



Cooperative Unknown Area Coverage by a Swarm of Agents with Limited Sensing and Identification Capabilities

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Abstract. To cover an unknown area, the agents usually work with SLAM or path-planning-based schemes, and they often rely on stable data communication for task assignment to minimize overlapped coverage. However, the unavailability of a wireless network in an extreme environment, resulting in reduced ability to identify a homogeneous agent and possession of limited sensing range, poses a challenge to the cooperation, since many existing control algorithms turn out to be inapplicable. For this configuration, the paper proposes an improved sweep coverage control strategy from our previous work which requires a constant connection among index neighbors to string them up and generate a flexible formation that adapts to the unstructured environment. In this work, efforts are made to build a coverage formation by establishing a connected linear sensing topology among the agents via coordinate compression and active reconnection tactics, where the adjacent agents are the closest ones without knowing each other's index number. The parameters in the proposed control law are discussed and examined in a bunch of simulations with a conclusion of how they affect the performance of the coverage control.

Keywords: Sweep coverage control · Limited sensing range · Coordinate compression · Active reconnection tactics

1 Introduction

Complex cooperative behaviors such as formation, coverage, and encirclement [1–8] of agent groups can be found in a wide range of civilian and military application. Normally, existing studies have built on the assumption of a connective communication topology. However, the network is susceptible to interference or rejection, cause to delay, and even interruption. Due to the difficulty of identifying another member under a limited recognition range of agents, so the detection-based networks often have difficulties in transferring information with other agents, and even cause the task to fail. Therefore, it

is very important to investigate the cooperative control method under the presence of a limited communication range.

In this paper, a novel sweep coverage control scheme for the agent swarm to cover unknown regions is proposed under a low capability of recognition and limited communication range of the agents. In previous literature [1–20], three control categories are presented to solve the cooperative problem of agents for area coverage.

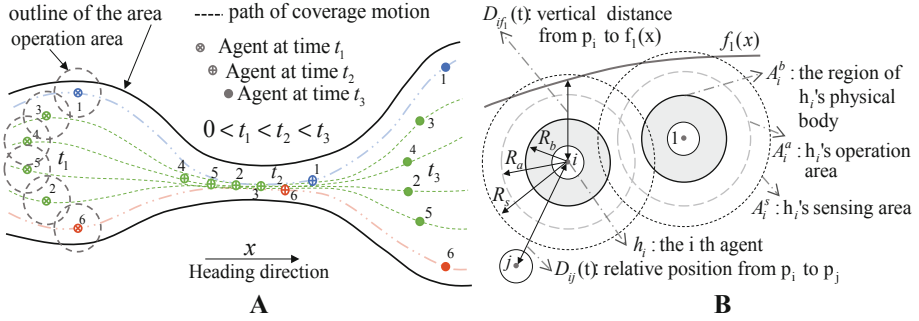


Fig. 1. (A) The anonymous and limited-sensing agents sweeping the unknown area; (B) The physical range, operation range and sensing range of an agents.

They are **slice division and path planning** [3–6], **coverage degree measurement** [7, 8], and **neighbor member interaction** [9–12]. The first two strategies allow a swarm of agents to perform distributed tasks, but often depend on strong communication [3, 4], geographic information predicted in advance [5, 13], or the identifiable degree of mission (e.g. lawn mowing level) [7, 13]. In addition, motion trajectories of agents in algorithms using these strategies are also repetitive and irregular [3–8, 18]. Therefore, these methods cannot guarantee operational efficiency when the communication equipment fails or suffers from electromagnetic interference. However, the above-mentioned studies usually have to rely on the agent’s identification. In the control problem for anonymous agents, to explore the problem of circle formation with multiple robots, some forgetting or non-forgetting methods to organize multi-agent systems with anonymous are proposed in [14–17], while they do not constrain the detection range of the agents. Additionally, the cooperative problem of anonymous agents under limited communication is investigated in [19, 20], while the agents had already gained the coordinates of the circle’s center.

