

Evaluation of Information Transfer Method and PID-Controlled Mobility in Coverage Control under Event-Triggered CSMA/CA Communication

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Abstract—Decentralized autonomous control with multiple agents, where each agent cooperates based on local information, has attracted attention. Among such methods, coverage control has promising applications in tasks such as surveillance, exploration, and environmental sensing. However, communication collisions and hidden terminal problems caused by CSMA/CA result in the loss of position information and degraded convergence performance in coverage control. To address these issues, an information transfer method has been proposed, in which each agent transfers its received position information to neighboring agents. In addition, we have previously introduced PID-controlled mobility and clarified the influence of PID gains on the effectiveness of the information transfer method. This paper introduces event-triggered communication and evaluates the information transfer method and PID-controlled mobility in coverage control under event-triggered CSMA/CA communication. We analyze the convergence performance by investigating the effects of the PID gain and the presence or absence of information transfer. Furthermore, we investigate the factors affecting convergence performance using the communication reduction rate and the neighbor information acquisition rate.

Keywords—Wireless control, distributed control, coverage control, CSMA/CA, information transfer, PID control, event-triggered communication

I. INTRODUCTION

Decentralized autonomous control using multiple agents has attracted attention as a control strategy in which the entire system behaves cooperatively, with each agent making decisions based on local information. Among such methods, coverage control autonomously deploys agents to efficiently cover a target area. It has promising applications in various fields, such as surveillance, exploration, and environmental sensing. Coverage control based on Voronoi partitioning has been widely studied for mobile sensing networks, and its convergence properties have been theoretically investigated [1]. In addition, event-triggered control has been studied as an effective approach to reduce communication and control updates in multi-agent systems [2, 3].

In coverage control using mobile agents, wireless communication is necessary for exchanging control packets. Communication collisions and packet loss degrade control quality. In particular, CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) communication causes packet collisions due to hidden terminals and identical backoff times. Previous studies [4-6] have proposed information transfer methods to achieve stable control even in CSMA/CA communication environments. These methods compensate for the loss of position information packets by transferring information through other agents, and their effectiveness has been evaluated. However, the agent motion model used in these previous studies was based on a uniform linear motion model, which does not sufficiently reflect the effects of acceleration, deceleration, and inertia in actual agent motion. To address this limitation, we have previously introduced a PID control model for agent motion and clarified that PID gain settings have a significant impact on the control quality of coverage control under severe observation noise [7]. Those evaluations assumed a communication method in which each agent transmits position information at every control period. Therefore, the effects of information transfer and PID gains on convergence performance have not been sufficiently investigated when transmission conditions are restricted, such as in event-triggered communication, to reduce the amount of communication.

This paper introduces event-triggered communication and evaluates the information transfer method and PID-controlled mobility in coverage control under event-triggered CSMA/CA communication. We analyze the convergence performance by investigating the effects of the transmission threshold, the PID gain, and the presence or absence of information transfer on the convergence success rate and the average convergence time. Furthermore, we investigate the factors affecting convergence performance under the event-triggered communication using the communication reduction rate and the neighbor information acquisition rate.

II. CONTROL MODEL

This paper deals with coverage control, in which multiple autonomous mobile agents move based on position information received from other agents within their

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communication range. Each agent is autonomously deployed over the target area to achieve efficient coverage. First, we formulate the PID control model used in this paper. Then, we describe the observation noise model and the control law used for coverage control.

A. PID Control Model

This paper considers a PID control model for agent i ($i \in \{1, 2, \dots, N\}$) moving on a two-dimensional (2D) plane. The motion model is defined by the following state equations:

$$\mathbf{x}_i[k+1] = \mathbf{x}_i[k] + \mathbf{v}_i[k]T_s \quad (1)$$

$$\mathbf{v}_i[k+1] = \mathbf{v}_i[k] + \mathbf{u}_i[k]T_s \quad (2)$$

Here, $\mathbf{x}_i[k]$ is the position of agent i on the 2D plane at time k , $\mathbf{v}_i[k]$ is the velocity, $\mathbf{u}_i[k]$ is the control input that represents acceleration, and T is the control period. The objective of each agent is to move so that it follows a target position. Therefore, each agent computes the acceleration using a PID controller. The control process is defined as follows:

$$\mathbf{v}_i^{target}[k] = K_p^{pos}(\mathbf{c}_i[k] - \mathbf{z}_i[k]) \quad (3)$$

$$\mathbf{e}_v[k] = \mathbf{v}_i^{target}[k] - \mathbf{v}_i[k] \quad (4)$$

$$\mathbf{u}_i[k] = K_p \mathbf{e}_v[k] + K_i \sum_{\tau=0}^k \mathbf{e}_v[\tau]T_s + K_d \frac{\mathbf{e}_v[k] - \mathbf{e}_v[k-1]}{T_s} \quad (5)$$

