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Time-Coobservability in the Decentralized Supervisory Control of Timed Discrete Event Systems

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Abstract : This paper presents the notion of time-coobservability as a core condition for the existence of a decentralized supervisor achieving a given language specification in a timed discrete event system (TDES). A TDES is modeled by the framework of Brandin & Wonham [5], and the decentralized supervisory control architecture presented is extended from the untimed architecture of Yoo & Lafortune [1]. To develop the time-coobservability of a language specification, specifically this paper presents the C&P time-coobservability and D&A time-coobservability in the consideration of the event tick and forcing mechanism of decentralized supervisors.

Keywords : timed discrete event systems, decentralized supervisors, time-coobservability

I. INTRODUCTION

A number of decentralized supervisory control techniques including [1-4] have been studied by the discrete event systems (DESs) community. In particular, Yoo & Lafortune [1] have established the general decentralized architecture based on C&P(conjunctive and permissive) and D&A(disjunctive and antipermissive) decision rules. Upon the framework, recently, the more advanced architectures of decentralized supervisory control have been presented in [2-4]. However, most of the literature has dealt with the decentralized supervisory control problems for untimed DESs. Many decentralized systems such as integrated sensor networks require meeting critical timing constraints in making decisions with locally distributed information.

This paper deals with the existence problem of a decentralized supervisor with the control actions developed to achieve a given language specification in a timed DES (TDES). We adopt the TDES framework of Brandin & Wonham [5] since various analysis techniques for untimed DESs can be applied to analyze the behavior of a TDES. The main features of the framework of [5] are the event *tick* representing the passage of one unit of time and the forcible events to preempt *tick*. A supervisor controls a TDES through two control actions: one is to disable controllable events and the other is to force forcible events in order to preempt *tick*. Based on the framework, various results of supervisory control for TDESs including [6-8] have been developed.

In this paper, we extend the decentralized control architecture for untimed DESs of [1] to the architecture for TDESs. For this purpose, in the consideration of the event *tick* and the forcing mechanism of a supervisor, we classify the forcible events into forcing-required ones and forcing-forbidden ones as a default setting. Based on the classification, we present the design method of local supervisors and a decentralized supervisor, and further develop the C&P time-coobservability and D&A time-coobservability of a given language specification. Using them, the notion of time-coobervability is presented, and we finally show that the time-coobervability of a language specification is the necessary and sufficient condition for the existence of a decentralized supervisor with the control actions developed to achieve the specification in a TDES.

II. MAIN RESULTS

A TDES (or plant) G to be controlled is represented as the finite state automaton $G=(Q,\Sigma,q_0,\delta)$ where Q is a finite set of states, Σ is a set of events, q_0 is the initial state, and $\delta: Q\times\Sigma\rightarrow Q$ is the transition function [5]. Σ is composed of $\Sigma=\Sigma_{act}\dot{\cup}\{tick\}$ where $\dot{\cup}$ means a disjoint union, Σ_{act} is the set of activity (or logical) events, and *tick* denotes one tick of the global clock, or the passage of one unit of time. Σ_{act} is categorized by three subsets: the controllable events set Σ_c, the uncontrollable events set Σ_u, and the forcible events set Σ_f. The controllable events can be disabled by a supervisor, but the uncontrollable events are always enabled. On the other hand, forcible events can preempt *tick* by a supervisor's forcing, and a forcible event may be either controllable or uncontrollable. Formally, $\Sigma_{act}=\Sigma_c\dot{\cup}\Sigma_u=\Sigma_f\dot{\cup}\Sigma_{nf}$ where Σ_{nf} is the set of non-forcible events.

