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Original Article

Adaptive Sliding Mode Control for Three-Wheel Omnidirectional Mobile Robot

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Abstract - *Nowadays, mobile robots are applied to many types of jobs in different industries such as industry, logistics, service and some dangerous fields that replace humans, such as mine detection, oil and gas exploitation, chemical production, and weapons. Therefore, there is more and more research on mobile robot control. This paper proposes a new control method that is to use a sliding mode controller (SMC) combined with adaptive law based on radial basis function neural network (RBFNN) for a three-wheeled omnidirectional mobile robot (TWOMR). In the process of working, the robot will be affected by external disturbances and model uncertainty, so the neural network is used to approximate these components. The system is proven stable based on Lyapunov's theory. The system simulation results show that the proposed controller meets the desired quality criteria.*

Keywords - *Sliding mode control, Three-wheel omnidirectional mobile robot, Radial basis function neural network, Adaptive control, External disturbances.*

1. Introduction

TWOMR uses three Omni wheels so it can move in any direction without changing the wheels' direction. Because the wheel has a different structure and layout, the robot is suitable for applications in tight spaces and is increasingly used in research and life. Robot with a combination of rotational and translational motion following a predetermined trajectory in a short time, moving is even easier. So, when the object is lost, the robot can use the point rotation feature to detect it. With these outstanding capabilities, the robot's strengths have been promoted for professional robot designs that need flexibility and quick navigation.

Fig. 1 Mobile robot using omnidirectional wheels

Fig. 2 Omni wheel model

In recent years, many researchers have proposed methods to control mobile robots. When the robot works in ideal conditions and is not affected by model uncertainty and external disturbances, the authors use a classical controller to implement as simple as a PID controller [1]. In the document [2], the orbital linearization controller (TLC) is used for both kinematic loops (outer loop) and dynamic loops (inner loop). To ensure the quality when controlling the robot considering the nonlinear uncertainties, the Backstepping technique has been shown to be a possible solution [3,4]. The backstepping technique is capable of synthesizing a stable nonlinear control system based on determining the Lyapunov control function for the closed system. However, in the case of a high-order nonlinear system with a large amount of computation, it will take a long time due to the need to calculate the derivative in each iteration. When the robot is affected by external disturbances, a sliding mode controller (SMC) is included in the design [5-12].

SMC is used because of its stability, fast response, and simple control law that can be used for nonlinear systems with uncertain parameters and impact noise. The limitation of SMC is chattering. Besides, other modern controllers are also proposed when the dynamic equation of the robot has uncertain parameters, such as adaptive control [13-16]. Robust adaptive sliding mode control in the presence of model uncertainty and external disturbances [17-24]. First, the SMC controller is designed and then uses the adaptive law to estimate the uncertainty component and the upper limit of the external disturbances. In addition, some studies using fuzzy logic systems as adaptive tuning mechanisms have significantly improved the quality of nonlinear controllers [25-31]. For example, combining traditional PI control with a fuzzy logic system for parameter setting ensures that the system works with constant quality when the object changes and there is interference [25,26]. To improve the control quality of nonlinear controllers, fuzzy adaptive controllers are built based on the combination of nonlinear control with a fuzzy tuning mechanism, such as a fuzzy sliding mode controller [27,28]. The basic advantage of fuzzy adaptive controllers is that they have adopted a simple tuning mechanism in design and implementation. However, when building control rules for fuzzy controllers often depends on the experience of the designer. With the ability to learn and approximate nonlinear functions with high accuracy, many publications have recently used neural networks in robot control systems. Neural networks are often combined with nonlinear control algorithms to approximate uncertain components suitable for controlling robot motion, objects with high nonlinearity, containing uncertain components such as friction, variable load, or unknown external disturbances.

Based on the study of published references in recent years, an adaptive sliding mode controller (ASMC) for TWOMR based on RBFNN is proposed for research. In which the SMC controller is designed first, and then RBFNN is used for online approximation of the model uncertainty components and unknown external disturbances.

The structure of the paper is presented with the following contents: The second content builds the kinematics and dynamics equations of TWOMR, the third content presents the ASMC controller design method, and the results are presented. In fourth content finally, conclusions and directions for further research are presented in the fifth content.

2. Mathematical Model of TWOMR

Figure 3 shows the configuration of the applied geometry model for TWOMR. The three omnidirectional wheels have the same radius r and are driven by DC motors. The center of displacement of the TWOMR is located at A and is assumed to coincide with the geometric center.

The circular robot chassis is very commonly used in the research and manufacturing of mobile robots and control cars. Designed with extremely sturdy plastic, mica or metal frame, the Omni wheel is extremely versatile. The motor has a deceleration for stable operation, making this product very interesting in robotics research.

