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Formation Control of Multiple Mobile Robots Based on Backstepping

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Abstract

Aiming at the formation control problem of multiple mobile robots with incomplete characteristics and the geometric center and the center of gravity do not coincide, the algorithm based on the leader-follower model is improved, and the system pose error kinematics equation is obtained, and then a backstepping method is used to design a Cooperative control formation strategy of multiple mobile robots in a nonlinear system. The feasibility of the algorithm is proved through the analysis of Lyapunov's stability theory. Finally, the formation control was realized through simulation experiments, and the effectiveness of the algorithm was verified.

Keywords

Leader-follower, backstepping method, multiple mobile robots, Lyapunov's stability theory.

1. Introduction

As one of the great inventions of the 20th century, robots have gradually developed from a single mechanical arm structure into a multi-structured and multi-functional robot. The wide application of robots in many fields such as industry and medical treatment greatly reduces people's work pressure[1-5].

In nature and real life, there are various groups, and these groups are generally composed of many individuals. These individuals in the group, while maintaining individual independence, directly or indirectly influence other members of the group in a special way to form a whole, and form a regular formation sequence. These groups composed of multiple simple individuals can not only complete simple tasks that a single individual can complete, but also can complete many tasks that a single individual cannot or are difficult to complete. It is precisely to see the high efficiency, stability, and parallelism of task execution brought by this kind of swarming behavior of animals in the natural world. Experts and scholars in many fields have begun to pay attention and are committed to the research of formation control of multi-agent systems. In recent years, the formation control and collaboration of multi-agents have increasingly become hot topics. The main reasons are as follows: First, with the rapid development of computer technology and artificial intelligence, higher requirements have been placed on intelligent systems, and multi-agent systems have gained a lot of application. Second, the cost of a multi-intelligence system composed of multiple relatively simple agents is much smaller than that of building a large and complex intelligent system. In addition, the research on multi-agent systems has great application value and has a profound influence on the promotion of the development of other disciplines.

When studying the problem of multi-agent formation control, the nonlinear system of robots is often more complicated. It is difficult to directly obtain the controller of the entire system. The Backstepping method is to decompose the system and introduce virtual control variables into

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each subsystem. , Designing the Lyapunov function to obtain the virtual controller of the subsystem, and gradually inversely deducing the real control law of the system, which greatly reduces the complexity of the system design. Therefore, the Backstepping method is widely used in the control process of the multi-robot system. Literature [6] designed a multi-robot collaborative formation method for two-wheel-drive mobile robots using Backstepping ideas. Literature [7] uses the Backstepping method to provide a general chaotic synchronization control method for feedback chaotic systems. The literature [8] studied the uncertain stochastic feedback system of stateless measurement, combined with Backstepping thought, proposed an adaptive fuzzy control method. Literature [9] used Backstepping method to integrate the extended state observer and the nonlinear robust controller for hydraulic systems with model uncertainties that do not match. Literature [10] first analyzed the longitudinal model of the aircraft, and then designed a fuzzy adaptive controller for the hypersonic aircraft using Backstepping. Although the problem of robot formation has been studied for a long time, most of the literature is focused on the characteristics of the linear motion of robots. Reference [11] combined event triggering strategies to study the formation control problem of general linear multi-agent systems. Literature [12] studied the formation control problem of fractional-order multi-agent systems with general linear dynamics. Literature [13] studies the time-varying output formation control problem of a high-order linear cluster system with a directional interactive topology. Literature [14] et al. studied the formation control problem of high-order linear group systems with constraints such as time-varying delays and external disturbances. However, the dynamic equations of many agent systems in the real world do not satisfy linear characteristics. Non-linear systems occupies a large proportion in practical applications. As far as we know, there are few literatures on nonlinear multi-agent systems. Therefore, combining the above-mentioned literature ideas and the design method of the controller, this article focuses on the nonlinear kinematics characteristics of the three-wheeled robot, and studies the multi-agent formation control problem.