Σ^* denotes the set of all finite strings over Σ including the empty string ε. Then, any subset of Σ^* is called the language over Σ. The transition function δ can be extended by $\delta(q,\varepsilon):=q$ and $\delta(q,s\sigma):=\delta(\delta(q,s),\sigma)$ for all $s\in\Sigma^*$, $\sigma\in\Sigma$. Let $pr(L):=\{t\in\Sigma^*\mid tu\in L \text{ for some } u\in\Sigma^*\}$ for $L\subset\Sigma^*$; $\Sigma_L(s):=\{\sigma\in\Sigma\mid s\sigma\in pr(L)\}$ for $s\in\Sigma^*$. The dynamic behavior of a plant G is formally represented as the language $L(G):=\{s\in\Sigma^*\mid\delta(q_0,s) \text{ is defined}\}$, and a language

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is called *controllable* if the following two conditions hold for any $s \in pr(K)$:

(i) $\Sigma_{L(G)}(s) \cap \Sigma_u \subseteq \Sigma_K(s)$;

(ii) $\Sigma_K(s) \cap \Sigma_f = \varnothing \wedge s\ tick \in L(G) \Rightarrow s\ tick \in pr(K)$ [5].

In this paper, we consider the decentralized supervisory control architecture composed of n local supervisors. Each local supervisor $S_i (i \in I := \{1, \cdots, n\})$ can observe, disable, and force the locally observable events of a set $\Sigma_{o,i}$, the locally controllable events of a set $\Sigma_{c,i}$, and the locally forcible events of a set $\Sigma_{f,i}$, respectively. Without loss of generality, we assume that $tick \in \Sigma_{o,i}$ for all $i \in I$. For local observation, a projection mapping and its inverse one are defined as $P_i : \Sigma^* \to \Sigma_{o,i}^*$ and $P_i^{-1} : \Sigma_{o,i}^* \to \Sigma^*$ for all $i \in I$, respectively, in usual manners.

Let $\Sigma = \Sigma_c \dot{\cup} \Sigma_u \dot{\cup} \{tick\}$ where $\Sigma_c := \cup_{i \in I} \Sigma_{c,i}$ and $\Sigma_u := \Sigma \setminus (\Sigma_c \cup \{tick\})$. The set Σ_c is partitioned into $\Sigma_{c,e}$ and $\Sigma_{c,d}$, i.e. $\Sigma_c = \Sigma_{c,e} \dot{\cup} \Sigma_{c,d}$ where $\Sigma_{c,e}$ is the set of controllable events whose default setting is enablement while $\Sigma_{c,d}$ is the set of controllable events whose default setting is disablement [1]. For $i \in I$, we let $\Sigma_{c,e,i} := \Sigma_{c,e} \cap \Sigma_{c,i}$ and $\Sigma_{c,d,i} := \Sigma_{c,d} \cap \Sigma_{c,i}$. In addition, the forcible events set Σ_f is partitioned into $\Sigma_{f,r}$ and $\Sigma_{f,f}$, i.e. $\Sigma_f = \Sigma_{f,r} \dot{\cup} \Sigma_{f,f}$, where the forcible events of $\Sigma_{f,r}$ should be forced by default, i.e. forcing-required as a default, and the forcible events of $\Sigma_{f,f}$ should not be forced by default, i.e. forcing-forbidden as a default. For $i \in I$, we let $\Sigma_{f,r,i} := \Sigma_{f,r} \cap \Sigma_{f,i}$ and $\Sigma_{f,f,i} := \Sigma_{f,f} \cap \Sigma_{f,i}$.

Now, let us define the control action of a local supervisor S_i for fixed partitions $\Sigma_c = \Sigma_{c,e} \dot{\cup} \Sigma_{c,d}$ and $\Sigma_f = \Sigma_{f,r} \dot{\cup} \Sigma_{f,f}$. For this purpose, the following notations are necessary:

$$\begin{aligned} fr(K) &:= \{s \in pr(K) \mid s\ tick \in L(G) \setminus pr(K) \\ &\quad \text{and } \exists\ \sigma \in \Sigma_f \ \text{ s.t. } \ s\sigma \in pr(K)\}, \\ ff(K) &:= \{s \in pr(K) \mid s\ tick \in pr(K) \\ &\quad \text{and } \exists\ \sigma \in \Sigma_f \ \text{ s.t. } \ s\sigma \in pr(K)\}. \end{aligned}$$

In order for a language specification K to be achieved, at least one forcible event should be forced after a string $fr(K)$ and none of forcible events should not be forced after a string in $ff(K)$. In addition, for $K \subseteq L(G)$, $s \in pr(K)$, and $i \in I$, let the estimation set $E_i(s) := P_i^{-1} P_i(s) \cap pr(K)$.

