# Liveness Problem of Petri Nets Supervisory Control Theory for Discrete Event Systems[1)]

Hong-Ye SU Wei-Min WU Jian CHU
(*National Laboratory of Industrial Control Technology* & *Institute of Advanced Process Control, Zhejiang University, Hangzhou* 310027 *P.R.China*)
(E-mail: {hysu, wmwu, chuj}@iipc.zju.edu.cn)

**Abstract** A quite great progress of the supervisory control theory for discrete event systems (DES) has been made in the past nearly twenty years, and now, automata, formal language and Petri nets become the main research tools. This paper focus on the Petri nets based supervisory control theory of DES. Firstly, we review the research results in this field, and claim that there generally exists a problem in Petri nets based supervisory control theory of DES, that is, the deadlock caused by the controller introduced to enforce the given specification occurs in the closed-loop systems, especially the deadlock occurs in the closed-loop system in which the original plant is live. Finally, a possible research direction is presented for the solution of this problem.

**Key words** Discrete event systems, supervisory control, Petri nets, liveness

## 1 Introduction

Discrete event system (DES) is a new kind of dynamical systems created along with the development of computer science, communication networks and sensor technology. The prime reason to study DES theory is the rapidly developed high technology, as pointed out by Zheng Dazhong and Zheng Yingping[1]. Examples of DES include computer communication networks, automated manufacturing system, especially flexible manufacturing system (FMS) and computer integrated manufacturing system (CIMS), computer control system, operation system, space traffic control system, military $C_3I$ system, supervisory control system in intelligent building and mobile telephone, intelligent transportation, distributed software system and so on. The systems mentioned above are controlled in large part by man-made operation rules. So its dynamic property is determined by the events randomly occurred at the discrete time instance, and the classical control theory based on differential or difference equations can not be used to analyze and synthesize DES. The main mathematic model of DES is random process model such as Markov chain and sequence theory, automaton and Petri nets (PN), etc. Automaton and PN is mainly applied to system synthesis while Markov chain is used in performance analysis.

Automaton and formal language are adopted as the main research tools for the initial supervisory control theory of DES by Ramadge and Wonham, the founder of the theory, and referred as RW theory [2∼5]. Though the automaton and formal language model of DES has the advantage that it separates the concept of open-loop dynamics (plant) from the feedback control[4], it has great difficulty of overcoming computation complexity, especially in the case that the controlled systems is a large system constituted by many interacting subsystems. For example, if an automated guided vehicle coordination system made of five vehicles is modeled by automaton, it would have well over a million system states, and thus the computation of its feedback control policy is nearly impossible[6]. Giua summarized the advantages of PN model for supervisory control of DES[7,8]:

1) PN has a higher language complexity than automaton since Petri net languages are a proper superset of regular languages;

2) The states of a PN are represented by the possible markings and not by the places, they allow a compact description, *i.e.*, the structure of the net may be maintained small in size even if the number of the markings grows;

3) Petri nets allow modular synthesis.

Because Petri nets have the advantages of the graphical and distributed representation for the system states and the computational efficiencies, in addition, the performance characteristics of PN

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such as liveness and deadlock have obvious engineering meaning[9], more and more scholars use them as research tool for the supervisory control theory of DES. However, salesmen continue to travel though the problem is complex and hard to be solved[10]. In fact, automaton based method also has its advantages[11]:

1) The obtained controlled system will not violate the given control specification and is non-blocking;

2) The obtained supervisors and control laws are maximally permissive, *i.e.*, all the events that will not violate the given control specification are allowed to occur.

In addition, in the phase of controller model refinement, automaton offers some advantages over PN in the sense that on automaton the states are explicitly enumerated in the model[7]. In fact, it is believed that which model is selected in the research depends on not only the model's virtue but also the culture tradition and what computing tools happen to be available at any given time to the group you belong to[12].

This paper only discusses the Petri nets based supervisory control theory of DES. Firstly, we review the research results in this field. However, the main aim of this paper is not to survey the theory in allsides. Based on the survey, we claim that there generally exists a problem in Petri nets based supervisory control theory of DES, that is, the deadlock caused by the controller introduced to enforce the given specification occurs in the closed-loop systems, especially the deadlock occurs in the closed-loop system in which the original plant is live.