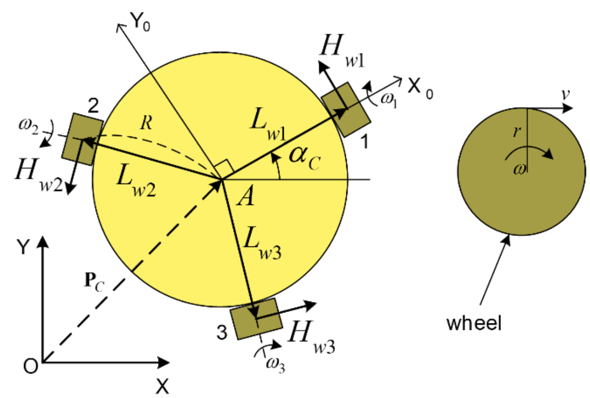

Fig. 3 Geometric structure of TWOMR

The location of the TWOMR is $\boldsymbol{q} = [\boldsymbol{x_A} \quad \boldsymbol{y_A} \quad \boldsymbol{\alpha_A}]^{\boldsymbol{T}}$; vector$\boldsymbol{P_C} = \overrightarrow{\boldsymbol{OA}} = [\boldsymbol{x_A} \quad \boldsymbol{y_A}]^{\boldsymbol{T}}$; $\boldsymbol{L_{wi}} \in \mathbb{R}^{\boldsymbol{2\times 1}}$ (i=1,2,3); $\boldsymbol{H_{wi}} \in \mathbb{R}^{\boldsymbol{2\times 1}}$ (i=1,2,3).

2.1. Kinematic Model

The rotation matrix $Q(\alpha_A)$ is represented

$$Q(\alpha_A) = \begin{bmatrix} cos\, \alpha_A & -sin\, \alpha_A \\ sin\, \alpha_A & cos\, \alpha_A \end{bmatrix} \quad (1)$$

The position vectors L_{w1}, L_{w2}, L_{w3} are calculated:

$$L_{w1} = R \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (2)$$

$$L_{w2} = Q\left(\frac{2\pi}{3}\right) \times L_{w1}$$

$$= \begin{bmatrix} cos\left(\frac{2\pi}{3}\right) & -sin\left(\frac{2\pi}{3}\right) \\ sin\left(\frac{2\pi}{3}\right) & cos\left(\frac{2\pi}{3}\right) \end{bmatrix} \times R \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} \end{bmatrix} \times R \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \frac{R}{2} \begin{bmatrix} -1 \\ \sqrt{3} \end{bmatrix} \quad (3)$$

$$L_{w3} = Q\left(\frac{4\pi}{3}\right) \times L_{w1}$$

$$= \begin{bmatrix} cos\left(\frac{4\pi}{3}\right) & -sin\left(\frac{4\pi}{3}\right) \\ sin\left(\frac{4\pi}{3}\right) & cos\left(\frac{4\pi}{3}\right) \end{bmatrix} \times R \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (4)$$

$$=\begin{bmatrix}-\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{\sqrt{3}}{2} & -\frac{1}{2}\end{bmatrix}\times R\begin{bmatrix}1\\0\end{bmatrix}=-\frac{R}{2}\begin{bmatrix}1\\ \sqrt{3}\end{bmatrix}$$

H_{wi} vectors are calculated according to the formula:

$$H_{wi}=\frac{1}{R}Q(\alpha_A)\times L_{wi} \qquad (5)$$

From the above formula, we can calculate H_{w1}

$$H_{w1}=\frac{1}{R}Q(\alpha_A)\times L_{w1}$$

$$=\frac{1}{R}Q\left(\frac{\pi}{2}\right)\times L_{w1}$$

$$=\frac{1}{R}\begin{bmatrix}cos\left(\frac{\pi}{2}\right) & -sin\left(\frac{\pi}{2}\right)\\ sin\left(\frac{\pi}{2}\right) & cos\left(\frac{\pi}{2}\right)\end{bmatrix}\times R\begin{bmatrix}1\\0\end{bmatrix} \qquad (6)$$

$$=\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}\times\begin{bmatrix}1\\0\end{bmatrix}=\begin{bmatrix}0\\1\end{bmatrix}$$