Definition 1: *For $s \in pr(K)$, the control action of a local supervisor S_i is defined as $S_i(P_i(s)) := (\gamma_{i,1}(s), \gamma_{i,2}(s))$ where*

$$\begin{aligned} \gamma_{i,1}(s) = &\{\sigma \in \Sigma_{c,e,i} \mid E_i(s)\sigma \cap pr(K) \neq \varnothing\} \cup \\ &\{\sigma \in \Sigma_{c,d,i} \mid E_i(s)\sigma \cap L(G) \subseteq pr(K)\} \\ &\cup\ (\Sigma_{c,e} \setminus \Sigma_{c,e,i}); \end{aligned}$$

$$\begin{aligned} \gamma_{i,2}(s) = &\{\sigma \in \Sigma_{f,r,i} \mid E_i(s)\sigma \cap pr(K) \cap fr(K)\sigma \neq \varnothing\} \cup \\ &\{\sigma \in \Sigma_{f,f,i} \mid E_i(s)\sigma \cap L(G) \subseteq pr(K) \cap fr(K)\sigma\} \\ &\cup (\Sigma_{f,r} \setminus \Sigma_{f,r,i}). \end{aligned}$$

It means that when S_i has observed the string $P_i(s)$, it enables the events of $\gamma_{i,1}(s)$ and forces the events of $\gamma_{i,2}(s)$.

Definition 2: *For $s \in pr(K)$, the decentralized supervisory control action is $S_{dec}(s) := (\gamma_{dec,1}(s), \gamma_{dec,2}(s))$ where*

$$\begin{aligned} \gamma_{dec,1}(s) &:= P_{c,e}[\wedge_i \gamma_{i,1}(s)] \cup P_{c,d}[\vee_i \gamma_{i,1}(s)], \\ \gamma_{dec,2}(s) &:= [P_{f,r}[\wedge_i \gamma_{i,2}(s)] \cup P_{f,f}[\vee_i \gamma_{i,2}(s)]] \\ &\quad \cap [\gamma_{dec,1}(s) \cup \Sigma_u], \end{aligned}$$

in which $P_{c,e}$, $P_{c,d}$, $P_{f,r}$, and $P_{f,f}$ are projection mappings: $P_{c,e} : \Sigma \to \Sigma_{c,e}$, $P_{c,d} : \Sigma \to \Sigma_{c,d}$, $P_{f,r} : \Sigma \to \Sigma_{f,r}$, and $P_{f,f}$: $\Sigma \to \Sigma_{f,f}$, respectively.

When a string s has occurred in a plant G, the decentralized supervisor S_{dec} enables the controllable events of $\gamma_{dec,1}(s)$ and forces the forcible events of $\gamma_{dec,2}(s)$. The fusion rules for $\Sigma_{c,e}$ and $\Sigma_{f,r}$ are conjunctive, and those for $\Sigma_{c,d}$ and $\Sigma_{f,f}$ are disjunctive. Then a supervised system is denoted by S_{dec}/G, and its closed-loop behavior is defined as: $\varepsilon \in L(S_{dec}/G)$, and for $s \in L(S_{dec}/G)$ and $\sigma \in \Sigma$ with $s\sigma \in L(G)$,

$$\begin{aligned} s\sigma \in L(S_{dec}/G) \Leftrightarrow &(i)\ \sigma \in \Sigma_{uc}, or \\ &(ii)\ \sigma \in \Sigma_{act} \text{ and } \sigma \in \gamma_{dec,1}(s), or \\ &(iii)\ \sigma = tick \text{ and } \gamma_{dec,2}(s) \cap \Sigma_{L(G)}(s) = \varnothing. \end{aligned}$$

Now let us define the time-coobservability for fixed partitions $\Sigma_c = \Sigma_{c,e} \dot{\cup} \Sigma_{c,d}$ and $\Sigma_f = \Sigma_{f,r} \dot{\cup} \Sigma_{f,f}$ as follows:

