Distributed formation control for a multi-agent system with dynamic and static obstacle avoidances*

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Formation control and obstacle avoidance for multi-agent systems have attracted more and more attention. In this paper, the problems of formation control and obstacle avoidance are investigated by means of a consensus algorithm. A novel distributed control model is proposed for the multi-agent system to form the anticipated formation as well as achieve obstacle avoidance. Based on the consensus algorithm, a distributed control function consisting of three terms (formation control term, velocity matching term, and obstacle avoidance term) is presented. By establishing a novel formation control matrix, a formation control term is constructed such that the agents can converge to consensus and reach the anticipated formation. A new obstacle avoidance function is developed by using the modified potential field approach to make sure that obstacle avoidance can be achieved whether the obstacle is in a dynamic state or a stationary state. A velocity matching term is also put forward to guarantee that the velocities of all agents converge to the same value. Furthermore, stability of the control model is proven. Simulation results are provided to demonstrate the effectiveness of the proposed control.

Keywords: multi-agent system, formation control, obstacle avoidance, consensus theory

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1. Introduction

Over the past few years, formation control for multi-agent systems has received increasing attention from scientific communities because of its wide applications to the automotive and aerospace areas such as satellite formation flying, disaster rescue, navigation in hostile environments and so forth. Generally speaking, the formation control problem is to find an appropriate control method such that the agents could achieve anticipated formation and accomplish cooperative missions.

Most of the research on formation control can be categorized into three kinds: leader-following approach,[1–3] behavior-based approach,[4–6] and virtual structure approach.[7–9] In addition, consensus protocols have also been applied to the formation control for multi-agent systems.[10–12] However, to the best of our knowledge, there is no research on the presence of obstacles in the aforementioned formation control methods. Because of the ubiquity of obstacles in real environments, obstacle avoidance is of practical importance in the process of formation control on the multi-agent system. Consequently, obstacle avoidance is taken into account in our formation control strategy.

Nowadays, sufficient attention has been paid to the obstacle avoidance of multi-agent systems. Three flocking algorithms proposed in Ref. [13] have been proven to achieve obstacle avoidance while the multiple agents performed flocking. A dual-mode control approach, based on conventional linear optimal control and a modified Grossbery neural network (GNN), was developed in Ref. [14] to solve the obstacle avoidance problem. In Ref. [15], a distributed robust model predictive control algorithm was employed to address the trajectory optimization problem with the presence of obstacles. An avoidance penalty function based on the traditional potential field function was introduced to address the consensus problem and obstacle avoidance in Ref. [16]. In the approaches of the obstacle avoidances referred to, the obstacles were all assumed to be in stationary states. However, most of the obstacles in the real environment are in motion. The scenario with moving obstacles was not taken into consideration. These methods are unable to satisfy the requirement of formation control on multi-agent systems with the presence of moving obstacles.

In this paper, both the formation control problem and obstacle avoidance are addressed in a unified consensus algorithm. A novel distributed control law based on the consensus algorithm is constructed such that the agents can converge to the anticipated formation. In addition, a modified potential field approach is utilized to establish a novel obstacle avoidance function so that the obstacle avoidance can be achieved. The obstacles either in dynamic states or in stationary states are both considered.

The outline of this paper is organized as follows: Section 2 introduces some preliminary concepts in algebraic graph theory; the problem is formulated and the results are presented in Section 3; simulation results and analysis are given in Sec-

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tion 4; and Section 5 concludes the paper.

2. Preliminaries

In this section, some preliminary concepts and notations about algebraic graph theory are introduced.

Let $\mathcal{G} = \{\mathcal{V}, \mathcal{E}, \mathcal{A}\}$ denote a weighted digraph, where $\mathcal{V} = \{v_1, \ldots, v_n\}$ is a vertex set of n agents, $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the edge set of paired agents, and $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{n\times n}$ with nonnegative elements is the weighted adjacency matrix of $\mathcal{G}$.[17] The nonnegative adjacency matrix $\mathcal{A} = [a_{ij}]$ represents the topology of all agents, where

$$a_{ij} = \begin{cases} 0, & i = j, \\ 1, & i \neq j \text{ and } (j,i) \in \mathcal{E}, \\ 0, & i \neq j \text{ and } (j,i) \notin \mathcal{E}. \end{cases} \tag{1}$$

For the undirected graph, the adjacency matrix is symmetrical, i.e., $a_{ij} = a_{ji}, \forall i \neq j$. An edge of $\mathcal{G}$ is denoted by (v_i, v_j), and $N_i = \{v_j : (v_i, v_j) \in \mathcal{E}\}$ represents the set of neighbors of agent i.