2. Robot kinematics model

When considering multiple robot formations, for the convenience of analysis and calculation, it is assumed that all mobile robots have the same robot kinematics model, due to the common use of two-wheel drive mobile robots in daily research. All the research work in this paper is based on a two-wheel drive mobile robot. Its kinematics model is shown in (composed of a trolley with two coaxial driving rear wheels and an auxiliary front wheel, two rear The wheels are driven by two independent motors to provide the required torque; the front wheel is a universal wheel, which can move in any direction without any resistance or restraint to the trolley). In real life, due to the interference of various factors, the robot kinematics model will become complicated. In order to facilitate the research, this article makes several assumptions: 1. Assume that the ground on which the robot walks has suitable friction and the robot will not slip. Case. 2. Since a finished robot is composed of many complex parts, the three-wheeled robot is regarded as a rigid body for analysis. 3. The center of gravity of the three-wheeled robot chassis does not coincide with the geometric center.

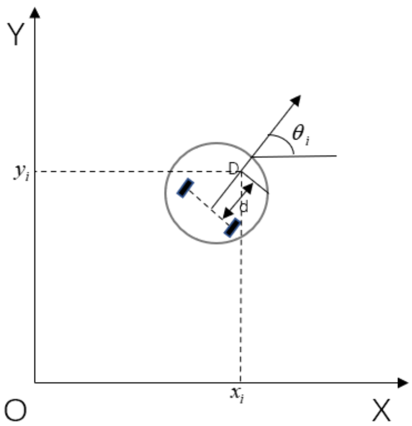

Figure 1. Robot kinematics model

First, take $[x_i, y_i, \theta_i]^T$ as the coordinate position of the robot in the inertial coordinate system OXY, θ_i is the azimuth, That is, the angle between the moving direction of the robot and the X -axis direction.

According to Figure 1, the kinematics model of the robot is

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

v_i and ω_i respectively represent the linear velocity and angular velocity of the robot, d represents the distance between the rear axle of the vehicle and the center of gravity of the vehicle.

3. Leader-follower model

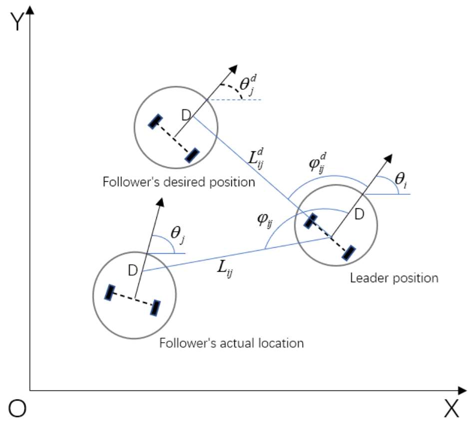

Figure 2. Leader-follower model

The position coordinate of the leader robot in Figure 2 is $[x_i, y_i, \theta_i]^T$, the actual coordinate position of the following robot is $[x_j, y_j, \theta_j]^T$, and the ideal coordinate position of the following robot is $[x_j^d, y_j^d, \theta_j^d]^T$. L_{ij}^d and L_{ij} respectively represent the relative distance between the ideal follower robot and the pilot robot and the relative distance between the actual follower robot and the pilot robot. φ_{ij}^d and φ_{ij} respectively represent the relative rotation angle of the ideal robot and the pilot robot and the relative rotation angle of the actual robot and the pilot robot.

According to the positional relationship between the pilot robot and the follower robot in Figure 2, it can be concluded that the ideal position of the follower robot satisfies the following

$$\begin{cases} x_j^d = x_i - d\cos\theta_i + L_{ij}^d \cos\left(\varphi_{ij}^d + \theta_i\right) \\ y_j^d = y_i - d\sin\theta_i + L_{ij}^d \sin\left(\varphi_{ij}^d + \theta_i\right) \\ \theta_j^d = \theta_i \end{cases} \tag{2}$$

