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Design and implementation of decentralised supervisory control for manufacturing system automation

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Supervisory control theory, which was first proposed by Ramadge and Wonahm, is a well-suited control theory for the control of complex systems such as semiconductor manufacturing systems, automobile manufacturing systems, and chemical processes because these are better modelled by discrete event models than by differential or difference equation models at higher levels of abstraction. Moreover, decentralised supervisory control is an efficient method for large complex systems according to the divide-and-conquer principle. This article presents a solution and a design procedure of supervisory control problem for the case of decentralised control. We apply the proposed design procedure to an experimental miniature computer-integrated manufacturing (CIM) system. This article presents the design of fourteen modular supervisors and one high-level supervisor to control the experimental miniature CIM system. These supervisors are controllable, non-blocking, and non-conflicting. After the verification of the supervisors by simulation, the collision avoidance supervisors for automated guided vehicle system have been implemented to demonstrate their efficacy.

Keywords: decentralised control; discrete event systems; manufacturing automation; supervisory control theory

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1. Introduction

As any manufacturing system becomes larger and more complex, more systematic and rigorous methods are needed for the modelling and control of such large complex systems. Supervisory control theory (Ramadge and Wonham 1987, Wonham and Ramagde 1987), which was proposed by Ramadge and Wonham and based on discrete event system (DES) methods, is recognised as one of the promising techniques for the design and control of large complex systems, such as semiconductor manufacturing systems, chemical processes, HVAC (heating, ventilation and air conditioning), and power plants. Recently, the supervisory control theory has received much focus in many applications, such as robotics (Ricker *et al*. 1996, Chung and Lee 2005), traffic control (Giua and Seatzu 2001), logistics (Jafari *et al*. 2002), failure diagnosis (Son and Lee 2007) and manufacturing systems (Golmakani *et al*. 2006), because it can satisfy control specifications of a plant to be controlled systemically by permitting eligible events in the plant maximally. Also, it has been proved that the supervisory control theory is very efficient for the control of highly complex systems (Cassandra and Lafortune 1989, Ramadge and Wonham 1989), which are modelled as Petri nets (Basile *et al*. 2004, Dai *et al*. 2009) or automata (Lee and Lee 2002, Ramirez-Serrano and Benhabib 2003).

A general problem in the design and control of target systems based on the supervisory control theory (Wonham 1998) is named as supervisory control problem (SCP). The SCP is, generally, used to find a supervisory controller, i.e. centralised supervisor, which satisfies the legal language (behaviour specification) of a system (Wonham 1998). However, as the system becomes larger and more complex, the computational complexity of the SCP increases exponentially due to the increase of eligible events. The divide-and-conquer principle is very useful to solve this problem because the computational complexity can be decreased exponentially if the SCP is solved by dividing the system into several sub-systems (Rudie and Wonham 1992). Based on this approach, supervisory controllers designed are called as modular supervisory controllers horizontally (Wonham and Ramadge 1988) and high-level supervisory controllers hierarchically (Leduc *et al*. 2006). Finally, a decentralised supervisory control system is defined as a supervisory control system, which consists of the modular supervisors and the high-level supervisors (Yoo and Lafortune 2002).

A hierarchical supervisory control is presented by Tittus and Lennartson (2002) as a Petri net-based

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approach, and by Leduc *et al.* (2005, 2009) as an automata-based approach. Theoretically, they proved that a proposed hierarchical supervisor is by far less complex than a non-hierarchical one. Yoo and Lafortune (2002) presented a generalised form of the conventional decentralised control architecture for DESs. They proposed a concept of fusion operation using both the union and the intersection of enabled events. Their method is extended to allow the making of conditional decisions also, 'enable if nobody disables' and 'disable if nobody enables', in addition to unconditional decisions, 'enable' and 'disable' (Yoo and Lafortune 2004). They, however, did not present a design procedure with a practical example for the easy use of the presented theory even though their method was rigorous. Feng *et al.* (2009) proposed a similar method for a decentralised non-blocking supervisory control. They briefly outlined the proposed theory with a practical example. The other approach, the so-called supervisor localisation, is proposed by Cai and Wonham (2010) for the distributed control architecture of large scale DESs. They analysed trade-offs between the decentralised and the distributed control architecture. A practical implementation method is not presented by Feng *et al.* (2009) and Cai and Wonham (2010).

Queiroz and Cury (2002) presented an implementation method of modular supervisory controller using a programmable logic controller (PLC). They explained their method with a simple manufacturing cell example. They, however, showed only simulation results using the proposed method. Supervisor implementation using the PLC is also presented by Ramirez-Serrano *et al.* (2002) and by Petin *et al.* (2007).

Petri net is, usually, more efficient as a modelling and analysis method for the deadlock avoidance (Lerrarini *et al.* 1999) and performance evaluation (Tsinarakis *et al.* 2005) of a manufacturing system. We, therefore, use automata to model the manufacturing system for the supervisory control in this article.

In this article, a concept of sub-plant is proposed to reduce the computational complexity for controllability in the SCP, and then, a generalised solution of the SCP for the modular supervisors is also proposed. A solution of the SCP for a high-level plant with respect to a high-level behaviour specification is also developed using the proposed concept of the sub-plant and Wonham et al.'s method. The developed solutions are proved theoretically.

Modular and high-level supervisors are designed, implemented and verified using an experimental miniature computer-integrated manufacturing (CIM) system using the proposed decentralised supervisory control scheme. The experimental miniature CIM system consists of three industrial robots, two automated guided vehicles (AGVs), two numerical controlled (NC) machines, several conveyor belts and sensors. A plant of the miniature CIM system is modelled as the deterministic automaton. The operation rules of the miniature CIM system are defined as the behaviour specifications (legal languages), and the supervisors are then designed with respect to these specifications. The designed supervisors are later transformed into the clocked Moore synchronous state machine (CMSSM; Wakerley 1990) for the implementation. We, finally, verify a supervisor for a collision avoidance of AGVs via an experiment, which is a critical problem for the material transfer in production lines (Singh *et al.* 2010).

This article is organised into six sections. In the section following this introduction, a background of the supervisory control theory is presented. In the third section, the design methodologies of the decentralised supervisory control and its theoretical proofs are presented. An application to the experimental miniature CIM system of the proposed control and an implementation of the designed controller are presented in the fourth and fifth sections, respectively. Finally, the main contributions of this article are summarised in the last section.

2. Background

2.1. System modelling

DES is modelled as the automaton $G = \{Q, \Sigma, \delta, q_0, Q_m\}$, where Q is the state set, Σ is the event set, δ: $Q \times \Sigma^* \rightarrow Q$ is the state transition function, q_0 is the initial state and Q_m is the marked state set, which is a subset of Q. In δ, Σ^* is the set of null event, and string (sequence) is expressed as ε and $\sigma_1\ \sigma_2\ \sigma_3 \ldots \sigma_k$, $k \geq 1$, respectively. In particular, the event set Σ is divided into two disjoint sets, i.e. the controllable event set Σ_c and the uncontrollable event set Σ_{uc}. And Σ is also partitioned into the observable event set Σ_o and the unobservable event set Σ_{uo}. The language that is generated by G is defined as shown in Equation (1)

$$L(G) = \{s | s \in \Sigma^*, \delta(q_0, s)!\} \tag{1}$$

where $\delta(q_0, s)!$ means that a next state is defined after the occurrence of the string s in the state q_0. The prefix closure of $L(G)$ is defined as

$$\overline{L(G)} = \{t \in \Sigma^* | t \leq s \text{ for some} s \in L(G)\} \tag{2}$$

And the marked language of G is defined as follows.

$$L_m(G) = \{s | \delta(q_0, s)! \in Q_m, L_m(G) \subseteq K(G)\} \tag{3}$$

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If G satisfies $\overline{L_m(G)} = L(G)$, then $L(G)$ is non-blocking. The non-blockingness is then the necessary condition to design a proper supervisor in the supervisory control theory. And if the prefix closures of two languages are disjoint, then these languages are non-conflicting as defined in Equation (4).

$$\begin{aligned}\overline{L(G)} &= \overline{L(G_1)} \cup \overline{L(G_2)}, \\ null &= \overline{L(G_1)} \cap \overline{L(G_2)} \\ &\Rightarrow L(G_1) \wedge (G_2)\end{aligned} \tag{4}$$

Finally, the projection map P is defined as $P(\sigma) = \varepsilon$ and $P(s\sigma) = P(s)$ for $\sigma \in \Sigma_{uo}$, $s \in L(G)$.