H_{w2} is calculated as follows

$$H_{w2}=\frac{1}{R}Q(\alpha_A)\times L_{w2}$$

$$=\frac{1}{R}Q\left(\frac{\pi}{2}\right)\times L_{w2}$$

$$=\frac{1}{R}\begin{bmatrix}cos\left(\frac{\pi}{2}\right) & -sin\left(\frac{\pi}{2}\right)\\ sin\left(\frac{\pi}{2}\right) & cos\left(\frac{\pi}{2}\right)\end{bmatrix}\times\frac{R}{2}\begin{bmatrix}-1\\ \sqrt{3}\end{bmatrix} \qquad (7)$$

$$=\frac{1}{2}\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}\times\begin{bmatrix}-1\\ \sqrt{3}\end{bmatrix}=-\frac{1}{2}\begin{bmatrix}\sqrt{3}\\ 1\end{bmatrix}$$

H_{w3} is calculated as follows

$$H_{w3}=\frac{1}{R}Q(\alpha_A)\times L_{w3}$$

$$=\frac{1}{R}Q\left(\frac{\pi}{2}\right)\times L_{w3}$$

$$=\frac{1}{R}\begin{bmatrix}cos\left(\frac{\pi}{2}\right) & -sin\left(\frac{\pi}{2}\right)\\ sin\left(\frac{\pi}{2}\right) & cos\left(\frac{\pi}{2}\right)\end{bmatrix}\times\left(-\frac{R}{2}\right)\begin{bmatrix}1\\ \sqrt{3}\end{bmatrix} \qquad (8)$$

$$=-\frac{1}{2}\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}\times\begin{bmatrix}1\\ \sqrt{3}\end{bmatrix}=\frac{1}{2}\begin{bmatrix}\sqrt{3}\\ -1\end{bmatrix}$$

In the global coordinate system, P_i and V_i are calculated as follows:

$$P_i=P_A+Q(\alpha_A)\times L_{wi}$$

$$V_i=\dot{P}_A+\dot{Q}(\alpha_A)\times L_{wi} \qquad (9)$$

$$V_i^T=\dot{P}_A^T+\dot{Q}^T(\alpha_A)\times L_{wi}^T$$

From the above expressions, we can calculate the angular velocity of the wheels.

$$\omega_i=\frac{1}{r}V_i^T\times Q(\alpha_A)\times H_{wi}$$

$$=\frac{1}{r}\left[\dot{P}_A^T\times Q(\alpha_A)\times H_{wi}\right] \qquad (10)$$

$$+\frac{1}{r}\left[L_{wi}^T\times\dot{Q}^T(\alpha_A)\times Q(\alpha_A)\times H_{wi}\right]$$

The kinematic equation of TWOMR is written as follows [5,6]:

$$\begin{bmatrix}\omega_1\\ \omega_2\\ \omega_3\end{bmatrix}=\frac{1}{r}\begin{bmatrix}-sin(\alpha_A) & cos(\alpha_A) & R\\ -sin\left(\frac{\pi}{3}-\alpha_A\right) & -cos\left(\frac{\pi}{3}-\alpha_A\right) & R\\ sin\left(\frac{\pi}{3}+\alpha_A\right) & -cos\left(\frac{\pi}{3}+\alpha_A\right) & R\end{bmatrix}\times\begin{bmatrix}\dot{x}_A\\ \dot{y}_A\\ \dot{\alpha}_A\end{bmatrix} \qquad (11)$$

2.2. Dynamic Model

The dynamic equation of the robot [5,6]:

$$M(q)\ddot{q}+M(q)\dot{q}+\tau_d=u \qquad (12)$$

In there:

$$M=\begin{bmatrix}m_1 & 0 & 0\\ 0 & m_2 & 0\\ 0 & 0 & m_3\end{bmatrix}$$

$$C=a\begin{bmatrix}0 & -\alpha_A & 0\\ \alpha_A & 0 & 0\\ 0 & 0 & 0\end{bmatrix}$$

$$m_1=m_2=M_r+\frac{3I_w}{2r^2}$$

$$m_3=I_r+\frac{3I_wR^2}{r^2}$$

$$a=\frac{3I_w}{2r^2};u=B\tau$$

$$B=\frac{1}{r}\begin{bmatrix}-sin(\alpha_A) & -sin\left(\frac{\pi}{3}-\alpha_A\right) & sin\left(\frac{\pi}{3}+\alpha_A\right)\\ cos(\alpha_A) & -cos\left(\frac{\pi}{3}-\alpha_A\right) & -cos\left(\frac{\pi}{3}+\alpha_A\right)\\ R & R & R\end{bmatrix}$$

3. Design Controller

3.1. Sliding Mode Controller (SMC)

The SMC method is increasingly used in applications. Because of the robustness of the SMC, it is especially suitable for working objects affected by disturbance.