The properties above will be utilized to derive the main results of this paper.

3. Formulation and main results

3.1. Formulation

Suppose that the multi-agent system, considered in this paper, consists of n agents. Let $x_i(t) \in \mathbb{R}^m$, $v_i(t) \in \mathbb{R}^m$, and $u_i(t) \in \mathbb{R}^m$ denote, respectively, the position, velocity, and control input of the i-th agent. Then the dynamics of the i-th $(i = 1, 2, \ldots, n)$ agent are described as

$$\begin{cases} \dot{x}_i = v_i, \\ \dot{v}_i = u_i. \end{cases} \tag{2}$$

Let

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{0}_{n\times n} & \boldsymbol{I}_n \\ \boldsymbol{0}_{n\times n} & \boldsymbol{0}_{n\times n} \end{bmatrix} \otimes \boldsymbol{I}_m, \quad \boldsymbol{B} = \begin{bmatrix} \boldsymbol{0}_{n\times n} \\ \boldsymbol{I}_n \end{bmatrix} \otimes \boldsymbol{I}_m,$$
$$\boldsymbol{X} = [\, \boldsymbol{x}^{\mathrm{T}} \;\; \boldsymbol{v}^{\mathrm{T}} \,]^{\mathrm{T}} = [\boldsymbol{x}_1^{\mathrm{T}}, \ldots, \boldsymbol{x}_n^{\mathrm{T}}, \;\; \boldsymbol{v}_1^{\mathrm{T}}, \ldots, \boldsymbol{v}_n^{\mathrm{T}}]^{\mathrm{T}},$$
$$\boldsymbol{U} = [\boldsymbol{u}_1^{\mathrm{T}}, \ldots, \boldsymbol{u}_n^{\mathrm{T}}]^{\mathrm{T}}.$$

The dynamic equation with respect to the i-th agent can be converted into matrix form

$$\dot{\boldsymbol{X}} = A\boldsymbol{X} + \boldsymbol{B}\boldsymbol{U}, \tag{3}$$

where $\boldsymbol{X} \in \mathbb{R}^{2nm}$ and $\boldsymbol{U} \in \mathbb{R}^{nm}$ are, respectively, the stack state and the stack control input of all agents, $\boldsymbol{I}_n$ and $\boldsymbol{I}_m$ denote the unit matrices with dimensions of n and m, respectively, and $\boldsymbol{0}_{n\times n}$ is the n-dimensional zero matrix.

When the multi-agent system achieves anticipated formation, the relative position of all agents would remain invariant and the velocity would converge to the same. The control law u_i for the i-th agent can be constructed as follows:

$$u_i = u_{i\alpha} + u_{i\beta} + u_{i\omega}, \tag{4}$$

where $u_{i\alpha}$ is used to regulate the relative distance between agents to make the agents form the anticipated formation, $u_{i\beta}$ is used to regulate the velocity of the i-th agent to make the velocities of all agents converge to the same, $u_{i\omega}$ is used to make sure the i-th agent can achieve obstacle avoidance. The anticipated formation is achieved when the system (2) is asymptotically stable.

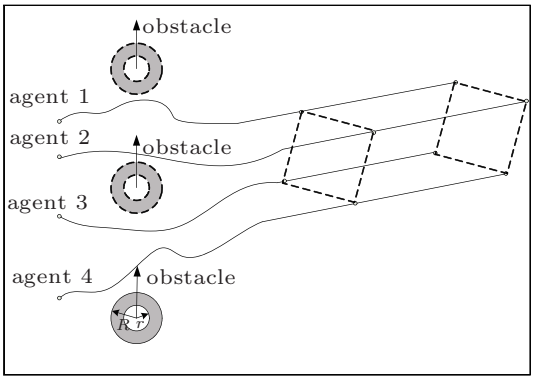


Fig. 1. Formation control for a multi-agent system with a moving obstacle.

An example scenario of formation control for a multi-agent system with a moving obstacle is shown in Fig. 1. Four agents start to move from different initial positions with different velocities. The obstacle moves along the positive Y axis. After a certain time, the presented distributed control law will drive the agents to avoid the moving obstacle and converge to a square. We denote the radius of the obstacle and the detection region as r and R, respectively.