2.2. *Supervisory control*

Supervisor is also defined as the automaton $S = \{X, \Sigma, \xi, x_0, X_m\}$, where X, Σ, ξ: $X \times \Sigma^* \rightarrow X$, x_0 and X_m are the state set, the event set, the state transition function, the initial state and the marked state, respectively. Let the plant to be controlled be defined as G, then the behaviour of plant G under the supervision of S is represented as Equation (5).

$$S/G = \{X \times Q, \Sigma, \xi \times \delta, (x_0, q_0), X_m \times Q_m\} \tag{5}$$

The controllability and the observability of $L(S)$ with respect to $L(G)$ are defined in Definitions 1 and 2, respectively.

Definition 1: For $S \subseteq G$, S is *controllable* with respect to (G, Σ_{uc}) if the following is satisfied.

$$(\forall s, \sigma) s \in \overline{L(S)}, \sigma \in \Sigma_{uc}, s\sigma \in L(G) \Rightarrow s\sigma \in \overline{L(S)} \tag{6}$$

The physical meaning of controllability is that an arbitrary string s, which is permissible by the supervisor S and an uncontrollable event σ, is eligible in the plant G, if the string $s\sigma$ is eligible in G and if S also permits $s\sigma$, then, S is controllable with respect to G.

Definition 2: For $S \subseteq G$, S is *observable* with respect to (G, P, Σ_{uo}) if the following is satisfied.

$$\begin{aligned}&\forall s, s', \sigma \in \overline{L(S)}, P(s) = P(s'), \sigma \in \Sigma_{uo}, s\sigma \in \overline{L(S)}, \\ &s'\sigma \in L(G) \Rightarrow s'\sigma \in \overline{L(S)}\end{aligned} \tag{7}$$

Observability means that if $s\sigma$ is permissible by S and $s'\sigma$ is eligible in G, then S also have to permit $s'\sigma$, where two strings s and s' are recognised as the same string by the projection map P and are also permissible by the supervisor S and where σ is an unobservable event.

SCP is defined in Definition 3 based on Definition 1.
Definition 3: For a given K and G, where $K \subseteq G$, find a supremal language S that satisfies $L(S/G) = K$ and $L(S/G) = \overline{L_m(S/G)}$ and is controllable with respect to (G, Σ_{uc}).

If K is, therefore, defined as the legal language for the plant G to be controlled, then the SCP is to find a supervisor, which satisfies $L(S/G) = K$ and is non-blocking and controllable with respect to G. In addition, the supervisor, which satisfies the constraints and is controllable, need not be unique. Among these supervisors, a supremal controllable sub-language of G with respect to K is the unique solution of the SCP. Therefore, the supervisor S, which satisfies Definition 3, can permit the language to occur in the plant G maximally. A supervisory control system is illustrated in Figure 1.

3. Decentralised supervisory control

3.1. *Design of modular supervisor*

Let us consider two fundamental issues in this section, the computational complexity and the implementation simplicity. First, a method to reduce the computational complexity is presented. Solving the SCP with respect to all the plants takes a tremendous computational complexity. Therefore, the computational complexity can be decreased exponentially if the SCP is solved with respect to several sub-plants. This approach is presented in Theorem 1.

Theorem 1: For a given plant G, which can be expressed as $G = G_1 \times G_2 \times \ldots \times G_n$, let us define a sub-plant $G_{sub,i} \in G$ for the legal language K_i, $i = 1, \ldots, m$. If S_i is a solution of the SCP with respect to $(K_i, G_{sub,i})$ and is non-conflicting with the $G_{sub,j}$, $i \neq j$, then S_i is the solution of the SCP with respect to (K_i, G).

Proof: Based on the SCP, we have to prove that S_i is controllable with respect to (K_i, G), is non-blocking and is the maximally permissible language. First, let us consider the controllability of S_i. If the event sets of G and $G_{sub,i}$ are defined as Σ and $\Sigma_{sub,i}$, respectively, then the new event set $\sum_{sub,i}^{c} = \Sigma - \Sigma_{sub,i}$ can be defined. Here, every uncontrollable event, which is an element of $(\Sigma_{sub,i}^c)_{uc} \subseteq \Sigma_{sub,i}^c$, is permitted by S_i because $\Sigma_{sub,i}^c$ is

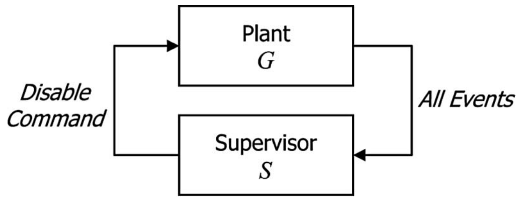

Figure 1. Concept of supervisory control system.

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the event set consisting of self-loops in S_i. Therefore, S_i is controllable with respect to G. And S_i is non-blocking because it is non-conflicting with respect to $G_{sub,j}$, $i \neq j$. Finally, K_i is the maximally permissible language because every event in $\Sigma^c_{sub,i}$ is permitted by S_i.

Next, let us consider finding an equivalent supervisor, which is less complex to implement because it has less states and less state transitions even if it generates same language with the original solution of the SCP. Generally, the supervisor S satisfies the following:

$$L(S/G) = L(S) \tag{8}$$

However, the supervisor S becomes much complex because it has much more states than those in the legal language K with respect to the events generated in the plant G. Practically, this complexity creates a problem in the implementation of the supervisor. Therefore, it will be relatively easier to implement the simpler supervisor S', which satisfies Equation (9).

$$L(S'/G) = L(S) \tag{9}$$

This means that the supervisor S', which is simpler than S, can be designed by satisfying Equation (9) while the language of plant behaviour under the supervision of S' is same with the one under the supervision of S. If the legal language K is defined, then the maximum number of state in S' is the same with that of K while the maximum number of states in S is the same with that of $K \wedge G$. We have summarised this issue in Theorem 2.

Theorem 2: If the supervisor S' satisfies the following conditions, then S' is an *optimal (or minimally restrictive) proper supervisor* with respect to the plant G.

(1) The supervisor S′ is controllable with respect to the plant G.
(2) $\overline{L_m(S')} = L(S')$
(3) $\overline{L_m(G) \wedge L_m(S')} = L(G) \wedge L(S')$
(4) If S is the supremal controllable sub-language with respect to K, then $L(S'/G) = L(S)$ has to be satisfied.

Proof: The first condition means that the designed supervisor has to satisfy the controllability with respect to the plant, and the second condition represents that the supervisor has to be non-blocking. The non-conflictness of the supervisor with the plant is represented in Condition (3). In other words, the third condition means that the supervisor has to be non-blocking with respect to the plant. Therefore, if S' satisfies Conditions (1), (2) and (3), then S' is a proper supervisor. Condition (4) represents the behaviour of the plant under the supervision of S', which has to generate the maximally controllable sub-language. Finally, S' becomes the optimal supervisor.

The modular supervisor is defined in Definition 4 based on Theorems 1 and 2.

Definition 4: For the legal languages K_j, $j = 1, 2,\ldots, n$, let us design the supervisors S_i, $i = 1, 2, \ldots, m$ which satisfy Theorems 1 and 2. And if S_i satisfies the non-conflictness condition $\bar{S} = \overline{S_1} \wedge \overline{S_2} \wedge \ldots \wedge \overline{S_m}$, then S_i is defined as the *modular supervisor*.

Finally, the solution of the modular SCP is presented in Theorem 3 using Theorems 1 and 2. The computational complexity of the algorithm for the controllability, the non-blocking, the non-conflictness tests, which is presented in Theorem 3, is same when compared with the one proposed by Ramadge and Wonham (1987, 1989).

Theorem 3: For a given plant G and legal languages K_i, $i = 1, 2, \ldots, m$, modular supervisors S_i or S_i' are the solutions of the SCP using the following procedure.

