Supervisor Controller-Based Elementary Siphons and Colored Petri Net for Deadlock Control and Machine Failures in Automated Manufacturing Systems

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Abstract

Deadlock control techniques for automated systems have been developed based on Petri nets. Some resources in these systems are unreliable or failing. Thus, the developed deadlock policies are not appropriate to these systems. Thus, this paper presents a strategy for solving deadlocks in systems with unreliable resources. The first step is to apply elementary siphon control method to design control places without considering resources failures. Second, all control places in the first step are merged into a global control place by using a colored Petri net. The third stage involves the design of a common recovery subnet based on colored Petri nets to handle all resource failures. Finally, the proposed strategy is evaluated using a manufacturing system from the literature. The results demonstrate that the suggested strategy is capable of handling all unreliable resources in the system, has a simpler structure, and has small computational overhead.

Keywords: Deadlock prevention, siphon, colored Petri net, automated manufacturing system

1 Introduction

An automated manufacturing system (AMS) is a conglomeration of production and material handling resources. Multiple products enter the production system as discreet events and process them based on a specified sequences of operations. Because of their interaction and shared resources, deadlock states occur and the system is indefinitely blocked and cannot finish its task (Li et al. 2008, Li et al. 2012, Abdulaziz et al. 2015, Chen et al. 2015). Thus, there is a needed to develop an effective deadlock-control methods to prohibit the occurrence of deadlocks in the AMSs. Petri nets are powerful mathematical tools that can be used to model, evaluate and control deadlocks AMSs. In addition, it can be used to describe the characteristics and behaviour of the developed AMSs such as synchronization, sequences, conflict, boundedness and liveness (Chen et al. 2011). Many polices were developed based on a Petri net tool to avoid the issue of deadlock in AMSs. These polices are categorized into three strategies: deadlock avoidance, deadlock detection and recovery, and deadlock prevention (Wysk et al. 1991, Chen et al. 2011). To design controller for AMSs, Three criteria are developed namely, behavioral permissiveness, structural complexity, and computational complexity (Chen et al. 2011). Therefore, the aim of many researchers is to establish deadlock prevention strategies that can provide supervisors with the above mentioned requirements (Chen et al. 2011). The deadlock approaches were developed for AMSs with reliable and unreliable resources. For reliable resources, structural analysis (Chao 2009, Chao 2011) and reachability graph analysis (Ghaffari et al. 2003, Uzam 2004, Uzam and Zhou 2004). Several policies have been developed to prevent deadlock states, including siphon control, theory of region, and iterative methods (Uzam 2002, Li and Zhou 2004, Uzam and Zhou 2004, Chao 2010, Chao 2011, Pan et al. 2017, Zhao and Uzam 2017, Cong et al. 2018).

For unreliable resources, the existing deadlock methods were developed for a class of Petri net. Lawley and Sulistyono (Lawley and Sulistyono 2002) investigated resource allocation in manufacturing systems with unreliable resources by developing policies of supervisory control that allocate system buffer space. Hsieh (Hsieh 2006) developed nominal supervisory algorithms to study the proposed controlled assembly/disassembly Petri net (CADPN) for assembly/disassembly processes with unreliable resources. (Wang et al. 2008) developed robust supervisory controllers for single-unit resource allocation systems with unreliable resources. (Chew et al. 2009) developed two controller supervisors for multiple unreliable resources. (Liu et al. 2013) proposed a robust deadlock prevention controller for unreliable resources for a class of Petri nets based on a divide-and-conquer deadlock control strategy. (Yue et al. 2014) developed a deadlock avoidance controller policy for a class of AMS with multiple unreliable resources by using the modified Banker's Algorithm and a set of remaining resource capacity constraints. (Yue et al. 2015) presented a robust supervisory control policy to prevent deadlock and blocking in the class of AMS subjected to multiple unreliable workstations. (Wang et al. 2016) proposed a deadlock prevention controller for an AMS with resource failures.

