Leader-follower Formation Control and Obstacle Avoidance of Multi-robot Based on Artificial Potential Field

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Abstract: Leader-Follower formation control of multi-robot was studied in this paper. A formation and obstacle avoidance method with multi-robot based on the combination of Closed-loop control and Artificial Potential Field was presented. According to the position information of leader, Closed-loop control was introduced to realize the tracking of the follower to the leader, and the formation control was achieved. The obstacle avoidance could be achieved by Artificial Potential Field method, and the robots can pass the area of obstacle smoothly. The simulation result shows that the proposed method can achieve the expected control effect, and it can solve this kind of problems effectively.

Key Words: Multi-robot formation, Leader-follower, Artificial Potential Field, Obstacle avoidance

1 INTRODUCTION

In recent years, the control and coordination of multi-robot [1] has become an interesting research topic in the field of robot. Mobile multi-robot technology has been widely used in the fields of industry, military, agriculture, space and marine development [2]. The robot formation control is an important part of multi-robot coordination. Faced with complicated tasks and fickle condition, obviously, it's not enough to just depend on the ability of single robot. So it attracts people's attention to develop the coordination and cooperation of multi-robot to finish the task that can never be done by single robot. The mobile multi-robot formation requires them as one formation which can arrive at the target area at the same time, and avoid obstacles in a safe manner. This kind of group behavior control is the basis to solve the problem of mobile multi-robot coordination, and it is of great significance to realize the cooperative missions of multi-robot in the distributed environment space. Nowadays, the formation control has been applied in many fields. For example, in industry field, people control the mobile multi-robot to carry large objects by certain formation [3]. In military, multiple autonomous vehicles have been used to patrol or reconnoiter [4]. In the field of police, people control the multi-robot to form a cambered encirclement or to arrest the invaders and so on [5]. AGV (Automated Guided Vehicles) have been widely used in practice. In this paper, we do research on multi-robot formation on the background of AGV.

Normally there are three kinds of approaches for formation control with applications towards multi-robots: leader-follower method, behavior-based method and virtual structure method [6]. In the behavioral approach, the control action for each robot is derived by a weighted average of each desired behavior [4]. This method has clear formation feedback, and it also realizes the distributed control, but it does not clearly define the group behavior. The mathematical analysis cannot be done and the stability of the formation cannot be guaranteed. In the virtual structure approach [7], the entire formation is treated as a single rigid body, and the motion of each agent is derived from the trajectory of a corresponding point on the structure. This method can control the motion of the whole robot formation by defining the rigid body, but it cannot change the formation when the environment has been changed, which limits the scope of its application. The leader-follower method is also named as master-slave mode [8]. In the group formed by multi-mobile robots, a certain robot is designated as the leader and the other robots are the followers. It realizes the formation control through the followers keeping a certain angle and distance with the leader, and it can establish different topologies. The leader-follower method also has a clear definition to the whole formation, so we can make mathematical analysis to guarantee the stability of the formation. In this paper, we put forward a method of robot formation and obstacle avoidance based on Closed-loop control and Artificial Potential Field. According to the leader's location information [9], we can realize the followers' trajectory tracking to the leader and formation control by the $l-\varphi$ Closed-loop control, and avoid the obstacles effectively combined with the Artificial Potential Field method.

In the second part of this paper, we put forward a robot formation control and obstacle avoidance method, a tracking control method is in the third part. We change the problem of followers' tracking control into a problem of the control in a system with a certain error. In the fourth part, we make the simulation verification and finally make a prospect for the future's work.

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2 FORMATTING CONTROL AND OBSTACLE AVOIDANCE

2.1 The Robot Formation Under the $l-\varphi$ Control

The optimized motion method that used in the robot formation control needs a great amount of calculation, but much less using the feedback rules, which can also combine with the simple advanced motion planning devices.

Two kinds of motion models with a feedback control are put forward in paper [10]. In the first scenario, through controlling the relative distance and orientation between the follower and the leader to command the formation（$l-\varphi$）and in another scenario, a robot maintains its position in the formation by maintaining a specified distance from two robots（$l-l$）.

As shown in Figure 1, in the given system composed by two robots, the purpose of the $l-\varphi$ control is to keep the relative distance l and the relative angle φ between the following robot and reference robot. As long as the two values are fixed in (l_d, φ_d), we can maintain a certain formation, and each robot's position information is $(x_i, y_i, \theta_i), i = 1, 2$.