Modular SCP solution procedure:

Step 0: Define the automaton G of the plant to be controlled and the automation K_i of the legal languages.

Step 1: Design the sub-plants $G_{sub,i}$.

Step 2: Check the controllability of K_i with respect to $G_{sub,i}$ using the controllable events in K_i. If K_i is controllable, go to Step 5, otherwise go to next step.

Step 3: Reconstruct K_i by considering the events that do not satisfy the controllability in the controllable events in K_i.

Step 4: Go to Step 2. If K_i cannot be reconstructed while satisfying the controllability, then go to Step 7.

Step 5: Check the non-blockingness of K_i. Delete the state that makes K_i as blocking, and then go to Step 2.

Step 6: Check the non-conflictness of K_i with respect to $G_{sub,i}$. If K_i is non-conflicting, then $S'_i = K_i$. Otherwise, reconstruct K_i by checking the string, which makes K_i as conflicting, and then go to Step 2.

Step 7: Find the supremal controllable sub-language S_i of K_i with respect to $G_{sub,i}$. S_i is the solution of the modular SCP with respect to (K_i, $G_{sub,i}$).

Step 8: If $L(S_i) = L(S'_i/G_{sub,i})$, then S'_i is the solution of the modular SCP with respect to (K_i, $G_{sub,i}$).

Proof: The proof is omitted because it is straightforward from the proofs of Theorems 1 and 2.

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3.2. *Design of high-level supervisor*

Let us represent the plant G as the low-level plant $G_{lo} = \{Q_{lo}, \Sigma_{lo}, \delta_{lo}, q_{lo,0}, Q_{10,m}\}$ and define the high-level plant G_{hi} which satisfies $L(G_{hi}) = \Theta\{L(G_{lo})\}$ with the information map Θ. The information map is defined as Θ: $L(G_{lo}) \rightarrow T^*$, where $T = \{\tau_0, \tau_1, \tau_3, \ldots\}$ is the set of events which have the physical meaning in the high-level plant among the low-level events. The information map is an arbitrary projection map. The high-level plant G_{hi} is also represented as the automation $G_{hi} = \{Q_{hi}, \Sigma_{hi}, \delta_{hi}, q_{hi,0}, Q_{hi,m}\}$ similar to G_{lo}. Therefore, the high-level supervisor can be designed if we solve the SCP with respect to the high-level plant G_{hi} and the high-level legal language K_{hi}.

The information map Θ is defined by mapping the high-level event τ as the state output of the states of G_{lo}. The state in G_{lo}, which has the state output about Θ, is defined as the vocal state. And then G_{hi} can be constructed from Θ and G_{lo}. Before constructing G_{hi}, G_{lo} has to be reconstructed using the following two conditions to make G_{hi} maintain the control structure of G_{lo}.

Condition 1 for the high-level plant: Output Control Consistency (OCC)

$$\Theta^{-1}\{L(G_{hi})\}^{\uparrow} = L(G_{lo}) \quad (10)$$

Condition 2 for the high-level plant: Strictly OCC (SOCC)

$$\Theta\Theta^{-1}\{L(G_{hi})\}^{\uparrow}] = L(G_{hi}) \quad (11)$$

Condition 1 means that in a certain low-level state, when there is a state transition by the low-level event which has the state output, and also, there is a state transition by the low-level event which, however, has no state output, this low-level state has to be divided with respect to two different state transitions. And Condition 2 represents that the state outputs have to be redefined according to whether the low-level event, which makes the state transition with respect to the reconstructed low-level states by Condition 1, is controllable or not. Both Conditions are defined as the hierarchical consistency.

The design procedure of the high-level supervisor is presented in Theorem 4 using Theorem 3 and OCC and SOCC conditions.

Theorem 4: For a given low-level plant G_{lo}, an information map Θ, high-level legal languages ($K_{hi,i}$, $i = 1, 2, \ldots, m$) and high-level supervisors ($S_{hi,i}$ or $S'_{hi,i}$) are solutions of the SCP using the following procedure.

High-level SCP solution procedure

Step 0: Define the automaton G_{lo} of the low-level plant to be controlled and the automation $K_{hi,i}$ of the high-level legal languages. And also define the information map Θ.

Step 1: Design the sub-plants $(G_{lo})_{sub,i}$.

Step 2: Construct $(G_{lo})^{vocal}_{sub,i}$ of $(G_{lo})_{sub,i}$ using Θ.

Step 3: Construct $\{(G_{lo})^{vocal}_{sub,i}\}_{OCC}$ of $(G_{lo})^{vocal}_{sub,i}$ using Equation (10).

Step 4: Construct $\{(G_{lo})^{vocal}_{sub,i}\}_{SOCC}$ of $\{(G_{lo})^{vocal}_{sub,i}\}_{OCC}$ using Equation (11).

Step 5: Construct $G_{hi} = \Theta\left[\{(G_{lo})^{vocal}_{sub,i}\}_{SOCC}\right]$, and define G_{hi} as the high-level plant.

Step 6: Run from Steps 2–8 of Theorem 3 with respect to $(K_{h,i}, G_{hi})$.

Proof: The proof is omitted because it is straightforward from the OCC and SOCC conditions and the proofs of Theorems 1 and 2.

Finally, the architecture of decentralised supervisory control is illustrated in Figure 2.

4. Application: miniature CIM system

4.1. *Layout*

In this article, an experimental miniature CIM system is experimented to verify the proposed decentralised supervisory control. The miniature CIM system consists of two NC machines, three industrial robots, two AGVs, several conveyor belts, detection sensors, etc. This system is designed to have two types of production lines, the cumulative and the non-cumulative way, under the assumption of the manufacturing of two products. The layout of the miniature CIM system is shown in Figure 3.

4.2. *Plant model*

The automaton of the plant G can be designed by the synchronous product (Wonham 1998) of all the

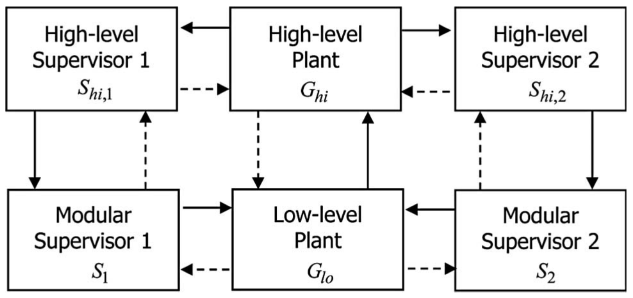
High-level Supervisor 1 $S_{hi,1}$
High-level Plant G_{hi}
High-level Supervisor 2 $S_{hi,2}$
Modular Supervisor 1 S_1
Low-level Plant G_{lo}
Modular Supervisor 2 S_2

Figure 2. Structure of decentralised supervisory control system.

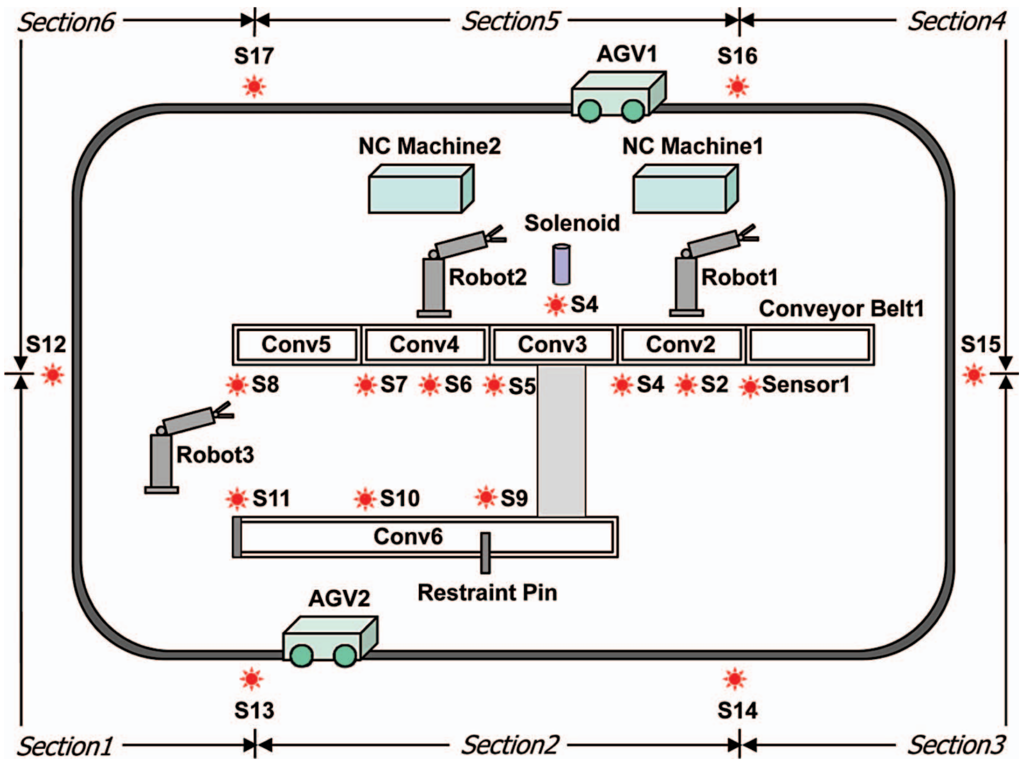

Figure 3. Experimental miniature computer-integrated manufacturing system.

