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Sliding Mode Variable Structure Based Path Following Control of Agricultural Robots with Differential Drive

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Abstract: It is difficult to establish the precise mathematical model of agricultural wheeled robots with differential drive for path tracking control, due to characteristics of nonlinear, strong coupling and multivariable. Here, path tracking control is studied for agricultural wheeled robot with differential drive based on sliding mode variable structure. Firstly, the motion model of agricultural wheeled robots with differential drive is established and control goal is determined for path tracking. Then, sliding mode variable structure is applied to design the controller. Finally, tracking simulations were conducted with circle and sine curves to verify the controller's performance, and further real tests were carried out on a circle with a radius of 7 m at a test field. The simulations show that the robot can asymptotically stabilize the given trajectory when there is external interference, and the real tests indicate a good tracking performance with a maximum tracking of 0.21 m. The effectiveness of sliding mode controller is verified for trajectory tracking control of agricultural wheeled robots with differential drive.

Keywords: Agricultural robots; differential drive; path following; tracking control; sliding mode variable structure.

1. INTRODUCTION

The use of agricultural robots has become the development direction of modern agriculture to save labour and reduce labour intensity (Bechar and Vigneault, 2017). And trajectory tracking is one of the most important research fields of agricultural robots (Li et al., 2015). The accuracy of trajectory tracking affects the quality of agricultural robot's task.

Some researchers have carried out a thorough study on tracking control of agricultural robots (Dørum et al., 2015; Fang et al., 2006). The existing tracking control methods mainly include linear feedback (Yaghmaie et al, 2012), backstepping (Hou et al., 2009), calculation moment control method (Zelei et al., 2011; Kayacan et al., 2014), and intelligent control method (Mohanty and Parhi, 2014) and so on. Among the above control methods, the linear feedback method is a common control method, but the control precision is low when the model of the robot is nonlinear and the reference trajectory is nonlinear too. And the design process of the controller based on the backstepping method is complicated and the cost is high, it is difficult to meet the real-time needs of the control of agricultural robots. The calculation moment method depends on the dynamic model of the controlled robot, but the dynamic modelling is a very complex work. The intelligent control makes the control system design no longer dependent on the mathematical model and the motion of the control system.

The agricultural wheeled robots with differential drive have the characteristics of nonlinear, strong coupling and multivariable (Xi et al., 2014). It is difficult to establish the precise mathematical model of the controlled robots. Also, the complexity of agricultural environment makes the uncertainty of the tracking process, such as parameter perturbation and load disturbance, which will cause the trajectory of the mobile robot to deviate from the ideal path (Jiao et al., 2015). Therefore, it is difficult to achieve path tracking control with high precision by using the control methods mentioned above. But, sliding mode variable structure control is not dependent on the precise mathematical model of the controlled object, and it has the advantages of fast response, insensitivity to parameters and environmental changes (Niu et al., 2013). It is suitable for the control of agricultural robots operating in the complex agricultural environment.

The purpose of this paper is to study the path tracking control of agricultural wheeled robots with differential drive by designing a trajectory tracking controller based on sliding mode variable structure. Then tracking simulations and real tests were conducted to verify the performance of the designed controller.

2. KINEMATICS MODEL OF AGRICULTURAL ROBOTS WITH DIFFERENTIAL DRIVE

For an agricultural robot with differential drive, its mechanical structure consists of a robot body and a driving wheel on both sides (Fig. 1), and the same side drive wheel is driven by the same motor controller. It is a two-wheel drive with nonholonomic constraints, which satisfies the following equation:

$$\frac{\dot{y}}{\dot{x}} = \tan\theta \tag{1}$$

where x, y and θ mean the Cartesian coordinates and the posture of the robot. When the speed of the left and right driving wheels is different, differential steering can be

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realized. In theory, the two-wheel drive mobile robots are generally assumed that the wheels are only pure rolling but not skidding. Therefore, the kinematic model of a two-wheel drive mobile robot can be obtained according to the rigid body mechanics method. The kinematics equations of the robot are as follows:

$$\dot{\boldsymbol{P}} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} = Jq \tag{2}$$

where $P=[x, y, \theta]^T$ represents the position and posture of the robot, $q=[v,\omega]^T$ are the control input of the robot, and J is the Jacobian matrix of the robot. Therefore, the position and posture of the robot can be obtained or changed as long as the linear velocity and angular velocity of the robot can be controlled.

