Modeling and Control of Heterogeneous Agricultural Field Robots Based on Ramadge–Wonham Theory

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Abstract—**Cooperation among heterogeneous agricultural field robots in an agricultural environment guarantees the advantages of effectiveness and scalability. However, traditional control theories for coordination among multiple heterogeneous robots lack a systematic modeling method and a control strategy under unstructured and uncertain environments. To handle these limitations, a novel approach based on the Ramadge–Wonham theory and discrete event system is proposed in this letter. Specifications and a supervisory controller based on discrete event models were defined from an agricultural perspective considering cooperation among heterogeneous agricultural field robots. Discrete event systems were modeled through the automata theory and the behavior of heterogeneous field robots satisfied the designed specifications. The resulting supervisor ensures that the control objectives of formation control, obstacle avoidance, movements, and path following are satisfied. The approach and architecture proposed in this study were validated using a physics-based simulator and field experiments.**

Index Terms—**Robotics in Agriculture and Forestry, Discrete Event Dynamic Automation Systems, Cooperating Robots.**

I. Introduction

With the continuous increase in the global population, the demand for novel agricultural products and systems also continues to rise [1]. Accordingly, a new concept in agricultural systems, called smart agriculture, has emerged and has been globally adopted to deal with climate change, while considering biodiversity, eco-friendly farming, and highly efficient production through the use of a smart farm. The fundamentals and core technologies of smart agriculture include the IoT, Big Data, AI, Nanobiotechnology, cloud, sensors, field robots, automation, and cyber-physical systems. One of the fastest-growing areas of smart agriculture is robotics technology [2], which is being applied to various agricultural environments such as outdoor culture and cultivation (i.e., orchards, paddy fields, greenhouses, and plant factories).

In traditional agricultural approaches, ground machines (i.e., tractors, pest control machines, and combines) are primarily used. However, agricultural robots that have been developed have various forms, such as an unmanned vehicle (e.g., aerial or ground) and mobile manipulator [3], [4]. The introduction of these agricultural robots has resulted in productivity improvements and a reduction in the working hours of farmers and laborers performing agricultural tasks. Nevertheless, these robots are insufficient for satisfying the rising demands for agricultural products. Therefore, the architecture of multi-robot systems, which can efficiently perform tasks by distributing areas to multiple robots, is being increasingly studied in the field of agriculture.

Recently developed multi-robot agricultural systems can be classified into UGV swarms and UAV swarms; representative studies of these systems include the swarm robotics for agricultural application (SAGA) and mobile agricultural robot swarms (MARS) projects being undertaken in Europe. Specifically, the SAGA aims to apply multiple UAVs to the field of agriculture by mimicking the behavior of bee clusters to create a map and remove weeds [5]. The MARS project aims to develop streamlined and small mobile robots to cause a paradigm shift in farming [6]. However, instead of homogeneous robotics, collaboration and cooperative control among heterogeneous agricultural field robots are required for the definitive automation and robotization of agriculture.

A heterogeneous multi-robot system can overcome the limitations of existing homogeneous multi-robot systems because the advantages of each robot type are utilized while its disadvantages are compensated [7]. For example, if a UAV identifies and shares information about areas where fruits are moderately ripe while performing remote sensing in an orchard, a mobile manipulator can harvest them faster and more accurately. As another example, if a UAV creates a three-dimensional map that includes the global positions of obstacles (e.g., people, trees, and poles), the UGV that locally detects an obstacle can decrease the risk of an accident based on the data from the map. Also, heterogeneous field robots can be actively applied to agricultural tasks such as image processing-based [8] variant spraying (e.g., aerial robots: tall trees, ground robots: low plants) and deep neural network-based [9] crop monitoring or inspection (e.g., aerial robots: global, ground robots: local). Thus, cooperation among heterogeneous agricultural robots maximizes their applicability, enabling this system to be a key future smart farming technology.

However, instead of the traditional control theory, a systematic approach is required to model the behavior of a system and dynamics and control heterogeneous field robots. Moreover, the problems of cooperative control are challenging in that it requires dynamic interaction with unstructured and uncertain

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environments. To solve these problems, discrete event system (DES)-based approaches and supervisory control theory [10], [11] have been introduced for controller design and plant modeling in the case of complex systems (i.e., multiple robot systems, communication networks, and computer systems). The Ramadge–Wonham (RW) theory based on a DES has proven to be effective for controlling complex dynamic systems through the design of a supervisory controller (supervisor) that satisfies behavior specifications and maximally permits the eligible events [12]. Moreover, a DES framework offers a simpler and systematic construction of multi-robot systems and does not require rigorous system modeling [13], [14]. Hence, the DES-based RW theory is ideally suited for heterogeneous agricultural field robot systems where system modeling and controller design are greatly challenging.

A. Objective of the Study

The objective of this study is to develop an approach based on a DES for cooperation among heterogeneous agricultural field robots. To achieve this, we apply the RW theory to design a supervisory controller systematically using specifications based on discrete event models. Please note that the RW theory was applied for manufacturing system automation in [13] while it is applied for the cooperation of heterogeneous agricultural field robots in this letter. We model the cooperative behavior among heterogeneous field robots as finite state automata from an agricultural point of view. This approach originated from the development of a system that allows heterogeneous agricultural field robots to collaborate on tasks to be performed while satisfying the given specifications. The resulting supervisor ensures that the heterogeneous agricultural field robots follow a target path while avoiding obstacles and forming a desired formation and movements. The heterogeneous robot systems include multiple UAVs (follower robot) and one UGV (leader robot). The proposed system and approaches based on the DES framework and RW theory are validated and verified through a physics-based simulator and field experiments.

