ADAPTIVE SLIDING MODE CONTROL FOR TWIN ROTOR MIMO SYSTEM USING RADIAL BASIS FUNCTION NEURAL NETWORK

Dinh Hieu Phan[1], Van Truong Nguyen[1], Thanh Lam Bui[1], Dinh Truong Nguyen[1]

DOI: http://doi.org/10.57001/huih5804.2025.266

ABSTRACT

This paper presents a adaptive sliding mode control method using radial basis function neural network (RBFNN) to control a yaw and pitch angle of a twin rotor multil input - multil output system (TRMS). This controller has the advantage of being able to learn and approximate unknown nonlinear functions with arbitrary precision regardless of the various system parameters while the tranditional sliding controller need to accurately calculate the nonlinear functions so the chatering occurs under the affect of the uncertain system parameters and disturbance. The adaptive controller using RBFNN will update the online neural network weights so that the output vectors of neural network are trained online to approximate uncertainty components of the system. The simulation results demonstrate the adaptive controller using RBFNN is capable tracking different reference trajectories in satisfactory manner.

Keywords: *RBFNN, adaptive control, parameter uncertainty, sliding mode control (SMC), pitch angle, yaw angle.*

[1]School of Mechanical and Automotive Engineering, Hanoi University of Industry, Vietnam

[*]Email: phandinhhieu@haui.edu.vn

Received: 10/3/2025

Revised: 28/4/2025

Accepted: 25/7/2025

1. INTRODUCTION

The TRMS consists of a beam that rotate freely in horizontal planes (pitch angle) and in vertical planes (yaw angle) [1]. These angle are driven by DC motors, with the main rotor generating a lifting force for vertical motion, the tail rotor controlling left or right turning. The aerodynamic force is regulated by adjusting the rotor speeds. As a result, from a control engineering perspective, the TRMS is noticed as a complex, nonlinear system with uncertain parameters [2]. The control objective for the TRMS is to stabilize it under coupled conditions and guarantee precisely and rapid trajectory tracking. Various control strategies can be employed to achieve this goal. Sliding mode control (SMC) methods are particularly appealing in this context, as they enhance robustness and invariance of the system against matched uncertainties and disturbances. Several SMC schemes have been proposed in previous studies. For example, in [3], the SMC using super - twisting algorithm was introduced to control the TRMS. Through simulation results, this controller demonstrated robustness against uncertainties and external disturbances, while it also reduce control input chattering. Mustafa and other researchers [4] compared adaptive sliding and adaptive integral sliding control for the TRMS system. Their proposed controller utilized an adaptive coefficient adjustment law to minimize chattering by accurately estimating the upper bound of uncertainty. In [5, 6], a terminal sliding control was proposed. The simulation results showcased the sustainability and effectiveness of this approach. In [7], the authors explored a TRMS system model and designed an SMC controller without an observer to regulate the pitch and yaw angle. The results underscored the effectiveness of SMC compared to the classic PID control strategy.

Recently, the application of neural networks for control purposes has attracted the attention of many scientists. Neural networks combined with control methods are considered as an effective solution to solve control problems for objects with uncertain models and affected disturbances. In paper [8], authors built an adaptive controller using RBF neural network for robotic arm. Fan Jin hui and authors team [9] designed an adaptive controller using RBF neural network to estimate the nonlinear, variable function of omnidirectional wheeled autonomous robot.

In this paper, the adaptive SMC controller using radial basic funtion neural network is proposed for the nonlinear TRMS. The adaptive SMC controller offers several benefits, including able to learn and approximate unknown nonlinear functions with arbitrary precision regardless of the various system parameters. The output weights of the neural network and the adaptive SMC controller parameters are determined by analyzing the system stability using the Lyapunov function. To demonstrate its efficiency, the adaptive SMC controller quality is shown in the simulation results. The simulation results indicate that the adaptive SMC controller brings high tracking performance and reduces chattering phenomenon for the TRMS system.

2. TRMS DYNAMICS

The TRMS is designed for experimental purposes, this system includes the mechanical part and the electrical part. The mechanical part of TRMS includes two rotors (these are DC electric motors independently excited by the excitation source using permanent magnets) combined with a counterweight. Both the rotor and the counterweight are placed on the free - free beam. These parts are attached to the tower. The electrical part located under the tower plays a role in controlling TRMS. The electrical part measures the signals and transmits them to the PC. It also transmits control signals to the actuator. The physical structure of TRMS is described in Fig. 1.

