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LETTER

Effectiveness of information transfer on control quality of CSMA/CA-based autonomous decentralized control

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Abstract In autonomous decentralized control of mobile agents such as robots and drones, packet loss that occurs in wireless communication has a significant impact on control performance. This paper proposes a simple information transfer method for CSMA/CA(Carrier Sense Multiple Access with Collision Avoidance)-based autonomous decentralized control to compensate for information lost due to communication failures. We evaluate the effectiveness of information transfer on control performance in two typical classes of autonomous decentralized control, i.e., consensus control and covered control, by computer simulation, and show that the improvement of control quality can be achieved regardless of the number of controlled agents and the contention window size of CSMA/CA.

Keywords: Wireless control, CSMA/CA, autonomous decentralized control, distributed control, consensus control, coverage control
Classification: Wireless communication technologies

1. Introduction

Autonomous distributed control, where the behavior of an entire system is determined by the interaction of only local autonomous mobile robots and drones (called agents), has attracted attention in the control field and is expected to be used in various situations such as agriculture and building inspection [1]. When the agents exchange state information via wireless communication, the degradation of control quality due to communication failure becomes a significant problem. Most research has been conducted to design control methods to reduce the effects of communication failure [2, 3, 4] assuming a certain probabilistic communication channel. In autonomous decentralized control using contention-based medium access such as CSMA/CA(Carrier Sense Multiple Access with Collision Avoidance), the number of agents within the communication range changes as the agents move, resulting in varying probabilities of communication failure due to packet collisions. To reduce communication failures in CSMA/CA-based autonomous decentralized control, the methods of adjusting the transmission probability [5] and the backoff time [6, 7] have been proposed. However, while these methods have reduced communication failures, they have not considered compensation for the lost information. These studies have focused only on consensus control, which is one of the fundamental problems of autonomous decentralized control, and their application to other problems has not been discussed together.

This paper proposes a simple information transfer method to compensate for the state information lost due to communication failures. Each agent not only transmits its own state information to adjacent agents, but also simultaneously transfers state information received from adjacent agents to achieve better control input. The concept of the information transfer itself is similar to packet forwarding in the research field of ad hoc networks, but has not been well discussed for autonomous decentralized control. In this paper, two typical control problems, consensus control and coverage control, are discussed together to clarify the effectiveness of information transfer. Simulation results show that the information transfer improves the quality of both consensus control and coverage control.

This paper is organized as follows: Section 2 describes the control and communication models. Section 3 describes the details of the proposed information transfer method. Section 4 presents the numerical results of computer simulations. Section 5 summarizes the conclusions.

2. System model

2.1 Control model

This paper deals with two typical autonomous decentralized control problems: One is the consensus control problem, in which multiple autonomous mobile agents move based on position information obtained from adjacent agents within a communication range and reach a single consensus position that is the average of their initial positions; the other is the coverage control problem, where, as in the consensus control problem, multiple autonomous mobile agents communicate and move to reach positions that are the centroids of Voronoi regions. Examples of the two control problems are shown in Fig. 1, where the initial positions of the agents are depicted as gray circles, the converged positions as red circles, and the movement trajectories as solid lines.

In both cases, the i-th agent ($i \in \{0, 1, \cdots, N\}$ and the number of agents is N) is assumed to be represented by the following state equation:

$$\mathbf{x}_i[k+1] = \mathbf{x}_i[k] + \mathbf{u}_i[k] \tag{1}$$

where $\mathbf{x}_i[k]$ and $\mathbf{u}_i[k]$ are two-dimensional vectors representing state information and control input at the k-th control period (one control period is T), respectively. The state

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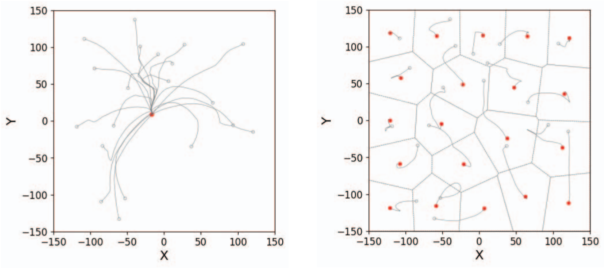


(a) Consensus control (b) Coverage control

Fig. 1 Considered control problems.