B. Related Works

The control of multiple robots based on the DES framework and RW theory has attracted considerable research attention over the past few years [15]. In [16], a supervisor was designed to maintain the formation of multiple mobile homogeneous robots and to avoid obstacles for their dynamic interaction. [17] studied the swarm for the formation control of homogeneous ground robots and [18] applied the RW theory for dynamic task allocation of multiple robots. In [19], a supervisory controller for failure diagnosis was studied while controlling a homogeneous ground robot system used in a warehouse and factory. This theory has been applied to various systems such as exploration [20], warehouse [21], search and rescue [22], and fight [23]; however, these applications are still in the early stages of research and development. Herein, we attempt to apply the DES and RW theory in the field of smart agriculture for cooperation among heterogeneous agricultural field robots, which, to the best of the authors knowledge, has not been investigated until now.

In the field of agriculture, the concept of cooperation among multiple robots is still in the early stages owing to the diversity of soil, crops (rice, apple, corn, etc.), terrains (land, orchard, greenhouse, etc.), agricultural tasks (irrigation, harvesting, monitoring, cultivation, etc.), and climate conditions (temperature, humidity, rainfall, etc.). [5] proposed a roadmap for monitoring and mapping using multiple homogeneous UAVs for their agricultural application. The study in [24] attempted to develop a farming system using multiple robots (tractors). In addition, remote sensing [25], water management [26], field coverage, and weed mapping [27], [28] have been studied using fleets of UAVs. Studies have also been conducted on heterogeneous agricultural robots [29]–[31]. However, in contrast to our study, they focus on agricultural work under certain conditions based on continuous-time system and do not deal with the systematic control of heterogeneous robot systems, flexible control architecture in dynamic environments, and various conditions for scalability. The proposed system in this letter is extended to a discrete-event system in a continuous-time system and has the advantages of potentiality, feasibility, and scalability in the application of heterogeneous multiple robots to agriculture. Therefore, a novel approach based on DES and RW theory, not the conventional control system perspectives, is discussed that can model, control, and analyze complex dynamic systems effectively and systematically by extending previous studies [32], [33].

C. Structure of the letter

The organization is as follows. In Section II, we shortly review the concept of DESs and the RW theory. In Section III, we introduce the finite state automata-based model for heterogeneous agricultural field robots. In Section IV, we propose a supervisory controller with specifications based on the RW theory and present the control architecture for cooperation among heterogeneous robots. In Section V, we implement the proposed DES and supervisor and verify the simulation and field experiments. Additionally, we present systematic results and discuss the analysis using a deeper evaluation. Finally, we draw conclusions and address the scope of future studies in Section VI.

II. Ramadge-Wonham Theory

Here, we briefly overview the RW theory and DES, please refer to [11], [12] and [13] for more details. DES is a dynamic system with characteristics of continuous time and discrete state space. DES is also an event-driven system that the state is thoroughly transitioned by the eligible events with the passage of time. In this study, we applied the automata theory as the discrete event modeling formalism to explain the system behavior.

The finite state automaton G for modeling a DES is a tuple consisting of the following five elements [34]:

$$G = \{A, \Upsilon, \zeta, a_0, A_m\} \tag{1}$$

where A is the set of all states, Υ is the set of all events, ζ is the state transition function of G ($\zeta : A \times \Upsilon^* \mapsto A$), a_0 is the initial state of G, and A_m is the subset of marker states, which indicates a goal state or a final state ($A_m \subset A$). In the transition function ζ, Υ^* represents a sequence (string) of events containing the null event ε. Moreover, the event set Υ is categorized as a set of controllable events Υ_c and a set of uncontrollable events Υ_{uc}.

The language occurred by the automaton G is defined as

$$L(G) := \{s \in \Upsilon^* | \zeta(a_0, s)!\} \tag{2}$$

where $\zeta(a_0, s)!$ indicated that the next state in which the string s occurred at a_0 is defined in G. The prefix closure of language $L(G)$ is defined as

$$\overline{L(G)} := \{t \in \Upsilon^* | t \leq s \quad \exists s \in L(G)\} \tag{3}$$

here, $L(G)$ is defined as prefix-closed when $L(G) = \overline{L(G)}$.

The marked language of automaton G is defined as

$$L_m(G) := \{s \in L(G) | \zeta(a_0, s) \in A_m\} \subseteq L(G) \tag{4}$$

if G satisfies $\overline{L_m(G)} = L(G)$, then $L(G)$ is defined as nonblocking. In other words, it indicates that the marked state can be reached after any string occurs in any states of G [11]. Nonblocking is a necessary condition for designing a proper supervisor in the RW theory, because the DES may fall into deadlocks or livelocks when $L(G)$ is blocking.

Supervisory control is a feedback control theory for DES; it is a control method that observes the occurrence of events or states of DES and then permits or inhibits controllable events to achieve the control objectives.

Also, the supervisor is defined as the automaton $S = (X, \Upsilon, \delta, x_0, X_m)$, where X, Υ, δ, x_0, and X_m represent the set of states, set of events, state transition function, initial state, and marker state, respectively. Consider that the plant is defined as DES G, and the behavior and generated language of plant G under the supervisor S are defined as

$$S/G = \{X \times A, \Upsilon, \delta \times \zeta, (x_0, a_0), X_m \times A_m\} \tag{5}$$

$$L(S/G) : \epsilon \in L(S/G), \forall s \in \Upsilon^*, \epsilon \in \Upsilon : \\ s \in L(S/G), s\upsilon \in L(G), \upsilon \notin \Theta \Rightarrow s\upsilon \in L(S/G) \tag{6}$$

where υ is a specific event, and Θ is a control mapping function defined as $\Theta : L(G) \mapsto 2^{\Upsilon_c}$.

The controllability of $L(S)$ *w.r.t.* G is described in Definitions 1.

