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Path tracking control for a wheeled mobile robot by integrating neural dynamics with adaptive approach

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Abstract: A path tracking control method for a wheeled mobile robot is presented, which combines adaptive approach and neural dynamics to force the robot to track a predefined path. A kinematic controller is introduced to the mobile robot; the control law of which is developed by the model reference adaptive method for ensuring the robot velocity asymptotically approaching to the desired velocity in uncertain system dynamics. To handle the jump-problem between speed and torque, a neural dynamic model is integrated with the above mentioned controls scheme; the stability of the combined system is analyzed by using Lyapunov theory. Simulation results illustrate the effectiveness of the proposed control scheme.

Key words: wheeled mobile robot; path tracking; model reference adaptive; neural dynamics

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基于自适应和神经动力学的轮式移动机器人路径跟踪控制

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摘要: 本文提出一种自适应和神经动力学相结合的轮式移动机器人路径跟踪控制方法. 首先, 设计运动学控制器用来获得机器人期望速度; 其次, 考虑机器人动力学模型参数的不确定性, 利用模型参考自适应方法来设计动力学控制规律, 使得机器人实际速度渐近逼近期望值; 再次, 为克服速度和力矩的跳变, 加入神经动力学模型对控制器进行优化, 并且通过Lypunov理论来证明整个控制系统的稳定性; 最后仿真结果表明该控制方法的有效性.

关键词: 轮式移动机器人; 路径跟踪; 模型参考自适应; 神经动力学

中图分类号: TP24 **文献标识码**: A

1 Introduction

Over the last decade, a lot of interest has been devoted to path tracking control of nonholonomic wheeled mobile robots(WMR). Many studies have been carried on in this field. Such studies have been divided into two main portions: one utilizes the kinematic path tracking controller to achieve only tracking issue, while the other one, which considers dynamic model of robot, is being adopted. In [1,2], a fuzzy controller was designed to realize tracking control for mobile robots. A sliding mode control scheme[3] was proposed to solve the path tracking problem based on the exact discrete time model of the robot. Do and Pan[4] proposed an output feedback controller for tracking a predefined path. However, these controllers considered only the kinematic model of the nonholonomic WMR.

Some researchers focused on solving the tracking control problem taking the dynamic model into account, even the uncertainties in the model. A new method[5] combining Kalman-based active observer controller and input-output feedback linearization was presented for path tracking. In [6,7], an adaptive controller obtained by analyzing Lyapunov function was proposed for mobile robot to attenuate the effects of the uncertainties and disturbances. But these control laws did not solve the speed and torque jump problem generated by initial errors between real posture and given path.

In this paper, considering the kinematic and dy-

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namic model, the path tracking problem of mobile robots is addressed by using adaptive technique and neural dynamics. The simulation results show that the presented controller can guide the robot to track a reference path with a quite small error.

2 Background

In this section, the model of a nonholonomic mobile robot is briefly introduced. Then, a typical neural dynamics model is presented.

2.1 Mobile robot model

The mobile robot with two independent driven wheels is shown in Fig.1. O-XY is the world coordinate system and C-$X'Y'$ is the coordinate system fixed to the mobile robot. The mass center C of robot is located in the middle of the driving wheels. r is the radius of rear wheels and l is the distance of rear wheels. m is the mass of the body, I is the moment of inertia of the body about the vertical axis through C.

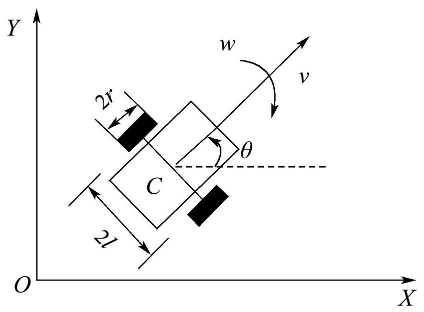


Fig. 1 Model of mobile robot

The kinematic model for the mobile robot under the nonholonomic constraint of pure rolling and nonslipping is given as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix} = S(q)\vec{v}(t), \tag{1}$$

where $q = [x\ y\ \theta]^{\mathrm{T}}$ is actual posture of robot, (x, y) are the coordinates of C, θ is the orientation angle of robot. $S(q) \in \mathbb{R}^{3\times2}$ and $\vec{v} \in \mathbb{R}^{2\times1}$ represent the full rank velocity transformation matrix and velocity vector. v and w are linear and angular velocity of mobile robot.

Note that the mobile robot has the nonholonomic constraint, where the driving wheels roll purely and do not slip, i.e.

$$A(q)\dot{q} = 0, \tag{2}$$

where $A(q) = [-\sin\theta\quad \cos\theta\quad 0]$.