Here, $\mathbf{z}_i[k]$ is the current position including observation noise, $\mathbf{c}_i[k]$ is the target position, which is defined as the centroid of the Voronoi region of agent i , $\mathbf{v}_i^{target}[k]$ is the target velocity for moving toward the target position, and $\mathbf{e}_v[k]$ is the error between the target velocity and the current velocity. K_p^{pos} is the proportional gain for position control. K_p , K_i , and K_d are the PID gains for the velocity error. Note that Eq. (3) is limited so that it does not exceed the maximum velocity v_{max} , and Eq. (5) is limited so that it does not exceed the maximum acceleration a_{max} .

B. Observation Noise Model

This paper considers observation noise from a position sensor. The observed position $\mathbf{z}_i[k]$ is modeled by adding Gaussian noise $\mathbf{n}$ (zero mean and variance σ^2) as follows:

$$\mathbf{z}_i[k] = \mathbf{x}_i[k] + \mathbf{n}, \quad \mathbf{n} \sim \mathcal{N}(0, \sigma^2) \quad (6)$$

C. Coverage Control Law

In coverage control, multiple agents exchange position information with others within their communication range. Based on this information, each agent autonomously adjusts its position to efficiently cover the target area. Each agent has a communication range of a radius R . At time step k , another agent j ($j \in \{1, 2, \dots, N\}$) is defined as a neighbor of agent i if it is within the communication range and communication is successful. The set of neighboring agents of agent i is defined as $\mathbf{N}_i[k]$.

Each agent uses the position information received during the control period, along with its own current position, to perform Voronoi partitioning. The agent determines its own Voronoi region and calculates the centroid of this region. Following the PID control model, the agent moves toward this centroid as its target position. Over time, all agents converge to the centroids of their respective Voronoi regions. Although each agent uses only local information, uniform coverage over the entire area is achieved collectively.

Furthermore, as described in Section III-C, the information transfer method allows agents to relay position information through their neighbors. This enables partial compensation for packet loss and communication failures.

III. COMMUNICATION MODEL

This paper considers wireless communication to exchange position information between agents. In this section, we describe the event-triggered and CSMA/CA communication mechanisms and the information transfer method.

A. Event-Triggered Communication

This paper introduces position-error-based event-triggered communication to reduce the amount of communication. In periodic communication, each agent becomes a transmission candidate at every control period. On the other hand, in event-triggered communication, agent i becomes a transmission candidate only when the distance between its current position $\mathbf{x}_i[k]$ and its position $\mathbf{x}_i[k']$ at the last transmission time k' exceeds the threshold d_{th} . That is, the agent transmits position information when the following condition is satisfied:

$$\|\mathbf{x}_i[k] - \mathbf{x}_i[k']\| \geq d_{th} \quad (7)$$

Here, d_{th} is the transmission threshold. The case of $d_{th} = 0$ corresponds to the periodic communication. A larger d_{th} leads to less frequent transmissions. Agents that satisfy the transmission condition communicate according to the CSMA/CA mechanism described in Section III-B.

B. CSMA/CA Communication

This paper adopts CSMA/CA-based communication, which is compliant with IEEE 802.11 DCF, for communication between agents. In the periodic communication, each agent generates one packet at every control period and transmits it within its communication range. In the event-triggered communication, only agents that satisfy the transmission condition described in Section III-A generate a packet for transmission. Without information transfer, each transmitted packet contains only the transmitting agent's current position. With information transfer, each packet additionally includes predicted position information, as described in Section III-C. This communication assumes broadcast transmission rather than unicast transmission; therefore, RTS/CTS exchange and ACK-based retransmission are not performed.

The transmission process proceeds as follows. First, a transmission candidate performs carrier sensing. If the channel remains idle for a DIFS duration, the agent waits for

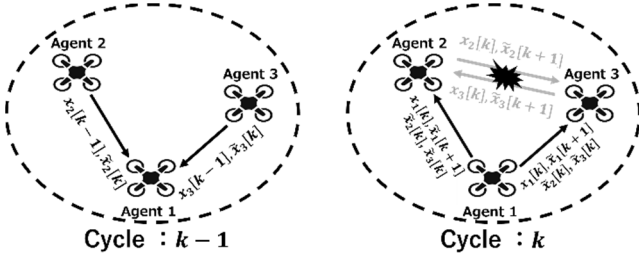


Fig. 1. Information transfer method.

