MODELING AND CONTROL OF AN EXPERIMENTAL SWITCHED MANUFACTURING SYSTEM

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Abstract: The notion of *switched discrete event systems* (DES) has been introduced recently. This is a class of DES where each automaton is the composition of two basic automata, but with different composition operators. A switching occurs when there is a change of the composition operator, but keeping the same two basic automata. A mode behavior is defined as the active DES behavior for a given composition operator. Composition operators are supposed to change more than once so that each mode is visited more than once. In this paper we study the modeling and control of an experimental manufacturing system as an example of switched DES.

1 INTRODUCTION

Supervisory control initiated by Ramadge and Wonham (Ramadge and Wonham, 1987) provides a systematic approach for the control of discrete event system (DES) plant. Most of the properties of a given composed system depend on the composition operator. The modular approach reflects the underlying physical properties of complex systems such as manufacturing systems.

The most common composition operators used in supervisory control theory are the product and the parallel composition (Cassandras and Lafortune, 1999), (Wonham, 2004). However many different types of composition operators have been defined, e.g., the prioritized synchronous composition (0), the biased synchronous composition (Lafortune and Chen, 1990), see (Wenck and Richter, 2004) for a review of most of the composition operators. Multi-Agent composition operator (Romanovski and Caines, 2002), (Romanovski and Caines, 2006) is another kind of operator, which differs from the synchronous product in the aspects of simultaneity and synchronization.

Related work concerns a) fault diagnosis for DES (the readers are referred to (Jensen, 2003) for a comprehensive survey), b) *mode-automata* for reactive system programming, introduced in (Maraninchi and Remond, 1998), c) supervisory uniqueness for operating mode systems studied in (Kamach et al., 2005) where the authors propose a multi-model approach to DES, and finally d) sensor failure tolerant supervisory control proposed in (Rohloff, 2005) where different automata are used to model the system observation behavior in the various modes of operations.

This paper studies the application of switched DES methodology to an Experimental Manufacturing Cell. This cell is composed of two robotized workstations connected to a central conveyor belt. Recently, three new semi-automated workstations have been added in order to increase the flexibility aspects of the cell. This flexibility allows the designer to study different mode behaviors of the experimental cell.

The paper is organized as follows. In Section 2, the notation and preliminaries are given. The notion of switched DES is recalled in Section 3. In Section 4, the controllability property is studied. Finally the experimental cell behavior is described in Section 5.

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2 NOTATION AND PRELIMINARIES

Let the discrete event system plant be modeled by a finite state automaton (Hopcroft and Ullman, 1979)

$$G = (Q, \Sigma, \delta, q_0, Q_m)$$

where Q is the finite set of states, Σ is the finite set of events associated with the transitions in G, $\delta : Q \times \Sigma \rightarrow Q$ is the partial transition function, q_0 is the initial state and $Q_m \subseteq Q$ is the set of marked states.

Let Σ^* be the set of all finite strings of elements in Σ including the empty string ε. The function δ can be generalized to $\delta : \Sigma^* \times Q \rightarrow Q$. The notation $\delta(s,q)!$ for any $s \in \Sigma^*$ and $q \in Q$ denotes that $\delta(s,q)$ is defined. Let $L(G) \subseteq \Sigma^*$ be the language generated by G, that is,

$$L(G) = \{s \in \Sigma^* | \delta(s, q_0)!\}$$

Let $K \subseteq \Sigma^*$ be a language. The set of all prefixes of strings in K is denoted by $\overline{K}$ with $\overline{K} = \{s \in \Sigma^* | \exists\, t \in \Sigma^*; st \in K\}$. A language K is said to be *prefix closed* if $K = \overline{K}$. The event set Σ is decomposed into two subsets Σ_c and Σ_{uc} of controllable and uncontrollable events, respectively, where $\Sigma_c \cap \Sigma_{uc} = \emptyset$. A controller, called a supervisor, controls the plant by dynamically disabling some of the controllable events. A closed language $K \subseteq L(G)$ is said to be *controllable* with respect to $L(G)$ and Σ_{uc} if (Ramadge, 1987)