## 2 PN based supervisory control theory of DES

For the type of the obtained controller, DES controller can be categorized into mapping controller and compiled controller[8]. The controller synthesized using the tool of automaton and formal language is usually a mapping one. The controller synthesized using the tool of PN maybe a mapping or compiled one. But compiled controller is usually synthesized using the tool of PN. The control policy of mapping controller is represented with a function, which determines the control action according to the current system states. The compiled controller itself is a Petri subnet (called controller subnet) and its control policy is smoothly integrated into the controlled Petri nets including controlled plant and controller subnet. Comparing with the open-loop system, the evolution of the controlled plant in the controlled system is restricted to meet the control specification due to the existence of the controller subnet. Because the control law is online determined according to the current states, the mapping controller is easier to implement the maximally permissive control compared to the compiled one. However, the (Petri nets) compiled controller has faster computation on control action since it does not need online computation, and the same Petri nets evolution algorithm can be synchronously applied to controlled plant and controller subnet. What is more, the closed-loop system (Petri nets) satisfying the given control specification can be constructed using the standard Petri nets constitution method.

Based on controlled Petri nets[13], Holloway and Krogh *et al.* used path algebraic method to obtain the algebraic expression through calculating the algebraic defined on the Petri net paths[6,14]. The expression can efficiently indicate when the forbidden state is reached in the process of system evolution and whether a control action is needed to impose on the system to assure the system evolves in the non-forbidden state, and then the optimal feedback control law is obtained. The drawback of this method is that it only applicable to a class of DES modeled by marked graphs. Boel *et al.* proposed the maximally permissive control algorithm for state graphs, which is dual to marked graphs, and the algorithm can prevent the system from reaching the forbidden states expressed as linear place marking inequation[16]. Recently, in[17,18] Ghaffari and Darondeaua *et al.* presented new results on the problem addressed in[6,14]. Their methods can deal with the control problems in non-safe and even unbounded marked graphs. Song and Wu *et al.* addressed the forbidden state problem of another class of Petri nets whose spanning subnets of the uncontrollable subnet is a TC net[19], while the same problem was resolved by Yuan and Xu using the method of coordination feedback control[20]. By defining the model named vector discrete event systems (VDES)[21], which is equivalent to Petri nets, Li and Wonham transformed the linear predicate constraint, *i.e.* linear place marking inequation constraint, into the problem of linear integer programming (LIP) and obtained the solution in the form of closed-loop using online computation. However for the Petri nets with TS1 structure, the obtained control law is not always optimal, and moreover, LIP method is incapacity of treating with the case that there exits loops in the net[22]. LIP method was extended by Dong and Wu et al to deal with the case that there exits loops in the net[23,24], and the extended LIP method is capable of dealing with the supervisory control problem of DES whose uncontrollable subnet is state graph or a so-called normalized cascade structures Petri nets[25].

For the controller type, the scholars mentioned above presented the control laws in the form of mapping controller, *i.e.* there is no actual controller in the closed-loop system. Differing with the above methods, Yamalidou and Moody *et al.* designed a PN compiled controller for DES with linear marking inequation constraint based on the concept of place invariant[26,27]. The basic idea behind their method is that it makes all the places in the constraint combined with the controller place as the place invariant of the expected closed-loop control system, and then the controller structure is obtained via matrix operation. The result obtained using place invariant is the same with Giua's, which was obtained early through appending a monitor on the controlled plant to satisfy the given constraint[28]. Closely related with the place invariant method, S-decrease method proposed by Chen can be understood as that the equation in place invariant method is extended to inequation[29,30]. However, S-decrease method is only applicable to the ordinary Petri nets with special structure. Literatures[31∼34] extended place invariant method in variant aspects. But, the computation efficiency of place invariant method is greatly affected in the case that the system is a large and complex system since the incidence matrix of the system is a high dimension matrix. In addition, when there are uncontrollable transitions in the net, the method is applicable only if some special conditions are satisfied and the obtained controller is usually not maximally permissive[27]. Based on the concept of finite capacity place, Wu and Su et al proposed a method for synthesizing a PN compiled controller for DES with linear marking inequation constraint. Comparing with Yamalidous's method, the method has greatly improved the computation efficiency since it needs not to compute the incidence matrix of Petri net and its matrix operation[35,36]. Wu, Su, Uzam and Cho *et al.* exploited inhibitor arc and enabling arc Petri nets to design compiled controller[37∼42]. The advantage of the method is that its control concept is clear and can be easily understood and accepted by control engineering. However, the analysis of its closed-loop is more difficult due to the introduction of inhibitor arc and enabling arc[43]. Recently, Uzam and Wonham have tried to combine supervisor in the form of automaton to design PN compiled controller[44], while Wu and Dong *et al.* proposed the synthesis method of combined controller, which exploits the advantages of both mapping and compiled controller[45]. In addition, it is also a worthy noticeable direction of synthesizing controller for DES using colored Petri nets[46,47].