In the same way, the actual position of the following robot can be satisfied

$$\begin{cases} x_j = x_i - d\cos\theta_i + L_j \cos\left(\varphi_{ij} + \theta_i\right) \\ y_j = y_i - d\sin\theta_i + L_j \sin\left(\varphi_{ij} + \theta_i\right) \\ \theta_j = \theta_i \end{cases} \tag{3}$$

According to the position relationship between the pilot robot and the follower robot, the relative distance between the center of the pilot robot's rear axis and the center of gravity of the follower robot can be obtained

$$L_{ij} = \sqrt{{L_{ijx}}^2 + {L_{ijy}}^2} \tag{4}$$

L_{ijx} represents the relative distance between the center of the pilot robot's wheel axis and the center of gravity of the following robot in the X-axis direction, L_{ijy} represents the relative distance between the center of gravity of the leader robot and the center of the wheel axis of the following robot in the Y-axis direction, Therefore, L_{ijx} and L_{ijy} satisfy

$$L_{ijx} = x_i - x_j - d\cos\theta_i \tag{5}$$

$$L_{ijy} = y_i - y_j - d\sin\theta_i$$

Derivation for L_{ij}, L_{ijx} and L_{ijy} respectively, and then put into the type (3) joint, the kinematics model of the leader follower model can be obtained as follows

$$\begin{cases} \dot{L}_{ij} = -v_i \cos\varphi_{ij} + v_j \cos\eta_{ij} + d\omega_j \sin\eta_{ij} \\ \varphi_{ij} = \dfrac{1}{L_{ij}}\left(v_i \sin\varphi_{ij} - v_j \sin\eta_{ij} + d\omega_j \cos\eta_{ij}\right) - \omega_i \end{cases} \tag{6}$$

Where η_{ij} is $\varphi_{ij} + \theta_i - \theta_j$.

In the leader follower control method, the angular velocity and linear velocity of the leader robot are known, and only the acceleration and linear velocity of the follower robot need to be controlled to maintain the desired formation with the leader robot. Choose to follow the position of the robot itself to establish a reference system oxy, Use x_e, y_e, θ_e to represent the distance error and angle error of the following robot and the leader robot in the x-axis direction, y-axis direction and azimuth. Taking Δx, Δy, $\Delta\theta$ as the inertial coordinate system OXY, the distance error between the ideal follower and the actual follower in the X-axis direction, the Y-axis direction and the angle error in the azimuth angle.

According to the geometric relationship

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$$\begin{cases} \Delta x = x_j^d - x_j \\ \Delta y = y_j^d - y_j \end{cases} \tag{7}$$

$$\begin{cases} x_e = \cos\theta_j\left(x_j^d - x_j\right) + \sin\theta_j\left(y_j^d - y_j\right) \\ y_e = -\sin\theta_j\left(x_j^d - x_j\right) + \cos\theta_j\left(y_j^d - y_j\right) \\ \theta_e = \theta_j^d - \theta_j \end{cases} \tag{8}$$

Combining formula 2 and formula 3 can be obtained

$$\begin{cases} x_e = L_{ij}^d \cos\left(\varphi_{ij}^d + \theta_{ij}\right) - L_{ij}\cos\left(\varphi_{ij} + \theta_{ij}\right) \\ y_e = L_{ij}^d \sin\left(\varphi_{ij}^d + \theta_{ij}\right) - L_{ij}\sin\left(\varphi_{ij} + \theta_{ij}\right) \\ \theta_e = \theta_j^d - \theta_j \end{cases} \tag{9}$$

Where $\theta_{ij} = \theta_i - \theta_j$.

