation. It is shown that the colored capacity of a place in CROPN will change along with the marking change. Based on the dynamically changing color capacity, combined with the new transitions firing rule proposed in this paper, all deadlock markings and impending deadlock markings in a flexible manufacturing systems (FMS) modeled by CROPN are forbidden, therefore, this FMS is deadlock-free and we do not need to add control places to the net.

The contributions in this paper are as follows:

1) In this paper, the colored concept for FMS modeled by CROPN is proposed, which is not considered in [5].

2) Based on the dynamically changing color capacity, combined with the new transition firing rule proposed in this paper, all deadlock markings and impending deadlock markings in a flexible manufacturing systems (FMS) modeled by CROPN are forbidden without the need to add control places to the net.

This paper is organized as follows. Section 1 is the introduction. Section 2 gives some basics for the model of CROPM. Section 3 defines the concept of colored capacity for CROPN. 4 proposes a method to determine the colored capacity. Section 5 presents a FMS example to explain the application of the proposed method. We conclude in section 6. The acknowledgment is in section 7.

2 Preliminaries

In this subsection, some notations and concepts about colored resource-oriented Petri net (CROPN) are presented. The reader can refer to [5], [16], [17] and [18] for more CROPN theory.

A CROPN is a five-tuple $N = (P, T, A, W, K)$, where P is a set of places and T is a set of transitions, $A \subseteq (P \times T) \cup (T \times P)$ is the relationship of the transitions and places in the graph, $W : A \rightarrow \{0, 1, \dots\}$ is the weight function on the arcs, and $K : P \rightarrow \{0, 1, \dots\}$ is the capacity function. In CROPN, we attach color to each token in places and the color set is equal to T. Let $M : P \times T \rightarrow \{0, 1, \dots\}$ be the marking of CROPN in a state M, such that $M(p, t)$ represents the number of tokens with color t in place p at marking M, where $p \in Q, t \in T$. We then show the execution rule for CROPN as follows:

Definition 1. *In a CROPN at marking M, a transition $t \in T$ is said to be process-enabled if and only if for all $p \in P$*

$$M(p, t) \geq W(p, t) \tag{1}$$

Definition 2. *A transition t is said to be resource-enabled at marking M if and only if for all $p \in P$*

$$K(p) \geq M(p) - W(p,t) + W(t,p) \tag{2}$$

, where $M(p)$ represents the number of tokens regardless of colors in place p at marking M. Then we define that a transition $t \in T$ can be enabled at M iff it is both process-enabled and resource-enabled at marking M. When transition $t \in T$ files at M, then $W(p,t)$ tokens with color t are removed from place p and $W(t,p)$ tokens are transmitted to place p for $p \in P$.

3 Definition of Colored Capacity

In this section, the formal definition of colored capacity is proposed. Then we define the new execution rule for CROPN.

Definition 3. *Given a CROPN with marking M, let $K_c : P \times T \times M \rightarrow \{0,1,\dots\}$ be the colored capacity such that for all $p \in P$, for all $t \in T$, for all marking M reachable from the initial marking, $K_c(p,t,M)$ represents the maximum free number of tokens with color t that p can retain at marking M.*

For example, if $K_c(p,t,M) = 1$, then only one token with color t can move into place p at marking M. However if $K_c(p,t,M) = 0$, then no token with color t can move into place p at marking M. We then define the new transition firing rule for CROPN.

Definition 4. *Given a CROPN, transition $t \in T$ is said to be enabled at M if*

1. *transition t is process-enabled.*
2. *assume that the firing of a transition $t \in T$ at marking M will add $W(t,p_1)$ tokens with color $t_1 \in T$ into place p_1 with $(t,p_1) \in A$. Then $K_c(p_1,t_1,M) \geq W(t,p_1)$.*

Remark 1. Note that in the normal capacity in CROPN, we can only control the number of tokens with colors in specified places by adding additional control places to CROPN. However, based on the colored capacity and new execution rule, we can control the number of tokens with colors in places without adding control places, which will be illustrated in the next section. Furthermore, the work in [5] assume that the color of a token will changed when this token goes from a place to another and the change of color is decided by a process plan and is known in advance.

4 Realization of Control Policies for Interactive Subnets by using Colored Capacity

In this section, we show that how to realize control Policies in CROPN by using colored capacity.

