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Analysis and Control of Coupled Discrete-Event Systems

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1 DES and Complexity Issues

Discrete-event systems (DES) are dynamical systems whose behavior is characterized by the occurrence of discrete state transitions induced by events. DES are widely modelled using the theory of languages and automata. In this project the Supervisory Control Theory (SCT) is used to analyze specific properties of a DES, in particular the controllability and observability, and to design a proper supervisory control. The control loop is illustrated in Figure 1.

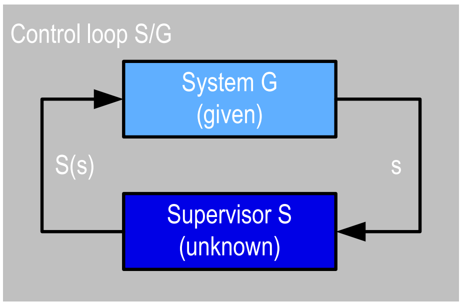


Figure 1: Control loop

The system G is characterized by its language $L(G)$. The overall behavior of the closed loop is specified by the language $L(S/G)$.

- **Control Problem:** The uncontrolled behavior $L(G)$ of the system G violates the given specifications. A supervisor is to be found that prevents the undesired strings.

This procedure leads to two important theoretical problems:

- **Solution:** Find a subset $K \subseteq L(G)$ representing the desired behavior of the controlled system.
- **Realization:** Design a proper supervisory control S so that $L(S/G) = L(S \otimes G) = \overline{K}$ with $S \otimes G$ the product automaton, thus to realize the desired behavior.

S supervises the string s generated by G so far and disables those possible subsequent events which are undesired in the next step by its control actions $S(s)$. This task has to be solved subject to the following restrictions:

- **Events:** Uncontrollable events, whose occurrence can not be prevented, and unobservable events, whose occurrence is not detectable, must be considered.
- **Existence:** A proper supervisor exists, if the key properties controllability and observability are verified.

Standard analysis and supervisory control design methods operate on monolithic representations of the system and the specifications. In addition, the outcome of the design methods always results in a centralized supervisory control. Both is undesired for coupled DES of industrial size. Monolithic modelling leads to an exponentially increasing state space. As a consequence, standard methods fail due to computational complexity. Otherwise the underlying physical distributivity of coupled DES requires a likewise distributed supervisory control.

2 Aim of the Project

The aim of the project is the complexity reduction to render the SCT applicable with respect to coupled DES by a consequent use of structured approaches:

- **Compositional modelling:** To set up a structured system model exploiting the physical modularity of the system.
- **Compositional analysis:** To analyze specific properties of coupled DES including controllability, observability and nonblocking.
- **Structured supervisory control design:** To design proper supervisory control for coupled DES either by synthesis or verification.

3 Compositional Modelling

Coupled DES consist of various coupled components. Compositional modelling as illustrated in Figure 2 is a feasible approach to treat them formally.

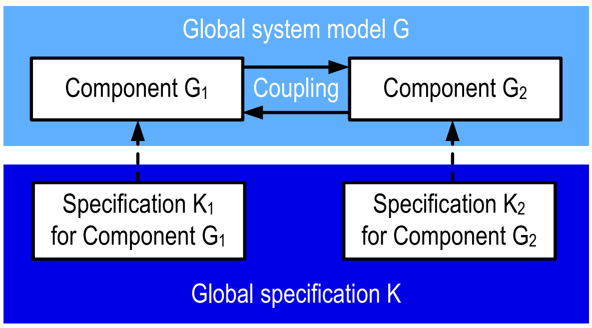


Figure 2: Coupled DES and its specifications

Each component is modelled individually, the couplings are identified and represented by appropriate compositional operators. Specifications are defined locally with respect to some components. In contrast to standard analysis and design methods, their structured counterparts operate directly on a compositional model. The composition is therefore avoided and consequentially a complexity reduction is obtained.

4 Compositional Analysis

Compositional analysis, introduced in [4], [5], [6] and [7], operates on a given structured model, Figure 3. The symbol $\|_{(\cdot)}$ denotes a specific compositional operator, reflecting the coupling between the components G_1 and G_2 identified a-priori.