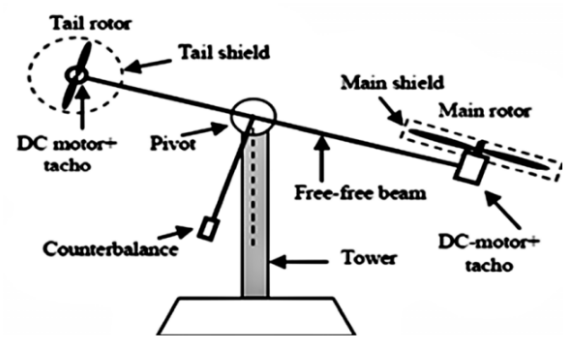

Fig. 1. Physical structure of TRMS

This paper using the results of mathematical model in [10] is presented as:

$$\begin{bmatrix} J_1\cos^2\varphi_v + J_2\sin^2\varphi_v + h^2(m_{T_1}+m_{T_2}) + J_3 & h(m_{T_1}l_{T_1}\sin\varphi_v - m_{T_2}l_{T_2}\cos\varphi_v) \\ h(m_{T_1}l_{T_1}\sin\varphi_v - m_{T_2}l_{T_2}\cos\varphi_v) & J_1+J_2 \end{bmatrix}\begin{bmatrix}\ddot{\varphi}_h \\ \ddot{\varphi}_v\end{bmatrix} + \begin{bmatrix} h(m_{T_1}l_{T_1}\cos\varphi_v + m_{T_2}l_{T_2}\sin\varphi_v)\dot{\varphi}_v^2 + 2(J_2-J_1)\dot{\varphi}_v\dot{\varphi}_h\sin\varphi_v\cos\varphi_v \\ (J_1-J_2)\sin\varphi_v\cos\varphi_v\dot{\varphi}_h^2 + g(m_{T_1}l_{T_1}\cos\varphi_v + m_{T_2}l_{T_2}\sin\varphi_v) \end{bmatrix} = \begin{bmatrix}M_{ih} \\ M_{iv}\end{bmatrix} \quad (1)$$

Where φ_h, φ_v denote the yaw and pitch angle; m_{T_1}, m_{T_2} denote the mass total of counterweight bar and the mass total of free beam respectively; l_{T_1}, l_{T_2} are the centroid free - free beam and counter weight bar; J_1, J_2, J_3 are the constant moments of inertia of free - free beam, counterweight bar and rotary joint; M_{ih}, M_{iv} denote the total of torques.

Let variable $q = \begin{bmatrix}\varphi_h \\ \varphi_v\end{bmatrix}$, from Eq. (1), the general dynamic of TRMS is rewritten as:

$$H(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau + n(t) \quad (2)$$

τ is the input torques; n(t) is the uncertain model and unwanted disturbance affecting the system.

3. TRMS CONTROL

3.1. Adaptive SMC controller design

Denote the tracking error as: $e = q_d - q$

Select the sliding variable as:

$$s = \dot{e} + \lambda e \quad (3)$$

Where C is a symmetric positive definite constant matrix and $C = C^T > 0$.

Therefore we have

$$\dot{q} = -s + \dot{q}_d + \lambda e$$

$$\begin{aligned} H\dot{s} &= H(\ddot{q}_d - \ddot{q} + \lambda\dot{e}) = H(\ddot{q}_d + \lambda\dot{e}) + C\dot{q} + G - \tau - n(t) \\ &= H(\ddot{q}_d + \lambda\dot{e}) - Cs + C(\dot{q}_d + \lambda e) + G - \tau - n(t) \\ &= -Cs - \tau - n(t) + f \end{aligned} \quad (4)$$

Where $f(x) = H(\ddot{q}_d + \lambda\dot{e}) + C(\dot{q}_d + \lambda e) + G$ is unknown and therefore f(x) is ap proximated by the RBFNN. The RBFNN is showed in Fig. 2 The network input is selected as follows:

$$x = [e^T\ \dot{e}^T\ q_d\ \dot{q}_d\ \ddot{q}_d]$$

The desired algorithm of RBFNN is:

$$\alpha_i = \exp\left(\frac{\|x - c_i\|^2}{\sigma_i^2}\right); \quad f(x) = W^T\alpha(x) + \varepsilon \quad (5)$$

