行政院國家科學委員會專題研究計畫　成果報告

S3PR 模型之增強至能處理一般資源的 S3PGR，S2NPGR and S2WPGR 模型

計畫類別：個別型計畫
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執行期間：93 年 08 月 01 日至 94 年 07 月 31 日
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計畫主持人：趙玉

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計畫參與人員：吳俊德, 翁懷嘉政治大學資管系

一、中文摘要

利用派翠網路(Petri nets)模擬的彈性生產系統(FMS)之活性和空的壞虹吸有相關。FMS 模型包括一大堆過程工作流程 (WP) 互相爭奪資源。 循環等待資源可能帶領系統進入死結使得有些 WP 可能從未完成的僵局。預防比規避好是因為計算過程只被執行一次和離線計算。 因此它較快速地運行在真實發生的案例。Ezpeleta 等提出了一 PN 類型叫簡單的循序過程資源系統 (S^3PR) 並且提出了死結預防方法。最近多數死結控制方法都是延伸 Ezpeleta 的工作。我們提議將其增強為 S^3GPR (簡單的循序過程系統延伸它以一般資源), S^2NPGR (以一般資源及同步選擇網路工作流程) 並且 S^2WPGR (以一般資源及加權的同步的選擇過程系統) 並且改進它的計算效率。 另外, 我們將推廣普通派翠網路(OPN)與虹吸相關理論到一般派翠網路 PN (GPN) 並且將改進我們 GPN 的合成規則。 SNC 擴大我們在與 PN 合成有關的重要紡織技術(Knitting Technique)工作。

關鍵詞：彈性生產系統, 派翠網, 死結, 虹吸

Abstract

Liveness in Flexible Manufacturing Systems (FMS) modelled by Petri nets (PN) are closely related to bad siphons whose tokens can be emptied completely. The FMS model consists of a set of working processes (WP) competing for resources. Circular wait for resources can bring the system into a deadlock where some WP can never finish. Prevention is preferred to avoidance because the computational effort is carried out once and off-line. Hence it runs much faster in real-time cases. Ezpeleta et al proposed a class of PN called Systems of Simple Sequential Processes with Resources (S^3PR) and a deadlock prevention approach. Most recent deadlock control approaches extend Ezpeleta's work. We propose to extend it to S^3PGR (systems of simple sequential processes with general resources), S^2NPGR (Systems of Synchronized choice Net processes with General Resource) and S^2WPGR (Systems of Weighted Synchronized choice Net processes with General Resource) and improve its computational efficiency. In addition, we will generalize some siphon-related theory of Ordinary PN (OPN) to General PN (GPN) and improve our synthesis rules for GPN.

Keywords: **Flexible manufacturing systems, Deadlock prevention, Petri nets, Siphons, S^3PR.**

二、緣由與目的

Liveness in Flexible Manufacturing Systems (FMS) modelled by Petri nets (PN) are closely related to bad siphons [3] whose tokens can be emptied completely. A siphon (trap) is a set of places where tokens can leak out (inject in). If a siphon is also a trap, then tokens in it cannot leak out completely. A bad siphon is a siphon that is not a trap. Once a bad siphon is found that can be emptied, output transitions of places in the siphon can never be fired. Hence the net is not live. In this situation, we can construct a control policy based on the total number of tokens in the bad siphon.

The FMS model consists of a set of working processes (WP) competing for resources. A state machine (SM) models each WP plus a set of resource places modeling the availability of resources. Each SM contains one idle state plus a number of states for the set of possible sequences of operations. The initial and the final state of a WP collapse into the idle state for cyclic models. The number of tokens at the idle state indicates the maximum number (constrained by the system resource capacity) of products that can be concurrently manufactured. Circular wait for resources can bring the system into a deadlock where some WP can never finish.

There are two approaches to control deadlocks: deadlock recovery and deadlock prevention/avoidance. Recovery is to restore the system to a normal state so as to be able to finish the production. Prevention/avoidance is to avoid such situations. Prevention establishes the control policy in a static way [2,16,22]; while avoidance [7,15,17,20-21,23-25] determines possible system evolutions at each system state and chooses the correct ones to proceed.

