Switched Asynchronous Sequential Machines With Relaxed Switching Operations

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***Abstract*—The model matching problem of input/state switched asynchronous sequential machines is studied in this paper. The considered machine consists of a number of input/state asynchronous machines, termed submachines, between which asynchronous switching is conducted by the switching signal. The control goal is to design a corrective controller such that the closed-loop system can mimic the stable-state behavior of a reference model. In particular, we focus on relaxing the condition for fundamental mode operations in switching operations so that the switched asynchronous sequential machine can enlarge its switching capability. The necessary and sufficient condition for the existence of a model matching controller is analytically derived in the framework of corrective control. We also provide a simple illustrative example to demonstrate the proposed notion and control scheme.**

***Index Terms*—asynchronous sequential machines, switched systems, corrective control, model matching.**

I. Introduction

Since first proposed by Hammer for general sequential machines [1], corrective control has been studied extensively as a novel automatic control scheme for asynchronous sequential machines. Though having the same structure as conventional feedback control systems, the corrective control scheme has distinctive features in activating feedback control processes. Most unique among them is the fact that the interaction between controllers and controlled machines is conducted very fast in an asynchronous mechanism. Hence, even though the controlled machine does not have desirable transitions, it can be compensated by the corrective controller so as to show the desirable input/state or input/output behavior if it has inherent stable reachability that can be used to make an appropriate feedback trajectory.

In the past, the research of corrective control was mainly done for controlling single asynchronous sequential machines with various deficiencies. [2] first addresses the problem of model matching for input/state asynchronous sequential machines with critical races. [3] presents input/output control of asynchronous sequential machines using output bursts. In [4], controlling input/state asynchronous sequential machines with infinite cycles is studied. In [5], [6], control of input/output asynchronous sequential machines with nondeterministic state transitions is addressed. In [7], [8], a matrix operation termed semi-tensor product (STP) is applied to quantifying the stable reachability of the considered single asynchronous sequential machines. On the other hand, corrective control has been successfully applied to the problem of fault diagnosis and fault tolerant control for asynchronous sequential machines. This accomplishment is also attributed to the feature of asynchronous sequential machines that their dynamics are not governed by any synchronizing clock. Refer to, e.g., [9]–[12] and references therein for recent results on this topic.

In this paper, we investigate the problem of model matching for a composite asynchronous sequential machine. The considered machine consists of switched composition of multiple input/state asynchronous sequential machines—termed *submachines* in this paper. The composite machine switches between submachines according to a rule (or control scheme) that orchestrates the switching behavior. Though the research of switched systems is already ripe in the field of continuous-time systems (see [13]), few studies exist in the field of event-driven systems, much less asynchronous sequential machines. We note that in systems biology, control of switched Boolean networks is studied by some researchers [14], [15]. But since [14], [15] do not consider significant features of asynchronous sequential machines such as stable/transient states and fundamental mode operations, they cannot be applied to our framework.

The main consideration of this paper is to study the model matching problem of input/ouput switched asynchronous sequential machines. We analyze the existence condition for a corrective controller that makes the stable-state behavior of the considered switched machine be equivalent to that of a given reference model. While similar researches are found in the author's previous studies [16]–[18], the present paper differs from them for the following reason. In all the prior work [16]–[18], a switching operation between two submachines is possible only if there exists an input character that makes stable pairs with both states of the two submachines at which the switching operation is executed. On the other hand, the present study relaxes this constraint for the purpose of enhancing the switching capability of the composite machine. We will represent this relaxed condition in terms of a new switching incidence matrix. The existence condition for a model matching corrective controller is also described with the new switching incidence matrix in the framework of corrective control. We will focus our concern on analyzing the existence condition for a controller. The design procedure for a controller is similar to that in the prior work [16], [17]. Besides switched asynchronous sequential machines, corrective control for other types of composite asynchronous sequential machines exist as well, e.g., for parallel compositions [19] and cascaded compositions [20], [21] .

The rest of this work is structured as follows. Section II provides a modeling formalism of input/state switched

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asynchronous machines and the problem statement of model matching. In Section III, a relaxed switching operation is presented and described by a new switching incidence matrix. The existence condition for a corrective controller achieving model matching is also addressed in terms of matrix expressions. A simple example is provided in Section IV to demonstrate the proposed notions and scheme. Finally, some concluding remarks are given in Section V.