Definition 1: S is defined as controllable *w.r.t.* (G, Υ_{uc}) when the following condition is satisfied

$$(\forall s, \upsilon) s \in \overline{L(s)}, \upsilon \in \Upsilon_{uc}, s\upsilon \in L(G) \Rightarrow s\upsilon \in \overline{L(S)} \tag{7}$$

In other words, s, which is allowable by S and an uncontrollable event υ, is eligible in G, if the sequence $s\upsilon$ is eligible in G and if S also allow $s\upsilon$, then S is controllable *w.r.t.* G.

Moreover, the supervisory control problem (SCP) used to design a supervisor is defined in Definition 2.

Definition 2: For a given $K \subseteq G$, find a supremal language S that is controllable *w.r.t.* (G, Υ_{uc}), satisfying $L(S/G) = K$ and $L(S/G) = \overline{L_m(S/G)}$.

Thus, if K is defined as the specification for G, the SCP is to find a supervisory controller that satisfies $L(S/G) = K = \overline{L_m(S/G)}$ and is nonblocking and controllable *w.r.t.* G. Here, there can exist a plurality of supervisors that satisfy specifications and are controllable. Among these K, a supremal controllable sublanguage of K is determined as the solution of the SCP. Therefore, S can allow the eligible language to occur in G maximally.

III. System Modeling

A. Problem Description

This letter addresses the supervisory control of heterogeneous agricultural field robots in agricultural environments. The heterogeneous agricultural field robots were set up using multiple UAVs and one UGV equipped with an agricultural working module, i.e., more specifically, a leader UGV and follower UAVs.

We express the behavior of field robots as finite state automata to model the cooperation based on DES. The detailed model of the cooperative behavior consists of path following, formation maintenance, obstacle avoidance, and movements, and is described in Section III-B. Through this approach, agricultural field robots can follow the given path, avoid obstacles, and maintain their formation while operating in agricultural environments. Therefore, the plant model for each field robot can be obtained through the component model based on finite state automata as mentioned above. The process of obtaining the overall plant model is described as follows.

In a DES consists of multiple robots, the overall plant consists of $n(>1)$ component models, where each robot $k(\in [1, \ldots, n])$ is modeled by the automata $G_k = (A_k, \Upsilon_k, \zeta_k, a_{k,0}, A_{k,m})$. Therefore, the overall plant G is the *parallel composition* of the n component robots, defined as

$$G = (A, \Upsilon, \zeta, a_0, A_m) = G_1 || \cdots || G_n, \\ G_i || G_j = A_C(A_i \times A_k, \Upsilon_i \cup \Upsilon_j, \zeta, (a_{0i}, a_{oj}), A_{mi} \times A_{mj}) \\ L_i || L_j = (L_i || (\Upsilon_j - \Upsilon_i)^*) \cap (L_j || (\Upsilon_i - \Upsilon_j)^*) \tag{8}$$

where the event set Υ of the overall plant model G is classified into two disjoint sets, i.e., the controllable events set $\Upsilon_c = \cup_{k \in \{1,\ldots,n\}} \Upsilon_{k,c}$ and uncontrollable events set $\Upsilon_{uc} = \cup_{k \in \{1,\ldots,n\}} \Upsilon_{k,uc}$.

B. Plant Modeling for Heterogeneous Agricultural Field Robots

In this study, the states and events are minimized in the discrete event model. This minimization is performed through the projection map of the events that are unobservable and are unneeded to observe by the supervisor and do not affect the behavior of specifications toward ϵ.

1) Component Model of Path Following G_p: The finite state automaton G_p shown in Fig. 1(a) models the behavior of path following for heterogeneous agricultural field robots. The events of G_p are explained in Table I. G_p has two states, described as follows:

- $A_p = \{P_1, P_2\}$ where P_1: *driving*, P_2: *following*

If the state of the automaton G_p is P_1 and the event α_1 that assigns the target path occurs, the state of G_p will transition to P_2. Subsequently, if the event α_2 where the robot reaches the goal area or α_4 where the path is cleared occurs at P_2, the state of

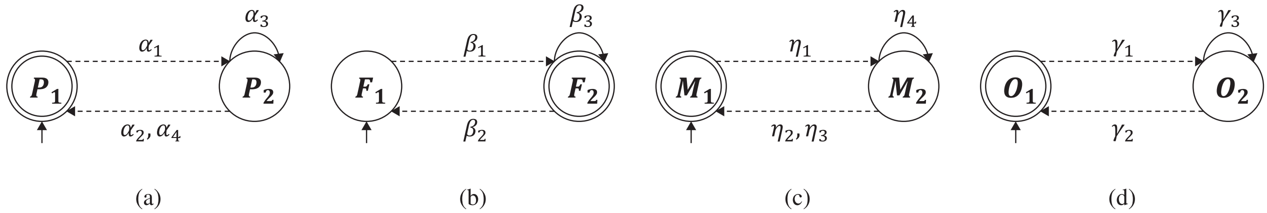

Fig. 1. DES models. (a) Path following G_p. (b) Formation maintenance G_f (c) Movements G_m. (d) Obstacle avoidance G_o.

TABLE I
EVENTS FOR DES MODELS

Model	Event	Description	Controllable
G_p	α_1	Path assigned	X
	α_2	Path reached	X
	α_3	Follow path	O
	α_4	Path cleared	X
G_f	β_1	Leader connected	X
	β_2	Leader disconnected	X
	β_3	Maintain formation	O
G_m	η_1	Mission received	X
	η_2	Mission finished	X
	η_3	Robot stopped	X
	η_4	Move forward	O
G_o	γ_1	Obstacle detected	X
	γ_2	Free space detected	X
	γ_3	Avoid obstacle	O

G_p will transition back to P_1. Otherwise, the controllable event α_3 is used to follow the given path.