In this section, we use SMC to design a clinging controller for TWOMR; the target is the trajectory of the robot moving in the reference trajectory. From the dynamic equation (12), we put the matrix

$$M(q) = M_1(q) + \Delta M; C(q) = C_1(q) + \Delta C$$

We have:

$$[M_1(q) + \Delta M]\ddot{q} + [C_1(q) + \Delta C]\dot{q} = u - \tau_d$$
$$M_1(q)\ddot{q} + C_1(q)\dot{q} = u - \tau_d - \Delta M\ddot{q} - \Delta C\dot{q} = u - D(q) \quad (13)$$

The materials

$$\ddot{q} = M_1^{-1}(q)[u - D(q) - C_1(q)\dot{q}] \quad (14)$$
$$= M_1^{-1}(q)u - M_1^{-1}(q)D(q) - M_1^{-1}(q)C_1(q)\dot{q}$$
$$= M_1^{-1}(q)u - G(q) - E(q)\dot{q}$$

The materials

$$G(q) = M_1^{-1}(q)D(q)$$
$$E(q) = M_1^{-1}(q)C_1(q) \quad (15)$$

Uncertainty is approximately equal to RBFNN. In SMC, assuming these components are zero, the dynamic equation of TWOMR:

$$\ddot{q} = M_1^{-1}u - E\dot{q} \quad (16)$$

The problem is to control TWOMR to follow the reference trajectory with tracking error $e_q = q_d - q \to 0$

The sliding surface is defined as: $s = \dot{e}_q + \lambda e_q$; λ is a positive definite matrix.

$$\dot{s} = \ddot{e}_q + \lambda\dot{e}_q = \ddot{q}_d - \ddot{q} + \lambda\dot{e}_q$$
$$= \ddot{q}_d + \lambda\dot{e}_q - M_1^{-1}(q)u + E(q)\dot{q}$$
$$= -k_1 s - k_2\, sgn(s) \quad (17)$$

$$sgn(s_i) = \begin{cases} \dfrac{s_i}{\|s_i\|}; \text{when } \|s_i\|>0 \\ 0; \text{ when } \|s_i\|=0 \end{cases} \quad (18)$$

The SMC controller is designed as follows:

$$u = M_1 \begin{bmatrix} k_1 s + k_2\, sgn(s) \\ +\lambda(\dot{q}_d - \dot{q}) + \ddot{q}_d + E\dot{q} \end{bmatrix} \quad (19)$$

We see that the control signal of the SMC has a sign function, and there is a chattering of oscillation states around the sliding surface. Therefore, in the next section, use RBFNN to replace the equivalent control component in the sliding control.

3.2. Structure of RBFNN

RBF neural network is considered one of the artificial neural networks with many advantages to solve the problem of approximation of the uncertain component. RBF neural network has been interesting in research, and there have been quite a few RBF network training algorithms applied in practical applications showing very positive results.

The RBF neural network in the study has 3 layers: an input layer, a hidden layer and an output layer. With simple structure but high efficiency, such as fast online learning ability and a good approximation of nonlinear functions [32-34].

The structure of the RBF consists of three layers, as shown in Figure 4.

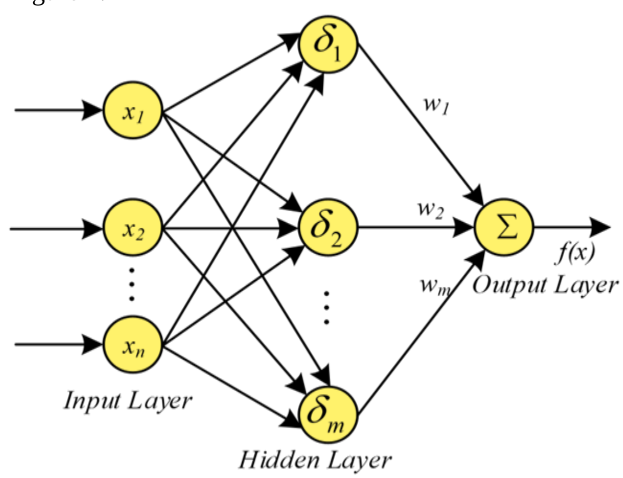

Fig. 4 Structure of RBFNN

Input layer $x = [x_1, x_2, \dots, x_n]^T$

$$\delta_j = exp\left(-\frac{\|x - c_j\|^2}{2b_j^2}\right); j = 1,2,3,\dots,m \quad (20)$$

The output layer of RBFNN is calculated as follows:

$$f(x) = W^T\delta + \varepsilon \quad (21)$$

W is the weight vector of RBFNN.