Definition 3: *A language $K \subseteq L(G)$ is C&P time-coobservable if $\forall s_1, s_2 \in pr(K)$, $\sigma_1 \in \Sigma_{c,e}$, and $\sigma_2 \in \Sigma_{f,r}$ s.t. $s_1\sigma_1 \in L(G) \setminus pr(K)$, $s_2\sigma_2 \in pr(K)$, and $s_2 \in ff(K)$,*

$(1)\ (\exists i \in I)\,[[\sigma_1 \in \Sigma_{c,d,i}] \wedge [E_i(s_1)\sigma_1 \cap L(G) \subseteq pr(K)]]$;

$(2)\ (\exists i \in I)\,[[\sigma_2 \in \Sigma_{f,f,i}] \wedge [E_i(s_2)\sigma_2 \cap pr(K) \cap fr(K)\sigma_2 = \varnothing]]$.

Definition 4: *A language $K \subseteq L(G)$ is D&A time-coobservable if $\forall s_1, s_2 \in pr(K)$ and $\sigma_1 \in \Sigma_{c,d}$ s.t. $s_1\sigma_1 \in pr(K)$, $s_2 \in fr(K)$, and $\Sigma_K(s_2) \cap \Sigma_{f,r} = \varnothing$,*

$(1)\ (\exists i \in I)\,[[\sigma_1 \in \Sigma_{c,d,i}] \wedge [E_i(s_1)\sigma_1 \cap L(G) \subseteq pr(K)]]$;

$(2)\ (\exists i \in I \wedge \sigma_2 \in \Sigma_{f,f,i})\,[E_i(s_2)\sigma_2 \cap L(G) \subseteq pr(K) \cap fr(K)\sigma_2]$.

Definition 5: *A language $K \subseteq L(G)$ is time-coobservable for fixed partitions $\Sigma_c = \Sigma_{c,e} \dot{\cup} \Sigma_{c,d}$ and $\Sigma_f = \Sigma_{f,r} \dot{\cup} \Sigma_{f,f}$ if K is C&P time-coobservable and D&A time-coobservable for the partitions.*

In Definition 3, local supervisors force the event σ_2 under insufficient information since $\sigma_2 \in \Sigma_{f,r}$. Hence, to prevent the event σ_2 from being forced after $s_2 \in ff(K)$, there should exist a local supervisor S_i to determine with certainty that there is no forcing-required string in the estimation of s_2, i.e. $E_i(s_2)$. In Definition 4, at least one forcible event should be forced after $s_2 \in fr(K)$ in order to prevent the illegal *tick* from occurring after s_2. In case there exists a forcible event of $\Sigma_K(s_2) \cap \Sigma_{f,r}$, all local supervisors decide to force the event according to Definition 1. However, in case of $\Sigma_K(s_2) \cap \Sigma_{f,r} = \varnothing$, there should exist at least one local supervisor S_i and $\sigma_2 \in \Sigma_{f,f,i}$ to determine with certainty that the event σ_2 should be forced after all the estimation of s_2, i.e. $E_i(s_2)$.

With the notion of time-coobservability, the main result of this paper can be presented as follows.

Theorem 1: *Given a specification $K \subseteq L(G)$ for a TDES G with the fixed partitions $\Sigma_c = \Sigma_{c,e} \dot\cup \Sigma_{c,d}$ and $\Sigma_f = \Sigma_{f,r} \dot\cup \Sigma_{f,f}$, there exists a decentralized supervisor S_{dec}* such that *$L(S_{dec}/G) = pr(K)$ if and only if K is controllable and time-coobservable for the partitions.*

Proof: (If) The proof is done by making induction on the length of the strings. It holds that $\varepsilon \in L(S_{dec}/G) \cap pr(K)$. Let us assume that for any string s with $|s| \le n$, $s \in L(S_{dec}/G)$ if and only if $s \in pr(K)$ ($|s|$ denotes the length of s). Then, let us prove that $s\sigma \in pr(K) \Leftrightarrow s\sigma \in L(S_{dec}/G)$ for any $\sigma \in \Sigma$. The cases of $\sigma \in \Sigma_u$ and $\sigma \in \Sigma_{act}$ can be proved by the controllability of K and Yoo & Lafortune [1], respectively. For $\sigma = tick$, let us show that $s\sigma \in L(S_{dec}/G)$ implies $s\sigma \in pr(K)$. Suppose that $s\sigma \notin pr(K)$. Then, there exists $\alpha \in \Sigma_f$ such that $s\alpha \in pr(K)$ by the controllability of K. Hence, it is true that $s \in fr(K)$. It follows from the definition of $L(S_{dec}/G)$ that $\gamma_{dec,2}(s) = \varnothing$, and additionally it holds that $\alpha \in \gamma_{dec,1}(s)$ since $s\alpha \in L(S_{dec}/G)$.