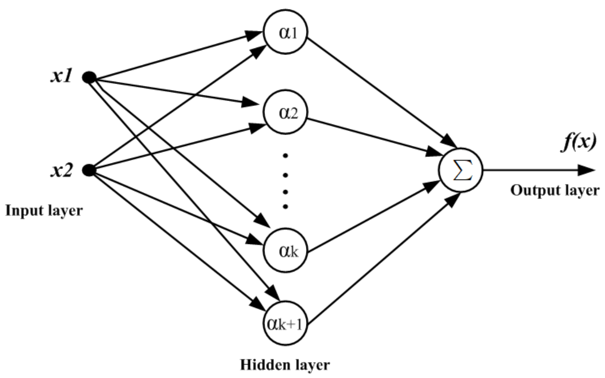

Fig. 2. The structure of RBFNN

The control law of TRMS is designed:

$$\tau = \hat{f}(x) + k_v s - v \tag{6}$$

Where v is the robust element required to overcome the network approximation error ε and the disturbance n(t). The robust element v is designed as:

$$v = -(\varepsilon_N + N)\operatorname{sgn}(s) \tag{7}$$

Where $\|\varepsilon\| \le \varepsilon_N; \|n(t)\| \le N$

From Eqs. (4), (6), we have

$$\begin{aligned} H\dot{s} &= -Cs - \tau - n(t) + f(x) \\ &= -Cs - \hat{f}(x) - k_v s + v - n(t) + f(x) \end{aligned} \tag{8}$$

RBFNN is adopted to approximate f(x) therefore, the output of RBFNN is:

$$\hat{f}(x) = \hat{W}^T \alpha(x) \tag{9}$$

From Eqs. (5), (8), (9), we have

$$\begin{aligned} H\dot{s} &= -Cs - \hat{W}^T \alpha(x) - k_v s + v - n(t) + W^T\alpha(x) + \varepsilon \\ &= -(C + k_v)s + \tilde{W}^T \alpha(x) + v - n(t) + \varepsilon \end{aligned} \tag{10}$$

3.2. Stability Analysis

Select the Lyapunov function as

$$L = \frac{1}{2}s^T H s + \frac{1}{2}\operatorname{tr}(\tilde{W}^T \Gamma^{-1} \tilde{W})$$

where H and Γ are positive matrices.

Therefore we have

$$\dot{L} = s^T H\dot{s} + \frac{1}{2}s^T \dot{H} s + \operatorname{tr}(\tilde{W}^T \Gamma^{-1} \dot{\tilde{W}})$$

$$= -s^T k_v s + \frac{1}{2}s^T(\dot{H} - 2C)s + \operatorname{tr}\tilde{W}^T(\Gamma^{-1}\dot{\tilde{W}} - \alpha(x)s^T) + s^T(v - n(t) + \varepsilon)$$

We know that $s^T(\dot{H} - 2C)s = 0$ and the adaptive rule of the RBFNN is

$$\dot{\tilde{W}} = \dot{\hat{W}} = \Gamma\alpha(x)s^T \tag{11}$$

so we have $\dot{L} = -s^T k_v s + s^T(v - n(t) + \varepsilon)$.

From Eqs. (7),

$$\begin{aligned} \dot{L} &= -s^T k_v s - s^T(\varepsilon_N + N)\operatorname{sgn}(s) - s^T(n(t) - \varepsilon) \\ &\le -s^T k_v s - |s^T|(\varepsilon_N + N) + |s^T|(\|n(t)\| + \|\varepsilon\|) \\ &\le -s^T k_v s \le 0 \end{aligned}$$

The control system of TRMS is stable according to the Lyaponov criterion.

4. SIMULATION RESULTS

Matlab/Simulinks software is used to simulate the TRMS control system. The TRMS dynamics parameters are given in Table 1.

Table 1. Physical parameters of TRMS

Symbol	Definition	Value
m_{T_1}	Mass total of free beam	0.825kg
m_{T_2}	Mass total of counter weight bar	0.0908kg
L_{T_1}	Centroid free - free beam	0.0186m
L_{T_2}	Centroid counter weight bar	0.2443m
J_1	Moments of inertia of free - free beam	0.0591kgm^2
J_2	Moments of inertia counter weight bar	0.0059kgm^2
J_3	Moments of inertia of rotary joint	0.0000168kgm^2
h	The length of rotary joint	0.06m

For adaptive SMC controller, The selection of the Gauss function of the RBFNN is very important to the control of the neural network. The input of RBFNN is $x = [e^T\ \dot{e}^T\ q_d\ \dot{q}_d\ \ddot{q}_d]$, the number of hidden nodes are 7.