## 3 Liveness problem

Though all the methods above addressed the optimal problem or maximally permissiveness control problem, an important problem in supervisory control theory, *i.e.* the designed controller should assure that the given control specification is met while as many as possible of events (transitions) are allowed to occur (fire) so as to make the closed-loop system has the biggest state space (the meaning of optimization here is not the same with that given by Liu and Hu[48], where it means the minimal control cost), they have a common shortcoming that all the controller design theories did not address the liveness problem of Petri nets controller, *i.e.* the designed controller should assure that the given control specification is met while every transition always has the possibility of firing in the system evolution in the sense of forever.

Because the concepts of liveness, deadlock, non-liveness and deadlock-free of Petri nets are slightly different in literatures[49,50], we emphasize that the concepts are shown as below. A PN is *live*, if regardless of the evolution, no transition will become unfireable on a permanent basis. A PN marking is a *deadlock* marking, if no transition is enabled at the marking. A PN is *non-live*, if there exits a transition that is not enabled any more at any marking. A PN is *deadlock-free*, if there exits at least one transition that is enabled at any reachable marking. Though sometimes the concept of non-blocking in automaton model of DES is regarded as equivalent to the liveness of PN[51], strictly speaking, their meaning are different. Non-blocking is equivalent to the reversibility concept of PN, moreover, the requirement of reversibility is strong than that of liveness[44]. However, a reversible PN is not always live and vice versa[50].

It has been clearly reported that the controller designed using no matter which method, Holloway's path algebra method or Yamalidou's place invariant method, will result in deadlock in the system. In fact, not only the above methods but also the other supervisory control theories of DES based on Petri nets have the similar problem[17,18,30,54]. The reason of the problem is that the closed-loop system will produce new deadlock structure in the view of Petri nets structure[55]. Therefore, it is very important to study how to design a live controller.

Though there are a lot of reported results on deadlock avoidance, prevention and supervisory control in Petri nets, e.g. the recently published IEEE transitions on systems, man and cybernetic[56], a special issue on deadlock resolution, we emphasize that the deadlock problem addressed in presented paper is different from that in the reported research. The deadlock addressed in the reported literatures is about the inherent deadlock structure of the system model even though it was discussed in the framework of supervisory control[57∼63], while the deadlock addressed in this paper is on the new produced deadlock structure caused by the controller introduced to enforce the given specification, especially the deadlock occurs in the closed-loop system in which the original plant is live. This type of deadlock is seldom studied and only reported in a few literatures[52∼54], what is more, there are various restrictions in the researches, e.g. the case that there exits uncontrollable transitions (events) in the system was not considered[54]. The former may be eliminated through improved modeling the system, but the latter has no inevitable relation with the model and only may be eliminated through revising control policy.

## 4 A possible research direction

This section discusses the research direction of synthesizing optimal live Petri nets compiled controller satisfying the given control specification for DES. The reason why the controller is selected as the compiled type is shown as below. Comparing with the mapping type, the Petri nets compiled controller does not need online computation and has a faster computation of control action. The same Petri nets evolution algorithm can be simultaneously applied to the controlled plant and the controller subnet. Moreover, the closed-loop system can be constructed using the standard PN constitute methods to meet the given control specification. The most important reason, however, is that in generally the closed-loop system is also a Petri net and this will greatly facilitate to analyze the deadlock and liveness of the closed-loop system, which is not possessed by the mapping Petri nets controller.

We believe that the *theory of regions*[64] and the PN partial order analysis method named *Petri nets unfoldings* technique[65,66] can be exploited to design a live PN controller such that the control specification is met in the closed-loop system while the system is assured to evolve furthest and periodically. The control specification considered here is a group of linear inequation constraints defined on the PN place marking. This kind of constraint has been received universal recognition and widely addressed [8, 14, 17, 18, 26, 27, 30, 35∼39, 44, 45, 53, 54, 60, 67∼69], and the other kinds of constraint such as deadlock may be transformed into the form of this kind of constraint[53,68,69]. Theory of regions is a formal synthesis method for deducing a Petri net model from finite state graph (automaton)[64]. The application of the theory of regions in DES supervisory control theory is still on its initial stage and there is only a few reported international researches, refer to the work of Uzam[70] and Ghaffari[71]. There is no related reported research in domestic. Because the method of designing controller in the full state space of DES supervisory control theory based on automaton is borrowed in the synthesis process, it is possible to design a live Petri nets compiled controller without online computation using the theory of regions. However, due to the same reason, the methods of Uzam and Ghaffari should be improved in the computation complexity at the design stage. In addition, the authors did not present the formal proof of the controller's liveness and thus their results are doubtful[51]. In [70, 71] , the system concurrency is not considered and the obtained results is only applicable to some special cases such as the PN model is not universal and the considered constraint is just several isolated forbidden states and so on. What is more, not all the DES have a PN compiled controller, and the controller is not sure to be optimal even if it exists[8,12].