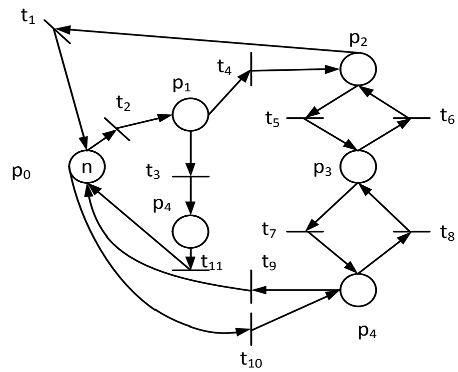

Fig. 1. A CROPN with one interactive subnet [5]

Consider CROPN in Fig. 1 [5]. Assume that $K(p_1) = K(p_3) = K(p_5) = 1$ and $K(p_2) = K(p_4) = 2$. In this net, the only interactive subnet $v^1 = \{p_2, t_5, t_6, p_3, t_7, t_8, p_4\}$. From the work in [5], we have three control policies to avoid deadlock to occur as follows:

$$u_1 : M(p_3, t_7) + M(p_4, t_8) \leq 2; \tag{3}$$

$$u_2 : M(p_2, t_5) + M(p_3, t_6) \leq 2; \tag{4}$$

$$u_3 : M(p_2, t_5) + M(p_4, t_8) \leq 3. \tag{5}$$

Note that if there exists marking M such that $M(p_3, t_7) + M(p_4, t_8) = 3$, then from place capacity, we have $M(p_3, t_7) = 1$ and $M(p_4, t_8) = 2$. In this marking, transitions t_7 and t_8 are process enabled but not resource enabled, implying that no tokens can pass these transitions any time and thus CROPN is deadlocked at marking M. This is why we need policy u_1 to restrict the number of tokens with colors t_7 and t_8 in places p_3 and p_4. One can easy check policies u_2 and u_3 in a similar way. Next, we discuss how to realize, for instance, policy u_1 by using colored capacity.

To realize policy u_1, clearly we have

$$\begin{aligned} K_c(p_3, t_7, M) &\leq 2 - M(p_3, t_7) - M(p_4, t_8) \\ K_c(p_4, t_8, M) &\leq 2 - M(p_4, t_8) - M(p_3, t_7) \end{aligned} \tag{6}$$

Because, for instance, if $K_c(p_3, t_7, M) > 2 - M(p_3, t_7) - M(p_4, t_8)$, then when $M(p_3, t_7) + M(p_4, t_8) = 2$, we have that $K_c(p_3, M, t_7) \geq 1$, implying that at least one token with color t_7 can add to place p_3. After doing this, we have that $M'(p_3, t_7) + M'(p_4, t_8) \geq 3$, which contradicts policy u_1, where M' is reachable from marking M. Furthermore clearly we have $K_c(p_3, t_7, M) \leq K(p_3)$ and $K_c(p_4, t_8, M) \leq K(p_4)$. Since the possible colors of tokens in places p_4 and p_3 are t_8, t_9, and t_7, t_6 respectively. Thus we have

$$\begin{aligned} K_c(p_3, t_7, M) &\leq K(p_3) - M(p_3, t_7) - M(p_3, t_6) \\ K_c(p_4, t_8, M) &\leq K(p_4) - M(p_4, t_8) - M(p_4, t_9) \end{aligned} \tag{7}$$

However, from policy u_3, if $M(p_2, t_5) = 2$, then the free number of tokens with color t_8 in place p_4 must less than one, implying that $K_c(p_4, M, t_8) \leq 1$. Thus $K_c(p_4, t_8, M)$ is related to policies u_1 and u_3. Thus we have

$$K_c(p_4, t_8, M) \leq 3 - M(p_2, t_5) \tag{8}$$

To make the maximal permissive of the tokens with colors t_7 and t_8 in places p_3 and p_4, from Eqs (6) to (8), we have

$$K_c(p_4, t_8, M) = min[(2 - M(p_4, t_8) - M(p_3, t_7)), K(p_4) - M(p_4, t_8) - M(p_4, t_9), 3 - M(p_2, t_5)] \tag{9}$$

and

$$K_c(p_3, t_7, M) = min[(2 - M(p_4, t_8) - M(p_3, t_7)), K(p_3) - M(p_3, t_7) - M(p_3, t_6)] \tag{10}$$

Clearly by using Eqs. (8) and (9), we can realize policy u_1 with the new execution rule defined in Definition 4. Next we show in Algorithm 1 to determine colored capacity given CROPN and control policies.