The parameters of RBFNN and SMC controller are:

$c_i = [0.15]_{7x5}; \sigma_i = 0.2; \Gamma = \operatorname{diag}\{15,15\}; k_v = \operatorname{diag}\{20;20\}$
$\lambda = \operatorname{diag}\{5,5\};\ \varepsilon_N = 0.2; N = 0.1$

The control law is given in Eqs. (6), and adaptive law is given in Eqs. (11).

The reference signal of yaw angle and pitch angle is $q_d = \begin{bmatrix} \varphi_{hd} = 0.1\sin t \\ \varphi_{vd} = 0.2\sin t \end{bmatrix}$.

The simulation results are shown in Figs. 3 - 6. Fig. 3 shows position tracking of yaw angle and pitch angle using adaptive SMC controller. It shows that the yaw and pitch angle of TRMS track closely their references afer 4s.

Fig. 4 shows the high tracking performance of the speed yaw and pitch angle after 5s. The control input signals for adaptive SMC controller are shown in Fg. 5. It is clear that the chattering phenomenon of control input signals is small. Moreover, the unknown disturbances of TRMS are estimated and compared to the actual disturbances in Fig. 6.

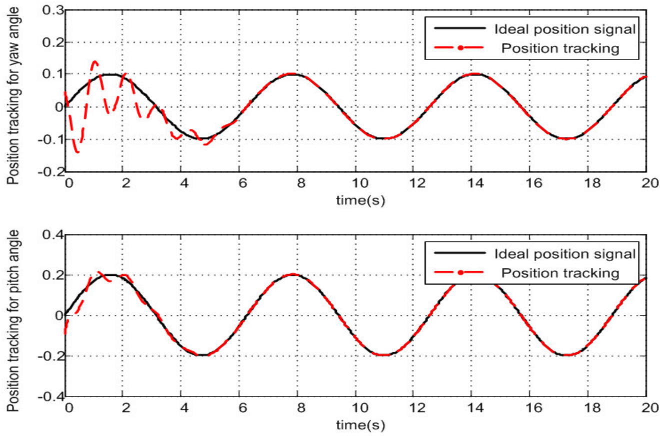

Fig. 3. Position tracking of yaw and pitch angle

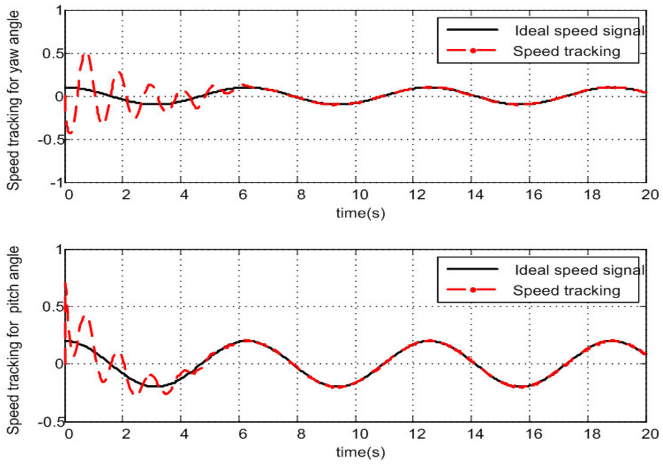

Fig. 4. Speed tracking of yaw and pitch angle

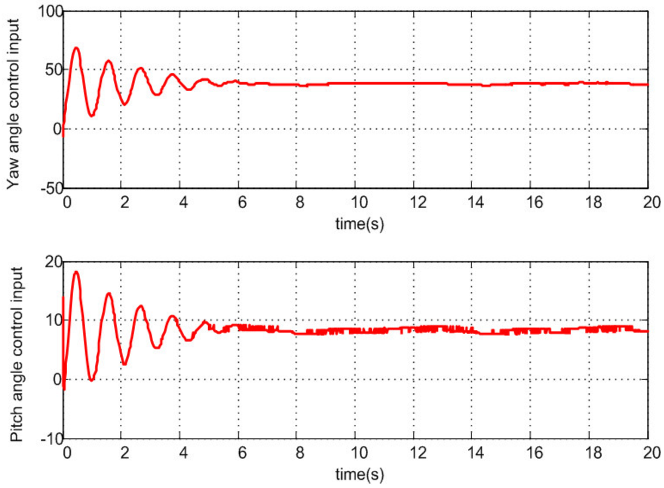

Fig. 5. Control signal using adaptive SMC controller

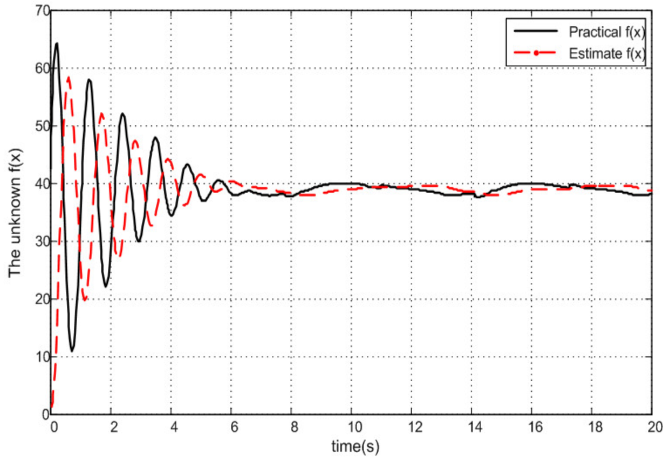

Fig. 6. The unknown disturbance of TRMS

5. CONCLUSION

This paper has addressed the adaptive SMC controller method for the TRMS. The adaptive SMC controller is designed based on RBFNN. RBFNN algorithm is able to learn and approximate unknown nonlinear functions with arbitrary precision regardless of the various system parameters while the sliding controller need to accurately calculate the nonlinear functions so the chatering occurs under the affect of the uncertain system parameters and disturbance. The control law and adaptive law are determined by Lyaponov criterion. The simulation results show that the adaptive SMC controller not only brings high tracking performance of yaw and pitch angle but also reduces the chattering of the control signals.