2) Component Model of Formation Maintenance G_f: The finite state automaton G_f, described in Fig. 1(b), models the behavior of formation maintenance for three follower UAVs. It has two states, which express the status of the robot regarding formation control, described as follows:

- $A_f = \{F_1, F_2\}$ where F_1: *hovering*, P_2: *forming*

The events of G_f are specified in Table I. This automaton is a representation of follower UAVs navigating with the leader UAV by forming the desired formation. When the state of G_f is F_1 and the event β_1 where communication connected with the UGV occurs, the state transitions to F_2. In F_2, if a controllable event β_3 occurs to allow the follower UAVs to form a formation, it can continuously maintain the formation. However, when β_2, which is an event where the communication with the leader UGV is disconnected, the state of G_f transits to F_1, and the field robots cannot form a formation.

3) Component Model of Movements G_m: The finite state automaton G_m models the robot movements as shown in Fig. 1(c). The events of G_m are listed in Table I. G_m also has two states for expression of movements, described as follows:

- $A_m = \{M_1, M_2\}$ where M_1: *stopping*, M_2: *moving*

The occurrence of the event η_1 is a mission (or task) assignment to the robot, which transmits the state of G_m from the stationary M_1 to the movements M_2. The events η_2 and η_3 indicate that the robot has been stopped owing to the completion of the mission, breakdown, or accidents. The occurrence of η_4 in state M_2 represents a controllable event that causes the robot to navigate forward. For example, when a simulation starts or a specific mission and task are assigned to a robot, the state of the robot transitions to M_2, the controllable event η_4 is allowed, and then the robot moves.

4) Component Model of Obstacle Avoidance G_o: The finite state automaton G_o shown in Fig. 1(d) models the behavior of obstacle avoidance for heterogeneous agricultural field robots. G_p has two states showing the status of the robot to avoid obstacles, described as follows:

- $A_o = \{O_1, O_2\}$ where O_1: *exploring*, O_2: *avoiding*

The events of G_o are explained in Table I. For cooperation in an agricultural environment, each robot must navigate while avoiding obstacles. Therefore, it requires events to handle unpredictable obstacles. When an obstacle is detected, the controllable event γ_3 is used to avoid obstacles and collision. γ_1 and γ_2 are uncontrollable events related to sensors attached to the robots. Thus, when the obstacles are detected, the state of the automaton G_o transitions from O_1 to O_2.

In this study, we only address the high-level control based on DES and the RW theory, but we do not deal with low-level control for coordination among the heterogeneous agricultural field robots. For further details of low-level control regarding controllable events, we refer the reader to [28] and [35].

IV. SUPERVISORY CONTROL

A. Modeling of Specification E

As the goal of the system is the cooperation among heterogeneous agricultural field robots, specifications for the leader and follower robots were designed. The specifications for the supervisor are as follows:

1) The leader robot and the follow robots move after receiving the mission.
2) The leader robot follows the path after receiving the mission.
3) The follower robot forms a formation before the leader robot follows the path.
4) When the obstacle is detected, the leader robot and follower robot assigns priority to obstacle avoidance rather than path following and formation maintenance, respectively.

For example, the automaton E_2 of Fig. 3(b) is the specification for maintaining formation. When the follower robot receives the mission (η_1), it moves forward. In this case, if the leader robot is assigned a path (α_1), the follower robot cannot form a formation. Therefore, the robots cannot cooperate, and the follower robot does not operate normally. Consequently, the

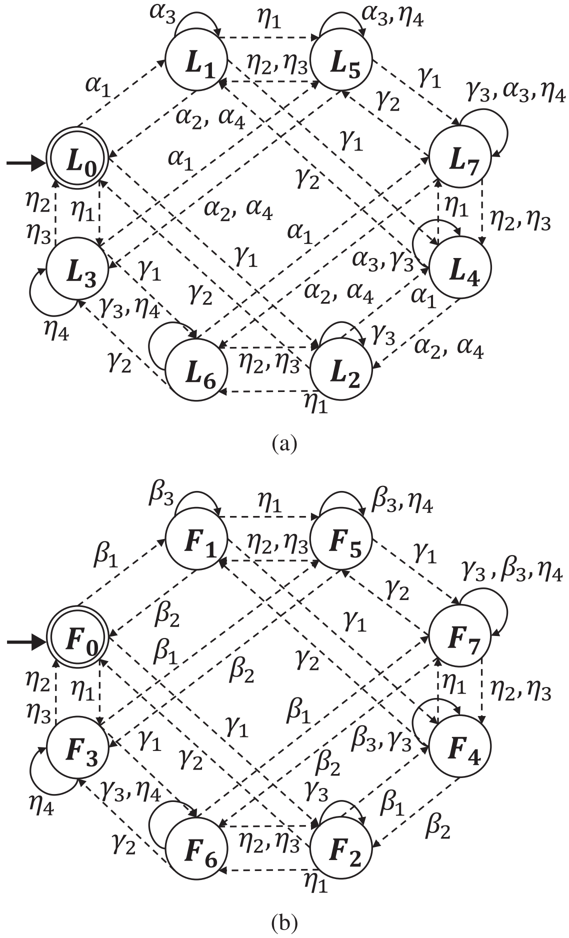

Fig. 2. DES models for heterogeneous field robots (a)Leader robot G_{leader}. (b) Follower robots G_{follower}.

behavior specification is designed to allow the follower robot to form the formation first before the state of the robot is transitioned to state 3.