3.2. Main results

Based on the consensus algorithm, we propose a distributed control law consisting of the following three components (formation control term, velocity matching term, and obstacle avoidance term):

$$u_i = -\sum_{j=1, j\neq i}^{n} \nabla_{x_i} \psi(x_{ij}) + \sum_{j=1, j\neq i}^{n} a_{ij} \varphi(v_i - v_j) - \nabla_{x_i} U_{\mathrm{obsi}}, \tag{5}$$

$$\psi(x_{ij}) = k_1 \ln \frac{d_{ij}^2 + x_{ij}^2}{2 d_{ij} x_{ij}}, \tag{6}$$

$$\varphi(v_i - v_j) = \mathrm{sign}(v_j - v_i) \left| v_j - v_i \right|^{k_2}, \tag{7}$$

where k_1 and k_2 are the positive variable parameters, $x_{ij} = \left\| x_i - x_j \right\|$ is the Euclidean distance between agent i and agent j, and d_{ij} is the anticipated distance between agent i and agent j. When the multi-agent system achieves consensus, the relative position of all agents will remain invariant and the multi-agent system can reach the anticipated formation.

The formation control matrix $\boldsymbol{D} = [d_{ij}]_{n\times n}$ denotes the anticipated formation, d_{ij} is the anticipated relative position between agent i and agent j, $d_{ij} = 0$ if $i = j$, and $d_{ij} = d_{ji}$ if $i \neq j$.

$$\boldsymbol{D} = [d_{ij}]_{n\times n} = \begin{bmatrix} 0 & d_{12} & \cdots & d_{1n} \\ d_{21} & 0 & \cdots & \vdots \\ \vdots & \vdots & \ddots & d_{(n-1)n} \\ d_{n1} & \cdots & d_{n(n-1)} & 0 \end{bmatrix}. \quad (8)$$

The artificial potential function $\psi(x_{ij})$ is shown in Fig. 2. We use $\psi(x_{ij})$ to denote the nonnegative function with the distance between agent i and agent j, which reaches its maximum as $\|x_i - x_j\| \to 0$, and attains its unique minimum when agent i and agent j are located at a desired distance d_{ij}.

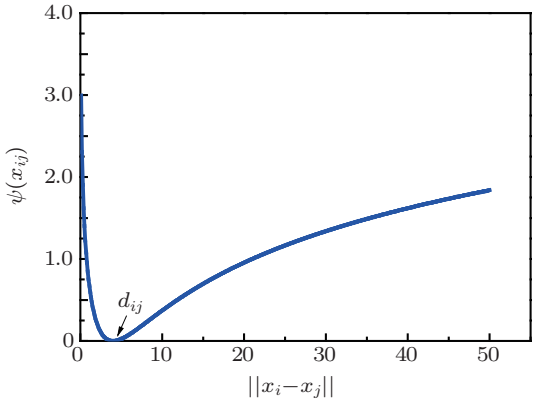


Fig. 2. Smooth pairwise potential function $\psi(x_{ij})$.

We denote the gradient of the obstacle avoidance potential function with respect to x_i as $\nabla_{x_i} U_{\text{obsi}}$, with an expression of

$$U_{\text{obsi}} = \begin{cases} 0, & \|x_i - O_{\text{b}}\| > R, \\ k_3\left[\dfrac{1}{\|x_i - O_{\text{b}}\| - r} + \dfrac{(\|x_i - O_{\text{b}}\| - r)}{(R-r)^2}\right], & \\ \quad r < \|x_i - O_{\text{b}}\| \le R, & \\ \text{not define}, \quad \|x_i - O_{\text{b}}\| \le r, & \end{cases} \quad (9)$$

$$\nabla_{x_i} U_{\text{obsi}} = \begin{cases} 0, & \|x_i - O_{\text{b}}\| > R, \\ k_3\left[-\dfrac{1}{(\|x_i - O_{\text{b}}\| - r)^2} + \dfrac{1}{(R-r)^2}\right], & \\ \quad r < \|x_i - O_{\text{b}}\| \le R, & \\ \text{not define}, \quad \|x_i - O_{\text{b}}\| \le r, & \end{cases} \quad (10)$$

where x_i is the position of agent i $(i = 1, \ldots, n)$, O_{b} is the coordinate of the center of obstacle, r and R represent the radius of obstacle and the detection region, respectively, and k_3 is a positive variable parameter.