The dynamic equations of the simple model of the mobile robot can be described as

$$\bar{M}(q)\dot{\vec{v}} = \bar{B}\tau, \tag{3}$$

where $\tau = [\tau_{\mathrm{l}}\ \tau_{\mathrm{r}}]^{\mathrm{T}}$ consists of motors' torque τ_{l} and τ_{r}, which act on the left and right wheels, respectively.

Assuming $\tau_1 = \dfrac{1}{r}(\tau_{\mathrm{l}}+\tau_{\mathrm{r}})$, $\tau_2 = \dfrac{l}{r}(\tau_{\mathrm{l}}-\tau_{\mathrm{r}})$, Eq.(3) becomes

$$\bar{M}(q)\dot{\vec{v}} = \bar{\tau}, \tag{4}$$

where $\bar{\tau} = [\tau_1\quad \tau_2]^{\mathrm{T}}$ are linear and angular torques, respectively. $\bar{M}$ and $\bar{B}$ are selected as

$$\bar{M} = \begin{bmatrix} m & 0 \\ 0 & I \end{bmatrix},\ \bar{B} = \frac{1}{r}\begin{bmatrix} 1 & 0 \\ l & -l \end{bmatrix}.$$

2.2 Neural dynamics model

Neural dynamic model describes the real-time adaptive behavior of individuals to complex and dynamic environment contingencies and has been applied in many areas, such as biological, machine vision, robotics and so on. A typical model is described as[8]:

$$\frac{\mathrm{d}\xi_i}{\mathrm{d}t} = -A\xi_i + (B - \xi_i)S_i^+ - (D + \xi_i)S_i^-, \tag{5}$$

where ξ_i is the membrane potential of the ith neuron. A represents the passive decay rate. B and D are the upper and lower bounds of the membrane potential. S_i^+ and S_i^- are excitatory and inhibitory inputs, respectively, which are defined as

$$\begin{cases} S_i^+(x) = \max(0, x), \\ S_i^-(x) = \max(0, -x). \end{cases} \tag{6}$$

The neural dynamics characterized by (5) is restricted to a bounded interval $[-D,\ B]$ for any excitatory and inhibitory inputs. The model is a continuous differential equation, and its output are continuous and smooth.

3 Problem statement

In general, the path tracking problem of mobile robot aims at tracking a given path $\varGamma$ in a horizontal plane parameterized by $q_{\mathrm{r}} = [x_{\mathrm{r}}(s)\ y_{\mathrm{r}}(s)\ \theta_{\mathrm{r}}(s)]^{\mathrm{T}}$ with s being the path parameter, see Fig.2. Therefore we define the errors between the actual and desired postures as

$$\bar{q} = q_{\mathrm{r}} - q = \begin{bmatrix} x_{\mathrm{r}} - x \\ y_{\mathrm{r}} - y \\ \theta_{\mathrm{r}} - \theta \end{bmatrix} = \begin{bmatrix} x_{\mathrm{e}} \\ y_{\mathrm{e}} \\ \theta_{\mathrm{e}} \end{bmatrix}, \tag{7}$$

where $\theta_{\rm r} = \arctan(y_{\rm r}'(s)/x_{\rm r}'(s))$ with $\cdot'$ denoting $\dfrac{\partial\cdot}{\partial s}$ is the reference angular.

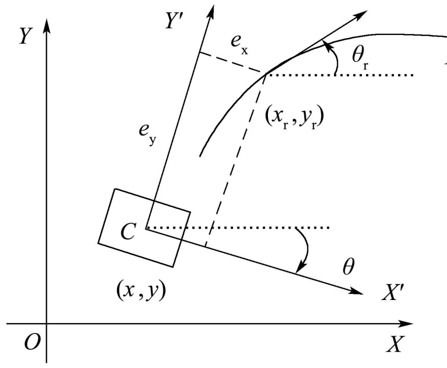


Fig. 2 Posture error coordinate

Then, the posture error $e_{\rm p}$ described in the frame of the real robot can be expressed as:

$$e_{\rm p} = \begin{bmatrix} e_{\rm x} \\ e_{\rm y} \\ e_\theta \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_{\rm e} \\ y_{\rm e} \\ \theta_{\rm e} \end{bmatrix} = T_{\rm e}(q_{\rm r} - q), \tag{8}$$

where $T_{\rm e}$ is transformation matrix.