II. Preliminaries

A. Switched Asynchronous Sequential Machines

We consider a switched asynchronous sequential machine Σ consisting of m submachines. Each submachine is supposed to be a single input/state asynchronous sequential machine, namely the current state of the machine is given as the output value. Σ is described as

$$\Sigma = \{\Sigma_i | i \in M\}$$
$$\Sigma_i = (A, X, x_0, f_i)$$

where $M := \{1, \ldots, m\}$, Σ_i is the ith submachine, A is the input set, X is the state set with $|X| = n$, $x_0 \in X$ is the initial state, and $f_i : X \times A \to X$ is the state transition function of Σ_i partially defined on $X \times A$. Since every submachine serves as structural redundancy of the composite machine Σ, the input and state sets of Σ_i are the same for all $i \in M$, while the transition characteristic f_i is different with each other.

Each submachine Σ_i possesses the property of a single asynchronous sequential machine, that is, no synchronizing clock governs dynamics of the machine; its state transition is conducted only in direct response to changes of external inputs. A state–input pair $(x, v') \in X \times A$ is valid in Σ_i if $f_i(x, v')$ is defined. A valid pair (x, v') is a stable pair if $f_i(x, v') = x$; else if $f_i(x, v') \neq x$, it is a transient pair. Note that x may be either a stable or transient state depending on the current input. Denote by

$$U_i(x) := \{v \in A | f_i(x, v) = x\}$$
$$T_i(x) := \{v \in A | f_i(x, v) \neq x\}$$

the set of inputs that make a stable and transient pair with x in Σ_i, respectively. Due to the absence of a global synchronizing clock, Σ_i stays at a stable pair (x, v') indefinitely. If the input v' changes to another value v that makes x a transient state ($v \in T_i(x)$), Σ_i initiates a chain of transient transitions, e.g.,

$$f_i(x, v) = x_1,$$
$$f_i(x_1, v) = x_2,$$
$$\vdots$$

during which the input v remains unchanged. This chain of transient transitions may or may not end. If it does not end, it makes an infinite cycle. In this paper, we assume that every Σ_i does not have infinite cycles. Σ_i then reaches the *next stable state* x' such that $x' = f_i(x', v)$ at the end of the chain. Since asynchronous sequential machines pass through transition transitions instantaneously (ideally in zero time), the meaningful behavior of asynchronous sequential machines can be represented only in terms of stable states. In this respect, we introduce the *stable recursion function* $s_i : X \times A \to X$ as [2]

$$s_i(x, v) := x'$$

where x' is the next stable state of (x, v). If (x, v) is a stable pair of Σ_i, $s_i(x, v) = x$. A series of transient transitions from a transient pair (x, v) to its next stable pair (x', v), as represented by s_i, is called a *stable transition*. The domain of s_i is often expanded to $X \times A^+$ as follows, where A^+ is the set of all nonempty strings of characters in A:

$$s_i(x, v_1 v_2 \cdots v_k) := s_i(s_i(x, v_1), v_2 \cdots v_k),$$
$$v_1 v_2 \cdots v_k \in A^+.$$

B. Problem Statement

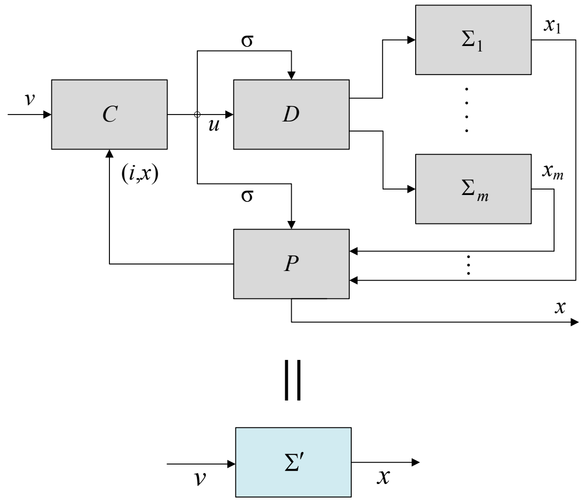

Fig. 1. Corrective control system for the switched asynchronous sequential machine Σ.