In our previous work [10], a distributed second-order control law was proposed to control a group of anonymous agents to cover an unknown irregular region, and the two outlines of this region are measurable. The scheme can control an agent swarm to sweep over an unknown region, and the swarm includes two leaders and other followers. In addition, the leaders track boundaries to protect their followers within the region to avoid them rushing out of the boundaries. However, long-distance communication is required for process synchronization and interaction among index neighbors. This paper designs a concept is called Y-neighbors according to the minimal distance between agents rather than index. Specifically, the agents are crudely identified as upper leaders (red), lower leaders (blue), and followers (green) instead of a specific index number (see Fig. 1).

So that the agents are able to create a detection-based interaction with their neighbors within a limited sensing range.

Our main contributions in this new work are as follows:

1. A distributed control strategy is proposed for unknown area sweep coverage by a dual-leader swarm of agents in the absence of data communication, and full coverage of an arbitrarily-shaped area is guaranteed by adopting sets of proper parameters;
2. The connectivity problem of detection network among the agents that brought by limited sensing range and crude identification merely of the members' roles (leader/follower) has been solved by appending extra controllers for coordinate compression and actively connecting behavior to the one proposed by [10];
3. We experimentally found how different parameters affect the control performance: When employing fewer agents than that those can conduct full coverage, growing values of stiffness coefficient and equilibrium length of the virtual springs among Y-neighbors lead to increasing coverage rate and smoother motion trajectories.

The paper is organized as follows: Sect. 2 formulates the control problem of this paper. The cooperative control strategy of the agent swarms for area coverage is proposed in Sect. 3. In Sect. 4, some experiment simulations are designed to verify the effectiveness of this method and provide the parameters adjustment scheme. Section 5 concludes the whole of this paper and discusses the further works.

2 Statement of the Limited-Sensing Coverage Problem

This section provides a mathematical definition for the research background of the sweep coverage scheme. Consider a group of agents performing a scanning task along an unknown corridor. First, a concept of two continuous and irregular boundaries is proposed. Then, the mathematical structure and coordinates of the agents and the expressions for the coverage area are set. Lastly, the agent's maximum yaw acceleration is defined.

Assume an n -agent system ($n > 2$), where the index data the union of the agent group is called $\beta = \{1, 2, \dots, n\}$. And the β is composed of leader $\bar{\gamma} = \{1, n\}$ and follower $\gamma = \{2, 3, \dots, n-1\}$. Besides, we define the physical radius of each agent as R_b , the radius of the operating area is called R_a , the sensing radius of the agent is called R_s , and the center coordinate of the i -th agent is set as $p_i(t) = [x_i(t), y_i(t)]^T$ (see Fig. 1-B).

Assumption 1: The property of an agent is constrained by $R_b \ll R_a$, $R_a \geq \frac{R_s}{2}$.

Remark 1: The item $R_a \geq \frac{R_s}{2}$ means that the operation area should exceed half of an agent's sensing range, so that the joint work of two neighboured agents at a time can cover the distance between them which should be limited by one's sensing range in order to maintain connection. Therefore, Assumption 1 can help people to choose the cheapest sensing device to gain a maximum profit when R_a is a certain constant.

Consider a two-dimensional corridor region is named as ξ , which is sandwiched between two consecutive curves that $f_1(x)$ and $f_n(x)$. And the boundaries $f_1(x)$ and $f_n(x)$ have to satisfy that $f_1(x) > f_n(x)$, and $f_1(t) \cap f_n(t) = \emptyset$. Then, the area ξ is defined as:

$$\xi \triangleq \left\{ (x, y) \in \mathbb{R}^2 \mid f_n(x) \leq y \leq f_1(x) \right\}. \quad (1)$$

Assumption 2: In the y -direction, the width of area ξ is used to calculate the theoretical values of the sensing and operating radius to provide a reference for cooperatively covering the whole area. Thus, the boundaries $f_1(x)$ and $f_n(x)$ have a max-interval and a min-interval as $W_{\max} \triangleq \max_x [f_1(x) - f_n(x)]$, $W_{\min} \triangleq \min_x [f_1(x) - f_n(x)]$, respectively, where $W_{\min} > 2R_b$.