$(Case\ 1)\ \alpha \in \Sigma_{f,r}$

$\Rightarrow (\forall\, i \in I \text{ with } \alpha \in \Sigma_{f,r,i})\quad \alpha \in \gamma_{i,2}(s) \text{ by Definition 1}$

$\Rightarrow \alpha \in P_{f,r}[\wedge_i \gamma_{i,2}(s)] \Rightarrow \alpha \in \gamma_{dec,2}(s) \text{ by } \alpha \in \gamma_{dec,1}(s)$

$\Rightarrow \text{It contradicts that } \gamma_{dec,2}(s) = \varnothing.$

$(Case\ 2)\ \alpha \in \Sigma_{f,f} \text{ and } \Sigma_K(s) \cap \Sigma_{f,r} = \varnothing$

$\Rightarrow \exists\, i \in I \text{ and } \alpha \in \Sigma_{f,f,i} \text{ s.t. } E_i(s)\alpha \cap L(G) \subseteq pr(K) \cap fr(K)\alpha$

$\quad \text{by D \& A time-coobservability}$

$\Rightarrow \alpha \in \gamma_{i,2}(s) \text{ by Definition 1} \Rightarrow \alpha \in \gamma_{dec,2}(s) \text{ by } \alpha \in \gamma_{dec,1}(s)$

$\Rightarrow \text{It contradicts that } \gamma_{dec,2}(s) = \varnothing.$

Second, let us show that $s\sigma \in pr(K)$ implies $s\sigma \in L(S_{dec}/G)$ using a contradiction method. Suppose that $s\sigma \notin L(S_{dec}/G)$. Then, there exists $\alpha \in \Sigma_f$ such that $\alpha \in \gamma_{dec,2}(s)$ and $s\alpha \in L(G)$. It then follows from Definition 2 that $\alpha \in \gamma_{dec,1}(s) \cup \Sigma_u$. From the definition of $L(S_{dec}/G)$, it holds that $s\alpha \in L(S_{dec}/G)$. Then, it holds that $s\alpha \in pr(K)$. Thus, $s \in ff(K)$.

$(Case\ 1)\ \alpha \in \Sigma_{f,r}$

$\Rightarrow \exists\, i \in I \text{ s.t. } \alpha \in \Sigma_{f,r,i} \text{ and } E_i(s)\alpha \cap pr(K) \cap fr(K)\alpha = \varnothing$

$\quad \text{by C \& P time-coobservablility}$

$\Rightarrow \alpha \notin \gamma_{i,2}(s) \Rightarrow \alpha \notin \gamma_{dec,2}(s) \Rightarrow \text{Contradiction.}$

$(Case\ 2)\ \alpha \in \Sigma_{f,f}$

$\Rightarrow (\forall\, i \in I \text{ with } \alpha \in \Sigma_{f,f,i})\quad \alpha \notin \gamma_{i,2}(s) \text{ by Definition 1}$

$\Rightarrow \alpha \notin \gamma_{dec,2}(s) \Rightarrow \text{Contradiction.}$

(Only if) The proof of controllability is trivial, and the condition (1)'s in the definitions (Definition 3 and 4) of C&P and D&A time-coobservabilities can be proved according to Yoo & Lafortune [1]. Thus, it suffices to prove the condition (2)'s in Definition 3 and 4.