Fig. 1 illustrates the configuration of the corrective control system for the switched asynchronous sequential machine Σ. C is the corrective controller having the form of an input/output asynchronous sequential machine, D is the demultiplexer, and P is the multiplexer. We denote by Σ_c the closed-loop system composed of C, D, P, and Σ. $v \in A$ is the external input, $u \in A$ is the control input, and $\sigma \in M$ is the switching signal. Both u and σ are generated by C, either of which is transmitted to Σ one at a time. The submachine whose dynamics is currently active is termed the *active submachine*. D relays u to the active submachine Σ_σ, which changes according to the switching signal σ. Hence changing σ equals activation of the switching operation. The multiplexer P extracts the state feedback x of the active submachine among m feedback values $x_1, \ldots, x_m$ and delivers it to the controller C along with the corresponding index $i \in M$ of the active submachine.

The control goal is to address the existence condition and design procedure for a corrective controller C that matches the stable-state behavior of Σ_c to that of a reference stable-state machine

$$\Sigma' = (A, X, x_0, s')$$

where $s' : X \times A \to X$ is the stable recursion function of Σ'. Model matching between Σ_c and Σ' implies that their stable-state behaviors are identical, i.e., beginning from the initial state x_0, they reach the same next stable state in response to every incoming input. Thus Σ' is supposed to have the same input and state sets as those of Σ.

To prevent unpredictable outcomes caused by the lack of a global synchronizing clock, it is assumed that Σ_c always

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complies with the principle of fundamental mode operations [22] whereby an input, state, or output variable should change its value only when both C and Σ are in stable states, and no two or more variables can be changed simultaneously.

III. Main Result

A. Relaxed Switching Operations

Let us first review the prior results on the model matching problem of a single asynchronous sequential machine $\Sigma_i = (A, X, x_0, f_i)$, or $m = 1$ in view of Fig. 1. It is known that the necessary and sufficient condition for the existence of a corrective controller achieving model matching between Σ_c and Σ' is that the stable reachability of Σ is greater than or equal to that of Σ' [2], [4]. The latter condition can be described in a compact way by a Boolean matrix called the *skeleton matrix* of an asynchronous sequential machine. Denote the state set by $X := \{x_1, \ldots, x_n\}$ hereafter.

Definition 1. *Given $\Sigma_i = (A, X, x_0, f_i)$, the skeleton matrix $K(\Sigma_i)$ is an $n \times n$ Boolean matrix whose (p, q) entry is defined as ($p, q \in \{1, \ldots, n\}$)*

$$K_{p,q}(\Sigma_i) := \begin{cases} 1 & \exists t \in A^+ \text{ s.t. } s_i(x_p, t) = x_q \\ 0 & \text{otherwise} \end{cases}$$

$K_{p,q}(\Sigma_i) = 1$ if x_q is reachable from x_p in Σ_i via a chain of stable transitions. Using $K(\Sigma_i)$ and $K(\Sigma')$, we express the existence condition for a model matching controller as

$$K(\Sigma') \leqslant K(\Sigma_i)$$

where matrix inequality must be valid on entry-by-entry basis.

In controlling the switched asynchronous sequential machine Σ, we can utilize not only stable reachability of each submachine, but also switching capability between different submachines. In the previous study [16], [17], switching capability is represented by the switching incidence matrix $W(i, j)$, which elucidates whether Σ can switch its mode from a submachine Σ_i to another submachine Σ_j at a specific state x_p. The condition for enabling this switching operation is the existence of an input character $u \in A$ such that

$$u \in U_i(x_p) \cap U_j(x_p).$$

Under the assumption that the principle of fundamental mode operations is preserved, Σ_i has to stay at the stable state x_p at the moment that the switching signal σ changes from i to j. Hence the current input value u makes a stable pair with x_p, i.e., $u \in U_i(x_p)$. Further, u must also make a stable pair with x_p in Σ_j, namely $u \in U_j(x_q)$; otherwise Σ_j could not maintain x_p upon completion of the switching operation. Thus $W(i, j)$ is an $n \times n$ Boolean matrix whose (p, q) entry is defined as [17]

$$W_{p,q}(i, j) := \begin{cases} 1 & p = q \text{ and } U_i(x_p) \cap U_j(x_q) \neq \emptyset \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Note that the condition $u \in U_j(x_p)$ may not be always valid for the current input u. Still, $W_{p,p}(i, j) = 1$ if $U_i(x_p) \cap U_j(x_p) \neq \emptyset$ is held true as defined above. The switching operation can be achieved by changing the input character from u to some $u' \in U_i(x_p) \cap U_j(x_p)$ right before transmitting the switching signal $\sigma = j$. Thus $U_i(x_p) \cap U_j(x_p) \neq \emptyset$ is a crucial condition for the success of switching in fundamental mode operations.