Prevention is preferred to avoidance because the computational effort is carried out once and off-line. Hence it runs much faster in real-time cases compared with deadlock avoidance algorithms where much time is consumed by doing on-line each time the system ought to change the state. Deadlock prevention control policy is essential when it is unacceptable to have deadlocks and real time response time is critical. Although the number of minimum siphons grows exponentially with the size of the PN, in practical cases, as indicated by [2,28], it is not exponential.

Ezpeleta et al proposed a class of PN called Systems of Simple Sequential Processes with Resources (S^3PR) [2] which generalizes that in [8] by allowing choices in W. Their idea is to compute all bad siphons of the given model and find the maximum number of tokens at each idle state followed by a control policy of adding arcs and nodes with tokens. Most recent deadlock control approaches [30,32-33] extend Ezpeleta's work.

Reveliotis [30-31] extends Xie's MIP [3] approach to propose Systems of Simple Sequential Processes with General Resources (S^3PGR) to generalize Ezpeleta's deadlock prevention approach. But Xie's approach posts the following disadvantages:

a. The worst-case time complexity is exponential.
b. It does not enumerate all bad minimum siphons at once, hence is not efficient for deadlock control since as many iteration steps as the total number of bad minimum siphons are required.
c. In case of detecting the presence of empty siphons, the FMS must be redesigned. The structure of the FMS (i.e., siphons) must be analyzed. Without the knowledge of the structure, it is rather hard to judge whether to add or delete transitions, places or arcs (and its weights). Add-hoc modifications simply result in many unsuccessful attempts and retests.
d. It has to analyze the net to ensure its structure boundedness (SB).

In addition, Reveliotis [30] did not discuss how to make the net SB; while our proposed scheme does. Further, S^3PGR is less powerful than our proposed S^2NPGR (Systems of Synchronized choice Net processes with General Resource) which can model not only assembly operation requiring multiple resources but also parallel activity and synchronization.

Xie proposed a linear programming approach that requires the examination of all minimal siphons. Its efficiency depends on the number of minimal siphons. Unfortunately, it is well known that the total number of minimal siphons (traps) grows quickly beyond practical limits and that, in worst case, it grows exponentially in the number of nodes. Xie showed that it is possible to check deadlock-freeness without generating minimal siphons based on the mixed integer linear programming approach where the net is assumed to be structurally bound. One way to reduce the complexity of the linear programming approach is to find efficient algorithms for generating minimal siphons that do not contain traps without generating other siphons such as that proposed by Jeng [28]. Xie's MIP [3] approach is based on the assumption that no such algorithms exist. Although theoretically the number of such siphons grows exponentially in the number of nodes, both Jeng and Ezpeleta indicated in their papers that in practice, it is usually small comparing to the number of basis siphons. Thus, the MIP approach may not be the best approach. *In addition, it finds maximum siphons. Computational efforts are still required to extract minimum siphons for deadlock prevention by adding control places.*

We propose to extend it to S^3PGR and with general resource requirements and improve its computational efficiency. Because at most one resource type is used in each job stage and the processes are modeled using state machines using S^3PR, its modeling power is limited, hence we further propose S^2NPGR (Systems of Synchronized choice Net processes with General Resource) where each process or WP is a WSNC (Weighted SNC) [14]. This is better than the RCNM (Resource Control Net-merged which cannot model parallel and synchronization activities [26]. Additional benefit of this research will be to generalize some siphon-related theory of Ordinary PN (OPN) to General PN (GPN). Our reachability paper [27] in SNC has received good comments and SNC [27] has been considered an important variant of PN classes since we already have two papers published in the prestigious Computer Journal. Note that SNC [11] extends our work on our important Knitting Technique [9,12-13] for PN synthesis. It is important to continue research in this line to establish and reinforce our reputation in PN field. We will stand over all researchers' shoulder in this field.

三、Results

To prevent deadlocks arising in flexible manufacturing systems (FMS), some control places and related arcs are added to minimal bad siphons (MBS) such that no siphon can be emptied. Since the number of minimal siphons grows in general exponentially with respect to a Petri net size, efficient techniques to enumerate them are urgently needed.