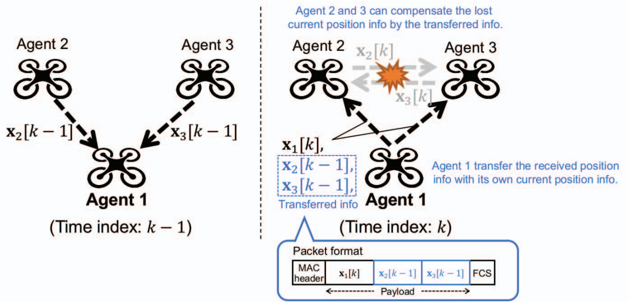


Fig. 2 Proposed information transfer method.

means position in a two-dimensional plane, and each agent moves linearly at a constant speed not exceeding the maximum speed $v_{\max}$. According to the control period, each agent periodically broadcasts a packet containing its own position information $\mathbf{x}_i[k]$ to agents within the communication range defined by radius R. The communication protocol follows CSMA/CA as described in **2.2**.

In the consensus control, $\mathbf{u}_i[k]$ of the i-th agent is given by (2) using its own position $\mathbf{x}_i[k]$ and the position $\mathbf{x}_j[k]$ received from adjacent agents within the current control period.

$$\mathbf{u}_i[k] = -\frac{1}{|\mathbf{N}_i[k]|+1} \sum_{j \in \mathbf{N}_i[k]} (\mathbf{x}_i[k] - \mathbf{x}_j[k]) \tag{2}$$

where $\mathbf{N}_i[k]$ is the set of adjacent agents whose packet was successfully received within the control period, and $|\mathbf{N}_i[k]|$ is the number of the adjacent agents. Consensus can be achieved by determining its own control input for each control period, and from arbitrary initial positions, the all agents' positions converge to the average of the initial positions.

In the coverage control, $\mathbf{u}_i[k]$ of the i-th agent is given by (3) using its own position $\mathbf{x}_i[k]$ and the centroid of a Voronoi region constructed by $\mathbf{x}_i[k]$ and $\mathbf{x}_j[k]$ received from adjacent agents within the current control period.

$$\mathbf{u}_i[k] = -K\Big(\mathbf{x}_i[k] - C_i(\{\mathbf{x}_i[k], \mathbf{x}_j[k] \mid j \in \mathbf{N}_i[k]\})\Big) \tag{3}$$

where K is an arbitrary gain and is set to $1/2$, and $C_i(\cdot)$ is the centroid of the Voronoi region to which the i-th agent belongs. Coverage can be achieved by determining its own control input for each control period, and from arbitrary initial positions, the position of each agent converges to the centroid of the Voronoi region to which it belongs.

2.2 Communication model

According to the control period, each agent periodically broadcasts a packet containing position information once per control periodto agents within the communication range defined by radius R. For simplicity, it is assumed that the packet can reach up to the communication range.

The agents transmit and receive position information to and from adjacent agents using broadcast communication with CSMA/CA based on IEEE802.11DCF. First, carrier sensing is performed, and if no signal is detected in the communication range (i.e., the channel is idle) for a DIFS duration, the agent transmits the position information packet after a backoff time has elapsed. This backoff time is given by *Random* × SlotTime, where *Random* is an integer uniform random number within $[0, CW]$ and CW is a contention window value. The backoff stops when the channel is detected as busy and resumes when the channel is detected as idle again for the DIFS duration. The agent is ready to receive packets except when it is transmitting its own packet, and the switch between transmitting and receiving is assumed to be instantaneous. Each agent can detect the packet transmission in the communication range and can know the positions of its adjacent agents only if the packet was received correctly. If the backoff exceeds the control period due to many transmitting agents in the communication range, the packet will be discarded. Also, if packet collisions occur due to the same backoff or the hidden terminals whose communication cannot be detected, the packet cannot be received. Since the agent performs one-to-many broadcast communication, it does not return ACK/NACK as specified in IEEE802.11DCF. Note that in both consensus control and covering control, it is irrelevant to the agent's own control whether its own position information has been correctly received or not.