Theorem 1 Consider the dynamic multi-agent system given by Eq. (2). Suppose that the fixed undirected interaction graph is connected and $\mathcal{A} = \mathcal{A}^{\text{T}}$. Then under the distributed control law given by Eq. (5), the velocity of every agent can converge to the same asymptotically. All agents can reach the anticipated formation and achieve obstacle avoidance regardless of whether the obstacle is in dynamic state or in stationary state.

Proof For the distributed control law (5), we consider a candidate Lyapunov function

$$V(x,v) = \frac{1}{2}\sum_{i=1}^{n} v_i^2 + \sum_{i=1}^{n} U_{\text{obsi}} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n} \psi(x_{ij}). \quad (11)$$

To make the function $V(x,v)$ a valid Lyapunov function, $V(x,v)$ should be continuously differentiable with respect to x and v, which is equivalent to proving that U_{obsi} is continuously differentiable with respect to x_i. According to Eqs. (9) and (10), it is sufficient to prove that U_{obsi} is continuously differentiable if the distance between agent and obstacle is in the safety region $\|x_i - O_{\text{b}}\| > r$. From Eq. (9), it is evident that U_{obsi} is continuous in the whole safety region $\|x_i - O_{\text{b}}\| > r$ since $\lim_{\|x_i - O_{\text{b}}\| \to R^-} U_{\text{obsi}} = 0 = \lim_{\|x_i - O_{\text{b}}\| \to R^+} U_{\text{obsi}}$. Furthermore, the derivative of U_{obsi} with respect to x_i is

$$\nabla_{x_i} U_{\text{obsi}} = \begin{cases} 0, & \|x_i - O_{\text{b}}\| > R, \\ k_3\left[-\dfrac{1}{(\|x_i - O_{\text{b}}\| - r)^2} + \dfrac{1}{(R-r)^2}\right], & \\ \quad r < \|x_i - O_{\text{b}}\| \le R, & \\ \text{not define}, \quad \|x_i - O_{\text{b}}\| \le r. & \end{cases}$$

It can be inferred that

$$\lim_{\|x_i - O_{\text{b}}\| \to R^-} \nabla_{x_i} U_{\text{obsi}} = 0 = \lim_{\|x_i - O_{\text{b}}\| \to R^+} \nabla_{x_i} U_{\text{obsi}}.$$

Therefore, $\nabla_{x_i} U_{\text{obsi}}$ is continuous at $\|x_i - O_{\text{b}}\| = R$ and in the whole safety region. Hence, U_{obsi} and the candidate Lyapunov function $V(x,v)$ are continuously differentiable with respect to x over the whole safety region. Consequently, function $V(x,v)$ is a valid Lyapunov function.

The derivative of V along the trajectories of the agents is given by

$$\begin{aligned} \dot{V}(x,v) &= \sum_{i=1}^{n} v_i u_i + \sum_{i=1}^{n} v_i \nabla_{xi} U_{\text{obsi}} \\ &\quad + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n} \nabla_{x_i}\psi(x_{ij})(\dot{x}_i - \dot{x}_j) \\ &= \sum_{i=1}^{n} v_i \Bigg\{ -\sum_{j=1,j\neq i}^{n} \nabla_{x_i}\psi(x_{ij}) \\ &\quad + \sum_{j=1,j\neq i}^{n} a_{ij}\varphi(v_i - v_j) - \nabla_{x_i} U_{\text{obsi}} \Bigg\} \\ &\quad + \sum_{i=1}^{n} v_i \times \nabla_{xi} U_{\text{obsi}} + \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n} \nabla_{x_i}\psi(x_{ij})(\dot{x}_i - \dot{x}_j) \\ &= \sum_{i=1}^{n} v_i \sum_{j=1,j\neq i}^{n} a_{ij}\varphi(v_i - v_j) \\ &= \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} a_{ij}(v_i - v_j)\varphi(v_i - v_j). \end{aligned} \quad (12)$$

According to Eqs. (7) and (12), it is obvious that

$$\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} a_{ij}(v_i - v_j)\varphi(v_i - v_j) \le 0. \tag{13}$$

Then, with Eqs. (12) and (13), the derivative of V along the trajectories of the agents turns out to be

$$\dot{V}(x,v) = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} a_{ij}(v_i - v_j)\varphi(v_i - v_j) \le 0. \tag{14}$$