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automata of each component, after modelling the components of the plant such as the NC machine, the industrial robot, etc. as automata. In this article, the number of states and events is minimised in the component model. This minimisation is done by the projection of the events, which are unnecessary to observe and unobservable by a supervisor and do not affect the behaviour of a legal language towards the null event ε. For example, a velocity change of AGV is not modelled in the automaton of AGV because the velocity is controlled not by the supervisor but by a local controller of the AGV. The designed automata are projected to generate same language regardless of the states because this article applies the supervisory control theory as the event-based approach. The number of states can also be minimised by this state projection. However, if the designed automata are changed to the non-deterministic ones after the state projection, the automata are transformed into the deterministic ones using the subset construction (Giua and Seatzu 2001).

Every component in the miniature CIM system (two AGVs, three robots, two NC machines, five conveyor belts, seventeen detection sensors, restraint pin and solenoid) is modelled as an automaton with two states. The designed plant models are shown in Figures 4–10. Every event defined in the miniature

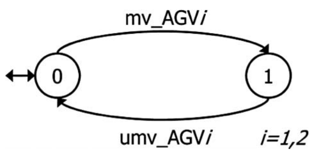


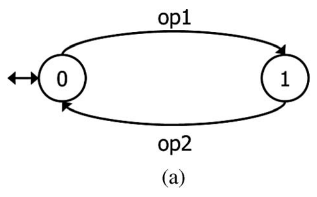
Figure 4. Automation model of AGVs, AGV_i.

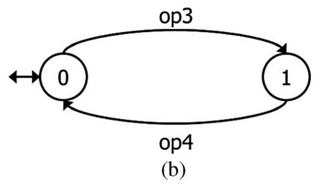
CIM system is listed in Table 1. The automaton of the plant G is constructed by Equation (12) using the designed automata of all components. This article used the open software for the supervisory control theory, TCT (Wonham 1998), for the design and calculation of the automata. The state number of G is 4, 294, 967, 296, which is constructed using $SYNC$ function of TCT as shown in Equation (12).

$$G = SYNC(AGV_i, ROBOT_j, NCMachine_k, ConvBelt_m, SENSOR_n, ResPin, Sol) \tag{12}$$

4.3. Modular supervisor

In this section, the modular supervisors are presented for the decentralised supervisory control of the





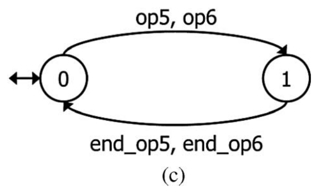


Figure 5. Automation model of robots, $ROBOT_i$. (a) Robot 1, (b) Robot 2 and (c) Robot 3.

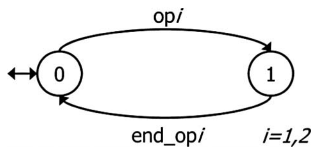


Figure 6. Automation model of NC machines, $NCMachine_i$.

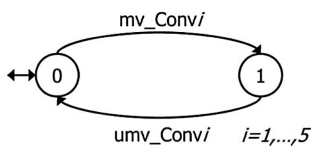


Figure 7. Automation model of conveyor belts, $ConvBelt_i$.

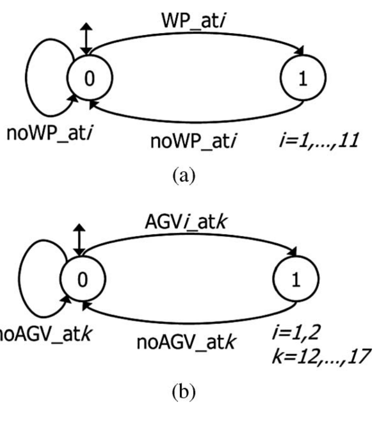


Figure 8. Automation model of sensors, $SENSOR_i$. (a) sensor for conveyor belt and (b) sensor for AGV.

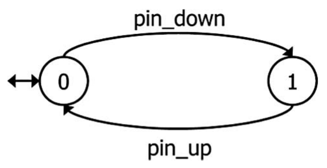


Figure 9. Automation model of restraint pin, *ResPin*.

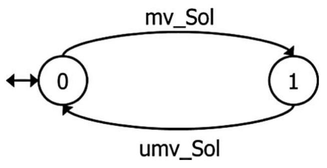


Figure 10. Automation model of solenoid, *Sol*.

experimental miniature CIM system using Theorem 3. The specifications for the modular supervisors are as follows:

(1) Buffer size of the conveyor belts 2, 4 and 6 are two work-pieces.
(2) The robot 1 picks up the work-piece from the conveyor belt 1 and moves it into the NC machine 1. After the completion of machining in the NC machine 1, the robot 1 picks up the work-piece and moves it onto the conveyor belt 2.
(3) The robot 2 picks up the work-piece from the conveyor belt 3 and moves it into the NC machine 2. After the completion of machining in the NC machine 2, the robot 2 picks up the work-piece and moves it onto the conveyor belt. 4
(4) The robot 3 picks up the work-pieces from the conveyor belts 5 and 6 and moves those into the AGV-1 and AGV-2 separately.
(5) The solenoid separates the work-pieces onto the conveyor belts 4 and 6.
(6) Two AGVs unload two types of work-pieces to the specific places separately; AGV-1 and AGV-2 unload work-pieces 1 and 2 at S16 and S14, respectively.
(7) AGVs travel only in counterclockwise direction and have to avoid the collision.

The modular supervisors are designed which satisfy the non-blockingness and the non-conflictness with respect to the specifications. The number of designed supervisors are eight for the specifications 1) $\sim$ 5) and six for the specifications 6) and 7).

4.3.1. *Modular supervisors for production line*

Firstly, the legal languages are designed for the specifications 1) $\sim$5). The eight modular supervisors

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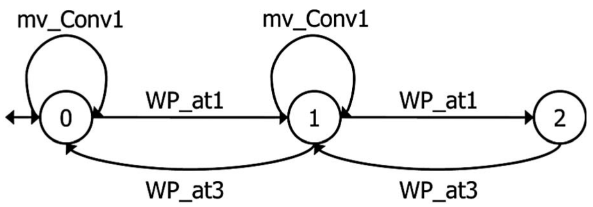
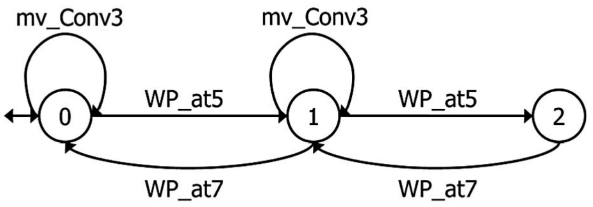
are designed with respect to the designed legal languages using Theorem 3. These supervisors are shown in Figures 11–13.

Table 1. Event list.