B. Design of Supervisor S

The DES models of the leader and follower robots (Fig. 2) were obtained using the following method:

$$G_{\text{leader}} = G_p||G_m||G_o \tag{9}$$

$$G_{\text{follower}} = G_f||G_m||G_o \tag{10}$$

where controllable events are $\{\alpha_3, \eta_4, \gamma_3\}$ and $\{\beta_3, \eta_4, \gamma_3\}$.

The supervisor S can selectively allow the controllable events generated by the plant, thereby controlling the heterogeneous field robots to satisfy the desired behavior. In this study, a supervisor-based architecture is proposed to design the desired controller to deal with the cooperation among heterogeneous agricultural field robots. For a given plant G and specifications $E_i, i = 1, 2, \ldots, n$, supervisors S_i are the solutions of the SCP obtained using the following procedure in Theorem 1.

Theorem 1:

1) Define the plant automaton G, the specifications automaton E_i, and the sub-plants $G_{\text{sub},i}$

TABLE II
CONTROL ACTION OF SUPERVISOR S/G

S_1/G_{leader}		$S_2/G_{follower}$	
State	Function Θ_l	State	Function Θ_f
L_0	$XX0$	F_0	$X00$
L_1	100	F_1	100
L_2	$X10$	F_2	$X10$
L_3	$XX1$	F_3	$X01$
L_4	$X11$	F_4	$X11$
L_5	100	F_5	100
L_6	101	F_6	101
L_7	101	F_7	101

2) Verify the controllability of E_i *w.r.t.* $G_{sub,i}$ using Υ_c in E_i
3) Verify the condition of nonblocking of E_i
4) Verify the condition of nonconflicting of E_i *w.r.t.* $G_{sub,i}$. If E_i is nonconflicting, then $S'_i = E_i$
5) Find S_i (the supremal controllable sublanguage) of E_i *w.r.t.* $G_{sub,i}$
6) S_i is the solution of the SCP *w.r.t.* $(E_i, G_{sub,i})$
7) If $L(S_i) = L(S'_i/G_{sub,i})$, then S'_i is the solution of the SCP *w.r.t.* $E_i, G_{sub,i}$

Proof: Please refer to [13]. ■

C. Behavior of Plant Under Supervisor S/G

In order to design the supervisor of the leader robot, we assigned $G_{sub,1}$ and $G_{sub,2}$ as G_{leader} and G_{follower}, respectively. And E'_1 is obtained by synthesizing E_1 and E_3, and E'_2 is obtained as a supervisory controller of the follower robot by synthesizing E_2 and E_4. All the events of the plant were synthesized in E'_1 and E'_2 to find the final specifications. According to Theorem 1, specifications E'_1 and E'_2 satisfied the controllability, nonblocking, and nonconflicting. We have verified the controllability, nonblocking, and nonconflicting of E'_1 and E'_1 *w.r.t.* G_{leader} and G_{follower} via a supervisory control synthesis tool called TCT [36]. Therefore, hereafter, specifications E'_1 and E'_2 are defined as supervisors S_1 and S_2, respectively. Table II shows the supervisory control actions of S_1 and S_2. Θ_1 and Θ_2 are control mapping function for α_3, η_4, and γ_3 and β_3, η_4, and γ_3, respectively, where X is an event that does not involve, 0 is an event that suppressed, and 1, an event that allowed by the supervisor.

V. RESULTS AND DISCUSSIONS

A. Simulation

In this study, a physics-based simulator is constructed to validate the proposed supervisory controller for a heterogeneous agricultural field robot system as shown in Fig. 4. The heterogeneous field robots include three follower UAVs and one leader UGV, and the virtual environment is set to a hypothetical environment similar to an orchard. The mission was to follow a given path and we verified that the behavior of the heterogeneous robot systems is consistent with the designed supervisor during the simulation. The control architecture of the entire system is described in Fig. 5. Here we have designed a hierarchical structure that combines a time-driven system with a

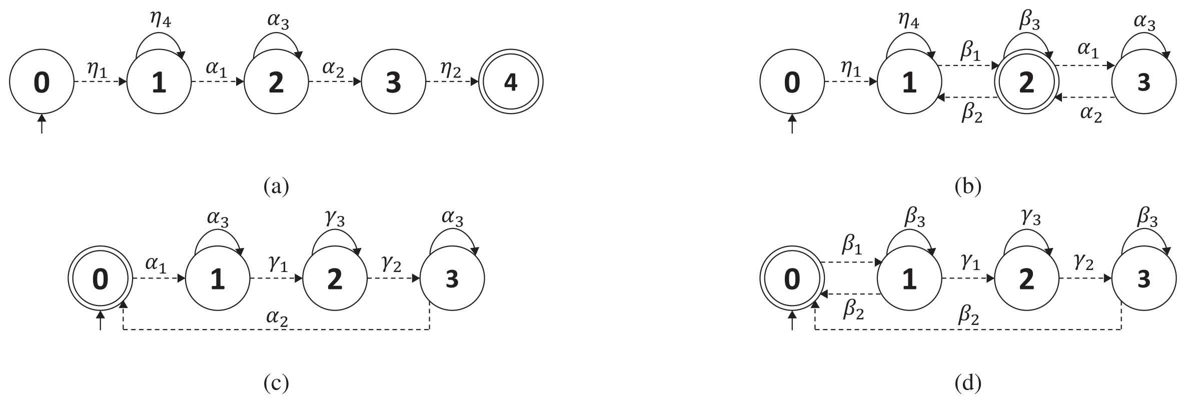

Fig. 3. Specifications. (a) Specification of path following E_1. (b) Formation maintenance specification E_2. (c) Obstacle avoidance specification for leader robot E_3. (d) Obstacle avoidance specification for follower robot E_4.