Let

$$\begin{aligned}\Re &\triangleq \{(x,v) : \dot{V}(x,v) = 0\}\\ &= \left\{(x,v) : \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} a_{ij}(v_i - v_j)\varphi(v_i - v_j) = 0,\right.\\ &\qquad \left. i = 1,2,\ldots,n-1\right\},\\ \Re &\triangleq \{(x,v) : v_1 = v_2 = \cdots = v_n\}. \end{aligned} \tag{15}$$

Assume that $v_1 = v_2 = \cdots = v_n = c$, it follows that $\dot{x}_i - \dot{x}_j = 0$. Then from Eqs. (5) and (6), it follows that

$$\nabla_{x_i}\left(\frac{1}{2}\sum_{i=1}^{n}\sum_{j=1,j\neq i}^{n}\psi(x_{ij})\right) = 0. \tag{16}$$

Consequently, the formation of the multi-agent system asymptotically converges to the anticipated formation which is an extremum of the system potentials. Notice that not all solutions of Eq. (16) converge to local minima such as a solution starting at the equilibrium, either a local maximum or a saddle point, but the solutions such as a local maximum and a saddle point are unstable equilibrium. Hence, the system potential converges to a local minimum. Thus, the agents achieve consensus, and the distance between adjacent agents remains invariant and all agents reach the anticipated formation. The velocities of all agents converge to the same asymptotically.

In addition, according to the analysis of $\dot{V}(x,v) \le 0$, it is obvious that $V(x,v) \le h$ for all time. Assume $\|x_i - O_b\| \to r$, then U_{obsi} will approach infinity asymptotically, which results in $V(x,v) \to \infty$. This is contradictory to $V(x,v) \le h$. Therefore, the case of $\|x_i - O_b\| \to r$ for any agent is naturally excluded and obstacle avoidance is achieved.

4. Simulation

In this section, some examples of formation control and obstacle avoidance for multi-agent systems are given. Since the method proposed in Ref. [16] achieved consensus and obstacle avoidance, the simulation result of Ref. [16] is also given to compare with the method of this paper. Simulation results demonstrate the effectiveness of the proposed distributed control strategy.

Suppose that there are four agents, which are labeled as 1, 2, 3, and 4. In this paper, the anticipated formation of four agents is a square, and the distances between adjacent agents are $\sqrt{2}$. Then, the formation control matrix $\boldsymbol{D} = [d_{ij}]_{n\times n}$ takes the form (e.g., $n = 4$)

$$\boldsymbol{D} = [d_{ij}]_{n\times n} = \begin{bmatrix} 0 & \sqrt{2} & \sqrt{2} & 2\\ \sqrt{2} & 0 & 2 & \sqrt{2}\\ \sqrt{2} & 2 & 0 & \sqrt{2}\\ 2 & \sqrt{2} & \sqrt{2} & 0 \end{bmatrix}.$$

The adjacency matrix $\mathcal{A}$ can be written as

$$\mathcal{A} = [a_{ij}] = \begin{bmatrix} 0 & 1 & 1 & 0\\ 1 & 0 & 0 & 1\\ 1 & 0 & 0 & 1\\ 0 & 1 & 1 & 0 \end{bmatrix}.$$

The undirected communication graph of the four agents is shown in Fig. 3.

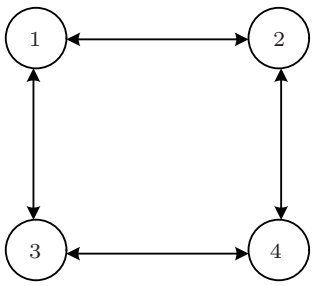


Fig. 3. Communication graph.

The variable parameters in the distributed control law are assumed to be $k_1 = 1.5$, $k_2 = 0.8$, and $k_3 = 0.01$. The initial positions of the four agents are randomly generated in a given bounded region such as $x \in (0,2)$ and $y \in (0,11)$. The initial velocities of the four agents are given as $(0.3,0.6)$, $(-0.6,0.3)$, $(-0.3,-0.6)$, and $(0.3,-0.3)$. Then according to the position and status of the obstacle, our simulations can be divided into two different scenarios.