The objective of this paper is to presents a strategy for solving deadlocks in systems with unreliable resources. The first step is to apply elementary siphon control method developed in (Li and Zhou 2004) to design control places without considering resources failures. Second, all control places in the first step are merged into a global control place by using a colored Petri net. The third stage involves the design of a common recovery subnet based on colored Petri nets to handle all resource failures.

2 Basics of Petri Nets

Definition 1 (Kaid et al. 2020): Let $N = (P, T, F, W)$ be a Petri net, where P and T are finite non-empty sets of places and transitions, respectively. Elements in $P \cup T$ are named nodes. Here, $P \cup T \neq \emptyset$ and $P \cap T = \emptyset$; P and T are depicted by circles and bars, respectively. Next, $F \subseteq (P \times T) \cup (T \times P)$ is the set of directed arcs that join the transitions with places (and vice versa), $W: (P \times T) \cup (T \times P) \rightarrow \boldsymbol{IN}$ is a mapping that assigns an arc's weight, where $\boldsymbol{IN} = \{0, 1, 2, ...\}$.

Definition 2 (Kaid et al. 2020): Let $N = (P, T, F, W)$ be a Petri net. N is known as an ordinary net if $\forall (p, t) \in F$, $W(p, t) = 1$, where $N = (P, T, F)$. N is named a weighted net if there is an arc between x and y such that $W(x, y) > 1$".

Definition 3 (Kaid et al. 2020): "Let $N = (P, T, F, W)$ and node $a \in P \cup T$. Then, $^{\bullet}a = \{b \in P \cup T \mid (b, a) \in F\}$ is named the preset of node a, and $a^{\bullet} = \{b \in P \cup T \mid (a, b) \in F\}$ is named the postset of node a".

Definition 4 (Kaid et al. 2020): "Let $N = (P, T, F, W)$ be a Petri net. A marking M of N is a mapping $M: P \rightarrow \boldsymbol{IN}$. Next, (N, M_o) is a marked Petri net (PN), represented as $PN = (P, T, F, W, M_o)$, where the initial marking of PN is $M_o: P \rightarrow \boldsymbol{IN}$.

Definition 5 (Kaid et al. 2020): Let $N = (P, T, F, W, M_o)$ be a Petri net. A transition $t \in T$ is enabled at marking M if for all $p \in {^{\bullet}t}$, $M(p) \geq W(p, t)$, which is denoted as $M[t\rangle$. When a transition t fires, it takes $W(p, t)$ token (s) from each place $p \in {^{\bullet}t}$, and adds $W(t, p)$ token (s) in each place $p \in t^{\bullet}$. Thus, it reaches a new marking M', denoted as $M[t\rangle M'$, where $M'(p) = M(p) - W(p, t) + W(t, p)$.

Definition 6 (Kaid et al. 2020): Let $N = (P, T, F, W, M_o)$ be a Petri net. N is called self-loop free if for all $a, b \in P \cup T$, $W(a, b) > 0$ implies $W(b, a) = 0$.

Definition 7 (Kaid et al. 2020): Let $N = (P, T, F, W, M_o)$ be a Petri net. Let $[N]$ be an incidence matrix of net N, where $[N]$ is an integer matrix that consists of $|T|$ columns and $|P|$ rows with $[N](p, t) = W(t, p) - W(p, t)$.

Definition 8 (Kaid et al. 2020): Let (N, M_o) be a marked Petri net. The set of markings that are reachable from M in N is named the set of reachability of the Petri net model (N, M) and denoted by $R(N, M)$. A transition $t \in T$ is live if for all $M \in R(N, M)$, there exists a reachable marking $M' \in R(N, M)$ such that $M'[t\rangle$ holds. A transition is dead at M_o if there does not exist $t \in T$ such that $M_o[t\rangle$ holds. M' is said to be reachable from M if there exists a finite transition sequence $\delta = t_1 t_2 t_3 \ldots t_n$ that can be fired, and markings $M_1, M_2, M_3, \ldots,$ and M_{n-1} such that $M[t_1\rangle M_1[t_2\rangle M_2[t_3\rangle M_2 \ldots M_{n-1}[t_n\rangle M'$, denoted as $M[\delta\rangle M'$, satisfies the state equation $M' = M + [N]\vec{\delta}$, where $\vec{\delta}: T \rightarrow \boldsymbol{IN}$ maps t in T to the number of appearances of t in δ and is called a Parikh vector or a firing count vector.