The new tracking errors $(e_{\rm x}, e_{\rm y}, e_\theta)$ defined in (8) are: $e_{\rm x}$ is the tangential tracking error, $e_{\rm y}$ is the cross-tracking error, and e_θ is the heading error. Differentiating Eq.(8), we have

$$\dot{e}_{\rm p} = \begin{bmatrix} \dot{e}_{\rm x} \\ \dot{e}_{\rm y} \\ \dot{e}_\theta \end{bmatrix} = \begin{bmatrix} we_{\rm y} - v + v_{\rm r}\cos e_\theta \\ -we_{\rm x} + v_{\rm r}\sin e_\theta \\ w_{\rm r} - w \end{bmatrix}, \tag{9}$$

where $v_{\rm r}$ and $w_{\rm r}$ are reference linear and angular velocities of the mobile robot on the path, which are defined as[4]:

$$\begin{aligned} v_{\rm r} &= \sqrt{x_{\rm r}'^2(s) + y_{\rm r}'^2(s)}\dot{s}, \\ w_{\rm r} &= \frac{x_{\rm r}'(s)y_{\rm r}''(s) - x_{\rm r}''(s)y_{\rm r}'(s)}{x_{\rm r}'^2(s) + y_{\rm r}'^2(s)}\dot{s}. \end{aligned} \tag{10}$$

Therefore, the tracking problem is to find a feedback control law to force the robot to track the reference path precisely such that tracking error $e_{\rm p} = [e_{\rm x}\ e_{\rm y}\ e_\theta]^{\rm T}$ tends to zero.

4 Controller design

In this Section, considering the model of mobile robot, a kinematic tracking controller is firstly designed and then a model reference adaptive dynamic control law is proposed. At last, the neural dynamics model is integrated into the presented approach.

4.1 The kinematic controller

It is necessary to find the appropriate velocity control law $\vec{v}_{\rm c} = [v_{\rm c}\ w_{\rm c}]^{\rm T}$, such that $q \to q_{\rm r}$ as $t \to \infty$. Using the nonlinear control theory, we consider the following Lyapunov function candidate[9]:

$$V_1 = \frac{1}{2}(e_{\rm x} + e_{\rm y})^2 + \frac{1 - \cos e_\theta}{k_2}, \tag{11}$$

Then, the derivative of V_1 is

$$\begin{aligned} \dot{V}_1 &= e_{\rm x}\dot{e}_{\rm x} + e_{\rm y}\dot{e}_{\rm y} + \frac{\dot{e}_\theta \sin e_\theta}{k_2} = \\ & e_{\rm x}(we_{\rm y} - v_{\rm c} + v_{\rm r}\cos e_\theta) + e_{\rm y}(-w_{\rm c}e_{\rm x} + v_{\rm r}\sin e_\theta) + \\ & \frac{(w_{\rm r} - w_{\rm c})\sin e_\theta}{k_2} = \\ & -e_{\rm x}(v_{\rm c} - v_{\rm r}\cos e_\theta) - \frac{\sin e_\theta}{k_2}(w_{\rm c} - w_{\rm r} - k_2 e_{\rm y} v_{\rm r}), \end{aligned} \tag{12}$$

Choose

$$\begin{cases} v_{\rm c} = k_1 e_{\rm x} + v_{\rm r}\cos e_\theta, \\ w_{\rm c} = w_{\rm r} + k_2 e_{\rm y} v_{\rm r} + k_3 \sin e_\theta. \end{cases} \tag{13}$$

where k_1, k_2 and k_3 are positive constants. Then (12) becomes

$$\dot{V}_1 = -k_1 e_{\rm x}^2 - \frac{k_3 \sin^2 e_\theta}{k_2} \leqslant 0, \tag{14}$$

So the kinematic model (1) is asymptotically stable. Where $v_{\rm r}, w_{\rm r}$ are reference linear and angular velocity of robot. The objective of such a controller is to generate the desired velocities $\vec{v}_{\rm c} = [v_{\rm c}\ w_{\rm c}]^{\rm T}$ of robot for the dynamic controller, as shown in Fig.3.

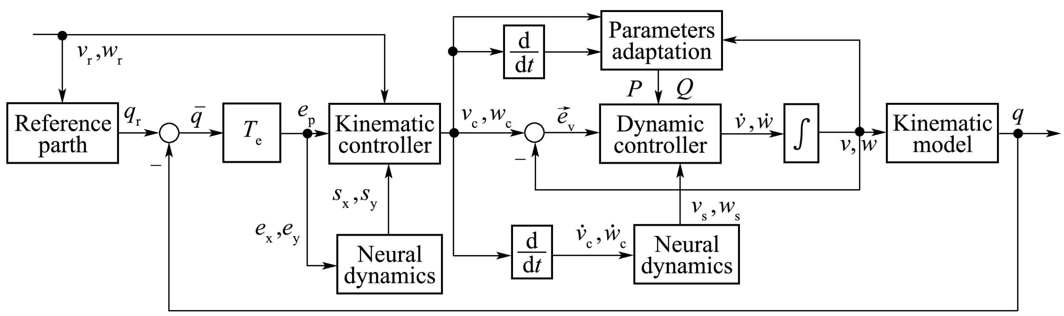


Fig. 3 Block diagram of control system

4.2 Design of an adaptive dynamic controller

Once given a desired velocity command $\vec{v}_{\rm c} = [v_{\rm c} \ \ w_{\rm c}]^{\rm T}$ from the kinematic controller, we need a dynamic controller which can generate another pair of linear and angular velocities to reach the desired velocity command shown in Fig.3.