3. Proposed method

In both consensus control and coverage control, it is important to obtain the position information of adjacent agents. However, due to the backoff and hidden terminal problem in CSMA/CA communication, not all the position information can be obtained. In the proposed method, to compensate for the lost position information, each agent not only transmits its own position information, but also simultaneously transfers position information received from adjacent agents within the previous control period. Figure 2 shows an operation of the proposed information method. It is drawn focusing on the transfer operation by Agent 1 at time index k. Note that Agents 2 and 3 also perform the transfer operation at $k-1$ if they received position information at $k-2$, but the position information at $k-2$ is irrelevant to the transfer operation at k. Thus, each agent simultaneously transmits $\mathbf{x}_i[k]$ and the positions $\{\mathbf{x}_j[k-1] \mid j \in \mathbf{N}_i[k-1]\}$. This allows the agent to receive not only current position $\mathbf{x}_j[k]$ but also transferred positions $\{\mathbf{x}_l[k-1] \mid l \in \mathbf{N}_j[k-1]\}$ from its adjacent agent j. As shown in Fig. 2, even if the current position information of an adjacent agent is not received, it can be compensated by receiving the transferred position information from the other adjacent agents. The proposed method differs from a simple single-hop network in the MAC layer in that it aggregates the position information received at each control period and transmits it together with its own position information in a single packet. Since the received packets themselves are not transferred, the proposed method does not increase the number of transmitted packets at all.

The agent uses not only $\mathbf{x}_j[k]$ but also $\{\mathbf{x}_l[k-1] \mid l \in \mathbf{N}_j[k-1]\}$ to obtain better control input. However, the transferred position information may contain older position information than that currently received from the same adjacent agents. It may also contain its own previously transmitted position information, and it may contain the position information of the same agent from multiple adjacent agents. In the proposed method, after removing these older position information and duplicates, the agent uses the transferred position information in the same way as the received current position information to compute the control input. That is, the control input $\mathbf{u}_i[k]$ in the proposed method is given as (4) for the consensus control and (5) for the coverage control.

$$\mathbf{u}_i[k] = -\frac{1}{|\mathbf{N}_i[k] \cup \mathbf{M}_i[k]| + 1}\left(\sum_{j \in \mathbf{N}_i[k]} (\mathbf{x}_i[k] - \mathbf{x}_j[k]) + \sum_{l \in \mathbf{M}_i[k]} (\mathbf{x}_i[k] - \mathbf{x}_l[k-1])\right) \tag{4}$$

$$\mathbf{u}_i[k] = -K\Big(\mathbf{x}_i[k] - C_i(\{\mathbf{x}_i[k], \mathbf{x}_j[k], \mathbf{x}_l[k-1] \mid j \in \mathbf{N}_i[k], l \in \mathbf{M}_i[k]\})\Big) \tag{5}$$

where $\mathbf{M}_i[k]$ is the set of agents whose packet is transferred but does not contain the same agent in $\mathbf{N}_i[k]$ and the i-th agent itself, and can be represented as follows:

$$\mathbf{M}_i[k] = \left(\bigcup_{j \in \mathbf{N}_i[k]} \mathbf{N}_j[k-1]\right) \setminus (\mathbf{N}_i[k] \cup \{i\}) \tag{6}$$

The convergence in the proposed method will be slower compared to the ideal case with the current position information. Although the transferred position information is from one control period ago, the position of each agent gradually converges so that the discrepancy between the current and previous positions becomes negligible. The information transfer method has the advantage of compensating for the lost position information, but has the disadvantage of increasing the payload length because the transferred position information is included in the packet. If the payload length of position information without the information transfer is D, the payload length in the proposed method is $(1 + |\mathbf{N}_i[k-1]|)D$ and at most ND.

4. Numerical results

The effectiveness of the information transfer method was evaluated by computer simulation. The simulation parameters are listed in Table I. The CSMA/CA parameters are based on the IEEE802.11 standard. Different from the previous studies [6, 7], this study does not aim to improve the performance by adjusting the CW, so a fixed CW is used. To clarify the influence of contention, the comparison is made with different values of fixed CW. The agents are initially uniformly distributed in the given square field, but cases where one of the agents is not within the communication range of any other agent at all are excluded. The positions of the agents are updated every 0.01[s] and are assumed to be stationary within this time step for ease of simulation. In the consensus control, convergence is defined as when the positions of all agents converge within a distance σ (called the convergence threshold). In the coverage control, convergence is defined as when the positions of all agents converge within σ from the centroid of their own Voronoi region.