The coverage region $\bar{\zeta}_{x_o}^{\bar{x}_e}$ for the agent swarm in a piece of corridor $\psi_{x_o}^{x_e} \triangleq \xi \cap \{(x, y) \in \mathbb{R}^2 | x \in [x_o, x_e]\}$ is defined as the union of all agents' operation areas when they pass through that piece. Specifically,

$$\bar{\zeta}_{x_o}^{\bar{x}_e} \triangleq \left[\bigcup_{\forall i \in \beta} \bigcup_{x \in [x_o, x_e]} A_i^a(x) \right] \cap \psi_{x_o}^{x_e}, \quad (2)$$

where $A_i^a(x)$ is the operated area on the i -th agent's trajectory when $x_i = x$, and the x_o is initial x coordinate.

Consider a region where agents can sense each other but will not collide that it is called the safety zone. Then the radius of the safety zone is denoted as $R_{bs} \in (R_b, R_s]$, we give the boundary constraints $|\dot{f}_k(x)| \leq \left(0, \sqrt{(R_{bs}/R_b)^2 - 1}\right)$, $k \in \bar{\gamma}$ according to the Assumption 1 in [10].

According to Fig. 2, the distance of the i -th agent from the boundary $f_k(x)$ is denoted as $D_{if_k}(t)$ and its distance from another j -th agent is denoted as $D_{ij}(t)$, and then these two distances are respectively denoted as

$$D_{ij}(t) = p_j(t) - p_i(t), D_{if_k}(t) = (0, f_k[x_i(t)] - y_i(t)), \forall i, j \in \beta, k \in \bar{\gamma}, i \neq j. \quad (3)$$

Therefore, the minimum distance between any two adjacent agents can be denoted as $D_{ij}^{\min} = \min_{\forall i, j \in \beta, i \neq j} (|D_{ij}|)$ and its maximum value is denoted as $D_{ij}^{\max} = \max_{\forall i, j \in \beta, i \neq j} (D_{ij}^{\min})$. When $D_{ij}^{\max} > R_s$ is satisfied, then two nearest agents cannot sense each other, and this situation is called as chain formation failed, and the opposite is completeness.

Condition 1: To avoid collision events during the operation of the agent group, if $\exists t_p$ has $\forall t > t_p$, the sport of the agent swarm need to satisfy the following constraints:

$$|D_{ij}(t)| > 2R_b, \quad |D_{if_k}(t)| > R_b, \quad y_i(t) \in [f_n(x_i(t)), f_1(x_i(t))]. \quad (4)$$

Condition 2: Let the positive x -axis direction be the sweeping direction of the agent groups (as shown in Fig. 1), if the system has a maximum running time t_{\max} , then for $\forall t_1, t_2$ will satisfy that $0 < t_1 < t_2 < t_{\max}$, and we can set $x_i(t_1) < x_i(t_2) : i \in \beta$.

Condition 3: In the interval $x \in [x_o, x_e]$, the agent strategy can cover all areas after the formation deployment when $\bar{\zeta}_{x_o}^{\bar{x}_e} = \psi_{x_o}^{x_e}$; inversely, the agents can cover only some areas.

Definition 1: (Full sweep coverage) Given a region ξ under Assumptions 1 and 2, a control law is said to be effective n -agent group sweep coverage control, if Conditions 1–3 are satisfied when the agent collective motion.

The coverage rate $C_{x_o}^{x_e}$ for the agents covering the corridor part that is cut by $x \in [x_o, x_e]$ is defined by $C_{x_o}^{x_e} = [1 - M(\bar{\zeta}_{x_o}^{\bar{x}_e})/M(\psi_{x_o}^{x_e})] \times 100\%$, where $M(\bullet)$ is an area

of the enclosed region (the measure on the enclosed point set); $\zeta_{x_0}^{x_e}$ and $\psi_{x_0}^{x_e}$ are the uncovered region and corridor region on that piece. Apparently, the coverage regions $\bar{\zeta}_{x_0}^{x_e} = \psi_{x_0}^{x_e} - \zeta_{x_0}^{x_e}$, and $C_{x_0}^{x_e} = 100\%$ in Condition 3.

