Synthesis of Decentralized Supervisors for Cyber-Physical Systems

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1. Background and Research Challenges

The synthesis of supervisors for discrete-event systems (DES) is an important research field in the study of cyber-physical systems. On the one hand, this problem arises in the study of complex automated systems where the behavior is inherently event-driven, as well as in the study of discrete abstractions of continuous, hybrid, and/or cyber-physical systems. On the other hand, working with discrete-event abstracted models is, in many cases, the most effective way of tackling control problems for many classes of complex cyber-physical systems. Due to the limited actuation and sensing capabilities in the plant, a DES in the real world is always partially-controlled/observed. Moreover, in large complex systems, due to the distributed nature, a decentralized approach is always the desired or the only way to implement the controllers. Thus, decentralized supervisory control is a suitable framework for tackling these requirements.

The research challenges for this problem arise in the following two aspects. First, in the DES literature, the existence condition for exactly achieving a specification by a set of local agents has been fully investigated. However, if the existence condition does not hold, the synthesis problem which asks whether we can restrict the system's behavior to be within the specification and as large as possible still remains open. Second, in the case where we want to to synthesize communication protocols between each local agent, the control, communication and estimation are always coupled with each other, which makes the synthesis problem more difficult to deal with. To the best of our knowledge, there is no standard method to solve the joint synthesis problem.

2. Proposed Research

In our recent work [1], we have revisited the synthesis of centralized supervisors for partially-observed discrete-event systems from a new angle, based on the construction of a new structure called the All Inclusive Controller (AIC), which is a bipartite transition system that embeds all safe supervisors. Our results show that the AIC is a general and powerful structure since it contains all desired solutions and some open problems (e.g., synthesis of maximally permissive non-blocking supervisors) can be solved within this framework.

In the proposed research, we wish to provide a new synthesis methodology for a set of decentralized discrete-event control laws as well as sensor activation and communication strategies for the system agents. Our technical approach is to extend our previous approach for the centralized case to the decentralized case, by constructing a new information structure, which is a bipartite system, reminiscent of a game between the supervisor and the system, with: (i) control states, where all safe control decisions are enumerated, and (ii) system states, where all feasible observable system events are executed. This structure is built from a centralized point of view by: (i)

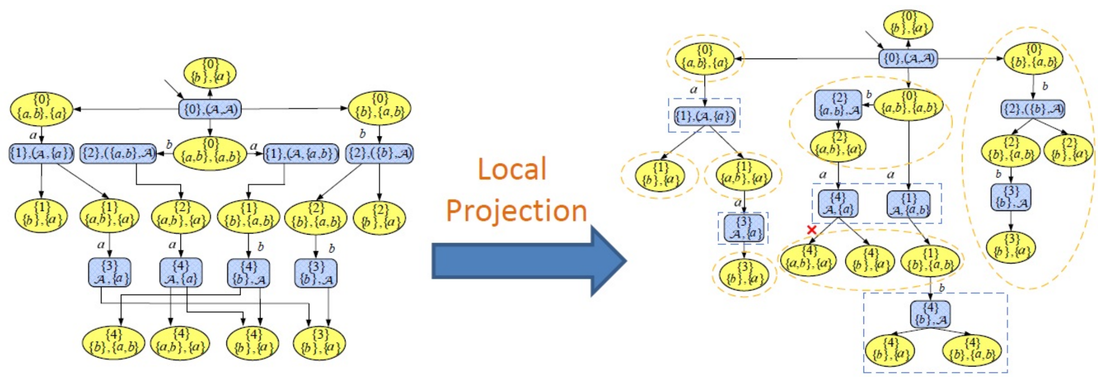

Figure 1: An illustration example of the proposed game structure, where the blue states are control states and the yellow states are environment states. The left hand side shows an example of the centralized information structure and the right hand side is its projection to a local agent.

eliminating all undesired behaviors and; (ii) updating each local control decision when the agent "saw" something. Further to make sure that the centralized solution is implementable with decentralized architecture, we need to recursively project this system to each local site and refine this structure to meet local control consistency constraint. To achieve more variety of functionalities, additional layers can be added in the bipartite structure, such as a communication layer, a sensor activation layer or a decision fusion layer. Once this previous step is achieved, we will solve optimization problems over the constructed bipartite transition system w.r.t. different criteria to obtain optimal solutions to implement on the system. Our "agenda" for the proposed research is:

1. Build a new game structure containing all information for the decentralized control problem;
2. Find a new synthesis method for both control strategies as well as sensor activation policies and communication protocols based on this structure;
3. Extract one optimal solution from the solution space w.r.t. some criterion;
4. Apply the above methodologies to a real world cyber-physical system as a case study, e.g., vehicular electric power system.

3. Potential Impact to CPS

The potential impact of the proposed research to CPS lies in the following two aspects. Theoretically, it will provide a general approach for the synthesis of supervisors (discrete controllers) for decentralized DES, which, to the best of our knowledge, does not exist in the literature. Practically, this design methodology can be applied to a large class of real world cyber-physical systems, e.g., vehicular electric power systems, in which the control actions involve actuation of discrete switches, so the proposed synthesis strategies will be directly applicable to the underlying system. In more general classes of cyber-physical systems, in which continuous dynamics need to be considered, the discrete control actions will need to be mapped back to continuous control actions on the underlying system, by performing an inverse of the abstraction and the bisimulation properties.

References

[1] Xiang Yin and Séphane Lafortune,"A general approach for synthesis of supervisors for partially-observed discrete-event systems.", *19th IFAC World Congress*, submitted, 2014.