Define the velocity error $\vec{e}_v = \vec{v}_{\rm c} - \vec{v} = [\tilde{v} \ \ \tilde{w}]^{\rm T}$, the following control laws are used to prepare tracking of $v_{\rm c}$ and $w_{\rm c}$[10]:

$$\bar{\tau} = K\vec{e}_v + \bar{M}\dot{\vec{v}}_{\rm c}, \tag{15}$$

where $K = \mathrm{diag}\{k_4, k_5\}$ is a diagonal matrix, k_4 and k_5 are positive constants.

In control law (15), the dynamic parameters m and I are assumed to be known. In fact, the values of these parameters have uncertainties. So the control strategy should be rewritten as follows:

$$\bar{\tau} = K\vec{e}_v + \hat{\bar{M}}\dot{\vec{v}}_{\rm c}, \tag{16}$$

where $\hat{\bar{M}} = \mathrm{diag}\{\hat{m}, \hat{I}\}$ is the estimate value of $\bar{M}$.

Substituting Eq.(4) in Eq.(16), the following closed loop equations of velocities are obtained:

$$\bar{M}\dot{\vec{v}} = K\vec{e}_v + \hat{\bar{M}}\dot{\vec{v}}_{\rm c}, \tag{17}$$

Pre-multiplying $\bar{M}^{-1}$, one can obtain

$$\dot{\vec{v}} = \bar{M}^{-1}K\vec{e}_v + \bar{M}^{-1}\hat{\bar{M}}\dot{\vec{v}}_{\rm c}. \tag{18}$$

Define $P = \bar{M}^{-1}K = \mathrm{diag}\{p_1, p_2\}$ and $Q = \bar{M}^{-1}\hat{\bar{M}} = \mathrm{diag}\{q_1, q_2\}$, Eq.(18) can be rewritten in this form:

$$\dot{\vec{v}} = P\vec{e}_v + Q\dot{\vec{v}}_{\rm c}, \tag{19}$$

Define following reference model for velocity error The reference model for velocity error is

$$\dot{\vec{v}}_{\rm e} + T\vec{v}_{\rm e} = 0, \tag{20}$$

where T is the time constant of error damping. Using $\vec{v}_{\rm e} = \vec{v}_{\rm c} - \vec{v}_m$, Eq.(20) becomes

$$\dot{\vec{v}}_m = \dot{\vec{v}}_{\rm c} + T\vec{v}_{\rm c} - T\vec{v}_m. \tag{21}$$

The adaptation error, which is the difference between $\vec{v}$ and the velocity of the reference model $\vec{v}_m$, is

$$\vec{\delta} = \vec{v} - \vec{v}_m = [\delta_v \ \ \delta_w]^{\rm T}. \tag{22}$$

Then, the parameter update rules are chosen as[10]

$$\begin{cases} \dot{p}_1 = -\alpha_1\delta_v\dot{v}_{\rm c}, \dot{q}_1 = -\alpha_2\delta_v(v_{\rm c} - v), \\ \dot{p}_2 = -\alpha_3\delta_w\dot{w}_{\rm c}, \dot{q}_2 = -\alpha_4\delta_w(w_{\rm c} - w). \end{cases} \tag{23}$$

where $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ are positive constants. And the system has been proven to be stable.

4.3 The proposed neural dynamics based adaptive tracking controller

By analyzing the control laws in (13) and (19), the speed jump is caused by the initial tracking errors $e_{\rm x}, e_{\rm y}$, and e_θ while the torque jump is produced by velocity error $\vec{e}_v$ and $\dot{\vec{v}}_{\rm c}$. To solve the two problems for path tracking control, a novel tracking controller is proposed as[8]:

$$\begin{cases} v_{\rm c} = k_1 s_{\rm x} + v_{\rm r}\cos e_\theta, \\ w_{\rm c} = w_{\rm r} + k_2 v_{\rm r} s_{\rm y} + k_3 \sin e_\theta, \end{cases} \tag{24}$$

and

$$\begin{cases} \dot{v} = p_1\tilde{v} + q_1 v_{\rm s}, \\ \dot{w} = p_2\tilde{w} + q_2 w_{\rm s}. \end{cases} \tag{25}$$