(i) C&P time-coobservability: Let $\sigma \in \Sigma_{f,r}$, $s\sigma \in pr(K)$, and $s \in ff(K)$. Then, it follows from $L(S_{dec}/G) = pr(K)$ that $\sigma \in \gamma_{dec,1}(s)$. Using a contradiction method,

$(\forall\, i \in I \text{ with } \sigma \in \Sigma_{f,r,i})\ E_i(s)\sigma \cap pr(K) \cap fr(K)\sigma \neq \varnothing$

$\Rightarrow (\forall\, i \in I)\ \sigma \in \gamma_{i,2}(s) \text{ by Definition 1}$

$\Rightarrow \sigma \in \gamma_{dec,2}(s) \text{ by } \sigma \in \gamma_{dec,1}(s) \Rightarrow s\ tick \notin L(S_{dec}/G)$

$\Rightarrow \text{Contradiction since } s\ tick \in pr(K) \text{ by } s \in ff(K).$

(ii) D&A time-coobservability: Let $s \in fr(K)$ and $\Sigma_K(s) \cap \Sigma_{f,r} = \varnothing$. Then, it follows from $\Sigma_K(s) \cap \Sigma_{f,r} = \varnothing$ and $L(S_{dec}/G) = pr(K)$ that $\gamma_{dec,1}(s) \cap \Sigma_{f,r} = \varnothing$. Using a contradiction method,

$(\forall\, i \in I \text{ and } \sigma \in \Sigma_{f,f,i} \text{ s.t. } s\sigma \in pr(K))$

$E_i(s)\sigma \cap L(G) \not\subseteq pr(K) \cap fr(K)\sigma$

$\Rightarrow (\forall\, i \in I)\ \gamma_{i,2}(s) = \varnothing \text{ by Definition 1}$

$\Rightarrow \gamma_{dec,2}(s) = \varnothing \text{ by } \gamma_{dec,1}(s) \cap \Sigma_{f,r} = \varnothing$

$\Rightarrow s\ tick \in L(S_{dec}/G)$

$\Rightarrow \text{Contradiction since } s\ tick \notin pr(K) \text{ by } s \in fr(K).$ ■

As an illustrative example, let us consider a simple TDES G shown in Fig. 1(a). Two local supervisors S_1 and S_2 are considered, and two language specifications are given as $K_1 = L(H_1)$ and $K_2 = L(H_2)$ shown in Figs. 1(b) and 1(c), respectively. The events are categorized as $\Sigma_{c,1} = \Sigma_{c,e} = \{a\}$; $\Sigma_{c,2} = \Sigma_{c,d} = \{b\}$; $\Sigma_{o,1} = \{a, u_1, c, tick\}$; $\Sigma_{o,2} = \{b, u_2, c, tick\}$; $\Sigma_{f,1} = \{a\}$; $\Sigma_{f,2} = \{b\}$.

First, let us consider K_1. (In case of $a \in \Sigma_{f,r}$): It holds that $u_1u_2 \in ff(K_1)$ since $u_1u_2\ tick, u_1u_2a \in pr(K_1)$ and $a \in \Sigma_f$, and then $E_1(u_1u_2)a \cap pr(K_1) \cap fr(K_1)a = \{u_1u_2a, u_2u_1a\} \cap \{u_2u_1a, u_1u_2tick\ a\} = \{u_2u_1a\}$. Hence, the condition (2) in the definition of C&P time-coobservability is not satisfied for u_1u_2. (In case of $a \in \Sigma_{f,f}$): It holds that $u_2u_1 \in fr(K_1)$ since $u_2u_1tick \in L(G) \setminus pr(K_1)$, $u_2u_1a \in pr(K_1)$, and $a \in \Sigma_f$. It also holds that $\Sigma_{K_1}(u_2u_1) \cap \Sigma_{f,r} = \{a\} \cap \Sigma_{f,r} = \varnothing$. Then,

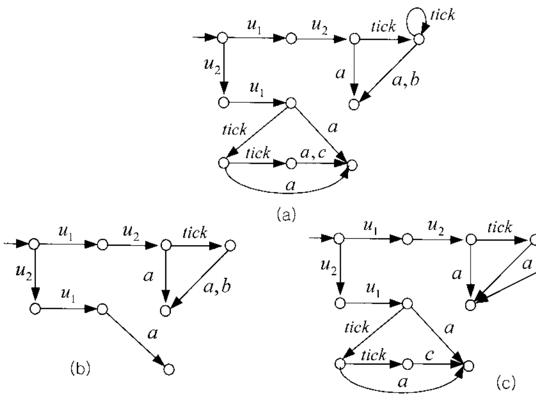

그림 1. Example: (a) G, (b) H_1, (c) H_2.
Fig. 1. Example: (a) G, (b) H_1, (c) H_2.