When the follower robot and the pilot robot form a formation, they will maintain a fixed formation, that is, the distance and azimuth between the follower robot and the pilot robot will remain unchanged, so $\dot{L}_{ij}^d = 0$ and $\dot{\varphi}_{ij}^d = 0$, Combining equation 3 and equation 4 to obtain the derivative of equation 9 can get the dynamic error equation of the system as

$$\begin{cases} \dot{x}_e = v_i\cos\theta_{ij} + \omega_j y_e - v_j - L_{ij}^d\omega_i\sin\left(\varphi_{ij}^d + \theta_{ij}\right) \\ \dot{y}_e = v_i\sin\theta_{ij} + \omega_j x_e - d\omega_j + L_{ij}^d\omega_i\cos\left(\varphi_{ij}^d + \theta_{ij}\right) \end{cases} \tag{10}$$

4. Controller design based on backstepping method

Backstepping is a method that combines the design of the control law with the selection of Lyapunov functions. It decomposes the nonlinear system into several subsystems, introduces virtual control variables for each subsystem and designs the corresponding Lyapunov function , And then gradually reverse the integration, and finally design the real controller of the entire system.

For system (10),the first step is to design the feedback control input ω_j and select the stabilization y_e

$$\omega_j = \left(k_2 y_e + v_i\sin\theta_{ij} - \omega_j x_e + L_{ij}^d\cos\left(\varphi_{ij} + \theta_{ij}\right)\right)/d \tag{11}$$

Can get $\dot{x}_e = -k_2 y_e - \omega_j x_e$.

Choose the Lyapunov function as $V_1 = \frac{1}{2}y_e^2$ and derive

$$\dot{V}_1 = -k_2 y_e^2 - \omega_j x_e y_e \tag{12}$$

when $x_e = 0$, then y_e is asymptotically stable.

In the second step, the Lyapunov function is selected as $V_2 = \frac{1}{2}x_e^2 + \frac{1}{2}y_e^2$ in the same way, and the derivative can be obtained

$$\dot{V}_2 = -k_1 x_e^2 + y_e \left(v_i \sin\theta_{ij} - \omega_j x_e - d\omega_j + L_{ij}^d \omega_i \cos\left(\varphi_{ij} + \theta_{ij}\right)\right) \tag{13}$$

Select control input $v_j = v_i \cos\theta_{ij} - L_{ij}^d \omega_i \sin\left(\varphi_{ij} + \theta_{ij}\right) + k_1 x_e$,get $\dot{V}_2 = -k_1 x_e^2 - k_2 y_e^2$ .This can show that system (10) is progressively stable.

The controller obtained in summary is

$$\begin{cases} v_j = v_i \cos\theta_{ij} - L_{ij}^d \omega_i \sin\left(\varphi_{ij} + \theta_{ij}\right) + k_1 x_e \\ \omega_j = \left(k_2 y_e + v_i \sin\theta_{ij} - \omega_j x_e + L_{ij}^d \cos\left(\varphi_{ij} + \theta_{ij}\right)\right) / d \end{cases} \tag{14}$$

The obtained closed-loop error system is

$$\begin{cases} \dot{x}_e = -k_1 x_e + \omega_j y_e \\ \dot{y}_e = -k_2 y_e - \omega_j x_e \end{cases} \tag{15}$$

Here k_1 and k_2 y are always larger than zero.

5. Stability analysis

In order to prove that the dynamic error system is asymptotically stable under the action of the controller and the tracking error converges to zero, Choose the Lyapunov function $V(t) = \frac{1}{2} x_e^2 + \frac{1}{2} y_e^2$. At this time $V(t) \geq 0$, when there is only $t = 0$, $V(t) = 0$. Take the derivative of the Lyapunov function to get $\dot{V}(t) = -k_1 x_e^2 - k_2 y_e^2 \leq 0$.

Because $V(t) \geq 0$, $\dot{V}(t) \leq 0$, it can be known from the Barbalat theorem that when $t \to \infty$ is $\dot{V}(t) \to 0$, then $t \to \infty$, $x_e \to 0$, $y_e \to 0$ can be obtained. It can ensure that the closed-loop error system is gradually stable under the action of the controller, and the tracking error converges to zero.