4.1. Formation control with static obstacle

The simulation result of Ref. [16] is shown in Fig. 4. The points $(-2,-2)$, $(2,-2)$, $(2,2)$, and $(-2,2)$ are chosen as the initial positions of four agents, respectively. The position of obstacle is $(1,1.3)$. The radius of obstacle and the detection region are assumed to be $r = 0.1$ and $R = 0.5$. It can be seen that the static obstacle is on the trajectories of agent 2 and agent 3. The static obstacle avoidance can be achieved by using the optimal control approach described in Ref. [16]. However, as the agents pass over the obstacle, they converge to the same path. Consequently, the optimal control approach used in Ref. [16] is unable to satisfy the requirement of formation control. Meanwhile the obstacle in Ref. [16] is assumed to be static. However, in the real environment, most of the obstacles

are in motion. The dynamic obstacle avoidance is not taken into consideration in Ref. [16].

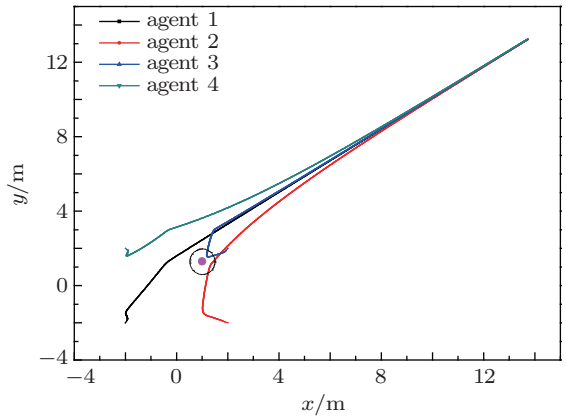


Fig. 4. Trajectories of agents controlled by method in Ref. [16].

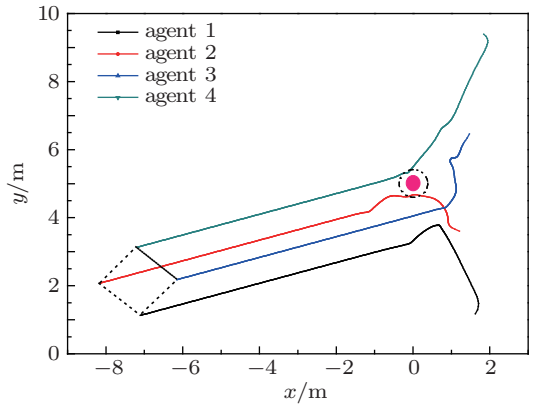


Fig. 5. Trajectories of agents with static obstacle.

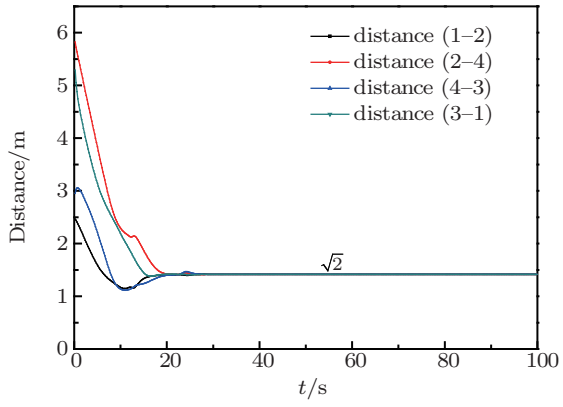


Fig. 6. Distances between adjacent agents.

Figure 5 shows the trajectories of the four agents controlled by the method proposed in this paper. The position of the obstacle is assumed to be $(0,6)$, it can be seen that the static obstacle is on the trajectories of agent 2 and agent 4. The radius of obstacle and the detection region are assumed to be $r = 0.2$ and $R = 0.4$. The simulation time is 100 s. It can be observed that agent 2 and agent 4 step into the detection region of obstacle. In this case, the control strategy of obstacle avoidance takes effect, so that agent 2 and agent 4 can be driven away from the detection region of obstacle. As they pass over the obstacle, the formation control function plays the dominant role. It can be seen that the direction and speed of every agent gradually converge to the consensus. In the end, all the agents form the anticipated formation and move with the same speed, so that the agents achieve consensus. The distances between adjacent agents are shown in Fig. 6. It can be observed that the distances between adjacent agents reach $\sqrt{2}$. The simulation results demonstrate the validity of the obstacle avoidance control and the distributed control strategy.

4.2. Formation control with moving obstacle

Figure 7 shows the trajectories of the four agents in the scenario that the agents encounter the moving obstacle in the process of movement. The initial position of the obstacle is set as $(0,4)$with speed of 0.04 along the y axis. The radius of the obstacle and the detection region are assumed to be $r = 0.2$ and $R = 0.4$. The simulation time is set to 100 s.