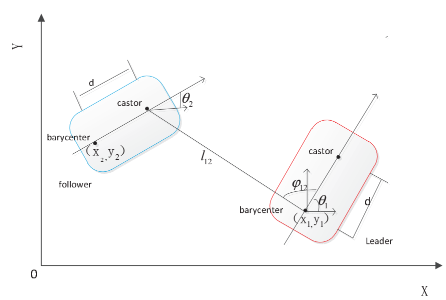

Fig.1 The structure of leader-follower

The kinematic equations for the system of two mobile robots shown in Figure 1 are given by formula (1):

$$\begin{cases} \dot{x}_i = v_i \cos\theta_i \\ \dot{y}_i = v_i \sin\theta_i \\ \dot{\theta}_i = \omega_i \end{cases} \tag{1}$$

The kinematics equation of the follower is:

$$\begin{cases} \dot{l}_{12} = v_2 \cos\gamma_1 - d\omega_2 \sin\gamma_1 - v_1 \cos\varphi_{12} + d\omega_1 \sin\varphi \\ \dot{\varphi}_{12} = \dfrac{1}{l_{12}}\{v_1 \sin\varphi_{12} - v_2 \sin\gamma_1 - d\omega_2 \cos\gamma_1 + d\omega_1 \cos\varphi_{12} - l_{12}\omega_1\} \end{cases} \tag{2}$$

Where, $\gamma_1 = \theta_1 + \varphi_{12} - \theta_2$, v_i 、 $\omega_i\,(i = 1, 2)$ are the linear and angular velocities at the center of the axle of each robot. In order to avoid collision between robots, we specify $l_{12} > d$, where d is the distance between the castor wheel and the center of rear wheels.

The law of closed-loop control is described as:

$$\begin{cases} \dot{l}_{12} = \alpha_1 (l_{12}^d - l_{12}) \\ \dot{\varphi}_{12} = \alpha_2 (\varphi_{12}^d - \varphi_{12}) \end{cases} \tag{3}$$

α_1 、 α_2 in the equation are positive numbers. So we can get the input control variables of follower from the equation (1), (2), (3):

$$\begin{cases} \omega_2 = \dfrac{\cos\gamma_1}{d}\{\alpha_2 l_{12}(\varphi_{12}^d - \varphi_{12}) - v_1 \sin\varphi_{12} + l_{12}\omega_1 + \rho_{12}\sin\gamma_1\} \\ v_2 = \rho_{12} - d\omega_2 \tan\gamma_1 \end{cases} \tag{4}$$

Where, $\rho_{12} = \dfrac{\alpha_1 (l_{12}^d - l_{12}) + v_1 \cos\varphi_{12}}{\cos\gamma_1}$

So we can get the conclusion that as long as the leader's angular velocity, speed, position and sailing directions are designated, the follower can guarantee to sail toward a position with a relative distance l and angle φ to the leader, so as to keep the formation.

2.2 Obstacle Avoidance

The robot may meet some obstacles as sailing, so we mainly consider the formation control in this case. For the leader robot, it will take action to avoid obstacles according to the position and direction when it meets the obstacles. The follower robot will change the relative position with the leader as the leader's position and trajectory changing, and finally pass the area with obstacles by changing the formation. In this part, we use the Artificial Potential Field method to realize the obstacles avoidance of multiple robots.

We use the model of Artificial Potential Field in the paper [11]. In this method, robot is considered as a particle in the potential field. The artificial potential field is composed of the gravity function and the repulsive force function. We build a gravitational potential field in the target location, and a repulsive force potential field around the obstacle. The two potential energy field work together and form a composite artificial potential field. The robot moves to the destination under the influence of the two fields. In math, this motion process can be described as a path without collision that a particle seeks a path to avoid the obstacles in direction of the search potential function falling from the initial position to the target position. The path planned by the potential field method is smooth and safe.