Definition 9 (Kaid et al. 2020): Let (N, M_o) be a marked Petri net. It is said to be k-bounded if for all $M \in R$ (N, M_0), for all $p \in P$, $M(p) \leq k$ ($k \in \{1, 2, 3, ...\}$). A net is safe if all of its places are safe, i.e., in each place p, the number of tokens does not exceed one. In other words, a net is k-safe if it is k-bounded.

3 Deadlock Control for Unreliable Resources

***Definition 10 (Nasr et al. 2015)*:** Let $\prod = \{S_1, S_2, \ldots, S_k\}$ be the set of strict minimal siphons, where $k = (1, 2, \ldots)$. Let $\prod_E$ and $\prod_D$ be the sets of elementary and dependent (redundant) ones, respectively. Let $\prod = \prod_E \cup \prod_D$. Let $S \subseteq P$ be a siphon of N. The P-vector λ_S is called the characteristic P-vector of S if $\forall p \in S$, $\lambda_S(p)=1$, otherwise, $\lambda_S(p)=0$".
***Definition 11 (Nasr et al. 2015)*:** "Let $N = (P, T, F, W, M_o)$ be a net with $|P| = m$, $|T|=n$, and assume that N has k SMSs, $S_1, S_2, \ldots$, and S_K, $m, n, k \in \boldsymbol{IN}$. Let $\lambda_{Si}(\eta_{Si})$ be the characteristic $P(T)$-vector of siphon S_i, $i \in \{1, 2, \ldots, n\}$. We then define $[\lambda]_{kxm} = [\lambda_{S1}, \lambda_{S2}, \ldots, \lambda_{Sk}]^T$ and $[\eta]_{kxn} = [\lambda]_{kxm}$. $[N]_{mxn}$ is called the characteristic $P(T)$-vector matrix of the siphons of N, where $[N]_{mxn}$ is an incidence matrix.
***Theorem 1 (Nasr et al. 2015)*:** Let a Petri net is to be N with $N = (P, T, F, W, M_o)$ and S_1–S_n be the siphons in N with respect to elementary siphons. Control place V_S is added to N, the new net system is denoted as (N_1, M_1), and the initial token of place control V_S is computed as $M(V_S) = M_0(S) - \xi_S$, $1 \leq \xi_S \leq M_0(S) - 1$, where ξ_S is called the control depth variable of siphon S, which implies the least number of tokens that the siphon can hold. Then, S is invariant-controlled.
***Theorem 2 (Nasr et al. 2015)*:** "Let a Petri net is to be N with $N = (P, T, F, W, M_o)$ and S_0 be a strictly dependent siphon with respect to elementary siphons S_1, S_2, ..., and S_n, if $S_1, S_2, \ldots$, and S_n are invariant-controlled by adding control places $Vs_1, Vs_2, \ldots$, and Vs_n, and $M_0(S_0) > \sum_{i=1}^{n} a_i \cdot M_0(S_i) - \sum_{i=1}^{n} a_i \cdot \xi_{Si}$ holds, where a_i is a constant, then S_0 is controlled".
***Definition 12 (Kaid et al. 2020)*:** Let (N, M_o) be N with $N = (P, T, F, W, M_o)$. The deadlock controller for (N, M_o) developed by (Li and Zhou 2004) is expressed as $(D, M_{Do}) = (P_D, T_D, F_D, M_{Do})$, where (1) $P_D = \{V_S \setminus S \in \Pi_E\}$ is a set of control places. (2) $T_D = \{t \setminus t \in {}^{\bullet}V_S \cup V_S^{\bullet}\}$. (3) $F_D \subseteq (P_D \times T_D) \cup (T_D \times P_D)$ is the set of directed arcs that join the control places with transitions (and vice versa). (4) For all $V_S \in P_D$, $M_{Do}(V_S) = M_{Do}(S) - 1$, where $M_{Do}(V_S)$ is called an initial marking of a control place V_S.