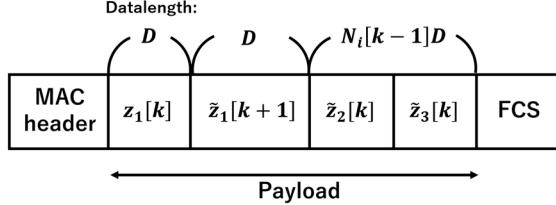


Fig. 2. Packet structure.

a random backoff time, and then initiates transmission. The backoff time is defined as $BO = \text{Uniform}[0, CW] \times \text{SlotTime}$, where CW is the contention window size. In the simulation model, communication processing is performed in time-slot units within each control period, and the communication status is updated slot by slot.

Collisions may occur due to overlapping backoff times or hidden terminals that are outside the communication range. Since broadcast communication does not use ACK-based confirmation, collision detection and retransmission are not performed. Therefore, any packet that causes a collision during the control period is discarded and is not used for the control input.

C. Information Transfer

In coverage control, it is essential that each agent obtains the position information of its neighboring agents and uses it to compute its control input. However, in CSMA/CA-based communication, packet collisions caused by hidden terminals and the relationship between the control period and the backoff time may prevent some agents from successfully transmitting packets during the control period. Furthermore, in event-triggered communication, setting a larger transmission threshold naturally reduces the frequency of position transmissions. In such cases, the decrease in available position information from neighboring agents leads to degraded control performance.

Without information transfer, each transmitting agent broadcasts only its own current position. Therefore, each receiving agent computes the centroid of its Voronoi region using only the position information directly received during the current control period, without using relayed information from neighboring agents.

To compensate for this information loss, this paper introduces an information transfer method that includes predicted positions [5, 6]. When an agent transmits a packet, the packet contains its current position as well as its predicted position, which is calculated using its current velocity as follows:

TABLE I. SIMULATION PARAMETERS

Parameters	Values	Parameters	Values
Convergence radius(δ)	1[m]	Packet header length	24[byte]
Communication range(R)	100[m]	Packet FCS length	4[byte]
Period(T_s)	0.1[s]	Position data size(D)	64[byte]
Max speed(v_{max})	30[km/h]	Data rate	6[Mbps]
Max accel(a_{max})	8.33[m/s ²]	Slot time	9[μs]
Trial time	60[s]	DIFS	34[μs]
Number of trials	1000	CW	1023

$$\tilde{z}_i[k+1] = z_i[k] + v_i[k]T_s \quad (8)$$

Here, although observation noise is added to the position data, the velocity used for prediction is assumed to be noise-free. Additionally, the agent transfers the set of predicted position information $\{\tilde{z}_j[k] \mid j \in N_i[k-1]\}$ extracted from packets received from neighboring agents during the previous control period (see Fig. 1).

Each packet contains the current position, the predicted position, and the predicted positions of neighboring agents obtained during the previous control period. Let D be the data length of one position, and $|N_i[k-1]|$ be the number of neighboring agents at time $k-1$. Then, the total data size of a packet is $(2 + |N_i[k-1]|) \times D$ (see Fig. 2).

Under the coverage control law with the information transfer, the receiving agent computes the centroid of its Voronoi region based on two sources of information. One is the set of current position information $\{z_j[k] \mid j \in N_i[k]\}$, which is obtained through direct communication during the control period. The other is the set of transferred position information $\{\tilde{z}_l[k] \mid l \in M_i[k]\}$, which is included in all received packets. Here, $M_i[k]$ represents the set of agents whose predicted positions were acquired only via transfer. This set excludes both the agents in $N_i[k]$ and agent i itself.

IV. SIMULATION

The simulation parameters are summarized in Table 1. Each agent is assumed to be a drone. Representative gain values for the PID control model are derived from autonomous flight experiments using a drone equipped with a PX4 flight controller, resulting in $K_p = 2.5$, $K_i = 4.0$, and $K_d = 0.0$. In this evaluation, K_p^{pos} is set to 1.3 and 3.4 to compare low-gain and high-gain conditions. Communication between agents is based on the CSMA/CA protocol defined by IEEE 802.11 DCF. The initial positions of the agents are randomly deployed within a 1 [m] $\times$ 1 [m] area near the center of a 300 [m] $\times$ 300 [m] square area. If an isolated agent exists (i.e., no neighboring agents are within its radius R), it is excluded from the simulation. All agents are assumed to operate under a synchronized control period. In addition, the threshold d_{th} of event-triggered communication is varied from 0 to 0.5 in increments of 0.1, where the case of $d_{th} = 0$ corresponds to periodic communication at every control