All the problems above will be discussed in the presented paper. For the complexity problem, we propose to compute the weakly forbidden state using reverse net since one reason is that the weakly forbidden states are not computed in advance such that the possibility of reducing the state search space is lost. To satisfy the given control specification, some states must be forbidden to reach by the system and these states constitute the so-called forbidden states. Due to the firing of the uncontrollable transitions, it is still possible that the system reaches the forbidden states even if all the controllable transitions are disabled. In the supervisory control theory of DES, a great effort has been devoted to handling the uncontrollable transitions and the weakly forbidden state problem caused by it. However, the efforts are not efficient. Given an original Petri net, its *reverse net* is a net such that it changes nothing of the original net but reversing the arcs direction[72,73]. Usually, the current methods of computing the weakly forbidden states focus on which states will lead the system to reach the forbidden states due to the firing of the uncontrollable transitions in the original Petri nets. Thus, these methods are reversible from the standpoint of the evolution and the reachability graph of the original Petri net (and this is the reason why these methods are not very efficient), because the basic idea behind these methods is that to obtain the weakly forbidden states by tracing back from the forbidden states. The tracing, however, is ordinal in the corresponding reverse net. So combining with the current analysis methods, the PN structure information can be fully exploited to compute the weakly forbidden states. We have made initial effort to compute the weakly forbidden states using reverse net[74]. The obtained result indicates that the method is effective. It is necessary to point out that the critical states of the forbidden states are obtained using reverse net in the case that there are no uncontrollable transitions in the system in the paper[20]. Another idea is to treat with the complexity problem using the PN unfoldings technique. The technique is a partial analysis method of treating with the state explosion problem of PN, and essentially a reachability graph analysis method. It unfolds a Petri net into an acyclic structure called an *occurrence net*. The places and transitions in the occurrence net are mapping into those in the original PN through defining a net homomorphism, and thus the state space of the original PN can be known by analyzing that of occurrence net[65,66]. By further defining the concept of *finite prefix* of occurrence net, the infinite state space can be handled in a "finite means", *i.e.* even though the reachability graph of the original PN is finite, its corresponding finite prefix is finite. The ultimate reason that PN unfoldings technique has advantage over the other reachability graph methods is that it preserves the causal relation among the transitions of the original PN in the unfolding process, *i.e.* some structure information is preserved. Therefore, it is possible to reduce the state search space in the design of DES controller using the theory of regions combining with PN unfoldings technique. What is more, PN unfoldings technique will be used to structurally analyze the liveness of the controlled system so as to obtain whether or not there is a deadlock in the controlled system, and then consequently to judge whether or not there exits a live PN compiled controller in the controlled system satisfying the given control specification and the control law is adjusted accordingly to finally obtain a live controlled system. The unresolved problem of[70,71] may be then resolved. It is necessary to point out that whether a PN marking is a deadlock or not relates with the initial marking. This is considered in the occurrence net obtained using PN unfoldings technique, and thus it is a feasible technique to analyze the livenenss of the controlled system in the framework of occurrence net. There exists an international report on the successful application of unfoldings technique in analyzing the liveness of PN[57], but no report on the deadlock caused by supervisory control. In domestic, no report on the two aspects can be founded.

## 5 Conclusions

In this paper, the Petri nets based supervisory control theory of DES, including the current research state, the unresolved problems and its possible resolution methods, are discussed. But the paper is not a thoughtful survey on the supervisory control theory for DES, even is not a PN based supervisory control theory for DES. We firstly review the research results in this field, and claim that there generally exists a problem in Petri nets based supervisory control theory of DES, that is, the deadlock caused by the controller introduced to enforce the given specification occurs in the closed-loop systems, especially the deadlock occurs in the closed-loop system in which the original plant is live. Finally, a possible research direction is discussed in detail for the solution of this problem. We believe that it is possible to design an optimal and live Petri nets compiled controller for DES satisfying the given control specification using the theory regions and PN partial order analysis method.

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**Hong-Ye SU** Received his bachelor degree in industrial automation from Nanjin University of Chemical Technology in 1990. He later obtained the master and Ph.D. degrees from Zhejiang University in 1993 and 1995 respectively. From 1995 to 1997, he was a lecturer in Department of Chemical Engineering, Zhejiang University. From 1998 to 2000, he was an associate professor in Institute of Industrial Process Control, Zhejiang University. Now he is a professor in Institute of Advanced Process Control, Zhejiang University. His recent research interests include robust control, time-delay systems, nonlinear systems, DEDS, advanced process control theory and application.

**Wei-Min WU** Ph.D. and lecturer. His research interests include DES, hybrid systems and Petri nets.

**Jian CHU** Ph.D. and Professor. His research interests include control theory and applications, R & D of computer control system and advanced process control software.