Algorithm 1 *Determination of the colored capacity given a CROPN and control policies developed form the method from [5].*
Input: control policies and CROPN
Output: colored capicity.

1. *By using the method from [5] we compute the control policies. Assume that there x control policies to forbid deadlock. The first control policy is of the form* $u_1 = M(p_{11}, t_{11}) + M(p_{12}, t_{12}) + \cdots + M(p_{1l(1)}, t_{1l(1)}) \leq N(1)$, *where* $l(1) \geq 1$ *and* $N(1) \geq 0$. *The second control policy is of the form* $u_2 = M(p_{21}, t_{21}) + M(p_{22}, t_{22}) + \cdots + M(p_{2l(2)}, t_{2l(2)}) \leq N(2)$, *where* $l(2) \geq 1$ *and* $N(2) \geq 0$. *The x control policy is of the form* $u_x = M(p_{x1}, t_{x1}) + M(p_{x2}, t_{x2}) + \cdots + M(p_{xl(x)}, t_{xl(x)}) \leq N(x)$, *where* $l(x) \geq 1$ *and* $N(x) \geq 0$.
2. *For all place* $p \in P$, *let* $C(p) := \{t \in T | (p, t) \in A\}$ *be the possible colors the token can labeled in place p. Let* $M_p := \sum_{t \in C(p)} M(p, t)$. *Consider the ith policy with* $i \in \{1, 2, \ldots, x\}$, *we write* $M(p, t) \in u_i$ *when there exists* $j \in \{1, 2 \ldots l(i)\}$ *such that* $M(p_{ij}, t_{ij}) = M(p, t)$. *We define* $M_{p_{ij}, t_{ij}} := \sum_{y \in \{1,2 \ldots l(i)\} \setminus j} M(p_{iy}, t_{iy})$. *Then for all* $k_1 \in \{1, 2, \ldots x\}$, $k_2 \in \{1, 2, \ldots l(k_1)\}$, *we set*

$$K_c(p_{k_1k_2}, t_{k_1k_2}, M) = min[(K(p_{k_1k_2}) - M_{p_{k_1k_2}}), N(k_1) - u_{k_1}, N(j_1) - M_{p_{k_1k_2}, t_{k_1k_2}}] \tag{11}$$

   where $M(p_{k_1k_2}, t_{k_1k_2}) \in u_{j1}$ *for* $j_1 \in \{1, 2, \ldots, x\} \setminus k_1$.
3. *output colored capacity for CROPN.*

Remark 2. From the above discussion, colored capacith is marking-variant. If the CROPN and the control policies to be considered satisfy that (1) the firing of any transition cannot add token to a place and remove token in the place with the same color from this place simultaneously, and (2) the control policies are maximally permissive, then clearly by using colored capacity proposed in this paper, we can realize these policies and do not forbid legal markings. If any one of the above conditions does not hold, then clearly by using colored capacity proposed in this paper, we can realize these policies and may forbid legal markings.

5 FMS Example

Consider a CROPN [5] in Fig. 2, where $K(p_1) = K(p_2) = K(p_3) = 1$. From [5], its reachability tree and detailed markings are shown in Fig. 3 and table. 1, respectively. Furthermore, the control policies to be considered to forbid markings M_4, M_5, M_9 are as follow:

$$u_1 = M(p_1, t_3) + M(p_3, t_6) \leq 1 \tag{12}$$

$$u_2 = M(p_2, t_5) + M(p_3, t_6) \leq 1 \tag{13}$$

$$u_3 = M(p_1, t_3) + M(p_2, t_4) \leq 1 \tag{14}$$

By using Algorithm 1 we can determine colored capacity as follows:

$$\begin{aligned} K(p_1, t_3, M) = \min\{&1 - M(p_1, t_3) - M(p_3, t_6), \\ &1 - M(p_1, t_3) - M(p_2, t_4), \\ &K(p_1) - M(p_1 t_3) - M(p_1, t_1)\} \end{aligned} \tag{15}$$

$$\begin{aligned} K(p_2, t_4, M) = \min\{&1 - M(p_1, t_3) - M(p_2, t_4), \\ &K(p_2) - M(p_2, t_4) - M(p_2, t_5)\} \end{aligned} \tag{16}$$

$$\begin{aligned} K(p_2, t_5, M) = \min\{&1 - M(p_2, t_5) - M(p_3, t_6), \\ &K(p_2) - M(p_2, t_4) - M(p_2, t_5)\} \end{aligned} \tag{17}$$

$$\begin{aligned} K(p_3, t_6, M) = \min\{&1 - M(p_1, t_3) - M(p_3, t_6), \\ &1 - M(p_2, t_5) - M(p_3, t_6), \\ &K(p_3) - M(p_3, t_6) - M(p_3, t_7)\} \end{aligned} \tag{18}$$