Noting that coverage rate is evaluated after knowing all the trajectories of the agents form a full experiment, we use $Y_x(I)$ to denote the y -value on the agent's trajectory which is indexed by $I \in \mathbb{I} = \{1, 2, \dots, n\}$ from top to bottom with respect to a specified x value, providing that $x \in [x_0, x_e]$ with the selected start and end position included by the coverage routine of all the agents. I is neither related to the agents' own indices nor fixed on one specific trajectory. With the help of the above definition, one gets

$$M(\psi_{x_0}^{x_e}) = \int_{x_0}^{x_e} \left[\sum_{I=1}^{n-2} \text{flat}(Y_x(I) + Y_x(I+1) - 2R_a) + \text{flat}(Y_x(n) - f_1(x) - R_a) \right], \quad (5)$$

where

$$\text{flat}(\alpha) = \begin{cases} a & , \quad a > 0 \\ 0 & , \quad \text{otherwise} \end{cases}. \quad (6)$$

Moreover, the maximum value of yaw acceleration is defined as a trade-off criterion to evaluate the smoothness of the agent population trajectory. Suppose that the agent's yaw angle is the angle between its instantaneous velocity and the sweeping direction, and its yaw acceleration is $\ddot{\theta}_i(t)$, then $O_{\max} = \max_{\forall t, i \in \beta} [\ddot{\theta}_i(t)]$. Therefore, with the smaller O_{\max} , the agents' moving paths are smoother.

3 The Multi-agent Sweep Coverage Control Strategy Under Crude Identification

Consider a second-order dynamical model for the i -th agent as

$$\dot{p}_i(t) = v_i(t), \quad m_i \dot{v}_i(t) = u_i(t) \quad \text{for } i \in \beta, \quad (7)$$

where the $v_i(t)$ and $u_i(t)$ are velocity and acceleration possessed by i -th agent at time t , respectively, m_i is the central mass of the agent $i \in \beta$. For the convenience of calculation, in this paper set $m_i = 1$.

Assumption 3: The initial position of each agent is limited in Eq. (1) and Condition 1 to avoid collision. According to the Assumption 5 in [10], the initial motion state is set to $v_i(0) = 0, \forall i \in \beta$.

Figure 2-A presents a heuristic model similar to the spring-ball system in our previous work [10], where a virtual elastic field is set between the leader agents and the borders to keep a safe distance, and the virtual springs among neighbors are designed to form a string-like formation. However, in this paper, the agents can only obtain information about an object that appears within a limited range, and are incapable of identifying a specific follower. Apparently, the former idea of shaping the agent chain by always attaching ID neighbors (the i -th and $(i+1)$ -th agents) with a virtual spring in [10] does not

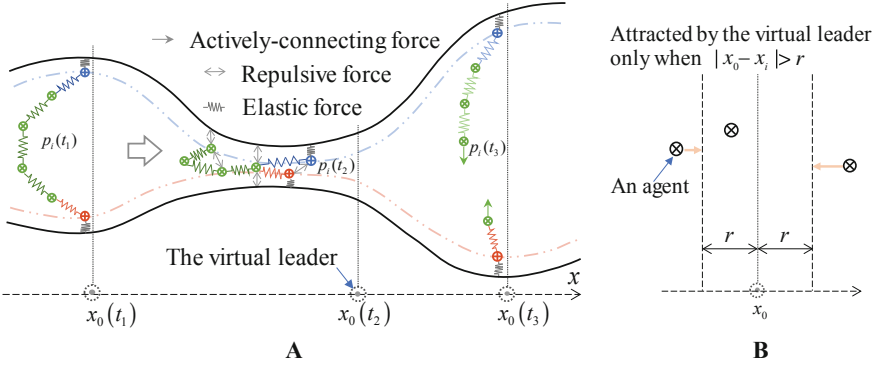


Fig. 2. (A) The heuristic model of a multi-agent system; (B) Mechanism of the attractive force.

work anymore. Therefore, to keep the agent swarm pace up and guarantee the formation with resilience, coordinate compression and reconnection tactics are introduced to the control scheme in the x -direction and y -direction, respectively.