REFERENCES

[1]. Juang J. G., Huang M. T., Liu W. L., "PID control using presearched genetic algorithms for a mimo system," *IEEE Transactions on Systems, Man, and Cybernetics - Part C: Applications and Reviews,* 38(5), 716-727, 2008.

[2]. Wen P., Lu T.W., "Decoupling control of a twin rotor MIMO system using robust deadbeat control technique," *IET Control Theory Appl.,* 2(11), 999-1007, 2008.

[3]. Mondal S., Mahanta C., "Second order sliding mode controller for twin rotor MIMO system," in *India Conference (INDICON)*, 1-5. 2011.

[4]. Mustafa S., Khan Q., Khan I., "Comparative analysis of robust and adaptive control strategies for twin rotor MIMO system," in *13th International Conference on Emerging Technologies* (ICET), 1-6, 2017.

[5]. Nguyen V. T., et al., "Adaptive nonsingular fast terminal sliding mode tracking control for parallel manipulators with uncertainties," in *2019 IEEE International Conference on System Science and Engineering*, 522-525, 2019.

[6]. Nguyen V. T., "Non-Negative Adaptive Mechanism-Based Sliding Mode Control for Parallel Manipulators with Uncertainties," *Computers, Materials & Continua*, 74(2), 2023.

[7]. Shaikh P. U., Karvekar S., "Implementation of Sliding Mode Controller for Twin Rotor Multi Input Multi Output System without state observer," in *1st IEEE International Conference on Power Electronics*, *Intelligent Control and Energy Systems*, 1-6, 2016.

[8]. Mahjoub S., et al., "Radial-basisfunctions neural network sliding mode control for underactuated mechanical systems," *Int J Dyn Control*, 2(4), 533-541, 2014.

[9]. Fan J., Songmin J., Xiuzhi L., "Direct Adaptive Control Based on Improved RBF Neural Network for Omni-directional Mobile Robot," in *International Conference on Mechatronics, Electronic, Industrial and Control Engineering*, 1108-1112, 2015.

[10]. Rahideh A., Shaheed M. H., "Mathematical dynamic modelling of a twin rotor multiple input-multiple output system," in *Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering*, 89-101, 2007.