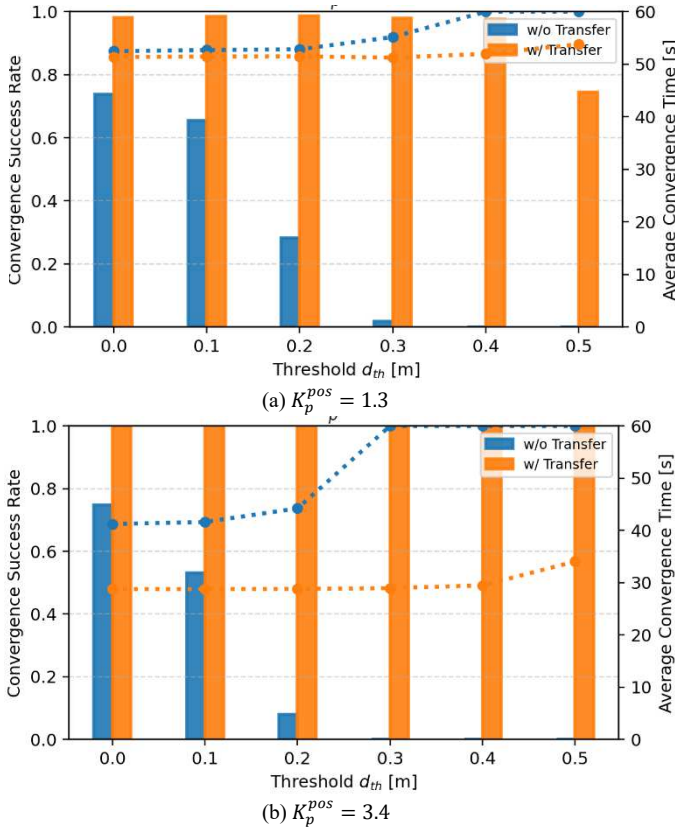


Fig. 3. Convergence performance.

period. Under these threshold conditions, cases with and without the information transfer are compared.

A. Evaluation Metrics

This paper evaluates convergence performance using two main metrics. The first metric is the convergence success rate, defined as the ratio of the number of successful trials to the total number of trials. Convergence is considered successful when the positions of all agents fall within a convergence radius δ from the centroids of their respective Voronoi regions. The second metric is the average convergence time, defined as the average time required for successful trials to reach convergence from the start of the simulation. In the following figures, conditions with a convergence success rate of 0 are represented as 60 [s], which corresponds to the maximum trial time.

In addition, this paper evaluates the communication reduction rate and the neighbor information acquisition rate to analyze the factors affecting convergence performance. The communication reduction rate is a metric representing the decrease in the number of transmissions when the event-triggered communication is employed compared to the periodic communication. The neighbor information acquisition rate is the ratio of neighboring agents whose position information is successfully obtained through either direct communication or information transfer to the total number of true neighboring agents. This metric evaluates how the event-triggered communication and the information transfer affect the acquisition of neighbor information required for calculating the centroid of the Voronoi regions.

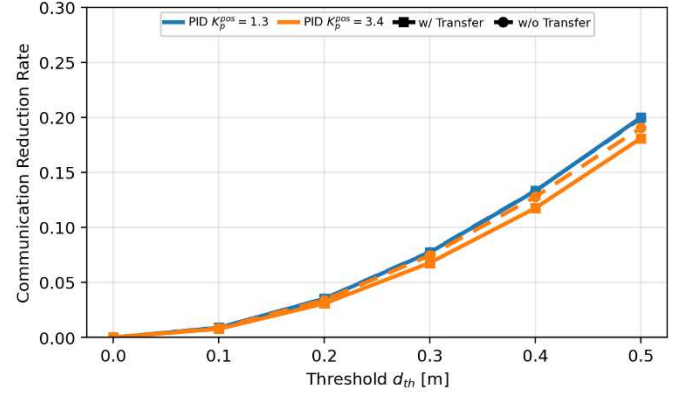


Fig. 4. Communication reduction rate.