To conquer this problem, we introduce a new definition of the interacting neighbors:

The Y-neighbors. An upper (or lower) Y-neighbor of an agent is normally another member on its y^+ (or y^-) side within its sensing range whose y -coordinate of position is the closest to the agent compared to the others on the same side. Then the chain-formation can be built upon the connection among the Y-neighbors. Considering the undesired situations that a follower goes higher than the 1-st leader or lower than the n -th leader, we give respective mathematical definitions of the i -th agent's upper and lower Y-neighbors ($b_i^{y^+}$ and $b_i^{y^-}$) as follows:

$$b_i^{y^+} = \begin{cases} \emptyset, & N_i = \emptyset \\ 1, & 1 \in N_i \text{ and } y_i < y_1 \\ \arg \min_{j \in N_i, y_j - y_i > 0} |y_j - y_i|, & \text{otherwise} \end{cases}, \quad b_i^{y^-} = \begin{cases} \emptyset, & N_i = \emptyset \\ n, & n \in N_i \text{ and } y_i > y_n \\ \arg \min_{j \in N_i, y_j - y_i < 0} |y_j - y_i|, & \text{otherwise} \end{cases}, \quad (8)$$

where $N_i = \{j \in \beta \mid |D_{ij}| \leq R_s, i \neq j\}$ denotes the detectable neighbors of the i -th agent. In addition, the distance of the i -th agent to its upper and lower Y-neighbors is denoted as $D_{ib_i^y}$.

Then we moderately modify the Lemma 1 of [10].

Lemma 1: Consider an agent swarm collective motion coordinate compression and reconnection policies are met, and $\exists t_p, \forall t > t_p$ that

$$\left| p_i(t) - p_{b_i^{y^-}}(t) \right| < 2R_a, \quad \left| p_{b_i^{y^+}}(t) - p_i(t) \right| < 2R_a, \quad |D_{kfk}| < R_s, \quad (9)$$

where $k \in \bar{\gamma}, \forall i \in \gamma$.

Remark 2: Lemma 1 infers that full coverage requires a constant connection between Y-neighbors. However, adapting to the dramatically varying width of the corridor can

easily break the connection, and may tear the group into parts and cause the agents to gain far away from each other, since they can not connect long-distance communication.

Assumption 4: Assume that the widest part of the corridor satisfies $W_{\max} < 2nR_a$. Therefore, the agents are able to cover that part by aligning across the corridor with a connected operational area, which assures Condition 3 according to Lemma 1.

To design a controller of agent swarms, three concepts of virtual forces are set. They are elastic force $\Gamma_{ij}(q, r, t)$, repulsive force $\bar{\Gamma}_{ij}(q, r, t)$ between agents, and repulsive force $\bar{\Gamma}_{if_k}(q, r, t)$ between agent and boundaries. Those forces are defined by the Eqs. (18) and (19) in [10]. In addition, the two types of virtual force are only exerted by objects within the i -th agent's sensing range, i.e., $|D_{ij}| \leq R_s$ and $|D_{if_k}| \leq R_s$. Besides, the attractive force $T_x(q, r, t)$ is propose to work on coordinate compression (see Fig. 2) is denoted by

$$T_x(q, r, t) = \begin{cases} q(v_{0x}t - x_i(t) - r, 0) & , \quad |v_{0x}t - x_i(t)| > r \\ (0, 0) & , \quad \text{otherwise} \end{cases}. \quad (10)$$

where the v_{0x} denotes a positive constant of velocity to use for x -direction coordinate compression, and equilibrium length of the attractive force $T_x(q, r, t)$ for a leader or follower is different for attracting agents to form a bow formation.

In order to explicitly state the proposed scanning coverage control algorithm, the force acting on each agent consists of five components, and the agent system has to meet Eqs. (7) and the agent's sensing range is set as R_s . Then the control input is given by

$$u_i(t) = \Gamma_i(t) + \bar{\Gamma}_i(t) + T_{ix}(t) + \Upsilon_{iy}(t) + F_i(t), \quad (11)$$

where $\Gamma_i(t)$ and $\bar{\Gamma}_i(t)$ denote all the virtual elastic and repulsive force exerted on the i -th agent, respectively; $F_i(t)$ denotes the friction force helping to buffer the i -th agent from violent oscillation; $T_{ix}(t)$ is the coordinate compression field that constrains the value of $x_i(t)$ not far away from that of the global reference signal $v_{0x}t$; $\Upsilon_{iy}(t)$ denotes actively connecting force driving the i -th agent to seek its Y -neighbors.