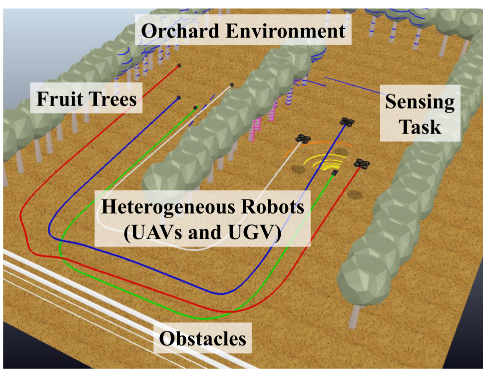

Fig. 4. Physics-based simulator environments for heterogeneous agricultural field robots.

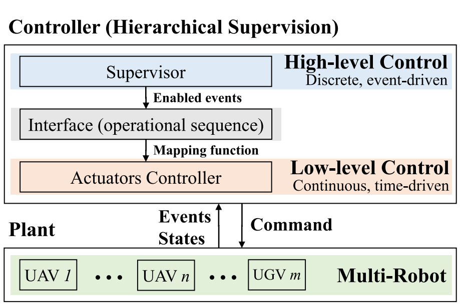

Fig. 5. Architecture of supervisory control system.

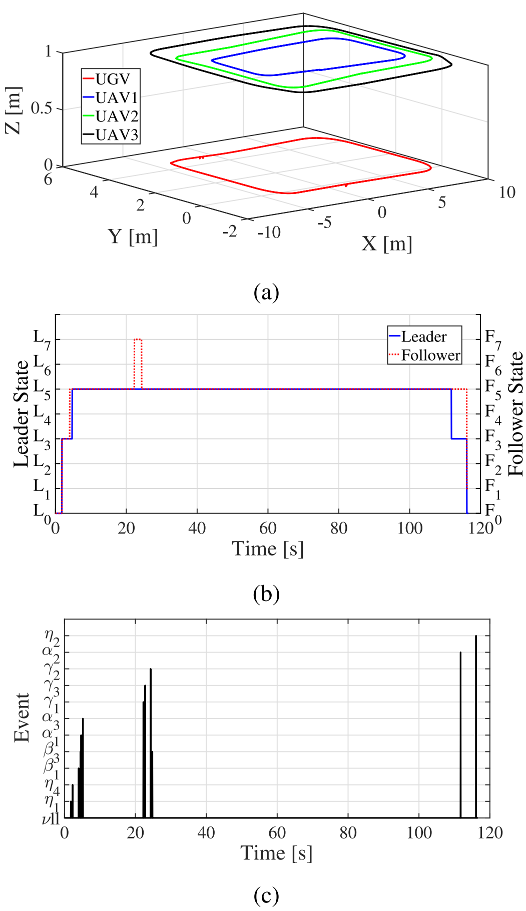

Fig. 6. Simulation results. (a) Trajectory of heterogeneous field robots. (b) State transitions. (c) Event occurrence.

low-level controller and an event-driven system with a high-level controller.

Fig. 6(a) presents the simulation results based on the proposed supervisor for heterogeneous agricultural field robots. From this trajectory, we confirmed that the leader UGV follows the given path, and the follower UAVs also navigate forming the desired formation. Moreover, the collision between the field robots and the obstacles did not occur during the simulation due to obstacle avoidance control. Also, Figs. 6(b) and (c) show the state transitions of the heterogeneous field robots and occurrence of events during simulations. From these results, it can be seen that the state of the heterogeneous robots is changed according to the occurrence of events, and multiple field robots operate according to the designed supervisor. Therefore, we fully verified that the DES- and RW-theory-based approach can control the heterogeneous agricultural field robots with systematic results.

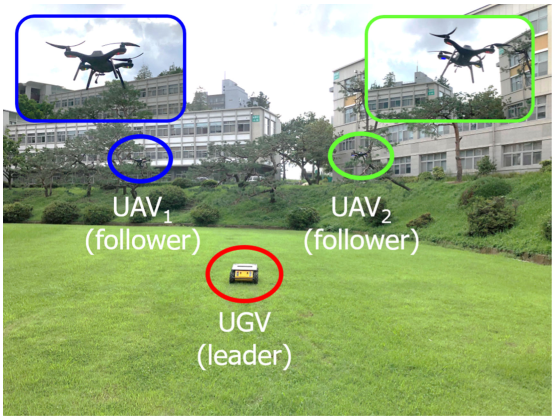

Fig. 7. Architecture of supervisory control system.

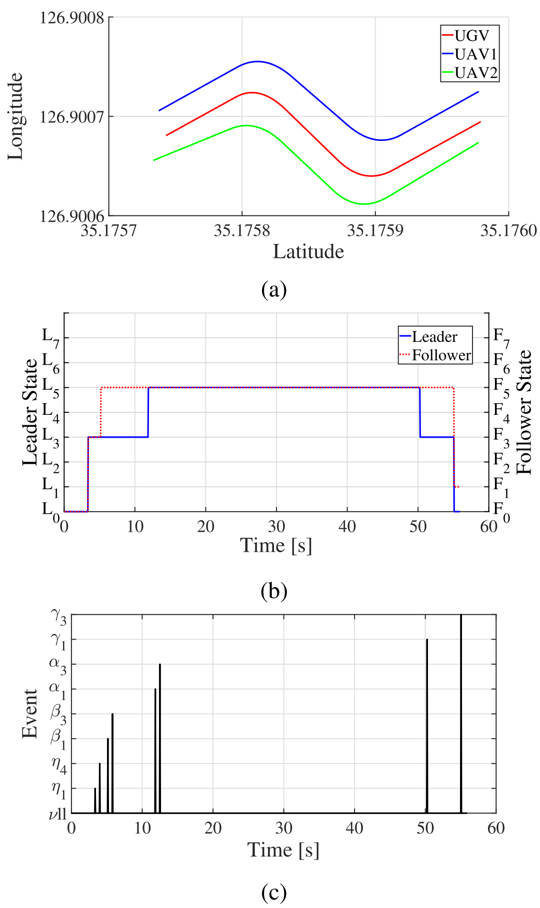

Fig. 8. Experiment results. (a) Trajectory of heterogeneous field robots. (b) State transitions. (c) Event occurrence.