***Definition 13 (Kaid et al. 2020)*:** Let (N, M_o) be N with $N = (P, T, F, W, M_o)$. The deadlock controller for (N, M_o) developed in (Li and Zhou 2004) is expressed as $(D, M_{Do}) = (P_D, T_D, F_D, M_{Do})$. Here, (D, M_{Do}) can be reduced and replaced by a colored common deadlock control subnet, which is a PN $N_{DC} = (\{p_{combined1}\}, \{T_{DCi} \cup T_{DCo}\}, F_{DC}, C_{vsi})$, where $p_{combined}$ is called the merged control place of all monitors $P_D = \{V_S \setminus S \in \Pi_E\}$. $T_{DCi} = \{t \setminus t \in {}^{\bullet}V_S\}$. $T_{DCo} = \{t \setminus t \in V_S^{\bullet}\}$. $F_{DC} \subseteq (\{p_{combined1}\} \times \{T_{DCi} \cup T_{DCo}\}) \cup (\{T_{DCi} \cup T_{DCo}\} \times \{p_{combined1}\})$ is the set of arrows that join the merged control place with transitions (and vice versa). C_{vsi} is the color that maps $p_{combined1}$ into colors $C_{vsi} \in SC$, where $SC = \cup_{i \in Vs}\{C_{vsi}\}$. ($N_{DC}$, M_{DCo}) is called a colored common deadlock control subnet. For all $V_S \in P_V$, $M_{DCo}(p_{combined1}) = \sum M_{Do}(V_S)$, where $M_{DCo}(p_{combined1})$ is an initial token with the colors marking of the merged monitor.
Definition 14 (Al-Ahmari et al. 2020) : "Let (N, M_o) be N with $N = (P, T, F, W, M_o)$ and (N_{DC}, M_{DCo}) a deadlock controller for (N, M_o) created by Definition 13 with $N_{DC} = \{p_{combined1}\}$, $\{T_{DCi} \cup T_{DCo}\}$, F_{DC}, C_{vsi}, M_{DCo}), we call (N_C, M_{Co}) a controlled marked Petri net, expressed as $(N_C, M_{Co}) = (N, M_o) \parallel (N_{DC}, M_{DCo})$ and called the composition of (N, M_o) and (N_{DC}, M_{DCo}), where $N_C = (P \cup \{p_{combined1}\}, T \cup T_{DCi} \cup T_{DCo}, F \cup F_{DC}, C_R, M_{Co})$ be a colored controlled marked net, and $R(N_C, M_{Co})$ be its reachable graph".
Definition 15 (Al-Ahmari et al. 2020): "Let $r_u \in P_R$ be an unreliable resource, a colored common recovery subnet of r_u is a PN $N_{cri} = (\{p_i, p_{combined2}\}, \{t_{fi}, t_{ri}\}, F_{cri}, C_{cri})$, where $F_{cri} = \{(p_i, t_{fi}), (t_{fi}, p_{combined2}), (p_{combined2}, t_{ri}), (t_{ri}, p_i)\}$, and an unreliable resource may fail when it is idle r_u or in a busy state (its holders), we define $P_{RH} = \{r_u\} \cup H(r_u)$ as a set of places, where $H(r_u)$ is a set of holders of r_u, indicated by $H(r_u) = \{p \backslash p \in P_A, p \in {}^{\bullet\bullet}r_u \cap P_A \neq \emptyset\}$, $p_i \in P_{RH}$. C_{cri} is the color that maps $p_i \in P_{RH}$ into colors $C_{cri} \in SC$. (N_{cri}, M_{crio}) is called a colored common marked recovery subnet, where $M_{crio}(p_i) \geq 0$ and $M_{crio}(p_{combined2}) = 0$".
Definition 16 (Al-Ahmari et al. 2020) : "Let (N_C, M_{Co}) be a colored controlled S^3PR , and P_{Ru} be the set of unreliable resources, for all $r_u \in P_{Ru}$, adding one common recovery subnet for all $p_i \in P_{RH}$ results in a colored controlled unreliable Petri net defined as $(N_{CU}, M_{CUo}) = (N_C, M_{Co}) \parallel (N_{cri}, M_{crio})$ that is the composition of (N_C, M_{Co}) and (N_{cri}, M_{crio})".