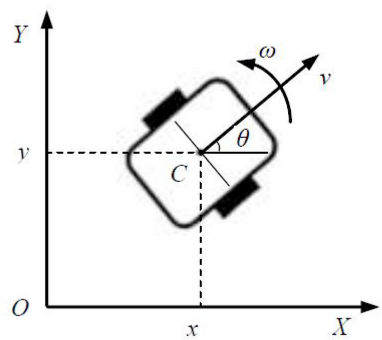

Fig. 1 Schematic figure of a two-wheel drive robot

3. TRAJECTORY TRACKING CONTROL

The reference trajectory from a reference robot is described in Fig. 2. Its motion of the reference robot must also satisfy the nonholonomic constraints (Pourboghrat and Karlsson, 2002), that is, the kinematic model of reference robot is expressed as the following equation:

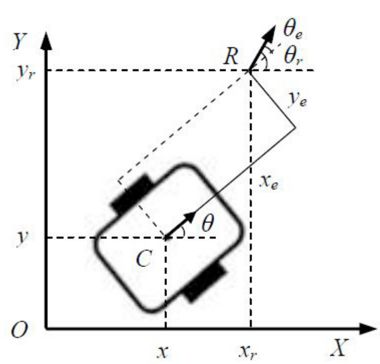

Fig. 2 Trajectory tracking

$$\dot{P}_{\mathrm{r}} = \begin{bmatrix} \cos\theta_r & 0 \\ \sin\theta_r & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_r \\ \omega_r \end{bmatrix} = J_r \cdot q_r \tag{3}$$

where $P_r=[x_r, y_r, \theta_r]^T$ represents the position and posture of the reference robot, $q_r=[v_r, \omega_r]^T$ are the control input of the reference robot, v_r is the linear velocity of its reference robot, ω_r is the angle velocity of the reference robot, and J_r is the Jacobian matrix of the reference robot.

The goal of trajectory tracking control is to design the appropriate control v and ω, so that tracking error tends to zero as the following equation:

$$\lim_{t\to\infty}[|x_r - x| + |y_r - y| + |\theta_r - \theta|] = 0 \tag{4}$$

Define the following transformations:

$$P_e = \begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} = T \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \tag{5}$$

where $P_e=[x_e, y_e, \theta_e]$ represents the transformed tracking error of the robot, and the transformation matrix T is a global differential homeomorphism. When $(x_e, y_e, \theta_e) = (0,0,0)$, it is equivalent to x_r-x=0, y_r-y=0, θ_r-θ=0. So, we can equivalently transform the control target (4) into the following equation.

$$\lim_{t\to\infty}[|x_e(t)| + |y_e(t)| + |\theta_e(t)|] = 0 \tag{6}$$

Differentiate (5), and the following error system is obtained by using (2) and (3):

$$\begin{aligned} \dot{x}_e &= (\dot{x}_r - \dot{x})\cos\theta + (\dot{y}_r - \dot{y})\sin\theta - (x_r - x)\dot{\theta}\sin\theta \\ &\quad + (y_r - y)\dot{\theta}\cos\theta \\ &= \omega y_e - v + v_r\cos\theta_e \\ \dot{y}_e &= -(\dot{x}_r - \dot{x})\sin\theta + (\dot{y}_r - \dot{y})\cos\theta - (x_r - x)\dot{\theta}\cos\theta \\ &\quad - (y_r - y)\dot{\theta}\sin\theta \\ &= -\omega x_e + v_r\sin\theta_e \\ \dot{\theta}_e &= \dot{\theta}_r - \dot{\theta} = \omega_r - \omega \end{aligned}$$