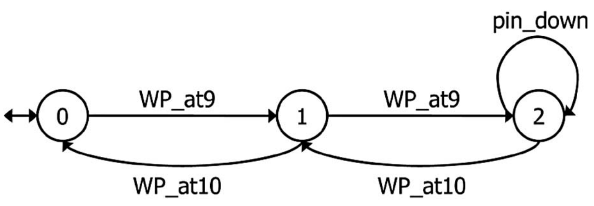
Plant	Event	Controllability
AGVs	mv_AGV_i	Controllable
	umv_AGV_i	Uncontrollable
Robots	$op1$	Controllable
	$op2$	Controllable
	$op3$	Controllable
	$op4$	Controllable
	$op5$	Controllable
	$op6$	Controllable
	end_op5	Uncontrollable
	end_op6	Uncontrollable
NC machines	opi	Controllable
	end_opi	Uncontrollable
Conveyor belts	mv_Convi	Controllable
	umv_Convi	Uncontrollable
Sensors	WP_ati	Uncontrollable
	$noWP\_ati$	Uncontrollable
	$AGVi\_atk$	Uncontrollable
	$noAGVi\_atk$	Uncontrollable
Restraint pin	pin_down	Controllable
	pin_up	Controllable
Solenoid	mv_Sol	Controllable
	umv_Sol	Uncontrollable



(a)



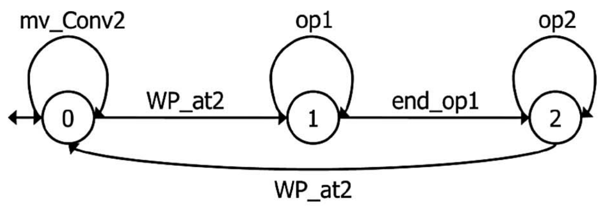
(b)



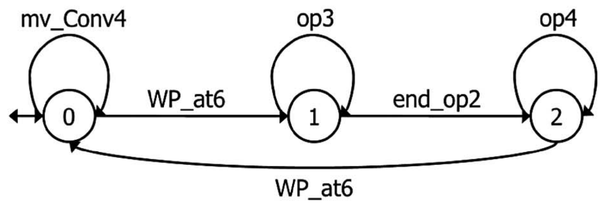
(c)

Figure 11. Buffer size supervisor. (a) buffer size supervisor for conveyor belt 2, (b) buffer size supervisor for conveyor belt 4, and (c) buffer size supervisor for conveyor belt 6.

Let us explain how the supervisor controls the plant using the example of the buffer size supervisor for the conveyor belt 2 as shown in Figure 11(a). The control data of this supervisor are enabling all events at the initial state and the state 1 and disabling the event *mv_Conv*1 at the state 2. This means that the buffer size supervisor for the conveyor belt 2 will not



(a)



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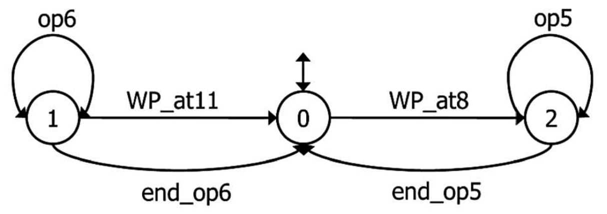

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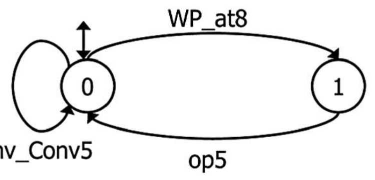

(d)

Figure 12. Routing supervisor. (a) routing supervisor for robot 1 and NC machine 1, (b) routing supervisor for robot 2 and NC machine 2, (c) routing supervisor for robot 3 and production lines 1 and 2 and (d) routing supervisor for robot 3 and conveyor belt 5.

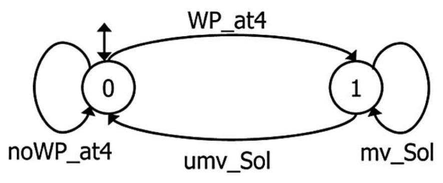

Figure 13. Workpiece selection supervisor.

permit the occurrence of the event mv_Conv1 after the occurrence of the string $\varepsilon \cdot mv\_Conv1 \cdot \varepsilon \cdot WP\_at1 \cdot \varepsilon \cdot mv\_Conv1 \cdot \varepsilon \cdot WP\_at1 \cdot \varepsilon$.

4.3.2. *Modular supervisors for AGV*

The seven modular supervisors for the supervisory control of AGVs are designed with respect to the specifications 6) and 7) using Theorem 3. The modular supervisor for the specification 6) is shown in Figure 14. The legal languages for the specification 7) are designed as six legal languages by dividing the AGV lane into six sections as shown in Figure 3 and then six supervisors are designed with respect to each legal language. The AGVs always travel under the supervision of these seven modular supervisors.

The AGV collision avoidance supervisor for the section 1 is shown in Figure 15. For other sections, the collision avoidance supervisors can be easily designed by changing only transition events according to the sensor signals of each section. The AGV collision avoidance supervisor for the section 1 has the control data which disables the event mv_AGV2 and mv_AGV1 at the state 2 and 4, respectively. This means that the event mv_AGV2 and mv_AGV1 will be disabled after the occurrence of the string $\varepsilon \cdot (mv\_AGV1 + mv\_AGV2) \cdot \varepsilon \cdot AGV1\_at12 \cdot \varepsilon \cdot (mv\_AGV1 + mv\_AGV2) \cdot \varepsilon \cdot AGV2\_at17 \cdot mv\_AGV1 \cdot \varepsilon$ and the string $\varepsilon \cdot (mv\_AGV1 + mv\_AGV2) \cdot \varepsilon \cdot AGV2\_at12 \cdot \varepsilon \cdot (mv\_AGV1 + mv\_AGV2) \cdot \varepsilon \cdot AGV1\_at17 \cdot \varepsilon \cdot mv\_AGV1 \cdot \varepsilon$, respectively.

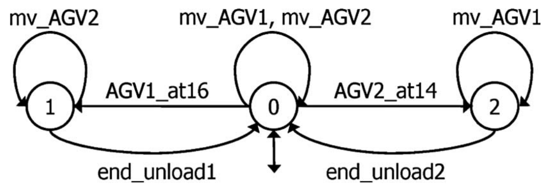

Figure 14. AGV unloading supervisor.

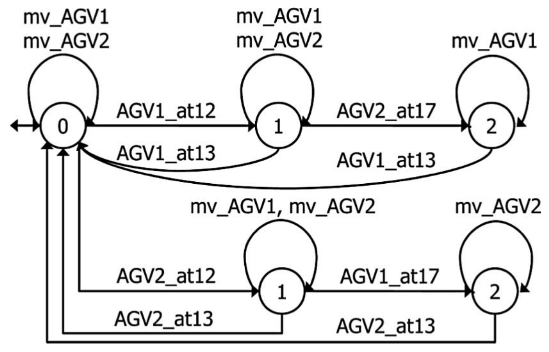

Figure 15. AGV collision avoidance supervisor for section 1.

4.4. ***High-level supervisor***

The high-level specification of the miniature CIM system is shown in the following.

High-level specification:

(1) The total buffer size of the conveyor belts 2 $\sim$ 4 is three work pieces.

The designed high-level supervisor for the high-level specification is shown in Figure 16. All high-level events which are not illustrated in Figure 16, form the self-loop events at all states.

The design procedure of the high-level supervisor, as shown in Figure 16, is specifically represented using Theorem 4 in the following. All automaton constructed during the design procedure are represented as the number of the states and the transitions because the states are too many to illustrate.

Design procedure for the high-level supervisor:

Step 0: The low-level plant G_{lo} is constructed as $SENSOR_1 \times SENSOR_2 \times SENSOR_3 \times SENSOR_4 \times SENSOR_5 \times SENSOR_6 \times SENSOR_7 \times ConvBelt_1 \times ConvBelt_2 \times ConvBelt_3 \times ConvBelt_4$. The number of states and transitions in G_{lo} are 1,024 and 13,312 respectively. The high-level legal language $K^0_{hi,1}$ is defined as the automation shown in Figure 16 except the self-loop at every states. The designed $K^0_{hi,1}$ has 4 states and 9 transitions. Finally, the information map Θ is defined in Table 2. The controllability of the high-level events is same with the low-level event defined in Table 1.

