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擴大多項式 reachability 問題的網的種類
研究成果報告(精簡版)

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計畫主持人： 趙玉

計畫參與人員： 臨時工：林立人、張哲瑋
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一、中文摘要

我們在以分解技術及多項式時間複雜性解決實際例子如 FMS 的可達性(Reachability) 問題上，是該領域的先趨。為了鞏固我們在此領域的領先地位，本計劃透過把多項式結果延伸到更錯綜複雜的種類。本研究已發現可達性問題的 NP-問題的基本原因。因為第一個階層架構在任何 SNC 裡是對稱的，我們提議這與非對稱的第一個階層架構有關(AFOS)。 我們叫這樣類型的派翠(Petri)網為**艱難的普通派翠網(OPN)**。 我們已研究其可達性問題可以被多項式時間複雜性解決的艱難的 OPN 的子類。 對於這樣的派翠網，為了多項式的結果存在門檻標記，這是因為Petri 網(PN)的行為不僅倚賴派翠網圖的表架構，而且倚賴在最初網的標記上。 我們提議找到這樣的門檻標記， 顯示，可達性問題的艱難起源于為一般的 PN(GPN) 的艱難可達性問題，這是因為他們經常可以變為 GPN。 我們已借著把他們轉變成簡單 GPN 以更進一步簡化那些簡單的艱難 OPN 可達性的問題。 因此我們提議為以前從未被研究的簡單的 GPN 研究可達性問題。 更進一步，我們已把分解原則用于稍微地偏離 SNC 的無界的 Petri 網的可達性分析。這與被修改的 Reachability 樹(MRT)相比較，有避開架構可達性圖方面的優勢。

關鍵詞: 派翠網 可達性 活的 分解

Abstract

We pioneered the decomposition technique to solve the Reachability problem with polynomial time complexity for real life classes of nets such as FMS. We propose to consolidate our leading position by extending the polynomial results to more complicated classes of nets. The basic cause of the NP-problem of the Reachability problem has not been studied before. We find in this research that it is related to asymmetric first order structures (AFOS) since the first order structures in any SNC are symmetric. We call such nets **hard ordinary Petri nets (OPN)**. We have studied subclasses of hard OPN whose Reachability problem can be solved with polynomial time complexity. We find that for such nets, there exist threshold markings for polynomial results since the behavior of a Petri net (PN) depends not only on the graphical structure, but also on the initial marking of the net. We find such threshold markings and show that hardness of Reachability problem originates from the hard problem for general PN (GPN) since they often can be converted into GPN. We further simplify the Reachability problem for simple hard OPN by converting them into simple GPN in this research. We have studied the Reachability problem for simple GPN which has never been studied before. Further, we have applied the decomposition principle to reachability analysis to unbounded Petri nets slightly perturbed from SNC. This has the advantage of avoiding building reachability graph compared with the modified Reachability Trees (MRT) approach.

Keywords: Petri nets reachability live decomposition

二、緣由與目的

We propose to extend the work in [1-2] to enlarge classes of nets whose reachability problem can be solved in polynomial time. In [3-5], a new local structure called Second Order Structure (SOS) was proposed to generate a new class of nets called Synchronized Choice Nets (SNC). SNC covers well-behaved FC. Reachability is no longer P-Space hard problem, but can be solved with polynomial time complexity. We extended them to non-SNC such as FMS and apply to deadlock detection with polynomial time complexity. The following contributions are noted by one reviewer:

1. Introducing a new class of Petri nets
2. Discussing the Reachability problem, which is an open problem for general Petri nets.
3. Well-behavedness of the introduced class.
4. Application to a large (special) class of discrete event systems.

He said "It is a major contribution in the field. In spite of the intensive literature of Petri nets and its applications, special classes of Petri nets have not been applied in real world systems (especially, FMSs)." In addition, our approach for reachability analysis based on matrix is the first in its kind. It neither builds reachability graph nor solves state equations. We are the first to detect deadlocks in FMS based on reachability analysis without setting up reachability graph and computing siphons. We propose to consolidate our leading position by extending the above results to more complicated classes of nets. Another motivation is discussed below.

An FMS model consists of a set of working processes (WP) competing for resources. A WP models a sequence of operations to manufacture a product. Ezpeleta et al. proposed a class of nets called Systems of Simple Sequential Processes with Resources (S^3PR) [6]. It is a state machine (SM) plus a set of places modeling the availability of resources. Each SM contains one idle place or 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.

Because only one resource is used in each job stage and the processes are modeled using state machines in S^3PR, its modeling power is limited. It cannot model iteration statements (loop) in each sequential process (SP) and the relationships of synchronization and communication among SP. At any state of a process, it cannot use multi-sets of resources. They compute all siphons (see Definition 5) that are not traps of the given model and find the maximum number of tokens at each idle state followed by a prevention control policy of adding arcs and nodes with tokens. Most recent deadlock control approaches [7, 8] extend this approach.