In (24) and (25), $s_{\rm x}$, $s_{\rm y}$, $v_{\rm s}$ and $w_{\rm s}$ are functions of neural dynamics model given by

$$\begin{cases} \dfrac{{\rm d}s_{\rm x}}{{\rm d}t} = -As_{\rm x} + (B - s_{\rm x})S^+(e_{\rm x}) - \\ \qquad (D + s_{\rm x})S^-(e_{\rm x}), \\ \dfrac{{\rm d}s_{\rm y}}{{\rm d}t} = -As_{\rm y} + (B - s_{\rm y})S^+(e_{\rm y}) - \\ \qquad (D + s_{\rm y})S^-(e_{\rm y}), \\ \dfrac{{\rm d}v_{\rm s}}{{\rm d}t} = -Av_{\rm s} + (B - v_{\rm s})S^+(\dot{v}_{\rm c}) - \\ \qquad (D + v_{\rm s})S^-(\dot{v}_{\rm c}), \\ \dfrac{{\rm d}w_{\rm s}}{{\rm d}t} = -Aw_{\rm s} + (B - w_{\rm s})S^+(\dot{w}_{\rm c}) - \\ \qquad (D + w_{\rm s})S^-(\dot{w}_{\rm c}), \end{cases} \tag{26}$$

where $S^+(x) = \max(0, x)$ and $S^-(x) = \max(0, -x)$.

At initial status, if we choose

$$\begin{cases} s_{\rm x}(0) = -v_{\rm r}(0)\cos e_\theta(0)/k_1, \\ s_{\rm y}(0) = -(w_{\rm r}(0) + k_3\sin e_\theta(0))/(k_2 v_{\rm r}(0)), \end{cases} \tag{27}$$

and

$$\begin{cases} v(0) = 0, \\ w(0) = 0, \\ v_{\rm s}(0) = 0, \\ w_{\rm s}(0) = 0. \end{cases} \tag{28}$$

Then, $v_{\rm c}(0) = 0, w_{\rm c}(0) = 0$, and $\dot{\vec{v}}(0) = 0$, that is to say, the control output $\bar{\tau}(0) = [0 \ \ 0]^{\rm T}$. So the new control law can solve the speed and torque jump problems, respectively.

4.4 Stability analysis

Consider the following Lyapunov function candidate[8]:

$$V_{\rm s} = \frac{1}{2}(s_{\rm x}^2 + s_{\rm y}^2) + \frac{1}{2}(v_{\rm s}^2 + w_{\rm s}^2), \tag{29}$$

where $s_{\rm x}, s_{\rm y}, v_{\rm s}$ and $w_{\rm s}$ are defined in (26). Obviously, $V_{\rm s} \geqslant 0$. For the derivative of $V_{\rm s}$, we have

$$\begin{aligned}
\dot{V}_{\rm s} = {} & s_{\rm x}\dot{s}_{\rm x} + s_{\rm y}\dot{s}_{\rm y} + v_{\rm s}\dot{v}_{\rm s} + w_{\rm s}\dot{w}_{\rm s} = \\
& -(A + S^{+}(e_{\rm x}) + S^{-}(e_{\rm x}))s_{\rm x}^2 - \\
& (A + S^{+}(e_{\rm y}) + S^{-}(e_{\rm y}))s_{\rm y}^2 - \\
& (A + S^{+}(\dot{v}_{\rm c}) + S^{-}(\dot{v}_{\rm c}))v_{\rm s}^2 - \\
& (A + S^{+}(\dot{w}_{\rm c}) + S^{-}(\dot{w}_{\rm c}))w_{\rm s}^2.
\end{aligned} \tag{30}$$

Referring to the Eq. (6), if $e_{\rm x} \geqslant 0$, $S^{+}(e_{\rm x}) = e_{\rm x}$, and $S^{+}(e_{\rm x}) = 0$, then

$$A + S^{+}(e_{\rm x}) + S^{-}(e_{\rm x}) = A + e_{\rm x} > 0, \tag{31}$$

If $e_{\rm x} < 0, S^{+}(e_{\rm x}) = 0$, and $S^{-}(e_{\rm x}) = -e_{\rm x}$, then