$$\overline{K}\Sigma_{uc} \cap L(G) \subseteq \overline{K}.$$

In the supervisory control theory, composition means synchronization of finite state automata. The basis for the definition of all the composition operators are $G_a = (Q_a, \Sigma_a, \delta_a, q_{0a}, Q_{ma})$ and $G_b = (Q_b, \Sigma_b, \delta_b, q_{0b}, Q_{mb})$ with disjoint state sets $Q_a \cap Q_b = \emptyset$ but generally overlapping event sets. The result of any composition is an automaton $G_i = G_a||_{op_i} G_b = (Q, \Sigma, \delta, q_0, Q_m)$ with the state $Q = Q_a \times Q_b$, the event set $\Sigma = \Sigma_a \cup \Sigma_b$ and initial state $x_0 = x_{0a}, x_{0b}$, where op_i is a composition operator. Each operator is defined by a distinct transition function with $\sigma \in \Sigma$ a single event and $q \in Q$ a state.

Among the different types of composition operators, we recall here the biased synchronous composition (BSC) and the strict product composition (SPC).

Definition 1 *(Lafortune and Chen, 1990)* The *Biased Synchronous Composition (BSC)* is defined as follows. The automaton G_a is called the master and G_b is called the follower.

$$\delta(q,\sigma) = \begin{cases} \delta_a(q_a,\sigma) \times \delta_b(q_b,\sigma) & \text{if}\ \delta_a(q_a,\sigma)! \wedge \delta_b(q_b,\sigma)! \\ \delta_a(q_a,\sigma) \times \{q_b\} & \text{if}\ \delta_a(q_a,\sigma)! \wedge \neg\delta_b(q_b,\sigma)! \\ \emptyset & \text{otherwise.} \end{cases}$$

Definition 2 The *strict product composition (SPC)* is defined as follows.

$$\delta(q,\sigma) = \begin{cases} \delta_a(q_a,\sigma) \times \delta_b(q_b,\sigma) & \text{if}\ \delta_a(q_a,\sigma)! \wedge \delta_b(q_b,\sigma)! \\ \emptyset & \text{otherwise.} \end{cases}$$

These two composition operators will be taken as example in the next sections.

3 SWITCHED DES

The basic idea is the following. Without loss of generality we consider two automata G_a and G_b as defined above. Let G_i be the composed automaton from G_a and G_b with operator op_i, that is $G_i = G_a||_{op_i} G_b$. In the same way let G_j be the composed automaton from the same G_a and G_b but with operator op_j, that is $G_j = G_a||_{op_j} G_b$, as it is depicted in Figure 2 and Figure 3.

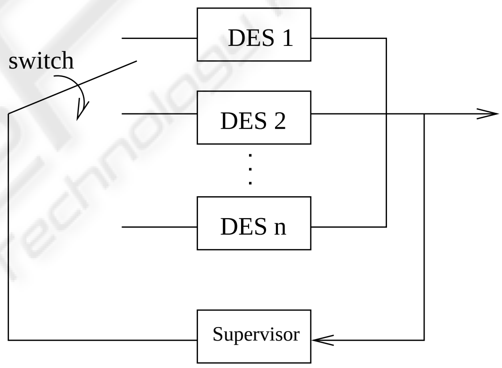

Figure 1: Switched DES.

Definition 3 Equivalent states.
The states $(q_a, q_b)^i$ of automaton G_i and $(q_c, q_d)^j$ of automaton G_j are said to be *equivalent* $(q_a, q_b)^i \equiv (q_c, q_d)^j$ if they result from the composition of the same pair of states but with different composition operators ($q_a = q_c$ and $q_b = q_d$).

Assumptions. Given two automata G_i and G_j, switching between automaton G_i and automaton G_j is possible if the following assumptions hold.