For the k -th leader agent, $k \in \bar{\gamma}$, i or $j \in \gamma$, the virtual forces are defined as

$$\begin{aligned} \Gamma_k(t) &= \Gamma_{kf_l}(q_f, r_f, t), \quad \bar{\Gamma}_k(t) = \sum_{j \neq k} \bar{\Gamma}_{kj}(q_w, r_w, t) + \bar{\Gamma}_{kf_l}(q_f, r_f, t), \\ F_k(t) &= -cv_k(t), \quad T_{ix}(t) = T_x(q_L, r_L, t), \\ \Upsilon_{ky}(t) &= H_k \cdot (0, v_{k\Upsilon}) \quad \text{for } |D_{kf_k}(t)| > R_s, \end{aligned} \quad (12)$$

where $l = n + 1 - k$ and the positive constant c is friction coefficient; H_k is set as the direction of $\Upsilon_{ky}(t)$ by $H_k = \frac{n-2k+1}{n-1}$; the positive constant $v_{k\Upsilon}$ denotes the strength of $\Upsilon_{ky}(t)$ by $v_{k\Upsilon} < q_f(R_s - r_f)$.

For the i -th follower agent, $i, j \in \gamma, i \neq j, k \in \bar{\gamma}$, the virtual forces are defined as:

$$\begin{aligned} \Gamma_i(t) &= \sum_{j \in \{b_i^{y+}, b_i^{y-}\}} \Gamma_{ij}(q_w, r_w, t), \quad \Upsilon_i(t) = \sum_{j \in N_i} \Upsilon_{ij}(q_w, r_w, t) + \sum_{k \in \bar{\gamma}} \Upsilon_{ik}(q_f, r_f, t), \\ F_i(t) &= -cv_i(t), \quad T_{ix}(t) = T_x(q_F, r_F, t), \\ \Upsilon_{iy}(t) &= \begin{cases} (0, v_{i\Upsilon}) & , b_i^{y+} = \emptyset \\ -(0, v_{i\Upsilon}) & , b_i^{y+} \neq \emptyset \text{ and } b_i^{y-} = \emptyset, \\ (0, 0) & , \text{ otherwise} \end{cases} \end{aligned} \quad (13)$$

where the positive constant $v_{i\Upsilon} < q_w(R_s - r_w)$.

Moreover, the parameters of differently configured virtual springs are denoted by r and q with different subscripts. The subscript W denotes that the parameters are used to calculate the virtual elastic force and repulsive force between agents. Similarly, the subscript f corresponds to the parameters of the force between agent and boundaries, and the subscript of the attractive force is F .

4 Simulation Experiments

This section testifies the control performance of the proposed strategy. The simulation experiments are performed in a region with continuous boundaries, and the scheme can work for many other shapes of boundaries, such as the funnel shape or V-shape.

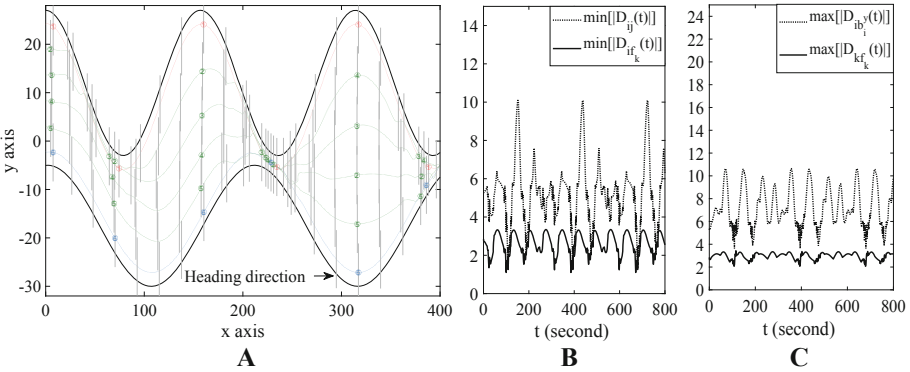


Fig. 3. Experiment 1: (A) The multi-agent system sweeping all areas; (B) Minimal distance among all agents and borders in case 1; (C) Maximal distance among Y-neighboring agents and borders in case 1.

