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ADAPTIVE FAST NONSINGULAR TERMINAL SLIDING MODE CONTROL FOR MANIPULATOR ROBOT

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Abstract. This study presented an improved adaptive nonlinear terminal sliding mode control technique for the manipulator robot to achieve better adaptability and faster finite-time convergence. First, an adaptive self-updating algorithm will be developed to relax the problems of fixed control gain for the main proposed controller. Next, an adaptive neural network estimator is applied by estimating the robot dynamics to increase the tracking control performance. In addition, a compensator-typed robust controller also is designed to guarantee the robustness, continuity, and smoothing properties of the control system. To verify the effectiveness of the proposed method, besides applying the Lyapunov theorem, the comparative numerical simulation results will be provided in more detail.

Keywords. Nonsingular terminal sliding mode control; Manipulator robot; Adaptive control; Neural networks.

1. INTRODUCTION

Nonlinear terminal sliding mode (NTSM) control techniques have been explored and widely applied the manipulation robot (MR) control systems, recently [1–8]. The advantages of NTSM control schemes [1] can be reflected in improving the tracking control performances with higher precision and better finite-time convergence of the state on the sliding surface. For more details, the NTSM control methods can achieve higher performances, better-chattering phenomena reduction, and more efficiency in singularity elimination when compared with the linear function-based sliding mode control or terminal sliding mode control methods. The authors in [3], by applying the NTSM techniques, used a nonlinear sliding manifold with the proportional derivative (PD)- typed sign function to obtain better fixed-time control effectiveness. In addition, this controller also had an even greater advantage that it did not require the uncertainty of acceleration and the dynamics of the MR control system. However, this method exists some disadvantages, such as the requirements of the nominal MR dynamic parameters and fixed control gains [3]. As published in [5], M. Van et al. provided a modified sliding surface in the type of the self-turning proportional-derivative-integral (PID) to gain faster finite-time convergence and better tracking control performances, as well as suppress chattering phenomena more effectively. This study also provided a good approach for increasing the adaptability of the NTSM methods. However, the problems of fixed proportional gains and the stability of the

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fuzzy system still have not been addressed clearly [5]. It noted that this proportional gain [5] played an important role in reinforcing the tracking errors to the steady states, which had not been tuned adaptively [7, 8].

In this study, a fast NSTM method will be proposed to address the drawbacks of traditional NSTM controllers. The improvements focus on the enforcement of adaptability, robustness, and tracking control performances in consideration of finite-time convergence. First, the PD gains of the proposed NTSM controller are adaptively adjusted online [9, 10] by a self-tuning adaptive algorithm. This will enhance the adaptability and solve the problems of fixed control gain of the NTSM controller [1 – 8]. Second, the uncertain unknown RM dynamics will be estimated by applying a neural networks (NN) estimator [7] without requiring knowledge of the nominal RM parameters. Third, an adaptive robust controller, as a compensator, will also be developed to deal with the other uncertainties of the MR control system, such as estimating errors and unknown disturbances. Moreover, the proposed robust controller is also capable of smoothing the control signals and reducing the chattering phenomena. Finally, in the design process, all adaptive estimating/updating rules are designed by applying the Lyapunov theorem to ensure the stability of the proposed fast NTSM control system.

The paper organization is arranged as follows. The design procedures are provided according to the stability analysis in Section 2. The simulation work is performed in Section 3. Section 4 presents the conclusions.