When the model has uncertain components and external disturbances, the sliding mode control law is written as follows:

$$u = M_1(q)\begin{bmatrix} k_1 s + k_2\, sgn(s) + \lambda(\dot{q}_d - \dot{q}) \\ +\ddot{q}_d + E\dot{q} + G \end{bmatrix}$$
$$= M_1[k_1 s + k_2\, sgn(s) + f(x)] \quad (22)$$

In there

$$f(x) = [\lambda(\dot{q}_d - \dot{q}) + \ddot{q}_d + E\dot{q} + G] \quad (23)$$

We use RBFNN to approximate f(x), and then we have:

$$u(t) = M_1(q)\left[k_1 s + k_2\, sgn(s) + \hat{f}(x)\right] \tag{24}$$

$$\hat{f}(x) = \widehat{W}^T \delta \tag{25}$$

Where $\widehat{W}^T$ is the weight matrix of the updated RBFNN and the approximate error of the function is calculated as follows:

$$\tilde{f} = f - \hat{f}$$

$$= W^T\delta + \varepsilon - \widehat{W}^T\delta = \widetilde{W}^T\delta + \varepsilon \tag{26}$$

$$\widetilde{W} = W - \widehat{W}$$

From expression $f(x)$, input states of RBFNN are chosen as: $x = [e_q \quad \dot{e}_q \quad q \quad \dot{q}]^T$

Weights RBFNN are updated as follows: $\dot{\widehat{W}} = \kappa\delta s$
The proposed control structure is shown in Figure 5

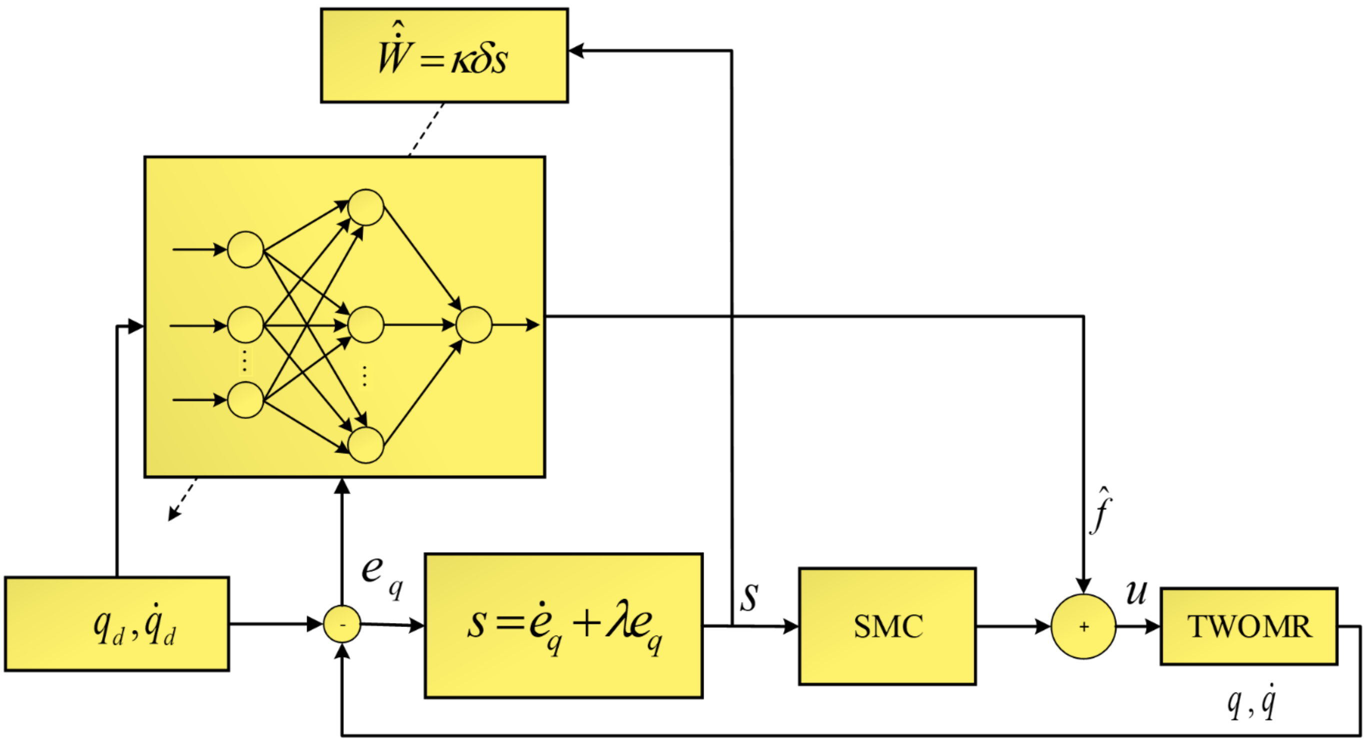

Fig. 5 ASMC control architecture based on RBFNN

3.3. Stability Analysis

The Lyapunov method is used to evaluate the stability of any higher-order nonlinear system. Besides this method is also used to analyze and design nonlinear controllers. There is no specific method to determine the Lyapunov function. Depending on the specific application, it is possible to choose based on the experience and practical meaning of the system. For systems in mechanics or engineering, the Lyapunov function can be chosen as the energy function.
Choose the Lyapunov function:

$$V = \frac{1}{2}s^T s + \frac{1}{2}\mathrm{tr}\left(\widetilde{W}^T\kappa^{-1}\widetilde{W}\right) \tag{27}$$

The time derivative of V is obtained as the following:

$$\dot{V} = s^T\dot{s} + \mathrm{tr}\left(\widetilde{W}^T\kappa^{-1}\dot{\widetilde{W}}\right)$$
$$= s^T\left(\ddot{e}_q + \lambda\dot{e}_q\right) + \mathrm{tr}\left(\widetilde{W}^T\kappa^{-1}\dot{\widetilde{W}}\right)$$
$$= s^T\left(\ddot{q}_d - \ddot{q} + \lambda\dot{e}_q\right) + \mathrm{tr}\left(\widetilde{W}^T\kappa^{-1}\dot{\widetilde{W}}\right)$$
$$= s^T\begin{bmatrix}\ddot{q}_d - M_1^{-1}u \\ +M_1^{-1}D + E\dot{q} + \lambda\dot{e}_q\end{bmatrix} + \mathrm{tr}\left(\widetilde{W}^T\kappa^{-1}\dot{\widetilde{W}}\right)$$
$$= s^T\begin{bmatrix}\ddot{q}_d - M_1^{-1}u \\ +G + E\dot{q} + \lambda\dot{e}_q\end{bmatrix} + \mathrm{tr}\left(\widetilde{W}^T\kappa^{-1}\dot{\widetilde{W}}\right) \tag{28}$$
$$= s^T\left[f(x) - M_1^{-1}(q)u(t)\right] + \mathrm{tr}\left(\widetilde{W}^T\kappa^{-1}\dot{\widetilde{W}}\right)$$

Substituting expression (24) into (28), we have:

$$\dot{V} = s^T \begin{Bmatrix} f(x) - M_1^{-1}(q)M_1(q) \\ \times \left[k_1 s + k_2\, sgn(s) + \hat{f}(x)\right] \end{Bmatrix}$$
$$+\mathrm{tr}\left(\tilde{W}^T \kappa^{-1} \dot{\tilde{W}}\right)$$

$$= s^T\left[f(x) - k_1 s - k_2\, sgn(s) - \hat{f}(x)\right]$$
$$+\mathrm{tr}\left(\tilde{W}^T \kappa^{-1} \dot{\tilde{W}}\right)$$

$$\begin{aligned} &= s^T\left[\tilde{f}(x) - k_1 s - k_2\, sgn(s)\right] \\ &\qquad + \mathrm{tr}\left(\tilde{W}^T \kappa^{-1} \dot{\tilde{W}}\right) \\ &= s^T\left[\tilde{W}^T \delta + \varepsilon - k_1 s - k_2\, sgn(s)\right] \\ &+\mathrm{tr}\left(\tilde{W}^T \kappa^{-1} \dot{\tilde{W}}\right) \\ &= s^T\left[\varepsilon - k_1 s - k_2\, sgn(s)\right] \\ &+\mathrm{tr}\tilde{W}^T\left(\kappa^{-1}\dot{\hat{W}} + \delta s^T\right) \end{aligned} \tag{29}$$

Where k_1, k_2 are positive definite matrices. Then we have: $\dot{\tilde{W}} = \dot{W} - \dot{\hat{W}} = -\dot{\hat{W}}$.

Expression (29) is written as follows:

$$\begin{aligned} \dot{V} &= s^T\varepsilon - k_1 s^T s - k_2\|s\| \\ &+\mathrm{tr}\tilde{W}^T\left(-\kappa^{-1}\dot{\hat{W}} + \delta s^T\right) \end{aligned} \tag{30}$$

We put

$$\begin{aligned} \dot{V}_1 &= s^T\varepsilon - k_1 s^T s - k_2\|s\| \\ &\leq \|\varepsilon\| s^T - k_1 s^T s - k_2\|s\| \\ &\leq \varepsilon_N\|s\| - k_1 s^T s - k_2\|s\| \leq 0 \end{aligned} \tag{31}$$

$\Rightarrow \dot{V} \leq 0$ deduce the system is stable.