Once we find all MBS, we can follow the approach in [34] to add control places and arcs to prevent deadlocks. Hence our efforts focus on finding all MBS for various enhanced models resulting in a number of papers.

We [35] first propose a trace procedure to illustrate the combinatorial problem of extracting minimal siphons for arbitrary strongly connected Petri nets and three ways to improve it. We [35] then develop theory to efficiently extract minimal bad siphons and specialize it for S^3PR (Systems of Simple Sequential Processes) proposed by Ezpeleta et al. in an incremental fashion using an algorithm rather than the traditional global approach. Only linear number of minimal bad siphons needs to be searched. The rest can be found by adding and deleting common sets of places from existing ones with search time significantly reduced.

We [36] further extend it to SNC-Based Resource Allocation System called S^2NPR where each WP is replaced by an SNC. Again, only a subset of all MBS needs to be searched. The rest SMS can be found by adding and deleting common sets of places from existing ones. And the enhanced model covers the Extended Resource Control Merged Net (ERCN*) as a subset. It is very **interesting** that both nets and siphons can be synthesized by first locating a circuit followed by adding handles.

Next, we [37] propose to decompose an S^2NPR into a number of S^3PR components and apply our earlier technique for S^3PR the technique to find MBS for each component. This has the advantage of simplifying the theory.

Based on the above research results, we found that each strongly connected resource subnet — containing no state places — correspond to an MBS. The same result holds for S^2PGR and S^2PWR. We [38] have developed an algorithm for finding all sub-SCC (strongly connected component).

Unlike other techniques, Li *et al.* [34] add control nodes and arcs for only elementary siphons greatly reducing the number of control nodes and arcs. Their method suffers from the expensive computation of siphons. We [39] propose a new T-characteristic vector ζ to compute MBS for S^3PR in an algebraic fashion. For a special subclass of S^3PR called S^4PR, the set of elementary siphons can be computed without the knowledge of all SMS. We discover that any elementary siphon is a basic siphon constructed from an elementary circuit where all places are resources. We also propose to construct characteristic *T*-vectors η by building a graph for all redundant siphons without their computations.

We discover and have proved that for non-S^4PR, redundant siphons built from compound resource circuits, the intersection between any two basic circuits must be a single resource place — **very interesting and significant.** We have adapted the above sub-SCC search-algorithm to find all elementary siphons instead of all MBS. **This significantly relieves the NP-complete problem of searching all minimal siphons.**

For S^2NPWR & S^2NPGR, we have also established new and outstanding results regarding the marking for liveness. We extend the concept of invariant-controlled siphons for OPN to GPN. We call it max'-controlled siphons. For details, please refer to [40].

For OPN, even if all siphons are controlled to be deadlock-free, the net may not be live. The proof of liveness for various new classes of nets is not intuitive and rather hard to understand. We [41] propose to find the maximum class, called non-virtual-net that are live as long as all minimal siphons never get empty of tokens and the maximum class, called virtual-net that may be weakly live if all minimal siphons never get empty of tokens. We show that weakly liveness is closely related to a structure called Virtual First Order Structure. We show that both Synchronized Choice Net and Extended Synchronized Choice Net belong to non-virtual-net. In [42], we show that they remain to be maximal for general Petri nets under a different condition — all siphons are max-controlled rather than always have tokens.

The above theory is important, because we can show that for S^3PR, S^2PGR, S^2NPR, and S^2WPGR, all belong to NV-net. Once if we prove that they are controlled, we can be sure of their liveness instead of a mere deadlock-freeness. In addition, we enhance our synthesis rules so that they relieve both structure and marking problems of Petri Nets [43].

For S^2PWR, we found that simple extension of the technique in [34] by adding control places and arcs do not work, we have discovered its issues and a new method to add control places and arcs.

In summary, our achievements are excellent and exceed all other scholars. Without timely support of NSC, this project may have not been so successful.

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附件：封面格式

行政院國家科學委員會補助專題研究計畫成果報告

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共同主持人：

計畫參與人員：吳俊德, 翁懷嘉政治大學資管系

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執行單位：

中　華　民　國　94　年　9　月　25　日