Step 1: $(G_{lo})_{sub,1}$ is designed as the synchronous product of the buffer size supervisor for the conveyor belt 2 and the buffer size supervisor for the conveyor belt 4 which are shown in Figure 11(a) and (b) respectively. The designed $(G_{lo})_{sub,1}$ has 9 states and 102 transitions.

Step 2: $(G_{lo})^{vocal}_{sub,1}$ is constructed from $(G_{lo})_{sub,1}$. The designed $(G_{lo})^{vocal}_{sub,1}$ has 27 states and 309 transitions. The part of this construction is illustrated in Figure 17. The event WP_at**1** makes the transition from the state 0 to the state 11 and the state output becomes τ_1 in $(G_{lo})^{vocal}_{sub,1}$ as shown in Figure 17(b). And the state 0 becomes the state 9 and 10 after the occurrence of the events WP_at7 and mv_conv1, respectively and the

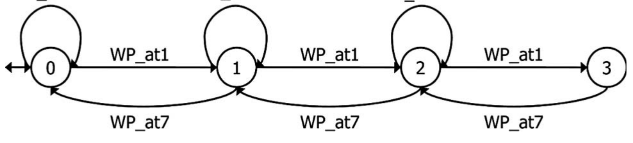

Figure 16. High-level supervisor.

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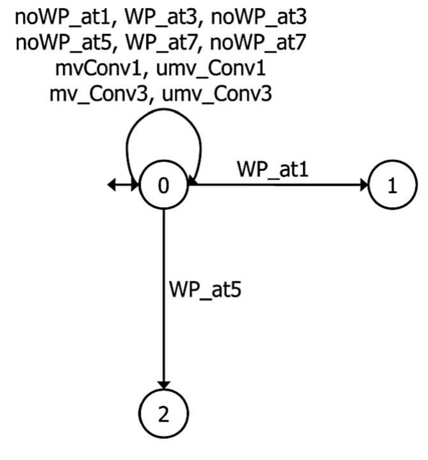
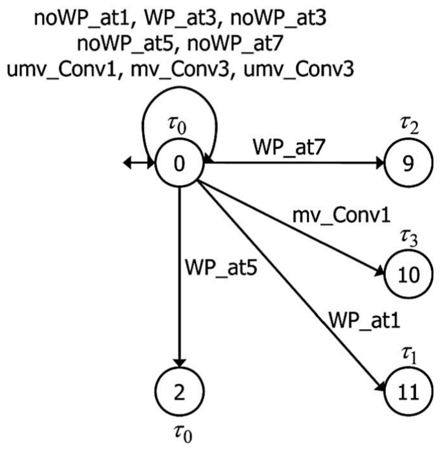
Table 2. Information map Θ.

Low-level event	$\tau = \Theta(\sigma)$	High-level event
*WP_at*1	τ_1	*WP_at*1
*noWP_at*1	τ_0	*null*
*WP_at*2	τ_0	*null*
*noWP_at*2	τ_0	*null*
*WP_at*3	τ_0	*null*
*noWP_at*3	τ_0	*null*
*WP_at*5	τ_0	*null*
*noWP_at*5	τ_0	*null*
*WP_at*6	τ_0	*null*
*noWP_at*6	τ_0	*null*
*WP_at*7	τ_2	*WP_at*7
*noWP_at*7	τ_0	*null*
*mv_Conv*1	τ_3	*mv_Conv*1
*umv_Conv*1	τ_0	*null*
*mv_Conv*2	τ_0	*null*
*umv_Conv*2	τ_0	*null*
*mv_Conv*3	τ_0	*null*
*umv_Conv*3	τ_0	*null*
*mv_Conv*4	τ_0	*null*
*umv_Conv*4	τ_0	*null*



(a)



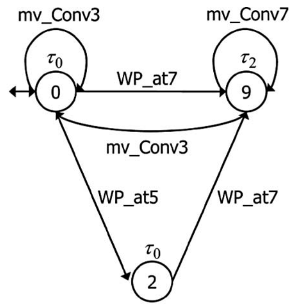
(b)

Figure 17. (a) Part of $(G_{lo})_{sub,1}$ (b) $(G_{lo})_{sub,1}^{vocal}$ for $(G_{lo})_{sub,1}$ shown in Figure 17(a).

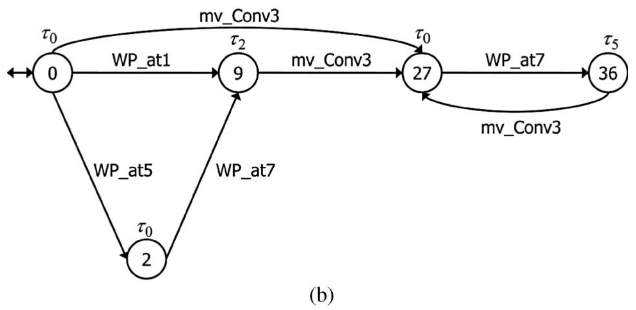
state output becomes τ_2 and τ_3 at the state 9 and 10, respectively. The state output at other states is τ_0.

Step 3: $\{(G_{lo})_{sub,1}^{vocal}\}_{OCC}$ is constructed from $(G_{lo})_{sub,1}^{vocal}$ $\{(G_{lo})_{sub,1}^{vocal}\}_{OCC}$ has 48 states and 548 transitions. This procedure is explained using Figure 18 as follows. The state output of the case, when the event *WP_at*7 has occurred without the occurrence of the event *mv_Conv*3 at the state 0, has to be defined differently with the case when the event *WP_at*7 has occurred after the occurrence of the event *mv_Conv*3 at the state 0. Because *mv_Conv*3 is the controllable event, the former case cannot disable the occurrence of *WP_at*7 while the latter case can disable *WP_at*7 by disabling *mv_Conv*3. Therefore, in the latter case, the state output has to be defined as the controllable event. The information map, which has to be added into the information map Θ defined in Table 2, is defined in Table 3 to solve this problem. In $\{(G_{lo})_{sub,1}^{vocal}\}_{OCC}$ shown in Figure 18(b), which is redesigned using the additional information map, the state 0 goes to the state 9 and the state output becomes τ_2 after the occurrence of *WP_at*7. And the next state becomes the state 27 after the occurrence of *mv_Conv*3 and if *WP_at*7 has occurred again, the state output becomes τ_5 but not τ_2.

Step 4: The designed $\{(G_{lo})_{sub,1}^{vocal}\}_{SOCC}$ has 39 states and 499 transitions. Because the new events τ_4 and τ_5 which are defined in Table 3 are not eligible in the plant, those events have to be redefined as τ_2 in this step, which are eligible high-level events. This means



(a)



(b)

Figure 18. (a) Part of $(G_{lo})_{sub,1}^{vocal}$ (b) $\{(G_{lo})_{sub,1}^{vocal}\}_{OCC}$ for $(G_{lo})_{sub,1}^{vocal}$ shown in Figure 18(a).

that the information map makes the state output as τ_2 if *WP_at*7 has occurred regardless of the previous string and new state outputs, i.e. new high-level events, have to be defined for the low-level event occurred after *WP_at*7. Let us make the partition for the low-level events as (13) before defining the new information map Θ.

$$\Pi\{(\Sigma_{10})_{sub,1}\} = \begin{cases} \Sigma_1 &= \{WP\_at1, WP\_at7, mv\_Conv1\} \\ \Sigma_2 &= \{mv\_Conv3\} \\ \Sigma_3 &= (\Sigma_{lo})_{sub,1} - \Sigma_1 - \Sigma_2 \end{cases} \tag{13}$$

The physical meaning of the partition $\Pi\{(\Sigma_{lo})_{sub,1}\}$ is as follows. The high-level events, which are defined in Table 2, are partitioned into Σ_1. The controllable events and the uncontrollable events in the other low-level events are partitioned into Σ_2 and Σ_3, respectively. The final information map Θ is defined in Table 4 according to this partition. New high-level events $\tau_6 \sim \tau_{17}$ only represent whether the controllable event, which occurred in the low-level plant, has transferred into the high-level plant. And those events are partitioned according to the state of $\{(G_{lo})^{vocal}_{sub,1}\}_{OCC}$ after the occurrence of the low-level string. The state output is τ_2 if *WP_at*7 has occurred at every state as shown in Figure 19 and it becomes τ_7 if *mv_Conv*3 has occurred.