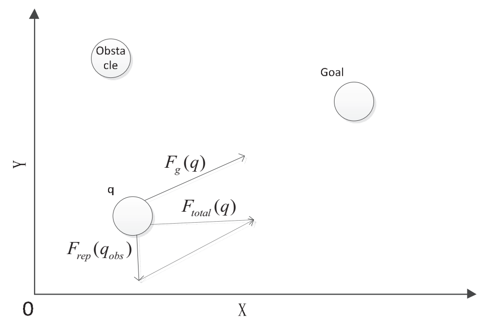

Fig2. Model of the artificial potential field

As shown in figure 2, let q be the position of the robot, $\rho(q,g)$ be the distance between the robot and the target g, the gravitational potential field U_g and gravitation F_g at robot q are defined as:

$$U_g(q)=\frac{1}{2}\xi\rho^2(q,g) \tag{5}$$

$$F_g(q)=\xi\rho(g,q) \tag{6}$$

Let $q_{obsj}\left(j=1,\ldots,m\right)$ be the position of the j^{th} obstacle, $\rho(q,q_{obsj})$ be the distance between robot q and the q_{obsj}, the repulsive potential field $U_{rep}(q)$ and gravitation $F_{rep}(q_{obs})$ at the robot q are defined as:

$$U_{rep}(q)=\begin{cases}\frac{1}{2}\xi\left(\frac{1}{\rho(q,q_{obsj})}-\frac{1}{\rho_s}\right)^2 & if\ \rho(q,q_{obsj})\leq\rho_s\\ 0 & if\ \rho(q,q_{obsj})>\rho_s\end{cases} \tag{7}$$

$$F_{rep}(q_{obs})=\begin{cases}\xi\left(\frac{1}{\rho(q,q_{obsj})}-\frac{1}{\rho_s}\right)^2\frac{1}{\rho^2(q,q_{obsj})} & if\ \rho(q,q_{obsj})\leq\rho_s\\ 0 & if\ \rho(q,q_{obsj})>\rho_s\end{cases} \tag{8}$$

So the resultant force of robot q in the APF is:

$$F_{total}(q)=F_g(q)+\sum_{j-1}^{m}F_{rep}(q_{obsj}) \tag{9}$$

3 TRACKING CONTROL

The robots are considered as a point mass. The leader's path is defined by the artificial potential functions, depending upon location of static obstacles and the goal position. The follower robot will follow the leader by keeping the separation distance l_{ij} and bearing angle φ_{ij}.

In the system given in Figure 1, each robot meets the nonholonomic constraints with pure rolling without sliding. The motion model is given as:

$$\dot{q}_j=\begin{bmatrix}\dot{x}_j\\ \dot{y}_j\\ \dot{\theta}_j\end{bmatrix}=\begin{bmatrix}\cos\theta_j & -d\sin\theta_j\\ \sin\theta_j & d\cos\theta_j\\ 0 & 1\end{bmatrix}\begin{bmatrix}v_j\\ \omega_j\end{bmatrix} \tag{10}$$

Where d is the distance from the rear axle to the front of the robot.

According to the tracking control system which was presented in the literature [12], the tracking control points could be given as formula (11):

$$\begin{cases}\dot{x}_{jr}=v_{jr}\cos\theta_{jr}\\ \dot{y}_{jr}=v_{jr}\sin\theta_{jr}\\ \dot{\theta}_{jr}=\omega_{jr}\end{cases} \tag{11}$$

So: $$\dot{q}_{jr}=\begin{bmatrix}\dot{x}_{jr}\\ \dot{y}_{jr}\\ \dot{\theta}_{jr}\end{bmatrix} \tag{12}$$

So the errors of tracking controller can be expressed as:

$$\begin{bmatrix}e_{j1}\\ e_{j2}\\ e_{j3}\end{bmatrix}=\begin{bmatrix}\cos\theta_j & \sin\theta_j & 0\\ -\sin\theta_j & \cos\theta_j & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}x_{jr}-x_j\\ y_{jr}-y_j\\ \theta_{jr}-\theta_j\end{bmatrix} \tag{13}$$

Where (x_j,y_j,θ_j) are the actual position and orientation of the robot, and $(x_{jr},y_{jr},\theta_{jr})$ are the position and orientation of a virtual trace point of the robot j [11].

The basic tracking control problems can be transformed to formation control. The navigation robot will be placed to the position of trace point.