The proposed deadlock control algorithm is stated as follows:

Input: Petri net model (N, M_o)
Step 1: Compute all strict minimal siphons of the net N.
Step 2: T-vector matrix of the SMS $[\eta]$.
Step 3: Find the elementary siphons of N. The others are the dependent siphons.
Step 4: **for** each elementary siphon S **do**
1. Add a control place V_S;
2. Add an arc (t, V_S), $t \in {}^{\bullet}V_S$;
3. Add an arc (V_S, t), $t \in V_S^{\bullet}$;
4. Define $M_{Do}(V_S) = M_{Do}(S) - \xi_S$, $1 \leq \xi_S \leq M_0(S) - 1$.

end for
Step 5: Combine all monitors P_D into one monitor ($p_{combined1}$), and **do**
5. Add an arc $(p_{combined1}, t_i)$, $t_i \in T_{DCo}$;
6. Add an arc $(t_i, p_{combined1})$, $t_i \in T_{DCi}$;
7. Define a color c_{vsi}, $vsi \setminus S \in \Pi_E$;
8. Define $M_{DCo}(p_{combined1}) = \sum M_{Do}(V_S)$.

Step 6: Add the single control place into the net (N, M_o). The obtained net is express as (N_C, M_{Co}).
Step 7: **for** each $r_u \in P_{Ru}$ **do**
9. Add a transition t_{fi};
10. Define a color c_{cri} for t_{fi};
11. Add a recovery place $p_{combined2}$;
12. Add a transition t_{ri};
13. Add an arc (p_i, t_{fi});
14. Add an arc $(t_{fi}, p_{combined2})$;
15. Add an arc $(p_{combined2}, t_{ri})$;
16. Add an arc (t_{ri}, p_i);

end for
Step 10: Output a colored controlled unreliable marked Petri net (N_{CU}, M_{CUo}).
Step 11: End

4 Numerical Example

To demonstrate the above algorithm, Figure 1 a and b shows respectively the AMS and operation route considered in this article, its Petri net model is illustrated in Figure 2. The Petri net model comprises of 4 transitions and 6 places. The net has 4 minimal siphons, one of which is a strict minimal siphon. It has one strict minimal siphon, which is $S = \{p_4, p_5, p_6\}$, suppose that $T_{DCi} = \cup_{i \in V_S}\{{}^{\bullet}V_{si}\}$, $T_{DCo} = \cup_{i \in V_S}\{V_{Si}^{\bullet}\}$, and $C_F = \cup_{i \in V_S} \{C_{vsi}\}$. }. We inserting a single recovery subnet for p_5 and p_6 results in a colored controlled net (N_C, M_{Co}), as illustrated in Figure 3, where $T_{DCi} = \{t_3\}$, $T_{DCo} = \{t_1\}$, $C_R = \{C_{vs1}\}$ and $M_{Do}(V_{S1}) = 1$.

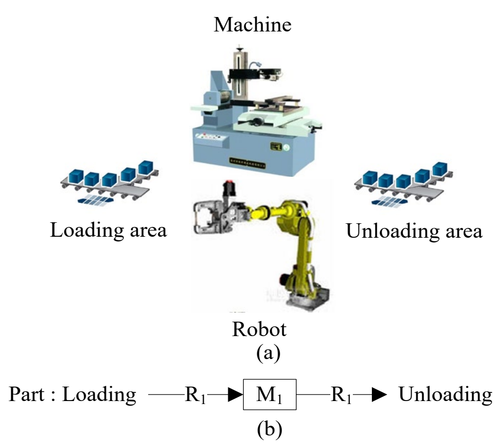

Figure 1. Example of Automated manufacturing system.