B. Experiments

We used two UAVs (3DR Solo) and the UGV (Husky robot) to implement the proposed supervisory controller and discrete event system. The robot operating system was used to communicate between the heterogeneous field robots and a hybrid system that combines a high-level controller and a low-level controller was constructed as shown in Fig. 5.

Fig. 8 represents the trajectory, state of the leader robot and the follower robot, and event occurrence, and we can clearly recognize how the state changes during the experiment. In more details, we can observe the occurrence of the event through Fig. 8(c), and the state of the leader robot and the follower robot changed based on these event string. For example, if an event η_1, which is a path assignment event, occurs, the states of the leader robot and the follower robot transit to L3 and F3, respectively. In this state, each robot is controlled by the low-level controller associated with η_4 since the η_4 event is permitted by the supervisor. Then, when the event, b1, that the communication between the leader robot and the follower robot is connected, the state of follower robot transits to the L5, and the desired formation can be formed by the formation control algorithm based on the continuous-time system. In this way, the designed supervisory controller, proposed hybrid system or discrete event system can effectively control the heterogeneous multiple robots and has the advantage of systematic results.

In other words, it is possible to analyze in detail how the system behaves and how the robot states transitions based on these results. However, in the conventional control system of the previous studies, it is impossible to perceive the state transition and the event occurrence (event string) in the continuous-time. Surely, it is necessary to check what events are generated (e.g., obstacle detection and target contact) using the sensor for practical implementation, but if we know these results, then it will be more efficient to manage/control the entire system (especially, complex dynamic systems). Besides, there are many event-driven systems in the real world (e.g., elevators, transportation systems, production systems, etc.). Therefore, if the proposed system is also introduced into the robotics field, it will have more practicality and feasibility.

VI. Conclusions

In this study, we proposed heterogeneous agricultural field robots with a supervisory controller based on a DES for cooperation. The plant models and supervisory controller were modeled and designed using an automata theory, and the supervisor was verified by a synthesis tool called TCT. We also verified that the heterogeneous field robot could satisfy the specifications through a physics-based simulator and field experiments. The results demonstrate that the occurred event changes the state of the DES and this approach is appropriate for cooperation among heterogeneous field robots. Therefore, we confirmed that the RW theory is effective in controlling complex dynamic systems consisting of heterogeneous multi-robot for agriculture. Furthermore, we verified that the heterogeneous robots can avoid obstacles, form the desired formation, and follow the path set by a supervisor in simulation and that the implemented supervisory control system has similar results with simulation in real environments. This approach can be considered an effective method to develop robust large-scale heterogeneous agricultural field robot systems that can interact with dynamic agricultural environments. Our future studies will consider more concrete scenarios and extend the discrete event models and supervisor proposed in this letter for various tasks (e.g., cooperative manipulation, spraying, mapping, sampling, sensing, and monitoring).

References

[1] T. Duckett, S. Pearson, S. Blackmore, and B. Grieve, "Agricultural robotics: The future of robotic agriculture," 2018, *arXiv:1806.06762*.

[2] M. Bergerman, E. Van Henten, J. Billingsley, J. Reid, and D. Mingcong, "IEEE robotics and automation society technical committee on agricultural robotics and automation," *IEEE Robot. Autom. Mag.*, vol. 20, no. 2, pp. 20–23, Jun. 2013.

[3] J. Kim, S. Kim, C. Ju, and H. Son, "Unmanned aerial vehicles in agriculture: A review of perspective of platform, control, and applications," *IEEE Access*, vol. 7, pp. 105100–105115, 2019.

[4] S. Yaghoubi, N. A. Akbarzadeh, S. S. Bazargani, S. S. Bazargani, M. Bamizan, and M. I. Asl, "Autonomous robots for agricultural tasks and farm assignment and future trends in agro robots," *Int. J. Mech. Mechatronics Eng.*, vol. 13, no. 3, pp. 1–6, 2013.

[5] D. Albani, J. IJsselmuiden, R. Haken, and V. Trianni, "Monitoring and mapping with robot swarms for agricultural applications," in *Proc. 14th IEEE Int. Conf. Adv. Video Signal Based Surveillance*, 2017, pp. 1–6.

[6] T. Blender, T. Buchner, B. Fernandez, B. Pichlmaier, and C. Schlegel, "Managing a mobile agricultural robot swarm for a seeding task," in *Proc. IECON 42nd Annu. Conf. IEEE Ind. Electron. Soc.*, 2016, pp. 6879–6886.

[7] M. Patil, T. Abukhalil, S. Patel, and T. Sobh, "Ub robot swarmdesign, implementation, and power management," in *Proc. 12th IEEE Int. Conf. Control Autom.*, 2016, pp. 577–582.

[8] M. Usman *et al.*, "An extensive approach to features detection and description for 2-D range data using active B-splines," *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2934–2941, Jul. 2019.

[9] N. Ratyal *et al.*, "Deeply learned pose invariant image analysis with applications in 3D face recognition," *Math. Problems Eng.*, vol. 2019, 2019, Art. no. 3547416.

[10] P. J. Ramadge and W. M. Wonham, "Supervisory control of a class of discrete event processes," *SIAM J. Control Optim.*, vol. 25, no. 1, pp. 206–230, 1987.

[11] W. M. Wonham, *Supervisory Control of Discrete-Event Systems*. Berlin, Germany: Springer, 2015.