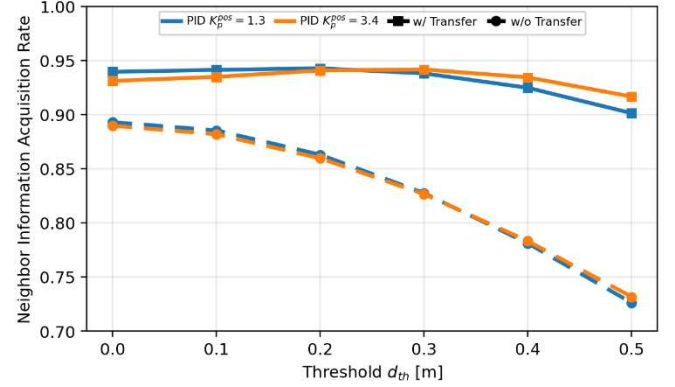


Fig. 5. Neighbor information acquisition rate.

B. Evaluation Results

Fig. 3 shows the convergence success rate and the average convergence time for each threshold d_{th} . Without information transfer, the convergence success rate tended to decrease significantly as d_{th} increased, and the average convergence time also tended to increase. In contrast, with information transfer, the decrease in convergence success rate was effectively suppressed compared with the case without information transfer. This indicates that the information transfer can mitigate the degradation of convergence performance even under event-triggered communication. However, this effect depends on the gain condition; specifically, under the low-gain condition, the convergence success rate still decreased as d_{th} increased. Focusing on the case with information transfer, the high-gain condition maintained a higher convergence success rate than the low-gain condition, and the average convergence time also tended to be shorter. This is because, under the high-gain condition, the response to the centroid position is faster, allowing agents to move more quickly toward the target centroid. On the other hand, under the low-gain condition, the response is slower; therefore, as d_{th} increased, the number of trials that failed to converge within the trial time increased.

Fig. 4 shows the communication reduction rate for each threshold d_{th} . The communication reduction rate naturally tended to increase as d_{th} increased. This confirms that the event-triggered communication can reduce the number of transmissions compared to periodic communication, which

corresponds to $d_{th} = 0$. On the other hand, the difference in the communication reduction rate was small among the gain conditions and between the cases with and without information transfer. Therefore, the communication reduction rate mainly changed depending on the transmission threshold d_{th} , regardless of the PID gains or the use of information transfer.

Fig. 5 shows the neighbor information acquisition rate for each threshold d_{th} . Without information transfer, the neighbor information acquisition rate significantly decreased as d_{th} increased. This is because the reduced number of transmissions decreased the amount of position information that could be obtained through direct communication. In contrast, with information transfer, the neighbor information acquisition rate was maintained at a high level even when d_{th} was increased. This is because position information that could not be directly received by each agent was compensated for by information transfer. As shown in Fig. 4, the difference in the communication reduction rate between the cases with and without information transfer was small. However, in Fig. 5, a large difference in the neighbor information acquisition rate was observed between the two cases. Therefore, the main reason why the degradation of convergence performance was mitigated by information transfer in Fig. 3 is that the neighbor information acquisition rate was maintained at a high level, even under conditions where the number of transmissions was reduced by event-triggered communication.

These results demonstrate that in event-triggered communication, increasing the threshold d_{th} reduces the frequency of position information transmission. Without information transfer, the neighbor information acquisition rate decreases, leading to significant degradation in convergence performance. In contrast, with information transfer, the neighbor information acquisition rate is maintained at a high level even when the number of transmissions is reduced. Consequently, the degradation of convergence performance is effectively mitigated. These results confirm that the information transfer is highly effective for maintaining convergence performance even under conditions where the transmission frequency is reduced by the event-triggered communication.

V. CONCLUSION

This paper has evaluated an information transfer method and PID-controlled mobility in coverage control under event-triggered CSMA/CA communication. We analyzed the effects of the transmission threshold for event-triggered

communication, the position proportional gain of PID-controlled mobility, and the presence or absence of information transfer on convergence performance.

Simulation results demonstrate that the communication reduction rate increases as the transmission threshold increases. This confirms that the position-error-based event-triggered communication reduces the number of transmissions, while differences caused by PID gain conditions or the use of information transfer are negligible. Simultaneously, without information transfer, the neighbor information acquisition rate decreases as the transmission threshold increases; consequently, the convergence success rate decreases, and the average convergence time increases.

In contrast, with information transfer, the neighbor information acquisition rate is maintained at a high level even when transmission frequency is reduced, thereby effectively mitigating the degradation of convergence performance. Furthermore, high-gain conditions maintained a higher convergence success rate and shorter average convergence time compared to low-gain conditions. These results indicate that while event-triggered communication successfully reduces the number of transmissions, incorporating information transfer and selecting appropriate gain conditions are crucial for maintaining convergence performance in coverage control.

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