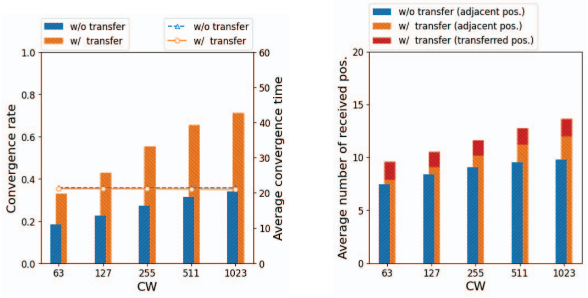
Table I Simulation parameters.

Parameter	Value
Field size	300[m] × 300[m]
Control period (T)	0.1[s]
Maximum speed ($v_{\max}$)	30[km/h]
Convergence threshold (σ)	1[m]
Communication range (R)	100[m]
Length of position info (D)	64[byte]
Length of packet header	24[byte]
Length of packet FCS	4[byte]
SlotTime	9[μs]
DIFS	34[μs]
Data rate	6[Mbps]

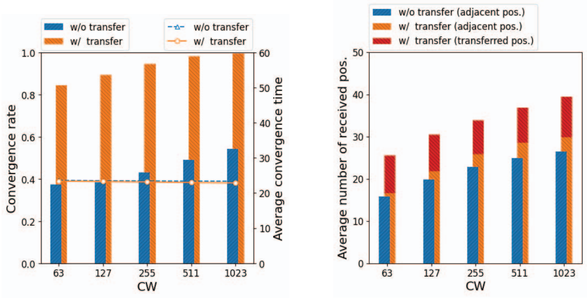
In both consensus control and covering control, the most important metric is the possibility of convergence of agents' positions. The second most important metric is the speed of convergence when all agents' positions converge. Therefore, we evaluate the control quality using both metrics simultaneously. To evaluate the control quality, the convergence rate is defined by the ratio of the number of simulations that achieved convergence to the total number of simulations, and the convergence time is defined by the time at which convergence is first achieved in each simulation. The average number of receiving position information is defined by the average number of position information received by each agent in one control period over all agents and all control periods. The duration of each simulation is limited to 60[s], and 10^5 simulations were performed.

Figure 3 shows the convergence rate, the average of convergence time, and the average number of received positions in the consensus control with $N = 20$ and 50. The convergence rate and the average convergence time are plotted on the same graph, where the bars indicate the convergence rate and the lines indicate the average convergence time.

The number of received positions indicates the number of positions received directly from adjacent agents within the communication range and positions received through the information transfer. The CW has the greatest effect on the performance of CSMA/CA, and the larger the CW, the better the convergence rate in this simulation. This is because packet collisions are reduced, as indicated by the number of received positions. It can be seen that the convergence rate is greatly improved by the information transfer. This is because the number of received positions has increased by the information transfer. The average convergence time is almost unchanged, but this is because it depends on the movement time of the agent farthest from the convergence position. Comparing (a) and (b) in Fig. 3, it can be seen that the larger the number of agents, the larger the effect of the

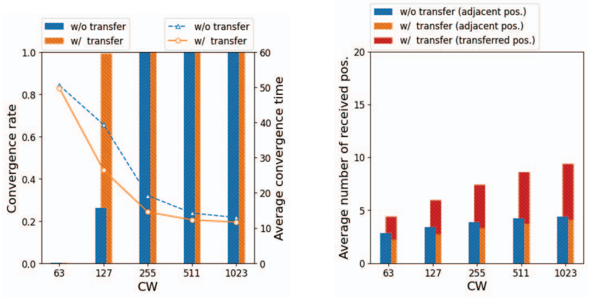


(a) $N = 20$

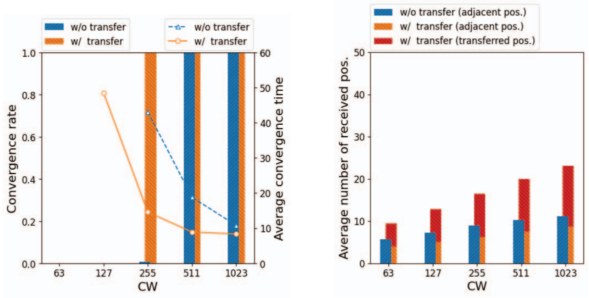


(b) $N = 50$

Fig. 3 Convergence rate/time and average number of received positions in the consensus control.