4. Simulation Results

Simulation on Matlab-Simulink software. The parameter table of TWOMR is given:

Table 1. Symbol of TWOMR

Symbol	Value	Measure
r	0.06	m
R	0.2	m
M_p	5	kg

At t=0, the actual position of the Omni robot is the origin of the global reference system. TWOMR at coordinates (0,0) will be controlled to run in a circle centered at the origin O of the global reference system, radius 5m.

Sample trajectory:

$$\begin{cases} x = 5\cos(0.1t) \\ y = 5\sin(0.1t) \\ \Phi = 0.1t + \dfrac{\pi}{2} \end{cases}$$

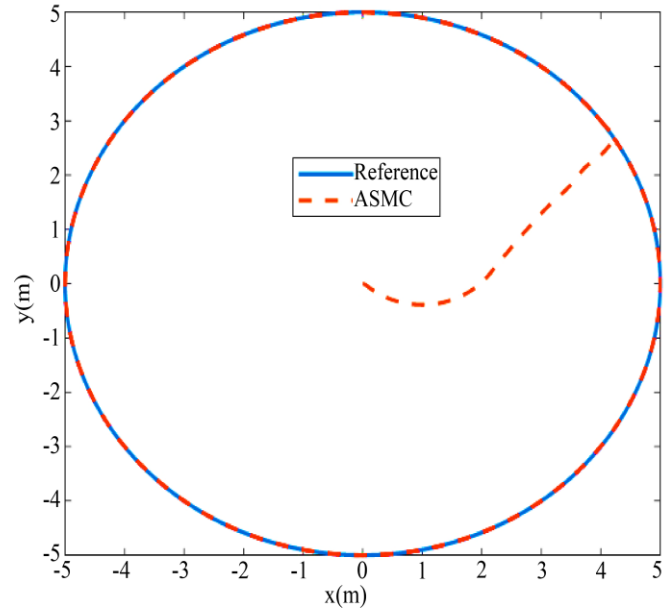

Fig. 6 Trajectory tracking of TWOMR

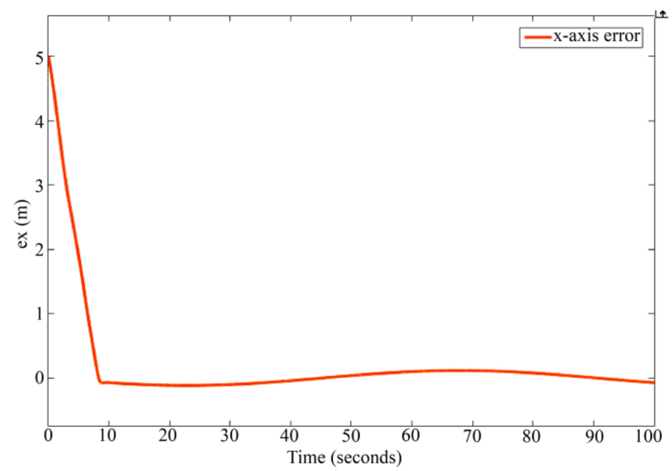

Fig. 7 Tracking error x-axis

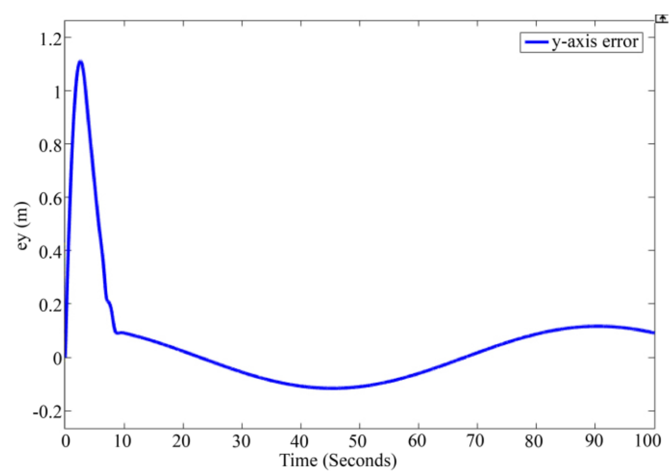

Fig. 8 Tracking error y-axis

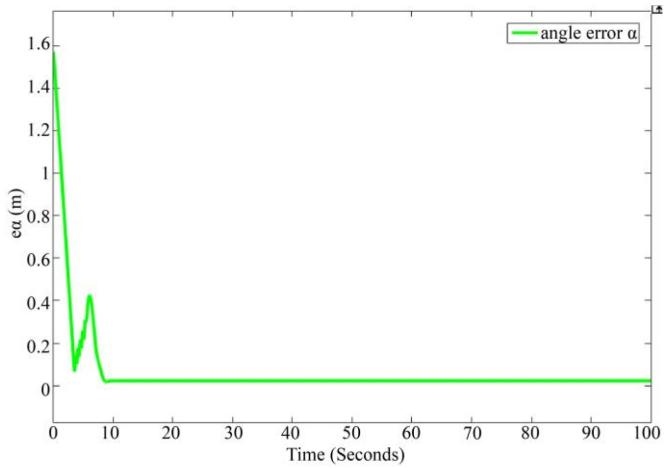

Fig. 9 Tracking error in direction angle

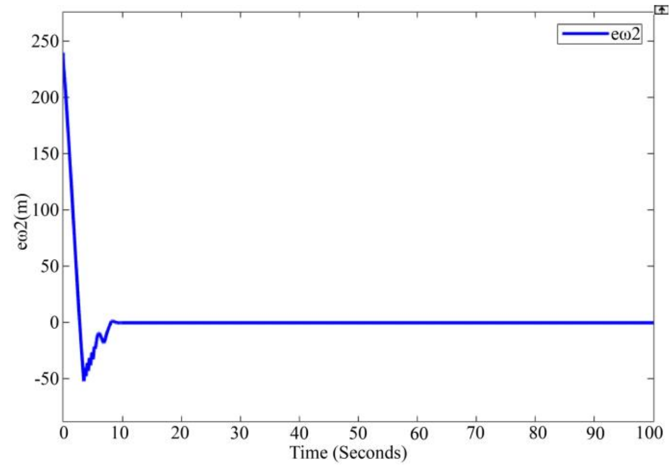

Fig. 11 Error of tracking speed of wheel 2

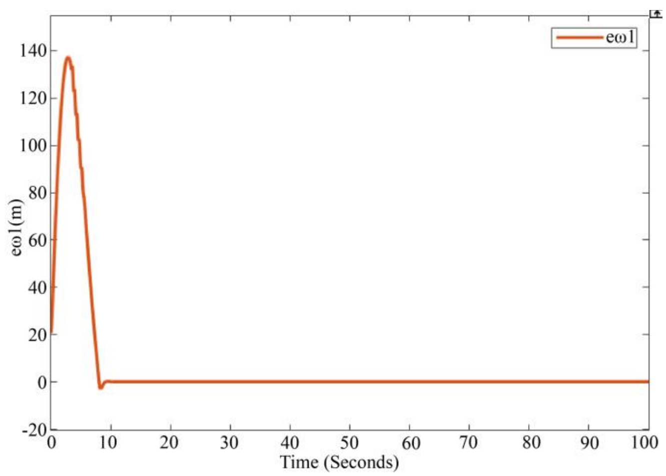