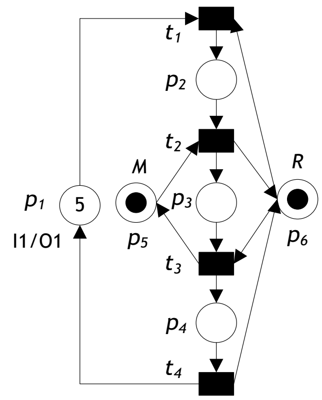

Figure 2. Petri net model of an AMS.

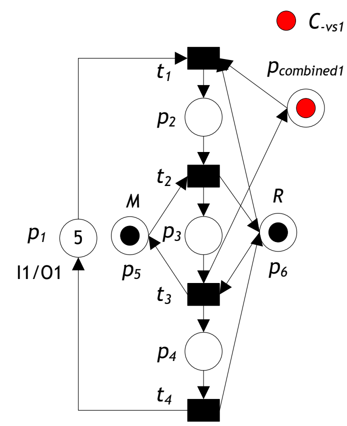

Figure 3. Colored controlled Petri net model.

Considering the net illustrated in Figure 2, suppose that the index set that may be used is NA = $\{i|p_i \in P_{RH}\}$. $T_F = \cup_{i\in \mathrm{NA}}\{t_{fi}\}$, $T_R = \cup_{i\in \mathrm{NA}}\{t_{ri}\}$, and $C_F = \cup_{i\in \mathrm{NA}}\{C_{cri}\}$. We have $P_{Ru} = \{p_5, p_6\}$, $H(p_5) = \{p_3\}$, and $H(p_6) = \{p_2, p_4\}$. Adding a single recovery subnet for p_5 and p_6 results in an unreliable net, as illustrated in Figure 4.

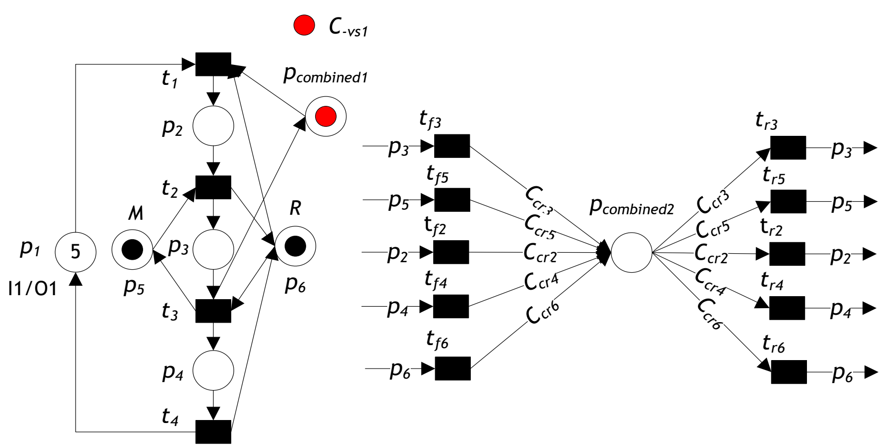

Figure 4. Colored controlled unreliable Petri net model.

5 Conclusion

Deadlock control techniques for automated systems have been developed based on Petri nets. Some resources are unreliable or failing. Thus, the developed deadlock policies are not appropriate to these systems. Therefore, this paper proposes deadlock control technique for systems with shared unreliable and resources. The first step is to apply elementary siphon control method to design control places without considering resources failures. Second, all control places in the first step are merged into a global control place by using a colored Petri net. The third stage involves the design of a common recovery subnet based on colored Petri nets to handle all resource failures. Finally, the proposed strategy is evaluated using a manufacturing system from the literature. The results demonstrate that the suggested strategy is capable of handling all unreliable resources in the system, has a simpler structure, and has small computational overhead.

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