From the reachability tree, only markings M_1, M_2 can reach marking M_4. In marking M_1, from table 1, we have $M_1(p_1, t_3) = 1$, implying that $K(p_3, t_6, M_1) = 0$ (Eq. 18). Thus transition t_8 cannot fire at marking M_1 by new firing rule defined in Definition 4 because the firing of this transition will add one token with color t_6 to place p_3, which contradicts $K(p_3, t_6, M_1) = 0$. Thus from marking M_1 we cannot reach marking M_4. In marking M_2, from table 1, we have $M_2(p_3, t_6) = 1$, implying that $K(p_1, t_3, M_2) = 0$ (Eq. 15). Thus transition t_2 cannot fire at marking M_2 by new firing rule because the firing of this transition

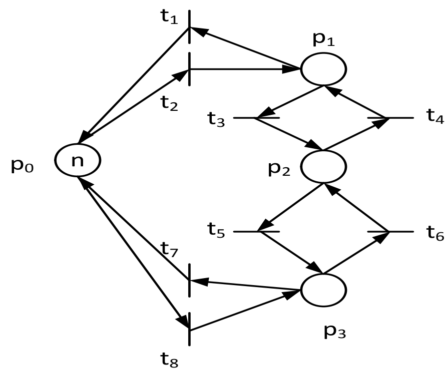

Fig. 2. The CROPN for FMS Example

will add one token with color t_3 to place p_1, which contradicts $K(p_1, t_3, M_2) = 0$. Thus from marking M_2 we cannot reach marking M_4. Thus bad marking M_4 is forbidden by using corlored capacity. In ths similar way one can easy to check that markings M_4, M_5, M_9 are all forbidden by colored capacity implying that all control policies are forbidden without adding control places.

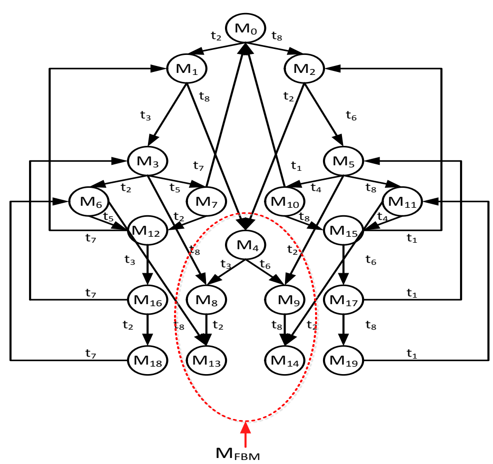

Fig. 3. Reachability graph of the non-colored capacity CROPN in Fig.3

6 Conclusion

In this paper, a novel CROPN concept called colored capacity is proposed. We define the colored capacity, which represents the maximum free number of to-