1. G_i and G_j have at least two equivalent states
2. Switching between G_i and G_j is performed through their equivalent states.
3. Switching from G_i to G_j has zero duration, as well as from G_j to G_i.

Definition 4 *(Rakoto, 2006b)* Switched DES.
A switched discrete event system is defined as follows.

$$L_{switched}(G) = L(G_i),\ i \in I = \{1,\ldots,n\} \qquad (1)$$

where G_i is the model of DES_i, and I is an index set. In this special case, $G_i = G_a||_{op_i}G_b$.

We can see in Figure 2 and Figure 3 the automaton G_1 and G_2, respectively. Then automata G_1 and G_2 can switch between them, as it is shown in Figure 4. Actually, the switching are made through the equivalent states of G_1 and G_2, see Figure 5.

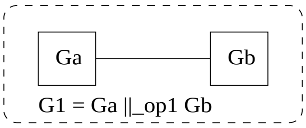

Figure 2: Automaton G_1.

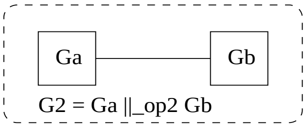

Figure 3: Automaton G_2.

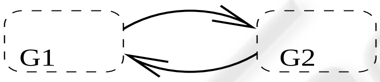

Figure 4: Switched automaton.

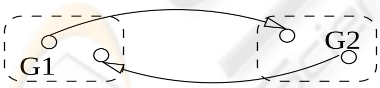

Figure 5: Automata switching through equivalent states.

We give here below some examples of switched DES:

- Manufacturing systems where the operating modes are changing (e.g. from normal mode to degenerated mode)
- Discrete event systems after an emergency signal (from normal to safety mode)
- Complex systems changing from normal mode to recovery mode (or from safety mode to normal mode).

We can distinguish, like for the switched continuous-time systems, the notion of *autonomous* switching where no external action is performed and the notion of *controlled* switching, where the switching is *forced*. The notion of switched DES has been adapted from the switched continuous-time systems. For a survey of switched continuous-time systems, one can refer to (Liberzon and Morse, 1999) and the references therein.

On one hand DES and continuous-time systems share the notion of controllability (but each domain has its own definition). On the other hand, stability analysis in continuous-time systems cannot be adapted to DES (even though some work exist on the stability of DES (Passino et al., 1994), (Passino and Burgess, 1998) and the references therein). Thus the notion of stability analysis has been changed to nonblocking analysis. Before defining the problems, we need to define the notion of switching sequence. A switching sequence is defined to be the successive active automata when the successive switchings occur. The following problems have been defined in (Rakoto, 2006b)

- *Problem A.* Find conditions that guarantee that the switched DES (1) is controllable with respect to the Language $L(G)$ and with respect to all the uncontrollable events, for any switching sequence.
- *Problem B.* Identify the classes of switching sequences for which the switched DES (1) is controllable with respect to the Language $L(G)$ and with respect to all the uncontrollable events.
- *Problem C.* Find conditions that guarantee that the switched DES (1) is nonblocking.
- *Problem D.* Identify the classes of switching sequences for which the switched DES (1) is nonblocking.

We can note that discretization of a switched continuous system (see e.g., (Rakoto, 2001) may be a solution to the adaptation to the DES context.

4 CONTROLLABILITY OF SWITCHED DES

In this section we address a specific problem related to the controllability of a switched DES (1).

Problem 1. Given a switched automaton $L_{switched} = L(G) = L(G_i), i \in I = \{1,2\}$ where $G_1 = G_a||_{op_1}G_b = G_a||_{BSC}G_b$ and $G_2 = G_a||_{op_2}G_b = G_a||_{SPC}G_b$, find the conditions that guarantee the controllability of the switched DES $L_{switched} = L(G)$.