Then have:

$$\begin{cases} \dot{x}_e = \omega y_e - v + v_r\cos\theta_e \\ \dot{y}_e = -\omega x_e + v_r\sin\theta_e \\ \dot{\theta}_e = \omega_r - \omega \end{cases} \tag{7}$$

Under the new state variables (x_e, y_e, θ_e), the trajectory tracking problem of the nonholonomic mobile robot is converted to the stabilization problem of the tracking error model (7), that is, the appropriate control input with v and ω is designed to stabilize the nonlinear system (7), making the tracking error (x_e, y_e, θ_e) tending to 0.

4. CONTROLLER DISIGN

The structure of the trajectory tracking control system of the mobile robot is shown in Fig. 3. The input of the system is reference position and posture P_r and reference speed vector q_r. The output of the system is the position and posture P of the robot at present. The system controller obtains the control speed vector q of the robot based on the position error P_e of the system and the reference speed vector q_r. Then, the position and posture P of the current moment are obtained through the kinematic equation and integration operation, and the control is repeated so that the system is controlled again and again. Finally, the posture error P_e of the system tends to zero.

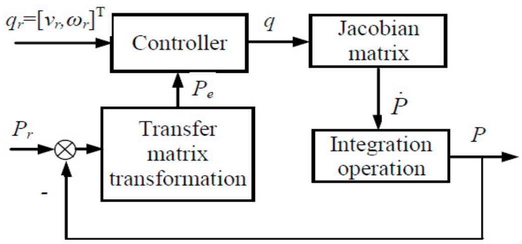

Fig. 3 Structure of the control system

Set the switching function s

$$s=\theta_e \tag{8}$$

Taking the law of exponential convergence

$$\dot{s}=-k_1\,\mathrm{sgn}\,s-k_2 s \tag{9}$$

Among them, k_1>0, k_2>0.

Define control law q

$$q=\begin{pmatrix} v \\ \omega \end{pmatrix}=\begin{pmatrix} y_e\omega+v_r\cos\theta_e+k_3x_e+k_3{y_e}^2x_e \\ \omega_r+k_1\,\mathrm{sgn}\,s+k_2 s \end{pmatrix} \tag{10}$$

where k_3>0.

Then stability analysis of the control system was done. Design the Lyapunov function V

$$V=\frac{1}{2}x_e^2+\frac{1}{2}\theta_e^2 \tag{11}$$

So, have

$$\dot{V}=x_e\dot{x}_e+\theta_e\dot{\theta}_e$$

Combine (8) and (9), have

$$\dot{V}=x_e(y_e\omega-v+v_r\cos\theta_e)+s\dot{s}$$
$$=x_e[y_e\omega-(y_e\omega+v_r\cos\theta_e+k_3x_e+k_3y_e^2x_e)+v_r\cos\theta_e]$$
$$-k_1|s|-k_2s^2$$
$$=-k_3x_e^2-k_3y_e^2x_e^2-k_1\,|\,s\,|-k_2s^2$$

When k_1, k_2 and k_3 are all positive numbers, the control system is globally asymptotically stable under the control law (10).

5. SIMULATIONS AND TESTS

To verify the control performance of the control algorithm, the MATLAB software was used to simulate the trajectory tracking with a circular trajectory and a curve trajectory as the reference trajectory of a reference robot respectively. Then real tests were done on an agricultural robot with differential drive tracking a circle.

5.1 Simulations

5.1.1 Circular tracking

It is assumed that the tracking trajectory is a circular curve with a tracking velocity of 0.5 m/s and an angular velocity of 1.0 rad/s. The given circular trajectory P_r=[x_r, y_r, θ_r]^T is expressed as

$$\begin{cases} x_r=2\cos t \\ y_r=2\sin t \\ \theta_r=t \end{cases}$$

Set the parameters k_1=50, k_2=1, k_3=50, and the initial position of the robot is [1.5 0 0]. According to the control law (10), we obtained the position errors, control input and tracking trajectory of the controlled robot, as shown in Fig. 4-6.