Suppose j is the followers, and i is the navigation leader. The kinematical equation of the robots can be expressed by formula (14).

$$\begin{bmatrix}\dot{x}_i\\ \dot{y}_i\\ \dot{\theta}_i\end{bmatrix}=\begin{bmatrix}\cos\theta_i & -d\sin\theta_i\\ \sin\theta_i & d\cos\theta_i\\ 0 & 1\end{bmatrix}\begin{bmatrix}v_i\\ \omega_i\end{bmatrix} \tag{14}$$

$$\begin{cases}x_{jr}=x_i-d\cos\theta_j+l_{ij}^d\cos(\varphi_{ij}^d+\theta_i)\\ y_{jr}=y_i-d\sin\theta_j+l_{ij}^d\sin(\varphi_{ij}^d+\theta_i)\\ \theta_{jr}=\theta_i\end{cases} \tag{15}$$

The actual position and orientation of the follower j with respect to leader i can be defined as:

$$\begin{cases}x_j=x_i-d\cos\theta_j+l_{ij}\cos(\varphi_{ij}+\theta_i)\\ y_j=y_i-d\sin\theta_j+l_{ij}\sin(\varphi_{ij}+\theta_i)\\ \theta_j=\theta_j\end{cases} \tag{16}$$

Using (14), (16) and the simple trigonometric identities, the error system can be rewritten as:

$$\begin{bmatrix}e_{j1}\\ e_{j2}\\ e_{j3}\end{bmatrix}=\begin{bmatrix}\cos\theta_j & \sin\theta_j & 0\\ -\sin\theta_j & \cos\theta_j & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}l_{ij}^d\cos(\varphi_{ij}^d+\theta_i)-l_{ij}\cos(\varphi_{ij}+\theta_i)\\ l_{ij}^d\sin(\varphi_{ij}^d+\theta_i)-l_{ij}\sin(\varphi_{ij}+\theta_i)\\ \theta_i-\theta_j\end{bmatrix} \tag{17}$$

After further simplification, the formula (17) becomes as formula (18):

$$e_j = \begin{bmatrix} e_{j1} \\ e_{j2} \\ e_{j3} \end{bmatrix} = \begin{bmatrix} l_{ij}^d \cos(\varphi_{ij}^d + e_{j3}) - l_{ij} \cos(\varphi_{ij} + e_{j3}) \\ l_{ij}^d \sin(\varphi_{ij}^d + e_{j3}) - l_{ij} \sin(\varphi_{ij} + e_{j3}) \\ \theta_i - \theta_j \end{bmatrix} \quad (18)$$

The error system above can be regarded as tracking controller. It can keep the relative distances and angles between the follower and the leader. In order to calculate the system error illustrated as (18), it is necessary to calculate the derivatives of l_{ij} and φ_{ij}, and it is apparent that the desired separation distance l_{ij}^d and the desired bearing angle φ_{ij}^d are constant. Consider the two robots formation as shown in Figure1. The *x* and *y* components of l_{ij} can be defined as

$$\begin{cases} l_{ijx} = x_{irear} - x_{jfront} = x_i - d\cos\theta_i - x_j \\ l_{ijy} = y_{irear} - y_{jfront} = y_i - d\sin\theta_i - y_j \end{cases} \quad (19)$$

After the derivation for (19), it becomes as formula (20):

$$\begin{cases} \dot{l}_{ijx} = v_i \cos\theta_i - v_j \cos\theta_j + d\omega_j \sin\theta_j \\ \dot{l}_{ijy} = v_i \sin\theta_i - v_j \sin\theta_j + d\omega_j \cos\theta_j \end{cases}$$

(20)

Where $l_{ij} = \sqrt{l_{ijx}^2 + l_{ijy}^2}$, $\varphi_{ij} = \arctan\left(\frac{l_{ijy}}{l_{ijx}}\right) - \theta_i + \pi$, we can give derivations for the relative distance and angle. It is similar to the kinematic equation described as formula (2):

$$\begin{cases} \dot{l}_{ij} = v_j \cos\gamma_j - d\omega_j \sin\gamma_j - v_i \cos\varphi_{ij} + d\omega_i \sin\varphi_{ij} \\ \dot{\varphi}_{ij} = \frac{1}{l_{ij}} \{ v_i \sin\varphi_{ij} - v_j \sin\gamma_j - d\omega_j \cos\gamma_j + d\omega_i \cos\varphi_{ij} - l_{ij}\omega_i \} \end{cases} \quad (21)$$

Where $\gamma_j = \varphi_{ij} + e_{j3}$.