[12] C. G. Cassandras and S. Lafortune, *Introduction to Discrete Event Systems*. Berlin, Germany: Springer, 2009.

[13] H. I. Son, "Design and implementation of decentralised supervisory control for manufacturing system automation," *Int. J. Comput. Integr. Manuf.*, vol. 24, no. 3, pp. 242–256, 2011.

[14] H. I. Son and S. Lee, "Failure diagnosis and recovery based on des framework," *J. Intell. Manuf.*, vol. 18, no. 2, pp. 249–260, 2007.

[15] Y. K. Lopes, S. M. Trenkwalder, A. B. Leal, T. J. Dodd, and R. Groß, "Supervisory control theory applied to swarm robotics," *Swarm Intell.*, vol. 10, no. 1, pp. 65–97, 2016.

[16] G. W. Gamage, G. K. Mann, and R. G. Gosine, "Discrete event systems based formation control framework to coordinate multiple nonholonomic mobile robots," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2009, pp. 4831–4836.

[17] Y. K. Lopes, A. B. Leal, T. J. Dodd, and R. Groß, "Application of supervisory control theory to swarms of e-puck and kilobot robots," in *Proc. Int. Conf. Swarm Intell.*, 2014, pp. 62–73.

[18] A. Tsalatsanis, A. Yalcin, and K. P. Valavanis, "Dynamic task allocation in cooperative robot teams," *Robotica*, vol. 30, no. 5, pp. 721–730, 2012.

[19] A. G. Gonzalez, M. V. Alves, G. S. Viana, L. K. Carvalho, and J. C. Basilio, "Supervisory control-based navigation architecture: A new framework for autonomous robots in industry 4.0 environments," *IEEE Trans. Ind. Inform.*, vol. 14, no. 4, pp. 1732–1743, Apr. 2018.

[20] X. Dai, L. Jiang, and Y. Zhao, "Cooperative exploration based on supervisory control of multi-robot systems," *Appl. Intell.*, vol. 45, no. 1, pp. 18–29, 2016.

[21] Y. Tatsumoto, M. Shiraishi, K. Cai, and Z. Lin, "Application of online supervisory control of discrete-event systems to multi-robot warehouse automation," *Control Eng. Pract.*, vol. 81, pp. 97–104, 2018.

[22] Y. Liu, M. Ficocelli, and G. Nejat, "A supervisory control method for multi-robot task allocation in urban search and rescue," in *Proc. IEEE Int. Symp. Safety, Secur., Rescue Robot.*, 2015, pp. 1–6.

[23] C. R. Torrico, A. B. Leal, and A. T. Watanabe, "Modeling and supervisory control of mobile robots: A case of a sumo robot," *IFAC-PapersOnLine*, vol. 49, no. 32, pp. 240–245, 2016.

[24] N. Noguchi and O. C. Barawid, Jr, "Robot farming system using multiple robot tractors in Japan agriculture," *IFAC Proc. Volumes*, vol. 44, no. 1, pp. 633–637, 2011.

[25] A. Barrientos *et al.*, "Aerial remote sensing in agriculture: A practical approach to area coverage and path planning for fleets of mini aerial robots," *J. Field Robot.*, vol. 28, no. 5, pp. 667–689, 2011.

[26] H. Chao *et al.*, "Band-reconfigurable multi-UAV-based cooperative remote sensing for real-time water management and distributed irrigation control," *IFAC Proc. Volumes*, vol. 41, no. 2, pp. 11744–11749, 2008.

[27] D. Albani, D. Nardi, and V. Trianni, "Field coverage and weed mapping by UAV swarms," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2017, pp. 4319–4325.

[28] C. Ju and H. Son, "Multiple UAV systems for agricultural applications: Control, implementation, and evaluation," *Electronics*, vol. 7, no. 9, pp. 1–19, 2018.

[29] P. Gonzalez-de Santos *et al.*, "Fleets of robots for environmentally-safe pest control in agriculture," *Precis. Agriculture*, vol. 18, no. 4, pp. 574–614, 2017.

[30] J. Roldán, P. Garcia-Aunon, M. Garzón, J. de León, J. del Cerro, and A. Barrientos, "Heterogeneous multi-robot system for mapping environmental variables of greenhouses," *Sensors*, vol. 16, no. 7, 2016, Art. no. 1018.

[31] P. Tokekar, J. Vander Hook, D. Mulla, and V. Isler, "Sensor planning for a symbiotic UAV and UGV system for precision agriculture," *IEEE Trans. Robot.*, vol. 32, no. 6, pp. 1498–1511, Dec. 2016.

[32] C. Ju and H. I. Son, "Discrete event systems based modeling for agricultural multiple unmanned aerial vehicles: Automata theory approach," in *Proc. 18th Int. Conf. Control, Autom. Syst.*, 2018, pp. 258–260.

[33] C. Ju and H. I. Son, "Hybrid systems based modeling and control of heterogeneous agricultural robots for field operations," in *Proc. ASABE Annu. Int. Meeting*, 2019, pp. 1–5.

[34] P. J. Ramadge and W. M. Wonham, "The control of discrete event systems," *Proc. IEEE*, vol. 77, no. 1, pp. 81–98, Jan. 1989.

[35] C. Ju and H. I. Son, "A distributed swarm control for an agricultural multiple unmanned aerial vehicle system," *Proc. Institution Mech. Eng., Part I, J. Syst. Control Eng.*, vol. 233, no. 10, 2019, pp. 1298–1308.

[36] L. Feng and W. M. Wonham, "TCT: A computation tool for supervisory control synthesis," in *Proc. 8th Int. Workshop Discrete Event Syst.*, 2006, pp. 388–389.