In this paper, we relax the foregoing condition on switching operations by allowing that the current input u does not necessarily have to make a stable pair with the state x_p in the next active submachine. In particular, assume that Σ is about to switch its mode from Σ_i to Σ_j at the state x_p for which $U_i(x_p) \cap U_j(x_p) = \emptyset$, namely no input exists that makes a stable pair with x_p in both Σ_i and Σ_j. In association with this, assume that the current input u has the property that $u \in U_i(x_p)$ but $u \in T_j(x_p)$, meaning that u makes a transient pair with x_p in Σ_j. Then, upon completion of the switching operation from Σ_i to Σ_j, Σ_j will initiate the transient transition to $f_j(x_p, u)$, eventually reaching the next stable state $s_j(x_p, u) := x_q$. This result implies the following two points.

(i) It means that as long as the current input makes a valid pair with the new active submachine Σ_j, the switching operation can be still regarded as valid. Hence this policy enhances the switching capability of Σ.
(ii) The former definition of the switching incidence matrix $W(i, j)$ must be adjusted so that it includes the switching operation with respect to the inputs that make transient pairs with the next active submachine.

According to the above discussion, in this paper we propose a new switching incidence matrix considering those inputs that make not only a stable pair but also a transient one with the next active submachine.

Definition 2. *Given $\Sigma = \{\Sigma_i | i \in M\}$ with $\Sigma_i = (A, X, x_0, f_i)$, $Q(i, j)$, the* extended switching incidence matrix *of two submachines Σ_i and Σ_j, is an $n \times n$ Boolean matrix whose (p, q) entry is defined as ($p, q \in \{1, \ldots, n\}$)*

$$Q_{p,q}(i, j) := \begin{cases} 1 & p = q \text{ and } U_i(x_p) \cap U_j(x_p) \neq \emptyset \\ 1 & p \neq q \text{ and } \exists u' \in U_i(x_p) \cap T_j(x_p) \\ & \text{s.t. } s_j(x_p, u') = x_q \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

It is easily seen that (2) is a generalized version of the former definition (1). More than one entries can have 1 value in each row of $Q(i, j)$. But that does not mean that the corresponding switching operation is nondeterministic. Any switching operation can be conducted deterministically by the corrective controller. For instance, assume that $Q_{p,p}(i, j) = 1$ and $Q_{p,q}(i, j) = 1$ for some $p, q \in \{1, \ldots, n\}$, $p \neq q$, and $i, j \in M$. Assume further that Σ stays at a stable pair (x_p, u) ($u \in U_i(x_p)$) of the active submachine Σ_i. If one has to switch the mode of Σ to Σ_j while maintaining the same state x_p, it can be accomplished by providing a control input $u' \in U_i(x_p) \cap U_j(x_p)$ before changing the switching signal σ from i to j. On the other hand, if one has to switch the mode of Σ to Σ_j but with the different next stable state x_q, the latter can be done by providing another control input $u'' \in U_i(x_p) \cap T_j(x_p)$ such that $s_j(x_p, u'') = x_q$. In this way, the switching capability of Σ is enlarged by combining the switching operation with transient transitions.

B. Existence Condition for a Controller

We now address the existence condition for a corrective controller that achieves model matching between Σ_c and Σ'.

We first describe the stable reachability of Σ that encompasses relaxed switching operations as presented in Definition 2.

Definition 3. *The* one-step switching skeleton matrix $\mathscr{S}^1(\Sigma)$ *is an $nm \times nm$ Boolean matrix defined as*

$$\mathscr{S}^1(\Sigma) = \begin{pmatrix} K(\Sigma_1) & Q(1,2) & \cdots & Q(1,m) \\ Q(2,1) & K(\Sigma_2) & \cdots & Q(2,m) \\ \vdots & \vdots & \vdots & \vdots \\ Q(m,1) & \cdots & Q(m,m-1) & K(\Sigma_m) \end{pmatrix}$$

The k-step switching skeleton matrix $\mathscr{S}^k(\Sigma)$ *($k \geqslant 2$) is recursively defined as*

$$\mathscr{S}^k(\Sigma) = \mathscr{S}^{k-1}(\Sigma) \times_{\mathscr{B}} \mathscr{S}^1(\Sigma)$$

where '$\times_{\mathscr{B}}$' denotes the Boolean product of two Boolean matrices where logic AND and OR are used instead of multiplication and addition operations in the matrix product.