Now, by performing derivation for (18), and integrating formula (21), applying simple trigonometric identities, the dynamic errors could be got by formula (22):

$$\begin{bmatrix} \dot{e}_{j1} \\ \dot{e}_{j2} \\ \dot{e}_{j3} \end{bmatrix} = \begin{bmatrix} -v_j + v_i \cos e_{j3} + \omega_j e_{j2} - \omega_i l_{ij}^d \sin(\varphi_{ij}^d + e_{j3}) \\ -\omega_j e_{j1} + v_i \sin e_{j3} - d\omega_j + \omega_i l_{ij}^d \cos(\varphi_{ij}^d + e_{j3}) \\ \omega_i - \omega_j \end{bmatrix} \quad (22)$$

We use the $l-\varphi$ method to realize the formation control. Only the velocity of the robot is taken as the control input. We assume that the robot's velocity is not much high, so when we calculate the control input, we can ignore the dynamic effects. The main objective of this paper is to study the effectiveness of multi-robot formation keeping and obstacle avoidance control in the leader-follower framework. So we ignore the influence of the factors such as nonlinear and disturbances in the process of research. Therefore, the appropriate velocity as the required control input can be calculated by using kinematic controller.

4 SIMULATION OF FORMATION CONTROL

4.1 Simulation of Trajectory Tracking

We will get the position error of the robot in different trajectory tracking of the route: curves and circular. As the illustrating of the simulation results below, we can find that robots can well realize trajectory tracking for curves and circular.