According to the proposed control scheme, the set of parameters in the model is divided into two different subsets: $S_j = \{n, R_s, R_a, R_b, c\}$ for the scenario configuration, $K_j = \{q_w, r_w, v_{0x}, r_f, v_{i\Upsilon}, q_f, q_L, q_F, r_L, r_F\}$ for control parameter configurations, where $v_{i\Upsilon}$ is a positive constant to denote the value of $v_{i\Upsilon}$ ($\forall i \in \beta$) to simplify the

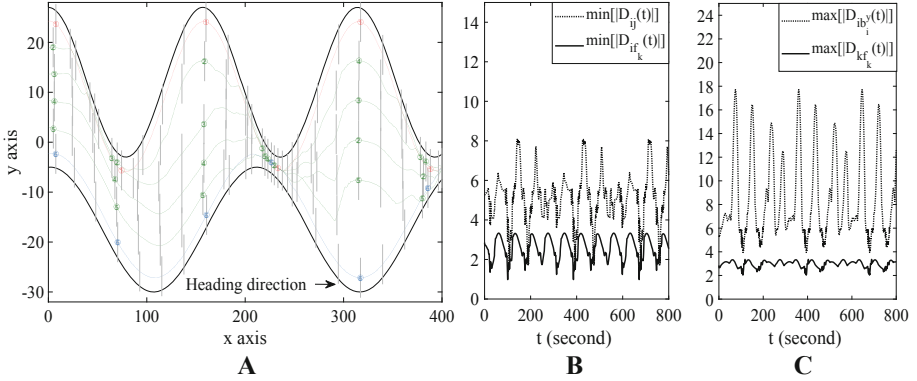


Fig. 4. Experiment 2: (A) An incomplete coverage sweeping by agents; (B) Minimal distance among all agents and borders in case 2; (C) Maximal distance among Y-neighboring agents and borders in case 2.

parameters, and the subscript j helps to distinguish different runs of simulations. Then, two cases of experiments are used to analyze the effects of different parameters on $\max_{\forall t} [D_{ib_i}^y]$, O_{\max} , and $C_{x_0}^x$ under the premise of full coverage (Case 1) or partial coverage (Case 2). For case 1, the parameters are set with $S_1 = \{6, 12, 6, 0.5, 4\}$ and $K_1 = \{2, 6, 2.2, 2.85, 6, 10.5, 0.6, 0.6, 1, 3\}$; for Case 2, the parameters are set with $K_2 = K_1$, and S_2 is mostly the same as S_1 except $R_s = 8$ and $R_a = 4$. Therefore, Experiment 1 is conducted with scenario Case 1 with parameters K_1 ; Experiment 2 is conducted with scenario Case 2 with parameters K_2 ; Experiment 3 is divided into two parts, first part shows two groups of experiments in Case 1 with parameters K_1 (see Fig. 5-A and B), and the second part shows a group of experiments in Case 2 with parameters K_2 that has the same variation as K_1 (see Fig. 5C). In each group of experiments, the varies in the parameters of $\{q_w, r_w, v_{0x}, r_f, v_{\gamma}\}$ evenly within the regions $[1.8, 3]$, $[4.5, 7]$, $[1, 2.4]$, $[2.5, 5]$, $[2, 10]$, and five times respectively.

The boundaries of region ξ are defined as $f_1(x) = 15 \cos(0.04x) + 12$, $f_n(x) = 12.5 \sin(0.03x + 1.5) - 17.5$. In addition, the values of the agent's position are defined as $p_1 = (0, 24.00)^T$, $p_2 = (0, 18.79)^T$, $p_3 = (0, 13.59)^T$, $p_4 = (0, 8.38)^T$, $p_5 = (0, 3.17)^T$, and $p_6 = (0, -2.03)^T$ at the initial moment t_p , respectively.

According to the simulation result of Experiment 1 in Fig. 3, where $2R_b = 1 < \min(D_{ij}) = 1.33$, $R_b = 0.5 < \min(D_{kf_k}) = 1.1$, $O_{\max} = 334.5 \text{ rad/s}^2$, and $C = 100\%$, the system achieves a full sweep coverage (meets Definition 1). Furthermore, two group experiments of scenario configurations S_1 in Fig. 5 have shown the trade-off strategy of parameters.