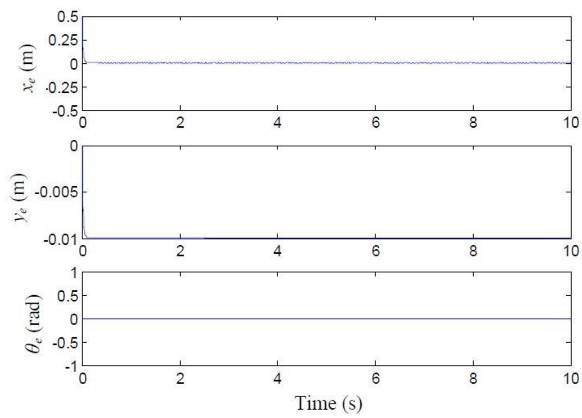

Fig. 4 Errors of tracking position and posture

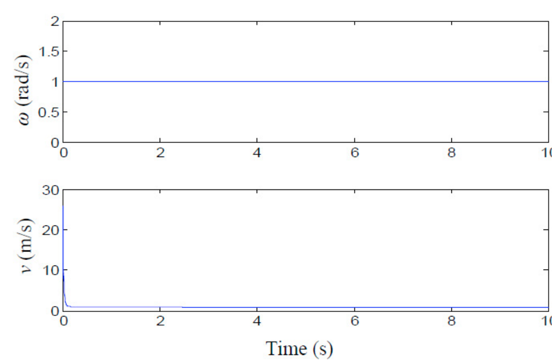

Fig. 5 Control input

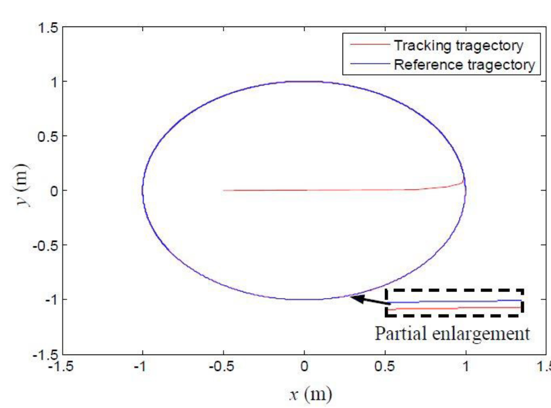

Fig. 6 Tracking trajectory and error

From Fig. 4, the control errors trends to 0, which accords to the control target (6). And from Fig. 6, it indicates good trajectory performance with a maximum trajectory error of 0.01 m.

5.1.2 Curve tracking

With a tracking velocity of 0.5 m/s and an angular velocity of 1.0 rad/s, the given circular trajectory $P_r=[x_r,\ y_r,\ \theta_r]^T$ is expressed as

$$\begin{cases} \dot{x}_r = v_r \cos t \\ \dot{y}_r = v_r \sin t \\ \dot{\theta}_r = \omega_r = t \end{cases}$$

Set the parameters k_1=50, k_2=1, k_3=50, and the initial position of the robot is [1.5 0 0]. According to the control law (10), we obtained the position errors, control input and tracking trajectory of the controlled robot, as shown in Fig. 7-9.