Step 5: The designed high-level plant $G_{hi} = \Theta[\{(G_{lo})^{vocal}_{sub,1}\}_{SOCC}]$ has 14 states and 78 transitions.

Step 6–0: The control data of $K^0_{hi,1}$ with respect to G_{hi} disables the uncontrollable event $\tau_{uc,1} \in T_{uc,1}$ which is not defined at each state. This means that $K^0_{hi,1}$ does not satisfy the controllability because it disables τ_2 and τ_1 at the state 0 and 3, respectively. Therefore, let us redesign the high-level legal language as $K^1_{hi,1}$ by adding the self-loop of these events at all states.

Step 6–1: The control data of $K^1_{hi,1}$ satisfies the controllability because it disables the controllable event τ_3 at the state 3.

Step 7: $K^1_{hi,1}$ is non-blocking as shown in Figure 19.

Step 8: $K^1_{hi,1}$ is non-conflicting with G_{hi} because $K^1_{hi,1}$ satisfies $\overline{L_m(G_{hi}) \wedge L_m(K^1_{hi,1})} = L(G_{hi}) \wedge L(K^1_{hi,1})$ therefore, the high-level supervisor is designed as $S'_{hi,1} = K^1_{hi,1}$. $G_{hi} \wedge K^1_{hi,1}$ has 52 states and 287 transitions and $S'_{hi,1}$ has 4 states and 59 transitions.

Step 9: The automaton of the supremal controllable sub-language of $K^1_{hi,1}$ has 52 states and 287 transitions with respect to G_{hi}. This automaton is the solution of the SCP, $S_{hi,1}$.

Step 10: Finally, $S'_{hi,1}$, is the solution of the SCP with respect to $(K^1_{hi,1}, G_{hi})$ which has less states and transitions than $S_{hi,1}$ because it satisfies $L(S'_{hi,1} \times G_{hi}) = L(S_{hi,1})$.

The designed high-level supervisor $S'_{hi,1}$ makes the state transition only for the high-level events τ_1 and τ_2. And it disables *mv_Conv*1 at the states 3 while it enables *mv_Conv*1 at the states 0, 1, and 2. Therefore, only high-level events defined in Table 2 have meaning.

Table 3. Additional information map to satisfy the condition for OCC.

Low-level sequence	$\tau = \Theta(\sigma)$	High-level event
*mv_Conv*3 *WP_at*1	τ_4	Controllable *WP_at*1
*mv_Conv*3 *WP_at*7	τ_5	Controllable *WP_at*7

Table 4. Additional information map to satisfy the condition for SOCC.

Low-level sequence	$\tau = \Theta(\sigma)$	High-level event
$\sigma_1\sigma_2$	τ_7, τ_9, τ_{11}, τ_{13}, τ_{15}, τ_{17}	Controllable event occur in G_{10}
$\sigma_1\sigma_2\sigma_3$	τ_6, τ_8, τ_{10}, τ_{12}, τ_{14}, τ_{16}	Uncontrollable event occur in G_{10}

5. Implementation

5.1. CMSSM transform

In this article, the designed modular supervisors are transformed into the CMSSM for implementation purposes. The CMSSM is a machine which has specific outputs for the current state, the input, and the clock (Wakerley 1990). The supervisor, which is transformed into the CMSSM, can be implemented as the PLC or the digital circuit (Brandin 1994). The CMSSM of the AGV collision avoidance supervisor for section 1 is shown in Figure 20. In Figure 20, $D0 \sim D2$ represents the state of the CMSSM and *mv_AGV*1 and *mv_AGV*2 are the outputs of each state. And the state output is operated as the edge trigger for the current input.

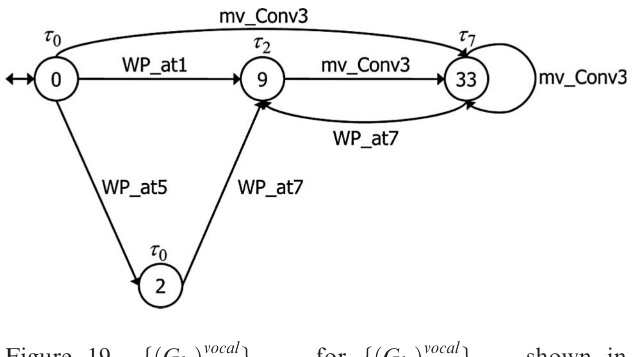


Figure 19. $\{(G_{lo})^{vocal}_{sub,1}\}_{SOCC}$ for $\{(G_{lo})^{vocal}_{sub,1}\}_{OCC}$ shown in figure 18.

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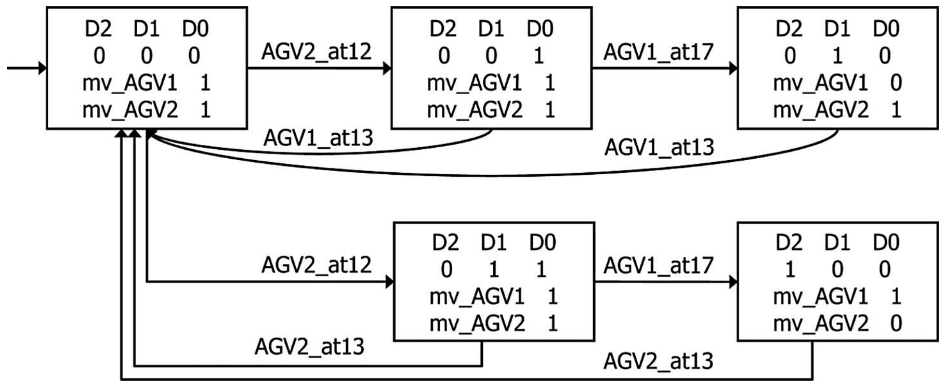

Figure 20. CMSSM of AGV collision avoidance supervisor for section 1.

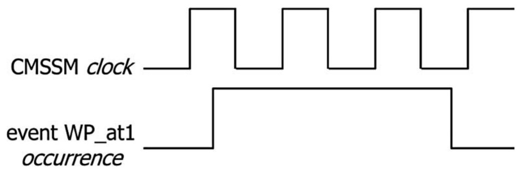

Figure 21. Event occurrence signal.

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There is an issue which has to be considered when the supervisor is transformed into the CMSSM. The event can be recognised into more than one event if the event occurrence time is longer than the CMSSM clock. An example of this problem is as follows. If *WP_at*1 has occurred at the initial state then the state will be state 1 and it will go to the state 2 after the additional occurrence of *WP_at*1 in the buffer size supervisor for the conveyor belt 2 shown in Figure 11(a). However, if the event occurrence time of *WP_at*1 is longer than one clock of the CMSSM as shown in Figure 21, the CMSSM will recognise this event as several occurrences of *WP_at*1. As a result, the initial state will go to state 2 even only one *WP_at*1 has occurred. Therefore, the event which can make state transition continuously has to be differentiated when the supervisor is transformed into the CMSSM. In the case of this example, the CMSSM has to be designed by differencing *WP_at*1 occurring at the initial state with *WP_at*1 occurring at the state 1. In the CMSSM of the buffer size supervisor, the latter case of *WP_at*1 is redefined as *WP_at*1 as shown in Figure 22. Also, this means that the additional sensor for the new event *WP_at*1 is needed for the implementation.