Definition 4. *The* combined switching skeleton matrix $Z(\Sigma)$ *of the switched asynchronous sequential machine Σ is an $nm \times nm$ Boolean matrix defined as*

$$Z(\Sigma) = \sum_{k=1}^{nm-1} {}_{+_{\mathscr{B}}} \mathscr{S}^k(\Sigma)$$

where '$+_{\mathscr{B}}$' denotes the Boolean addition of two matrices.

In Definitions 3 and 4, the state x_p of the submachine Σ_i, where $p = 1, \ldots, n$ and $i = 1, \ldots, m$, is given the index $p' \in \{1, \ldots, nm\}$ such that

$$p' = (i-1)n + p. \tag{3}$$

$\mathscr{S}^1(\Sigma)$ in Definition 3 represents one-step stable reachability between any state pair of Σ. Note that $\mathscr{S}^1(\Sigma)$ displays not only stable reachability between two states in the same submachine, but also switching capability between two different submachines. For instance, assume that $\mathscr{S}^1_{p',q'}(\Sigma) = 1$ where $p' = (i-1)n + p$ and $q' = (j-1)n + q$ for some $p, q \in \{1, \ldots, n\}$ and $i, j \in M$. If $i = j$, then by Definition 3 $K_{p,q}(\Sigma_i) = 1$, which means that x_q is stably reachable from x_p in the submachine Σ_i. On the other hand, if $i \neq j$, it follows that $W_{p,q}(i, j) = 1$. This implies that Σ can switch its mode from Σ_i to Σ_j during which the state changes from x_p to x_q. In short, $\mathscr{S}^1(\Sigma)$ characterizes whether a state of a submachine can be reached from another state of another (or the same) submachine either by a chain of stable transitions ($K(\Sigma_i)$) or by a relaxed switching operation ($Q(i, j)$).

$\mathscr{S}^k(\Sigma)$ represents whether a state can be reachable from another state by k steps of chains of stable transitions and switching operations. Finally, the combined switching skeleton matrix $Z(\Sigma)$ is a generalized description of stable reachability and switching capability of the switched asynchronous sequential machine Σ. Not only does $Z(\Sigma)$ represent stable reachability within the same submachine, it also characterizes whether a state of a submachine can be reached from another state of a different submachine by a combination of stable transitions and relaxed switching operations as defined in Definition 2.

Because Σ is endowed with m submachines $\Sigma_1, \ldots, \Sigma_m$, Σ has m equivalent states for every state of $X = \{x_1, \ldots, x_n\}$. A *subordinate state list* $\Theta \subset \{1, 2, \ldots, nm-1, nm\}$ of X is a set of n indices, where each index represents the state x_p of a submachine, $p = 1, \ldots, n$ [17]. Using the index setting (3) of the switching skeleton matrix, we can express an instance of Θ as follows.

$$\begin{aligned} &\Theta := \{\theta_1, \ldots, \theta_n\}, \\ &\theta_p := (a_p - 1)n + p, \\ &\theta_p \in \{1, 2, \ldots, nm-1, nm\},\ a_p \in M \end{aligned} \tag{4}$$

where θ_p corresponds to x_p of the submachine Σ_{a_p}. For notational convenience, let us define $K(\Theta)$ as the $n \times n$ skeleton matrix of Θ whose (p, q) entry is ($p, q \in \{1, \ldots, n\}$)

$$K_{p,q}(\Theta) := K_{\theta_p,\theta_q}(\Sigma).$$

We are now in a position to address the existence condition for a corrective controller that achieves model matching between Σ_c and Σ' in which the switched asynchronous sequential machine Σ is given relaxed switching operations. The following theorem is the main result of this report.

Theorem 1. *Given $\Sigma = \{\Sigma_i | i \in M\}$ with $\Sigma_i = (A, X, x_0, f_i)$ and a model $\Sigma' = (A, X, x_0, s')$, a corrective controller C exists that matches the stable-state behavior of Σ_c to that of Σ' if and only if a subordinate state list Θ as described in (4) exists such that*

$$K(\Sigma') \leqslant K(\Theta). \tag{5}$$

If Θ satisfying condition (5) is found, we can design a corrective controller C that employs n states that correspond to Θ. A detailed procedure of controller synthesis is given in [17].