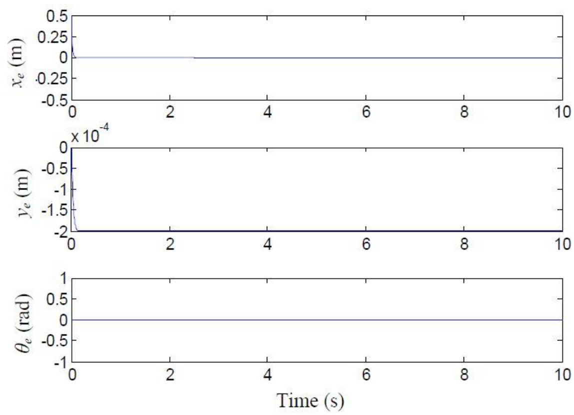

Fig. 7 Errors of tracking position and posture

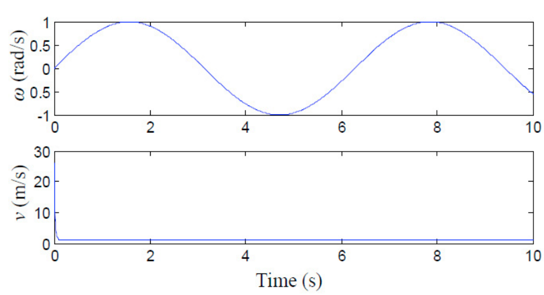

Fig. 8 Control input

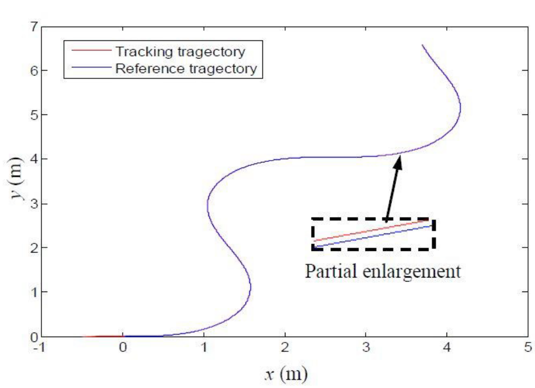

Fig. 9 Tracking trajectory and error

From Fig. 7, the control errors trends to 0, which also accords to the control target (6). And from Fig. 9, it shows good trajectory performance with a maximum trajectory error of 2 $\times 10^{-4}$ m.

5.2 Tests

Tests of tracking circle were carried out on an agricultural robot with differential drive at a test field in the agricultural machinery appraisal station of Nanjing Agricultural University, as shown in Fig. 10. With a radius of 5 m, the tracking circle can be expressed as

$$\begin{cases} x_r = 14 \cos t \\ y_r = 14 \sin t \\ \theta_r = t \end{cases}$$

The robot is driven by a host controller of a laptop and a slave controller of a Basic Atom microcontroller. An RTK-GPS receiver of S86T GPS was mounted on the robot platform to record the tracking trajectory in intervals of 0.2 s. The initial position of the robot is [5 0 0]. The initial speeds of two side wheels are all 0 with a maximum speed of 2 m/s.

Fig. 11 is the results of circle tracking, it shows a good tracking performance, although with a maximum tracking error of 0.21 m due to the influence of centrifugal force and sideslip on a little wet ground.

Fig. 10 Test scene

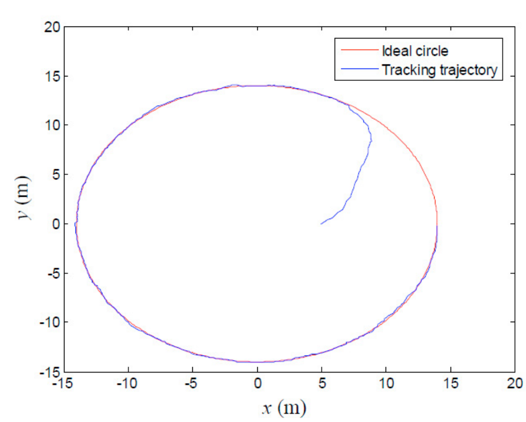

Fig.11 Results of tracking tests

6. CONCLUSIONS

Path tracking control is presented with sliding mode variable structure for agricultural wheeled robots with differential drive. Then we track and simulate the two tracks of circle and sine curve. The experiment shows that the robot can asymptotically stabilize the given trajectory when there is external interference. The effectiveness of sliding mode controller in trajectory tracking control of wheeled differential drive agricultural robot is verified.

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