$$A + S^{+}(e_{\rm x}) + S^{-}(e_{\rm x}) = A - e_{\rm x} > 0. \tag{32}$$

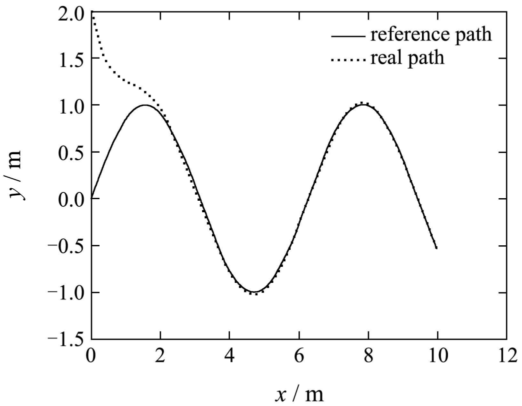
Similarly, we have that

$$\begin{aligned}
& A + S^{+}(e_{\rm y}) + S^{-}(e_{\rm y}) > 0, \\
& A + S^{+}(\dot{v}_{\rm c}) + S^{-}(\dot{v}_{\rm c}) > 0, \\
& A + S^{+}(\dot{w}_{\rm c}) + S^{-}(\dot{w}_{\rm c}) > 0.
\end{aligned}$$

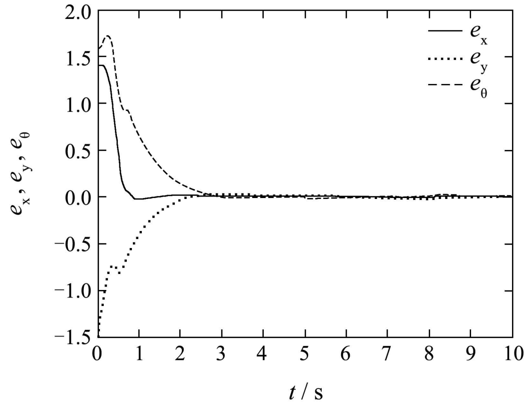
Then the derivative of $V_{\rm s}$ is always non-positive. Therefore, the whole system is stable.

5 Simulation results

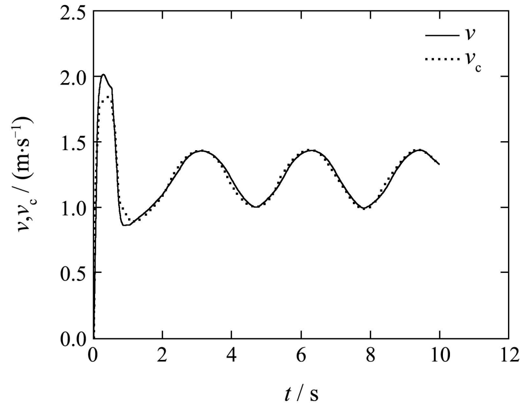
In this Section, two test cases in different situations are used to demonstrate the effectiveness of the proposed control scheme, considering the robot's physical parameters $m = 4$ kg and $I = 2.5$ (kg· m^2). The tracking and stabilization performance is shown in Fig.4 and Fig.5.