(a) $N = 20$



(b) $N = 50$

Fig. 4 Convergence rate/time and average number of received positions in the coverage control.

information transfer. This is due to the fact that the number of positions obtained by the transfer increases.

Figure 4 shows the convergence rate, the average of convergence time, and the average number of received positions in the coverage control with $N = 20$ and 50. As with the consensus control, the larger the CW, the better the convergence rate in this simulation. This is also because packet collisions are reduced, as indicated by the number of received positions. It can be seen that the convergence rate is improved and the average convergence time is reduced by the information transfer. This is because the number of received positions has increased by the information transfer. In contrast to the consensus control case, the coverage control case has the disadvantage that the number of positions received directly from adjacent agents is reduced due to the increased packet length, because packet collisions caused by hidden terminals occur more frequently as the agents move away from each other. However, the increase in the number of received positions due to the transfer overcomes this disadvantage and improves the control performance. Comparing (a) and (b) in Figure 4, it can be seen that convergence is more difficult when the CW is small. This is because packet collisions increase due to the hidden terminal problem. However, the effect of information transfer is significant even when the number of agents is large.

5. Conclusion

A simple information transfer method is proposed to compensate for the state information lost due to communication failures in CSMA/CA-based autonomous decentralized control, and its application to two typical control problems, consensus control and coverage control, is discussed together. Numerical results show that the control quality can be improved in both consensus control and coverage control regardless of the number of controlled agents and the contention window size of CSMA/CA. Although the proposed method has the disadvantage of increasing the packet length, which increases contention and could result in performance degradation, the advantage of obtaining more state information through the information transfer is much greater.

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References

[1] A. Dorri, S. S. Kanhere, and R. Jurdak, “Multi-Agent Systems: A Survey,” *IEEE Access*, vol. 6, pp. 28573–28593, Apr. 2018. DOI: 10.1109/ACCESS.2018.2831228

[2] F. Acciani, P. Frasca, G. Heijenk, and A. A. Stoorvogel, “Achieving Robust Average Consensus Over Lossy Wireless Networks,” *IEEE Trans. Control of Network Systems*, vol. 6, no. 1, pp. 127–137, Mar. 2019. DOI: 10.1109/TCNS.2018.2800407

[3] L. Xu, Y. Mo, and L. Xie, “Distributed Consensus Over Markovian Packet Loss Channels,” *IEEE Trans. Automatic Control*, vol. 65, no. 1, pp. 279–286, May. 2019. DOI: 10.1109/TAC.2019.2915747

[4] R. C. Ballam, A. McFadyen, and D. E. Quevedo, “Local Averaging for Consensus Over Communication Links With Random Dropouts,” *IEEE Control Systems Letters*, vol. 7, pp. 1387–1392, Nov. 2022. DOI: 10.1109/LCSYS.2022.3223799

[5] K. Kobayashi, S. Noro, H. Okada, M. Katayama, “Adaptive transmission probability for CSMA/CA based consensus control of multi-agent systems,” *IEICE ComEX*, vol. 8, no. 9, pp. 393–398, Jul. 2019. DOI: 10.1587/comex.2019XBL0092

[6] M. Lei, X. Cao, G. Chen, and C. Sun, “A Consensus-State-Aware Adaptive Algorithm for Tuning CSMA Parameters in Multi-Agent Networks,” Proc. 2019 IEEE 28th Int. Symp. Industrial Electronics (ISIE), pp. 1769–1774, Jan. 2019. DOI: 10.1109/ISIE.2019.8781184

[7] T. Nishino and K. Ishii, “Backoff Period Control for Consensus Problem based on CSMA/CA,” *IEEJ Trans. Electronics, Information and Systems (Japanese Edition)*, vol. 141, no. 9, pp. 1008–1015, Sep. 2021. DOI: 10.1541/ieejeiss.141.1008