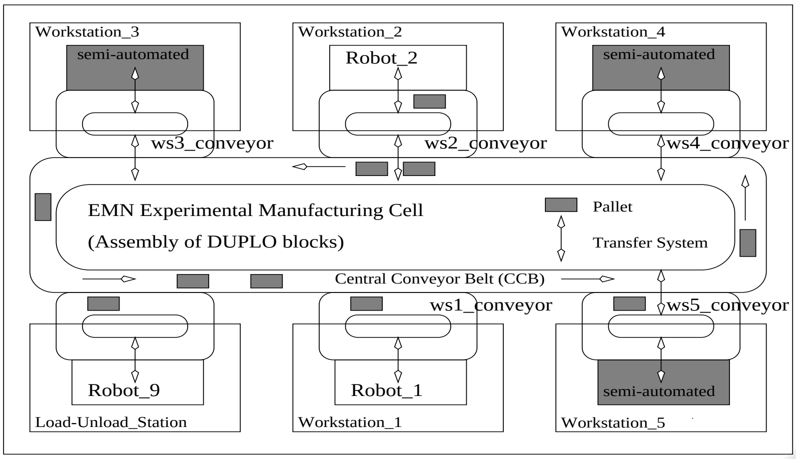

Figure 6: Experimental Manufacturing Cell.

Theorem 1 *Given a switched automaton $L_{switched} = L(G) = L(G_i), i \in I = \{1,2\}$ where $G_1 = G_a||_{BSC}G_b$ and $G_2 = G_a||_{SPC}G_b$, the switched automaton $L(G) = L(G_i)$ is controllable with respect to both $L(G_1)$ and $L(G_2)$ and with respect to $\Sigma_u c$ if*

1. *$K_a, K_b, L(G_2)$ are pairwise non conflicting*
2. *$K_b, L(G_a)$ are non conflicting*
3. *K_b is controllable w.r.t. $L(G_a)$*

Proof. The proof can be found in (Rakoto, 2006b). It is based on four propositions that have been given in (Wenck and Richter, 2004).

5 EXPERIMENTAL MANUFACTURING CELL

An automated manufacturing system generally consists of a number of interconnected material processing stations capable of processing a wide variety of part types, a material transport system, a communication system for integrating all aspects of manufacturing and a supervisory control system. The experimental manufacturing cell is composed of the following components (Chen et al., 2004): a) a central conveyor belt, b) two robotized workstations, with a station conveyor each, c) a transfer system between the central conveyor belt and the station conveyor, d) another transfer system between the station conveyor and the corresponding robot, and e) a load-unload robotized worksation.

Recently, three semi-automated workstations have been added to increase the flexibility aspects of the cell. Indeed, each semi-automated workstation can perform either manual or automated tasks. The experimental manufacturing cell is depicted in Figure 6.

Behavioral specifications of such an automated manufacturing system include: a) logic-based specifications (e.g. safety, error recovery, the sequencing of operations, part routing and production volume requirement), b) temporal production specification: production times, and c) utility optimality specification: e.g. costs.

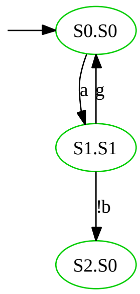

Figure 7: Composed Automaton.

The results were obtained using the tool Supremica (Akesson et al, 2006). Only two types of composition product were used. However this can be extended to different types of composition products.

6 CONCLUSIONS

This paper studies the application of the switched DES methodology, introduced previously to an Experimental Manufacturing Cell. The different mode behaviors were possible to obtain thanks to the re-

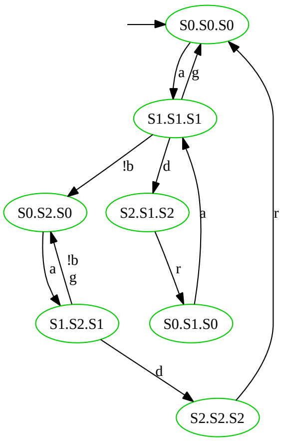

Figure 8: Composed Automaton (with priority).

cently added semi-automated workstations. These latter increased the flexibility of the system, and it allows the designer to apply the switched DES approach. Future work will be focused on a) obtaining more different mode behaviors for controllability, and b) study nonblocking properties in some specific cases.

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