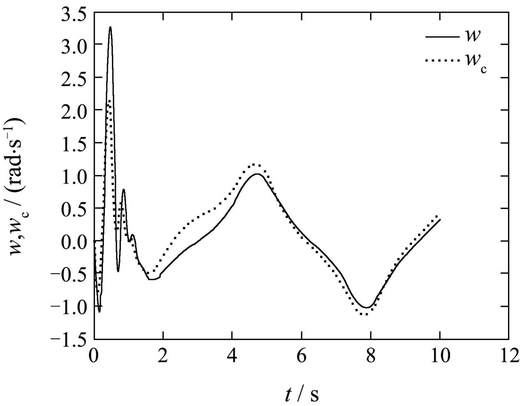
(a) Reference and real paths



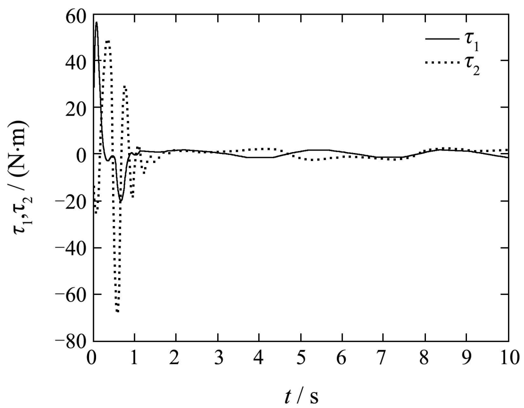
(b) Posture errors



(c) Real and desired linear velocities

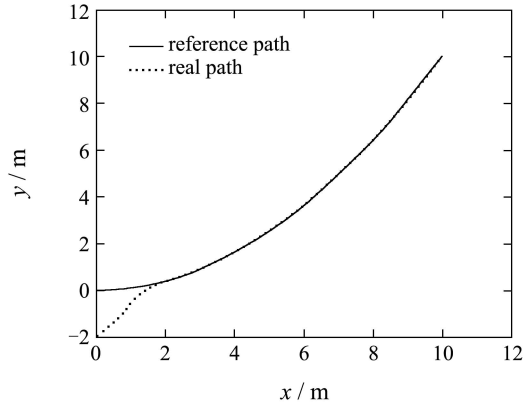


(d) Real and desired angular velocities

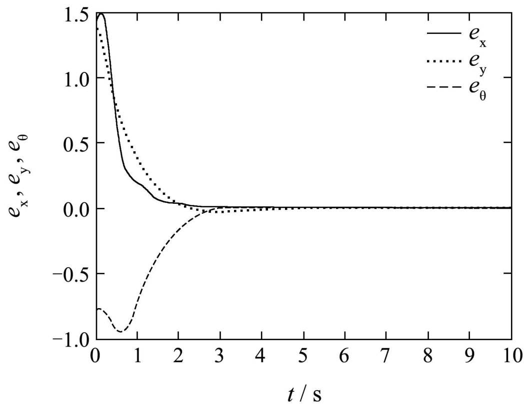


(e) Linear and angular torques

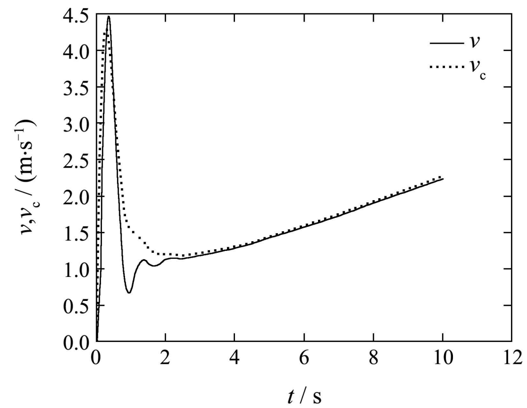
Fig. 4 Tracking results



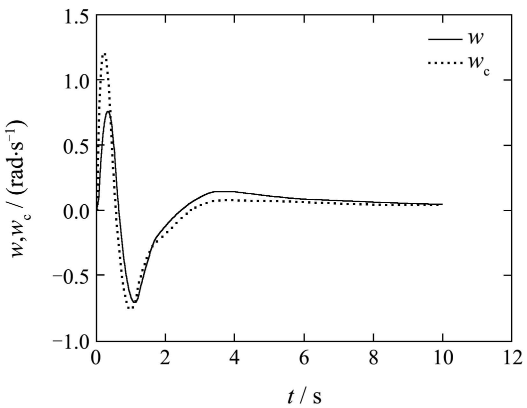
(a) Reference and real paths



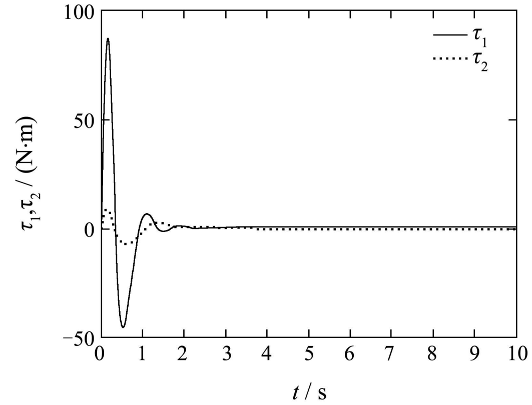
(b) Posture errors



(c) Real and desired linear velocities



(d) Real and desired angular velocities



(e) Linear and angular torques

Fig. 5 Tracking results

5.1 Tracking a sinusoidal path

The sinusoidal path is generated from $x_r = s$, $y_r = \sin x_r$, $s = t$. According to Eq.(10), the reference velocities and angular of the path are $v_r = \sqrt{1 + (\cos x_r)^2}\dot{s}$, $w_r = -\sin x_r \dot{s}/[1 + (\cos x_r)^2]$ and $\theta_r = \arctan(\cos x_r)$, respectively, $\forall s,\ \dot{s} = 1 \neq 0$. The initial posture of the reference path is set at $(x_r(0), y_r(0)) = (0, 0)$ while the initial posture of robot is $q(0) = [0\ \ 2\ \ -\pi/4]^{\mathrm{T}}$. The tracking results are shown in Fig.4, including (a) reference and real paths, (b) posture errors, (c) real and desired linear velocities, (d) real and desired angular velocities, and (e) linear and angular torques.