The logic is designed for the inputs and the outputs of the CMSSM (Wakerley 1990). In the case of the CMSSM shown in Figure 22, the sensor signals *WP_at*1, *WP_at*1′, *WP_at*3, and *WP_at*3′ are the inputs and the control signal for the conveyor belt 1 *mv_Conv*1 is the output. Finally, the logic for the CMSSM of the buffer size supervisor in the conveyor belt 2 is shown in (14), (15), (16), (17), and (18).

$$D2_{new} = (D1 \wedge D0 \wedge AGV1\_at17 \wedge \sim AGV2\_at13) \\ \vee (D2 \wedge \sim AGV2\_at13) \tag{14}$$

$$D1_{new} = (\sim D1 \wedge D0 \wedge AGV2\_at17 \wedge \sim AGV1\_at13) \\ \vee (D1 \wedge \sim D0 \wedge \sim AGV1\_at13) \\ \cdots \wedge (\sim D2 \wedge \sim D1 \wedge \sim D0 \wedge AGV2\_at12) \\ \vee (D1 \wedge D0 \wedge \sim AGV1\_at17 \wedge \sim AGV2\_at13) \tag{15}$$

$$D0_{new} = \{(\sim D2 \wedge \sim D1 \wedge \sim D0) \\ \wedge (AGV1\_at14 \vee \sim AGV2\_at12)\} \\ \cdots \vee (\sim D1 \wedge D0 \wedge \sim AGV2\_at17 \\ \wedge \sim AGV1\_at13) \vee (D1 \wedge D0 \wedge \\ \sim AGV1\_at17 \wedge \sim AGV2\_at13) \tag{16}$$

$$mv\_AGV1 = \sim D2 \tag{17}$$

$$mv\_AGV2 = \sim D1 \vee D0 \tag{18}$$

5.2. *Simulation*

The designed CMSSMs are verified using the circuit design and analysis software PSpice. In simulation, the outputs are tested with the arbitrary input to the CMSSM. All designed supervisors are simulated and the simulation result of the AGV collision avoidance supervisor for the section 1 is shown in Figure 23.

In Figure 23, *AGV*1_*at*12, *AGV*2_*at*12, *AGV*1_*at*13, *AGV*2_*at*13, *AGV*1_*at*17, and *AGV*2_*at*17 are the sensor signals which are used as the input and

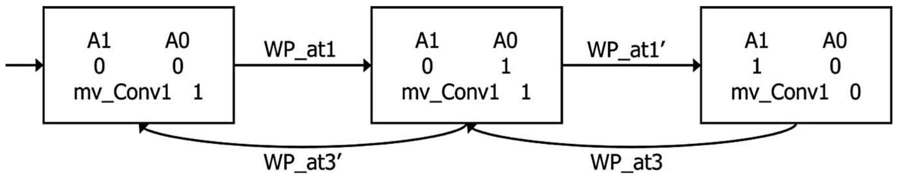

Figure 22. CMSSM of buffer size supervisor for conveyor belt 2.

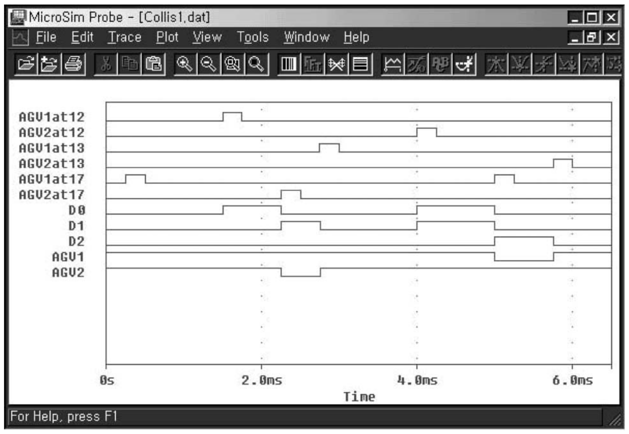

Figure 23. Simulation result for AGV collision avoidance supervisor for section 1.

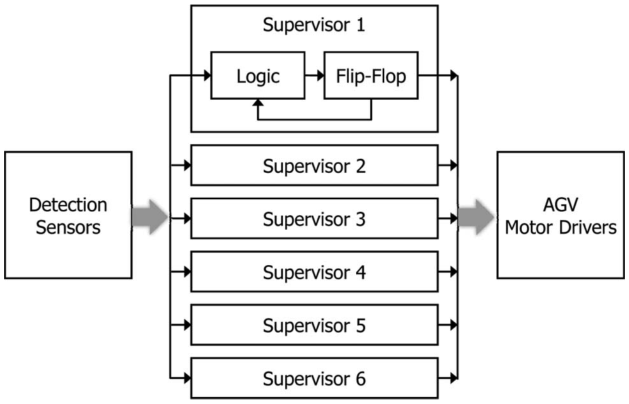

Figure 24. Block diagram of AGV collision avoidance system.

the output signals are $AGV1$ and $AGV2$ which are the control signals of the AGVs. And $D0$, $D1$, and $D2$ are the states of the CMSSM. Let us analyse the simulation result shown in Figure 23. In the beginning, all states are 0. The state does not change even after the occurrence of $AGV1\_at17$ because $AGV1\_at17$ is the self-loop event at the initial state. And then $D0$ becomes 1 due to the occurrence of $AGV1\_at12$. At the same time, if $AGV2\_at17$ has occurred, $D\mathbf{1}$ becomes 1 while $D0$ becomes 0. Therefore, the state of the CMSSM becomes 2 and $AGV2$ is disabled. If

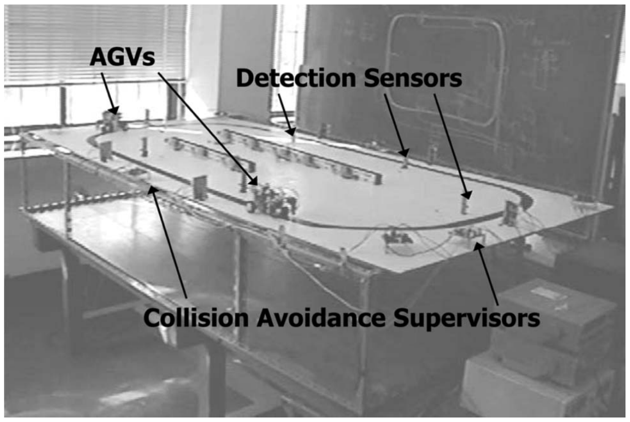

Figure 25. Experimental AGV collision avoidance system.

$AGV1\_at13$ has occurred, the state goes back to 0 and $AGV2$ will be enabled again. This means that if a certain AGV enters the section 1 and also if the other AGV enters the section 1 before the previous AGV leaves the section, the supervisor will disable the latter AGV until the previous supervisor leaves the section 1. We can see the same control action when the AGV2 enters the section 1 at first, i.e. when $AGV2\_at12$ has occurred at the state 0 in Figure 23.

5.3. *Implementation*

The AGV collision avoidance supervisors for all sections are implemented and experimented as shown in Figure 24. These supervisors control the AGVs as follows. The sensors located in the AGV lane will detect the AGV 1 and 2 and then these signals will be transmitted to the collision avoidance supervisors. Each supervisor will output the control signal to the motor driver of the AGVs using the embedded logical circuits with the transmitted sensor signal. The implemented AGV collision avoidance system is shown in Figure 25. The implanted collision avoidance supervisors are operated in an exactly similar manner as that of the simulation result.

6. Conclusion

In this article, the decentralised supervisory control scheme is presented for large complex systems which

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are modelled as DESs. The proposed decentralised control scheme is divided into the modular supervisory control and the high-level supervisory control. The generalised solution for the modular SCP is presented with the concept of the sub-plant to reduce the computational complexity and it is also proved theoretically. The modular supervisors, designed using the proposed solution, are the maximum permissible and controllable sub-language of the given legal languages with respect to the plant to be controlled. For the high-level SCP, the generalised solution is also presented and then proved, which guarantees the hierarchical consistency. The high-level supervisors are also the maximum permissible and controllable sub-language of the given high-level legal languages with respect to the high-level plant designed using the proposed Theorem.

The proposed decentralised control scheme is applied for the control of the experimental miniature CIM system. The miniature CIM system is modelled as 31 automata. The first eight and next six modular supervisors are designed using the proposed modular SCP solution procedure with respect to the legal languages for the production line and the AGV control respectively. In addition, one high-level supervisor, which has 52 states and 287 transitions, is designed using the high-level SCP solution procedure proposed in Theorem 4 to control the buffer size of all conveyor belts.

The designed decentralised supervisors are transformed into the CMSSM in order to apply and verify the proposed control scheme for real-world problems. The control logic is designed based on the transformed CMSSM and this logic is implemented and embedded in the digital circuits. Finally, the AGV collision avoidance system is constructed to verify the performance of the proposed control scheme. The implemented supervisors accurately perform their functions which satisfy the control specifications.

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