it follows $E_1(u_2u_1)a \cap L(G) = \{u_2u_1a, u_1u_2a\}$ and $pr(K_1) \cap fr(K_1)a = \{u_2u_1a, u_1u_2tick\,a\}$. Hence, the condition (2) in the definition of D&A time-coobservability is not satisfied for u_2u_1. Thus, we conclude that K_1 is not time-coobservable for any partition of Σ_f.

Second, let us consider the specification K_2. Suppose that $\Sigma_{f,r} = \{a\}$ and $\Sigma_{f,f} = \{b\}$. Let $s_1 = u_2u_1tick$. It then holds that $s_1 \in ff(K_2)$ and $E_1(s_1)a \cap pr(K_2) \cap fr(K_2)a = \{u_2u_1tick\,a, u_1u_2tick\,a\} \cap \{u_1u_2tick\ tick\}a = \emptyset$. Hence, the condition (2) of C&P time-coobservability is satisfied for the string s_1. Let $s_2 = u_1u_2tick\ tick$. Then, it holds that $s_2 \in fr(K_2)$ and $\Sigma_{K_2}(s_2) \cap \Sigma_{f,r} = \{b\} \cap \{a\} = \emptyset$. Then, it follows that $E_2(s_2)b \cap L(G) = \{u_1u_2tick\ tick,\ u_2u_1tick\ tick\}b \cap L(G) = \{u_1u_2tick\ tick\ b\}, pr(K_2) \cap fr(K_2)b = \{u_1u_2tick\ tick\ b\}$. Hence, the condition (2) of D&A time-coobservability is satisfied for the string s_2. According to Yoo & Lafortune [1], it can be verified that the condition (1)'s of C&P and D&A time-coobservabilities are satisfied for any partition of Σ_c. Thus, we can conclude that K_2 is time-coobservable for $\Sigma_{f,r} = \{a\}$ and $\Sigma_{f,f} = \{b\}$. Then, for $s_1 = u_2u_1tick$ and $s_2 = u_1u_2tick\ tick$, the control actions of a decentralized supervisor S_{dec} satisfying $L(S_{dec}/G) = pr(K_2)$ are summarized as follows:

$$S_1(P_1(s_1)) = (\gamma_{1,1}(s_1), \gamma_{1,2}(s_1)) = (\{a\}, \emptyset);$$
$$S_2(P_2(s_1)) = (\gamma_{2,1}(s_1), \gamma_{2,2}(s_1)) = (\{a\}, \{a\});$$
$$S_{dec}(s_1) = (\gamma_{dec,1}(s_1), \gamma_{dec,2}(s_1)) = (\{a\}, \emptyset).$$
$$S_1(P_1(s_2)) = (\gamma_{1,1}(s_2), \gamma_{1,2}(s_2)) = (\emptyset, \emptyset);$$
$$S_2(P_2(s_2)) = (\gamma_{2,1}(s_2), \gamma_{2,2}(s_2)) = (\{a,b\}, \{a,b\});$$
$$S_{dec}(s_2) = (\gamma_{dec,1}(s_2), \gamma_{dec,2}(s_2)) = (\{b\}, \{b\}).$$

III. CONCLUSION

In this paper, we have shown that the time-coobservability of a given language specification is the necessary and sufficient condition for the existence of a decentralized supervisor to achieve the specification in a TDES. As a future work, it is needed to develop a polynomial-time algorithm for verifying the time-coobservability and also solve supervisor synthesis problems.

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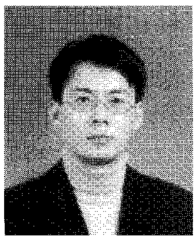

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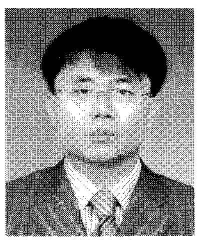

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