Fig.4(a)(b) shows that the robot can track the sinusoidal path and correct deviations quickly (about 2.8 s). $\dot{\vec{v}}_c$ has a great impact on $\bar{\tau}$ by analyzing Fig.4(c)(d) and Eqs.(16)(25). Because of the large errors at initial moment, $\dot{\vec{v}}_c$ alters from zero to large value quickly, then it reduces towards opposite direction. This action is done repeatedly until $\bar{\tau}$ reaches a proper value, so the fluctuating of $\bar{\tau}$ is heavy in the initial process shown in Fig.4(e). In addition, the velocities and torques start from zero as described in Fig.4(c)(d)(e).

5.2 Tracking a parabola path

The parabola path is generated from $x_r = s$, $y_r = 0.1x_r^2$, $s = t$. Calculating Eq.(10), the reference velocities and angular of the path are $v_r = \sqrt{1 + 0.04x_r^2}\dot{s}$, $w_r = 0.2\dot{s}/(1 + 0.04x_r^2)$ and $\theta_r = \arctan(0.2x_r)$, respectively, $\forall s\ \dot{s} = 1 \neq 0$. The initial posture of the reference path is set at $(x_r(0), y_r(0)) = (0, 0)$ while the initial posture of robot is $q(0) = [0\ \ -2\ \ \pi/4]^{\mathrm{T}}$. The tracking results are shown in Fig.5.

Fig.5(a) shows that the robot can track the parabola path. From Fig.5(b), it can be observed that the controller can correct posture errors quickly (about 4.0 s) and the steady-state errors can be totally eliminated. The cause of the fluctuating $\bar{\tau}$ depicted in Fig.5(e) is similar to the explanation in section 5.1. Besides, smooth and continuous signals are generated from static state.

Therefore, all of the simulation results demonstrate that the proposed control strategy is effective to solve the path tracking problem.

6 Conclusion

In this paper, considering the dynamic uncertainties, a path tracking controller has been proposed, combined the kinematic controller and model reference adaptive dynamic controller, which allows the mobile robot to achieve complete tracking of the desired path. In addition, by incorporating a neural dynamics model with the proposed approach, the controller is capable of solving the speed and torque jump problems. Using Lyapunov theory, the control scheme is demonstrated to be stable. All the simulation results indicate that the proposed strategy is indeed feasible and effective.

参考文献(References):

[1] GAO Xingquan, CHEN Hong. Tracking control for wheeled mobile robot via T-S fuzzy model[J]. *Control Theory & Applications*, 2007, 24(6): 873 – 878.
(高兴泉, 陈虹. 基于T-S模型的轮式移动机器人轨迹跟踪控制[J]. 控制理论与应用, 2007, 24(6): 873 – 878.)

[2] ANTONELLI G, CHIAVERINI S, FUSCO G. A fuzzy logic based approach for mobile robot path tracking[J]. *IEEE Transaction on Fuzzy Systems*, 2007, 15(2): 211 – 221.

[3] NINO-SUAREZ P A, ARANDA-BRICAIRE E, VELASCO-VILLA M. Discrete-time sliding mode path-tracking control for a wheeled mobile robot[C] *//Proceedings of the IEEE Conference on Decision and Control*. San Diego, USA: IEEE, 2006: 3052 – 3057.

[4] DO K D, PAN J. Global output feedback path tracking of unicycle-type mobile robots[J]. *Robotics and Computer Integrates Manufacturing*, 2006, 22(2): 166 – 179.

[5] COELHO P, NUNES U. Path following control of mobile robots in presence of uncertainties[J]. *IEEE Transactions on Robotics*, 2005, 21(2): 252 – 261.

[6] SOETANTO D, LAPIERRE L, PASCOAL A. Adaptive, non-singular path following control of dynamic wheeled robots[C] *//Proceedings of the IEEE Conference on Decision and Control*. Maui, United states: IEEE, 2003: 1765 – 1770.

[7] ASHOORIRAD M, BARZAMINI R, AFSHAR A, et al. Model reference adaptive path following for wheeled mobile robots[C] *//2nd International Conference on Information and Automation*. Colombo, Srilanka: ICIA, 2006: 289 – 294.

[8] YANG H, YANG S X, MITTAL G S. Tracking control of a non-holonomic mobile robot by integrating feedback and neural dynamics techniques[C] *//IEEE International Conference on Intelligent Robots and Systems*. Las Vegas, USA: IEEE, 2003: 3522 – 3527.

[9] FUKAO T, NAKAGAWA H, NORIHIKO A. Adaptive tracking control of a nonholonomic mobile robot[J]. *IEEE Transactions on Robotics and Automation*, 2000, 16(5): 609 – 614.

[10] GHOLIPOUR A, YAZDANPANAH M J. Dynamic tracking control of nonholonomic mobile robotwith model reference adaptation for uncertain parameters[C] *//European Control Conference*. Cambridge, UK: ECC, 2003.

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