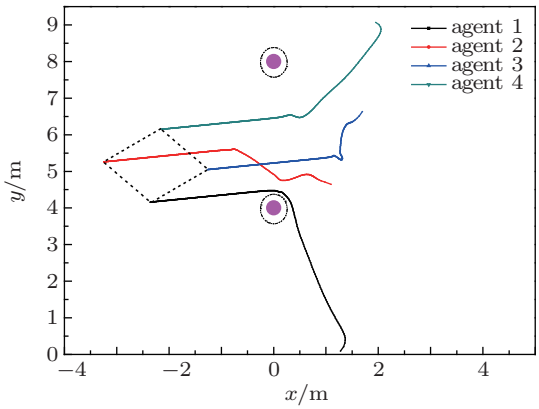


Fig. 7. Trajectories of agents with moving obstacle.

From Fig. 7, it can be observed that agent 1 and agent 2 encounter the moving obstacle and step into the detection region. In this case, the control strategy of moving obstacle avoidance plays a dominant role. Because of the obstacle avoidance control, the directions of agent 1 and agent 2 are changed and they can be driven away from the detection region of the obstacle. As time goes on, agent 1 and agent 2 pass over the obstacle, then the formation control function plays a dominant role. From Fig. 7, it can be seen that the direction and speed of every agent converge to the consensus asymptotically. In the end, the four agents achieve the anticipated formation and the velocities of the four agents reach consensus in the end. The distances between adjacent agents are shown in Fig. 8. It can be observed that the distances between adjacent agents reach $\sqrt{2}$. Figure 9 shows the distances between agents and obstacle. It can be seen that agent 1 and agent 2 step into the detection region of the obstacle, but not collide with the

obstacle. The distances between agents and obstacle are always larger than the radius of obstacle. The simulation results demonstrate the validity of the obstacle avoidance control and the distributed control strategy.

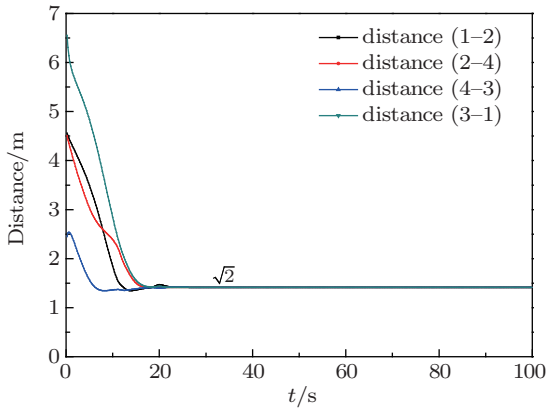


Fig. 8. Distances between adjacent agents.

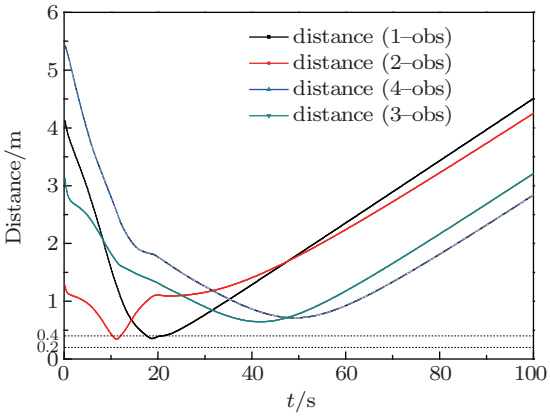


Fig. 9. Distances between agents and obstacle.

5. Conclusion

This paper proposes a novel distributed control model for the formation control and obstacle avoidance of multi-agent system. Formation control and obstacle avoidance were both addressed in the unified control function. Based on the consensus algorithm, a distributed control function consisting of three terms (formation control term, obstacle avoidance term, velocity matching term) was constructed. Under the effect of formation control, the agents could reach consensus and achieve the anticipated formation. The problem of obstacle avoidance is categorized into stationary scenario and dynamic scenario. By modifying potential field approach, a novel obstacle avoidance function is constructed. Obstacle avoidance is achieved whether the obstacle was in stationary state or dynamic state. Stability of the multi-agent system is proven. Simulation results are provided to demonstrate the effectiveness of the proposed control strategy..

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