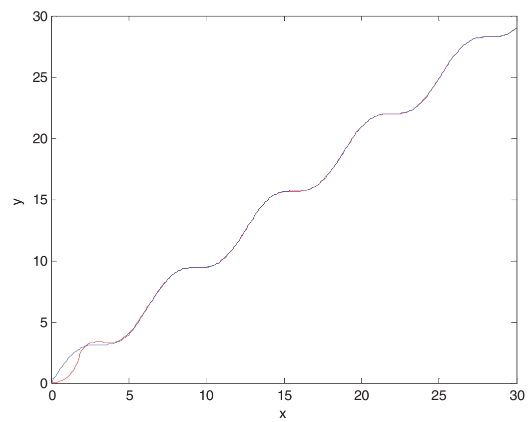

Fig3. Trajectory tracking for curves

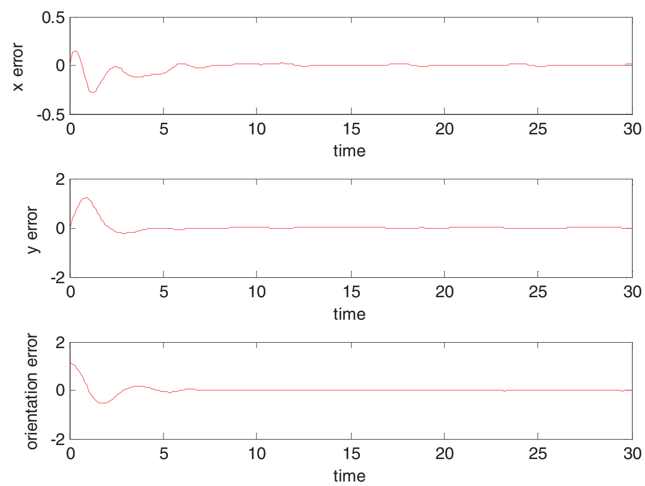

Fig4. Position error of trajectory tracking for curves

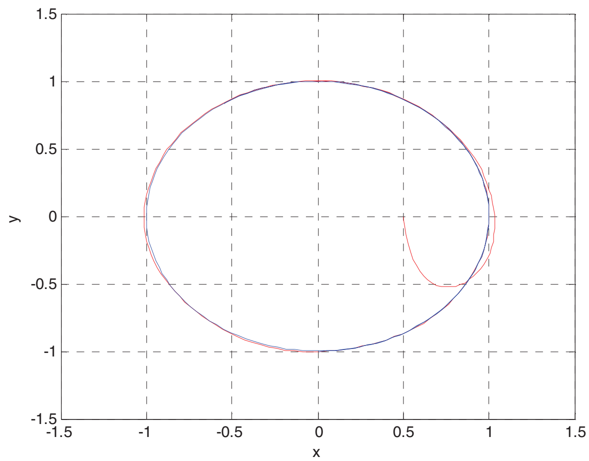

Fig5. Trajectory tracking for circular

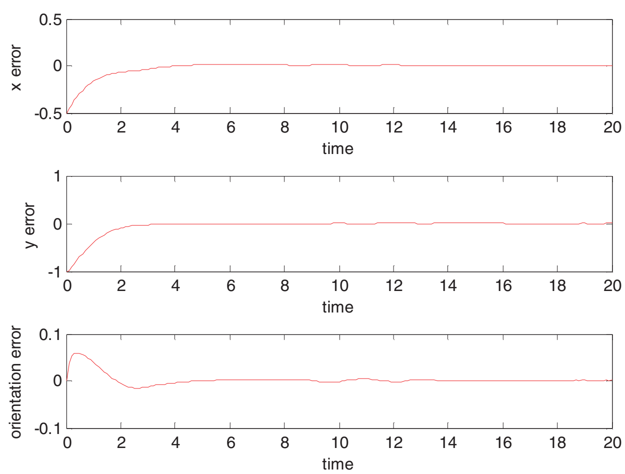

Fig6. Position error of trajectory tracking for circular

4.2 Simulation of Robots Formation and Obstacle Avoidance

For the obstacle avoidance simulation, the leader-follower formation is combined with artificial potential field, and the leading robot is regarded as the only robot in artificial potential field. The other robots follow the leader, and march with formation. The experiment region is a rectangle area of 30*40. The point coordinates of obstacles are [22, 15], [25, 13], [21, 10], [20, 13] respectively, and their radius is 1. The coordinate of the target point is [35, 25], its radius is 1. The next position of the leader is determined by the artificial potential field method. In the region of obstacle, followers will follow the trajectory of the leader with the column to pass this area. When leaving the obstacle region, the followers will recover their original formation to march again. Figure 6 and Figure 7 are the simulation results with two followers and tour followers respectively.

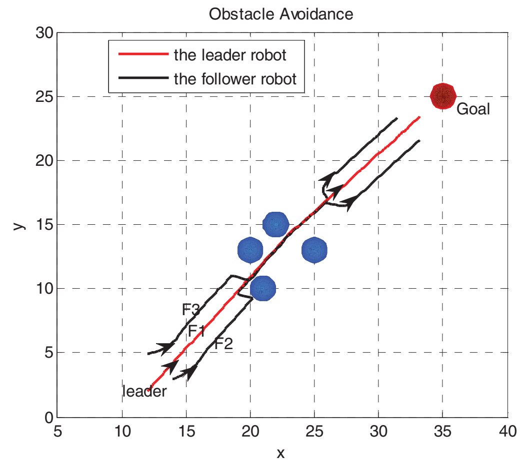

Fig7. Obstacle avoidance with three robots

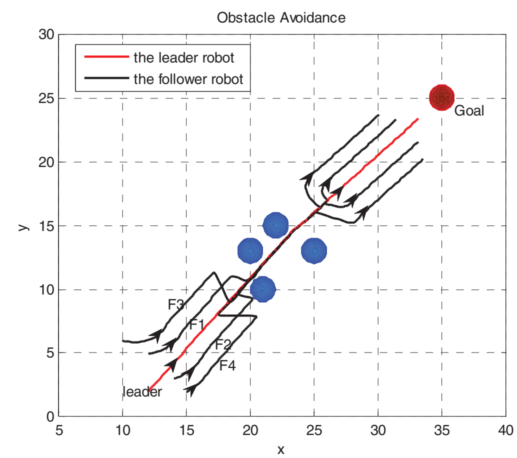

Fig8. Obstacle avoidance with five robots

As shown above, after forming formation of multi-robots, when the leader robot detects the obstacles in the process of navigation with formation, the repulsive potential field force will be formed between the leader and the obstacles, and considering the gravitational potential field force between the leader and the target point, the leader will avoid the obstacles to navigate to the target point under the action of resultant potential field force. According to the trajectory of the leader robot, the formation is changed correspondingly to avoid obstacles. Once through the obstacle region, the robots will regain the formation and continue to voyage to the target point.

5 CONCLUSIONS

Based on the kinematics model of robot, the paper establishes the new system dynamic model of robot formation. The tracking controller with feedback linearization of inputs and outputs was designed. It can be used to transform the tracking control problem into control problem of specific error system. Combined with the obstacle avoidance algorithm of artificial potential field, we can successfully realize the function of formation tracking and obstacle avoidance for multi-robots.

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