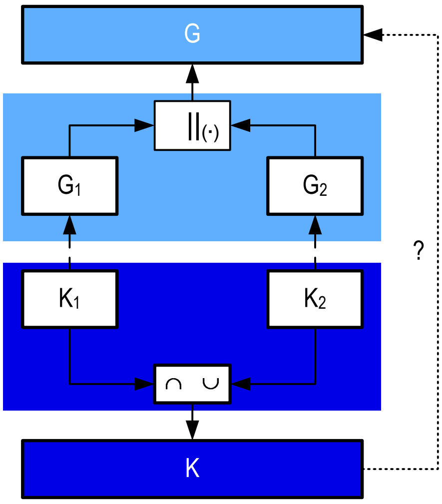


Figure 3: Compositional analysis

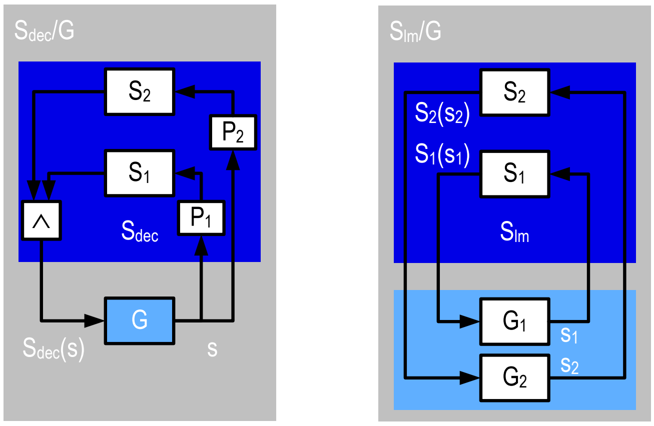
The analysis task, namely the question whether e.g. controllability or observability of the pair (K,G) holds, is illustrated by the dotted line in Figure 3. The approach answers this question without computing $G = G_1\|_{(\cdot)}G_2$ explicitly.

5 Structured Supervisory Control

Besides compositional analysis, various structured design approaches are present in the literature. They differ in structuring the controller design problem and in there methodology. The real difficulty is to decide at early stage, which approach is most suitable with respect to both the physical system and controller hardware. Subject to the decision, compositional modelling is to be adjusted in order to support the design as well as to obtain a more distinctive complexity reduction

Synthesis approaches: Synthesis approaches automatically compute the supremal controllable desired behavior $K^{\uparrow C} \subseteq K \subseteq L(G)$, thus the minimal restrictive supervisor S to solve the control problem. Using the decentralized or local-modular approach leads to a minimal restrictive supervisory control in a single step, Figure 4. Within the decentralized approach several supervisor act jointly on the global system, thus the control task is split. In addition, local-modular design supports compositional system modelling.

Verification approaches: Similar to compositional analysis, verification approaches do not provide the extraction of $K^{\uparrow C}$ from an uncontrollable K. Hierarchical interface-based supervisory control design is based on an iterative verification procedure, Figure 5. In each design-circle the proposed supervisory control is to be either verified or falsified. The approach provides both the compositional modelling of system and control task. A two-level hierarchy is introduced additionally to render coordinating supervision. Concerning each level, system and supervisory control are indistinguishable.



(a) Decentralized (b) Local Modular

Figure 4: Structured supervisory control synthesis

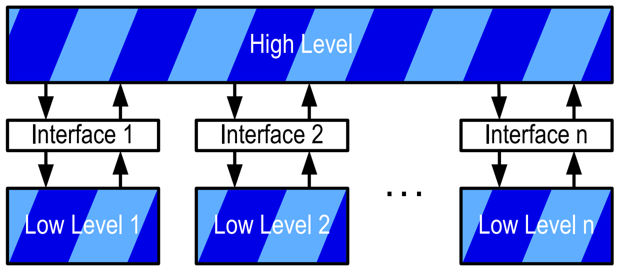


Figure 5: Hierarchical interface-based supervisory control

Various structured supervisory controls have been designed for a complex bottling plant [1], [2] and are evaluated regarding suitability and complexity reduction in [3].

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