Fig. 10 Error of tracking speed of wheel 1

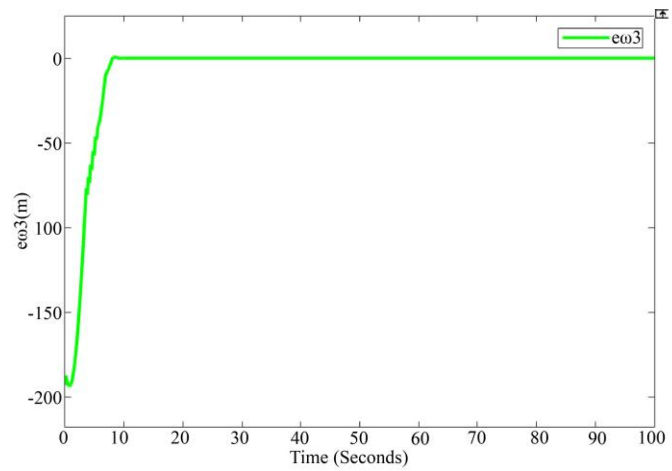

Fig. 12 Error of tracking speed of wheel 3

Remark: From the simulation results of Figures 6,7,8,9,10,11,12, we see that the controller gave very good grip quality. The actual trajectory of the robot has followed the reference trajectory; the tracking error is almost zero.

5. Conclusion

This paper presents the design method of the adaptive sliding mode controller for TWOMR. In which the SMC is designed so that the robot tracks the reference trajectory, The adaptive rule based on the RBFNN is introduced to approximate the model uncertainty component, the unknown external disturbances. The stability of the whole closed-loop system is proven based on the Lyapunov theory. Simulation results have shown the effectiveness of the proposed method. The next research direction will put the installation algorithm for the actual model.

Acknowledgments

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