6. Simulation result analysis

In order to prove the effectiveness of the above tracking controller, for the sake of simplicity, a leader and four followers were selected to implement trajectory tracking. When forming a formation, set $k_1 = 1.5$ and $k_2 = 3$. The initial pose of the navigator robot $R_i = (1, 0, \pi/2)$, $v_i = 3$, $\omega_i = 2$. The simulation results obtained are as follows:

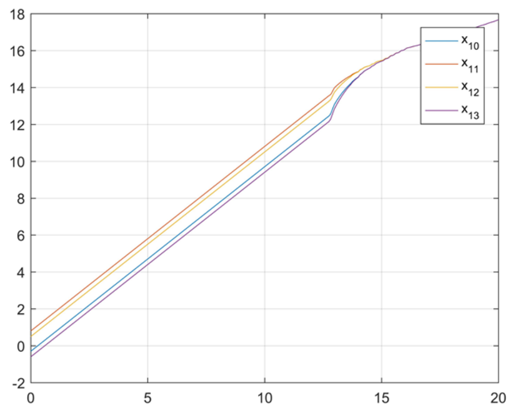

Figure 3. Formation shape

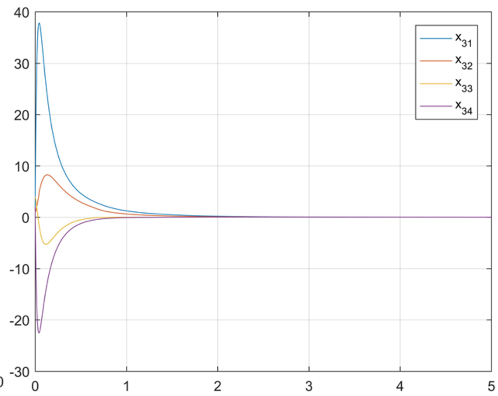

Figure 5. Formation position error

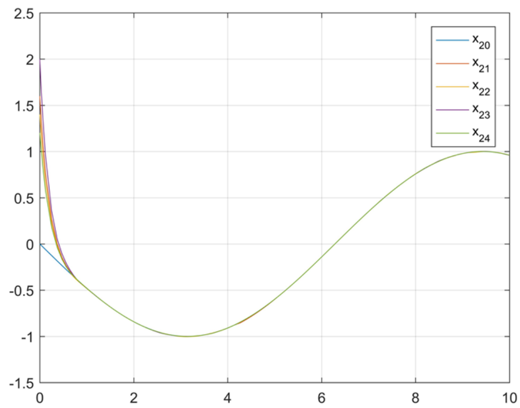

Figure 4. Formation azimuth

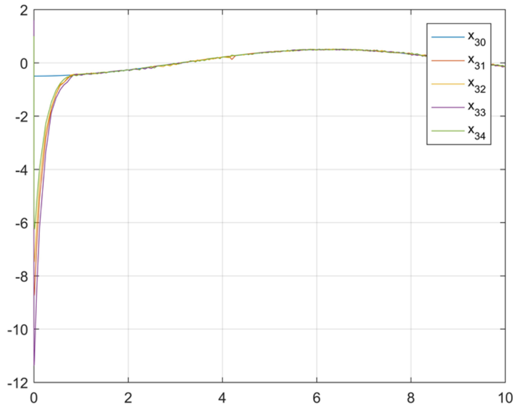

Figure 6. Azimuth error

Figure 3 shows the formation of each robot. It can be seen that the follower robot and the leader robot can form a good formation. Figure 4 shows the change of the azimuth angle of the entire formation. The azimuth angle of each tracking robot will eventually be consistent with the azimuth angle of the leader robot over time. Figures 5 and 6 are the position error and azimuth error diagrams of the system. It can be seen that under the action of the controller, the position and angle tracking errors can converge to zero over time, indicating that the system gradually reaches stability. Prove that the controller can effectively control.

7. Conclusion

This paper studies the formation control of three-wheeled robots based on the backstepping method, and proposes a new robot formation control strategy. Through the simulation experiment, it can be known that under the action of the controller, the robots gradually form an ideal formation, and maintain the formation movement with a very small error. The next step will be to study the formation control of multiple mobile robots in intermittent communication, formation avoidance and other aspects.

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