Unfortunately, the total number of siphons grows quickly beyond practical limits and that, in worst case, it grows exponentially [9, 10] in the number of nodes. Thus, for large complicated systems, the prevention policy may no longer be appropriate. In this case, it is better [11] to perform reachability analysis which explores all possible states, and hence can check various properties such as livelocks and race conditions other than liveness. It is conceptually simple and relatively straightforward to automate and can be used in conjunction with model-checking procedures to check for application-specific as well as general properties. Also many control problems can be modeled by the reachability problem indicated by Ichikawa et al. [12].

To improve on the above Sequential Resource Allocation System (RAS) [6], Ezpeleta et al. [11] proposed a Non-Sequential Resource Allocation System (NS-RAS), they proposed a general Petri net model where even multiple copies of one type of resource is allowed to be used at each processing step. The modeling power is much enhanced, but the analysis becomes complicated. They, hence, proposed a deadlock avoidance approach with polynomial result by constructing reachability graph for the isolated execution of each production order, tiny compared with the size of the reachability graph of the whole system, to find strongly connected components (not possible with siphon analysis).

However, 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 on-line analysis 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. They indicated that “the whole time to know if a system state is safe can take about 2 CPU/s in the worst case” and “the proposed control method would be more or less permissive”. In their model, each WP is still an ordinary net as shown in Fig. 2 of [11] (actually an SNC).

This motivates us to find more complicated classes of nets whose reachability problem can be solved in polynomial time.

Further, we propose to apply the decomposition principle to reachability analysis to unbounded Petri nets slightly perturbed from SNC. Karp-Miller’s Finite Reachability Trees (FRTs) [12] approach is a universal tool for analysis of Petri nets. However, some certain useful information is lost by the use of ω symbol, the reachability, liveness and deadlock problems cannot be solved by the FRT method alone. Therefore, a modified Reachability Trees (MRT) [13] approach has been developed to extend the capability of FRTs in solving these problems of Petri nets. The MRT approach is creative and very useful to the analysis of unbounded Petri nets since the nodes contain more information regarding the structure of Petri nets to be analyzed.

However, it suffers from a bug in one theorem which gives the necessary and sufficient condition of deadlocks. Further, it has to build the reachability graph whose size can be large for moderate size of Petri nets. As said earlier, for SNC, there is no need to build the

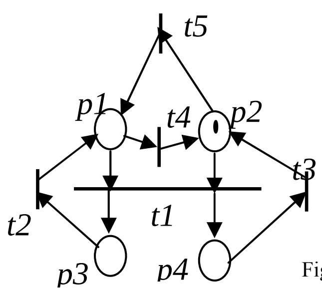

Fig. 1(a). An example of a net which can be reduced to a GPN.

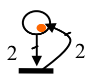

Fig. 1(b). The reduced GPN of that in Fig. 1(a).

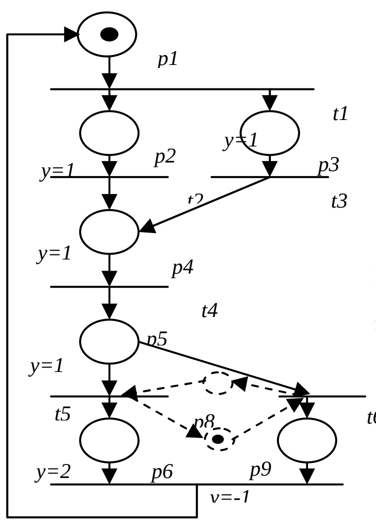

Fig. 2(a). A second example of a net which can be reduced to a GPN. tokens.

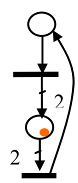

Fig. 2(b). The reduced GPN of that in Fig. 2(a).

reachability graph. In addition, we can construct the relationship of ω's among different places unavailable for the MRT approach.

三、Results

We have accomplished the following:

1. Basic cause of the NP-problem of the Reachability problem
2. Reachability analysis of **hard ordinary Petri nets (OPN)**.
3. Discovery subclasses of hard OPN whose Reachability problem can be solved with polynomial time complexity.
4. Analysis of threshold markings of hard OPN with polynomial time complexity
5. Reachability analysis for simple GPN.
6. Application of the decomposition principle to reachability analysis to unbounded Petri nets slightly perturbed from SNC.
7. Application of the decomposition principle to reachability and deadlock analysis to Systems of Simple Sequential Processes with General Resources Requirement (S^3PGR^2)

   An SCI paper is in the work and will be finished in 3 months. Reachability analysis is essential for optimal design of supervisors of FMS, but it suffers from the complexity problem. This research aims to relieve the complexity problem of reachability analysis and hence is essential for optimal design of FMS. Papers [14-24] regarding FMS have been written this year. Most interesting relates to the optimal design of FMS. So far, I have achieved outstanding results. Further application of this research would produce outstanding papers.

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