The quasi-linear correlation between the parameters $\{q_w, r_w, v_{0x}, r_f\}$ and $\max_{\forall t} [D_{ib_i}^y]$ in Fig. 5A displays how the growth or decline of these parameters affect the latter, where the influence of the parameters v_{0x} , q_w , r_w are huge. Furthermore, as the global reference velocity v_{0x} decreases, the extreme distance between agents shrinks. Therefore, with the decrease in $\max_{\forall t} [D_{ib_i}^y]$, a smaller operation range of each agent is

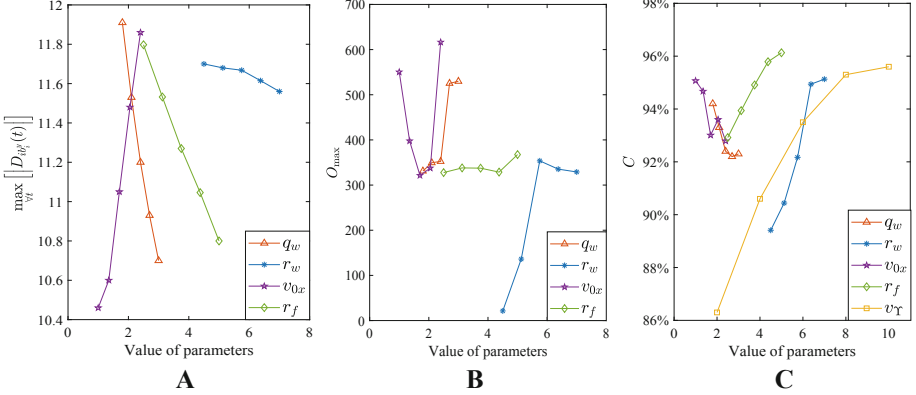


Fig. 5. Experiment 3: (A), (B) The influence of parameters on the maximal distance among Y-neighbors in all time and maximal yaw acceleration, respectively. (C) The simulation results of coverage with various parameters.

able to cover full area between neighbors. Besides, due to the big change of yaw acceleration usually implies the agents' entrance of narrower terrain, a smaller r_w is more suitable to change the formation of agents to diminish the O_{\max} (see Fig. 5-B).

Considering the parameter configuration S_2 (see Fig. 4), where $2R_b = 1 < \min(D_{ij}) = 1.67$, $R_b = 0.5 < \min(D_{fk}) = 0.98$ (meets Definition 1), the coverage rate $C = 93.47\% < 100\%$ shows that the agent swarms can only partially cover the region ξ . Therefore, the target of Experiment 3 is to improve the coverage rate of the swept area by a trade-off in various parameters. Then, Fig. 5-C shows that the r_w and v_γ are bigger, the operating coverage of agent swarms in the crude identification region is higher.

Inspired by the method of parameter adjustment, we design experiment 4 under Condition 1 and Case 1. Compared with the parameter configuration of Experiment 2, we finetune parameters q_w and v_{0x} to the same value, i.e., $q_w = v_{0x} = 2.1$, it will reduce $\max_{\forall t} [|D_{ib_i^y}|]$ and O_{\max} simultaneously but without conflict. Furthermore, we reduce the parameter r_w to 4.8 to further reduce the value of O_{\max} to 122.3. Finally, the value of $\max_{\forall t} [|D_{ib_i^y}|]$ decreases significantly to 11.15 by increasing the parameter r_f to 3.6. These results show that the parameter trade-off method is effective.

5 Conclusions

In this paper, we have proposed an improved sweep coverage control protocol for the second-order multi-agent system. In contrast to our previous work [10], we add Y-neighbor and global reference signals to the controller to be adapted to a more realistic situation where the agent's perception capability is limited.

Experimental results show that for the full coverage case, a better controller performance can be enhanced by increasing r_f and decreasing r_w , respectively. In addition, for the case of partial coverage, we can adjust v_γ to make the communication topology recover faster.

In the current work, the validity of the proposed trade-off strategy is demonstrated only in terms of experimental data validation, but the process of mathematical proof is not given. Therefore, we will improve the deficiencies and try to replace the particle model with a motion model of the agent in a more complex environment in the future.

Acknowledgments. This research was supported in part by the Science and Technology Department of Sichuan Province (2021YFG0130, 2020YJ0044), and the University of Electronic Science and Technology of China (ZYGX2020J020).

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