Table 1. Reachable Markings of the CROPN in Fig. 3

Marking	
M_0	$M_0(p_0, t_2) = n$ and $M_0(p_0, t_8) = n$
M_1	$M_1(p_0, t_2) = n$, $M_1(p_0, t_8) = n$ and $M_1(p_1, t_3) = 1$
M_2	$M_2(p_0, t_2) = n$, $M_2(p_0, t_8) = n$ and $M_2(p_3, t_6) = 1$
M_3	$M_3(p_0, t_2) = n$, $M_3(p_0, t_8) = n$ and $M_3(p_2, t_5) = 1$
M_4	$M_4(p_0, t_2) = n$, $M_4(p_0, t_8) = n$, $M_4(p_1, t_3) = 1$ and $M_4(p_3, t_6) = 1$
M_5	$M_5(p_0, t_2) = n$, $M_5(p_0, t_8) = n$ and $M_5(p_2, t_4) = 1$
M_6	$M_6(p_0, t_2) = n$, $M_6(p_0, t_8) = n$, $M_6(p_1, t_3) = 1$ and $M_6(p_2, t_5) = 1$
M_7	$M_7(p_0, t_2) = n$, $M_7(p_0, t_8) = n$ and $M_7(p_3, t_7) = 1$
M_8	$M_8(p_0, t_2) = n$, $M_8(p_0, t_8) = n$, $M_8(p_2, t_5) = 1$ and $M_8(p_3, t_6) = 1$
M_9	$M_9(p_0, t_2) = n$, $M_9(p_0, t_8) = n$, $M_9(p_1, t_3) = 1$ and $M_9(p_2, t_4) = 1$
M_{10}	$M_{10}(p_0, t_2) = n$, $M_{10}(p_0, t_8) = n$ and $M_{10}(p_1, t_1) = 1$
M_{11}	$M_{11}(p_0 t_2) = n$, $M_{11}(p_0, t_8) = n$, $M_{11}(p_2, t_4) = 1$ and $M_{11}(p_3, t_6) = 1$
M_{12}	$M_{12}(p_0, t_2) = n$, $M_{12}(p_0, t_8) = n$, $M_{12}(p_1, t_3) = 1$ and $M_{12}(p_3, t_7) = 1$
M_{13}	$M_{13}(p_0, t_2) = n$, $M_{13}(p_0, t_8) = n$, $M_{13}(p_1, t_3) = 1$, $M_{13}(p_2, t_5) = 1$ and $M_{13}(p_3, t_6) = 1$
M_{14}	$M_{14}(p_0, t_2) = n$, $M_{14}(p_0, t_8) = n$, $M_{14}(p_1, t_3) = 1$, $M_{14}(p_2, t_4) = 1$ and $M_{14}(p_3, t_6) = 1$
M_{15}	$M_{15}(p_0, t_2) = n$, $M_{15}(p_0, t_8) = n$, $M_{15}(p_1, t_1) = 1$ and $M_{15}(p_3, t_6) = 1$
M_{16}	$M_{16}(p_0, t_2) = n$, $M_{16}(p_0, t_8) = n$, $M_{16}(p_2, t_5) = 1$ and $M_{16}(p_3, t_7) = 1$
M_{17}	$M_{17}(p_0, t_2) = n$, $M_{17}(p_0, t_8) = n$, $M_{17}(p_1, t_1) = 1$ and $M_{17}(p_2, t_4) = 1$
M_{18}	$M_{18}(p_0, t_2) = n$, $M_{18}(p_0, t_8) = n$, $M_{18}(p_1, t_3) = 1$, $M_{18}(p_2, t_5) = 1$ and $M_{18}(p_3, t_7) = 1$
M_{19}	$M_{19}(p_0, t_2) = n$, $M_{19}(p_0, t_8) = n$, $M_{19}(p_1, t_1) = 1$, $M_{19}(p_2, t_4) = 1$ and $M_{19}(p_3, t_6) = 1$

kens with the specific color that the place can retain. A method is presented to determine the colored capacity in CROPN by simple computation. Then all given control policies are realized without adding additional control places, thus making the net simple. However, the colored capacity method may forbid legal markings, which is the future work.

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References

1. Yufeng Chen, Gaiyun Liu.: Computation of Minimal Siphons in Petri Nets by Using Binary Decision Diagrams. ACM 12(1), 1-15 (2013)
2. X Li, G Liu, Z Li, N Wu, K Barkaoui.: Elementary Siphon-Based Robust Control for Automated Manufacturing Systems With Multiple Unreliable Resources. IEEE ACCESS 12(1), 1-15 (2013)
3. Liu, Gai, Yun, Chao, Daniel, Yuh, Uzam, Murat.: A merging method for the siphon-based FMS maximally permissive controllers with simpler structures. IMA Journal of Mathematical Control and Information 31(4), 551-573 (2014)

4. G Liu, D Chao, F Yu, Murat.: Control policy for a subclass of Petri nets without reachability analysis. IET Control Theory Applications 7(8), 1131-1141 (2013)
5. H. Chen, N. Q. Wu, and M. C. Zhou.: A novel method for deadlock prevention of ams by using resource-oriented petri nets. Information Sciences 363 178-189 (2016)
6. Y. Feng, K. Xing, M. Zhou, and H. Liu, Liveness analysis and deadlock control for automated manufacturing systems with multiple resource requirements. IEEE Transactions on Systems, Man, and Cybernetics: Systems 1–14 (2017).
7. Z. W. Li, N. Q. Wu, and M. C. Zhou, Deadlock control of automated manufacturing systems based on petri nets—a literature review. IEEE Transactions on Systems Man Cybernetics Part C 42(4), 437–462, (2012).