IV. Example

Consider a simple switched asynchronous machine $\Sigma = \{\Sigma_1, \Sigma_2\}$ ($M = \{1, 2\}$) and a reference model Σ' shown in Fig. 2, where $X = \{x_1, x_2, x_3\}$ with $x_0 = x_1$ and $A = \{a, b, c, d\}$. For simplicity, we define all the machines such that $f_i(x, v) = s_i(x, v)$ for all $i = 1, 2$ and all valid $(x, v) \in X \times A$.

To investigate the existence of a model matching corrective controller, we first derive the skeleton matrix of each submachine and the model. From Fig. 2, we induce $K(\Sigma_1)$, $K(\Sigma_2)$, and $K(\Sigma')$ as

$$K(\Sigma_1) = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

$$K(\Sigma_2) = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

$$K(\Sigma') = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Next, we compute the extended switching incidence matrix $Q(i, j)$ according to Definition 2. Note that whereas the previous switching incidence matrix has the property that $W(i, j) = W(j, i)$ for all $i, j \in M$, $Q(i, j) \neq Q(j, i)$ in general.

Thus we must derive two matrices $Q(1,2)$ and $Q(2,1)$ as follows.

$$Q(1,2) = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$Q(2,1) = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{pmatrix}$$

Derivation of $Q(1,2)$ and $Q(2,1)$ is made by a slight examination of Fig. 2. For instance, if Σ switches its mode from Σ_2 to Σ_1 at the state x_3, the next stable state can be either x_1 or x_3 since $U_2(x_3) \cap T_1(x_1) = \{d\}$ with $s_1(x_3, d) = x_1$ and $U_2(x_3) \cap U_1(x_3) = \{c\}$. Hence we have $Q_{3,1}(2,1) = Q_{3,3}(2,1) = 1$.

Assembling $K(\Sigma_1)$, $K(\Sigma_2)$, $Q(1,2)$, and $Q(2,1)$, we compute the switching incidence matrices $\mathscr{S}^1(\Sigma), \ldots, \mathscr{S}^5(\Sigma)$ (omitted) and derive the combined switching skeleton matrix $Z(\Sigma)$ according to Definition 4.

$$Z(\Sigma) = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

Clearly, we can find a subordinate state list Θ that satisfies condition (5) for the existence of a model matching corrective controller. For instance, let $\Theta = \{1, 2, 6\}$, that is, take x_1 and x_2 from Σ_1 and x_3 from Σ_2. Then, since

$$K(\Theta) = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix},$$

we have $K(\Sigma') \leqslant K(\Theta)$.

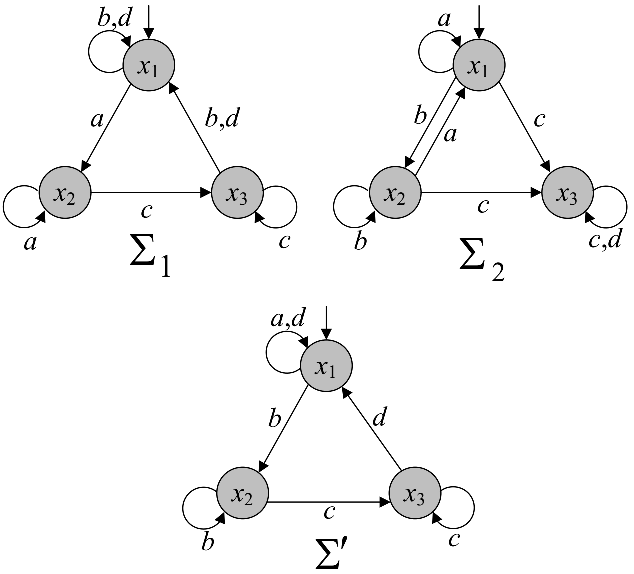

Fig. 2. Switched asynchronous sequential machine $\Sigma = \{\Sigma_1, \Sigma_2\}$ and a model Σ'.

V. Summary

In this paper, we have studied an automatic control theoretic strategy for the model matching problem of a class of switched asynchronous sequential machines. When a switched asynchronous sequential machine is composed of multiple input/state asynchronous sequential machines, the composite machine can have expanded reachability in terms of the stable-state behavior. In particular, we have proposed relaxed switching operations that do not need the preservation of fundamental mode operations. The enhanced switching capability has been described as a novel switching incidence matrix, based on which the existence condition for a model matching controller is addressed. The examination of the controller existence has been demonstrated in the simple illustrative example.

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