2. CONTROL ALGORITHMS

2.1. Design procedure

By applying the model of n-links MR dynamics as provided in [10], it yields

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(\dot{q}) + \tau_d = \tau. \tag{1}$$

In this research, our goal is to enhance the adaptability of the RM control system to achieve better tracking control performances besides improving the finite-time convergence rate of the tracking errors. Therefore, first, as a basis for accelerating the finite-time convergence, the fast NSTM surface can be applied in the following form [1, 2, 5]

$$S = e + K_\xi e^\xi + K_\alpha^{-1}\dot{e}^{a/b}, \tag{2}$$

where, $e(t) = q_d(t) - q(t) \in R^{n\times 1}$ is the tracking position errors, $q_d(t) \in R^{n\times 1}$ is the desired positions, $K_\xi = \operatorname{diag}(K_{\xi 1},\ldots,K_{\xi n}) \in R^{n\times n}$ and $K_\alpha = \operatorname{diag}(K_{\alpha 1},\ldots,K_{\alpha n}) \in R^{n\times n}$ are the positive constin orderant matrices, a, and $b(1 < a/b < 2)$ are positive odd numbers, ξ is chosen as $\xi > a/b$. From here, the derivative of $S(t)$ can be obtained as

$$\begin{aligned}\dot{S} &= \dot{e} + K_\xi \xi \operatorname{diag}(e^{\xi-1})\dot{e} + \tfrac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\ddot{e}\\ &= \dot{e} + K_\xi \xi \operatorname{diag}(e^{\xi-1})\dot{e} + \tfrac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})(f+\tau-\tau_d),\end{aligned} \tag{3}$$

where $f = \ddot{q}_d - (I+M)\ddot{q} - C\dot{q} - G - F$. Based on the defined sliding surface, the fast NSTM control rule can be considered in the following form

$$\tau = \tau_d - f - \frac{b}{a}K_\alpha(\dot{e}^{2-\frac{a}{b}}) - \frac{b}{a}\xi K_\xi \operatorname{diag}(e^{\xi-1})K_\alpha(\dot{e}^{2-\frac{a}{b}}) - K\operatorname{sign}(S) - KS \tag{4}$$

where $K = \operatorname{diag}(K_1,\ldots,K_n) \in R^{n\times n}$ is also a positive constant matrix. The ideal control rule in (4) may ensure that the tracking errors can converge to steady states in a finite-time and the stability of the RM control system. Unfortunately, with the existence of uncertainties (τ_d, f) and the chattering problems (by applying the sign(.) function), this ideal control rule is not easy to implement, especially in realistic applications, without prior knowledge of the RM control system. Therefore, the improved fast NSTM control rule can be designed in the following form

$$\tau = \tau_r - \hat{f} - \frac{b}{a} K_\alpha (\dot{e}^{2-\frac{a}{b}}) - \frac{b}{a} \xi K_\xi \mathrm{diag}(e^{\xi-1}) K_\alpha (\dot{e}^{2-\frac{a}{b}}) - \hat{K} S, \tag{5}$$

where $\hat{K}$ is self-updated to provide an adaptive value for the K control gain, to enhance the adaptability of the NTSM controller. The τ_r is considered the compensator-typed robust controller (as the $K\mathrm{sign}(S)$ term in (4)) that will be developed to eliminate the RM control system's disturbances and other uncertainties. The $\hat{f}$ is the NN estimator for the unknown function f [10, 11]. The inevitable NN errors in estimating process may be considered in the following form [10]

$$\tilde{f} = f - \hat{f} = (\mathrm{W}^{*T} - \hat{\mathrm{W}}^T)\phi + \varepsilon = \tilde{\mathrm{W}}^T \phi + \varepsilon, \tag{6}$$

where, $\mathrm{W}^{*T} = [\mathrm{w}_1^*, \mathrm{w}_2^*, \ldots, \mathrm{w}_h^*] \in R^{n \times h}$ is considered as the optimal weight matrix of the NN estimator and $h \in N$ is the number of NN hidden nodes, $\hat{\mathrm{W}}^T \in R^{n \times h}$ is the approximation value of W^{*T}, the $\phi(x) = [\phi_1, \phi_2, \ldots, \phi_h]^T \in R^{h \times 1}$ is Gaussian function, $x = [\ddot{q}_d, \ddot{q}, \dot{q}, q]^T$ is the NN inputs, $\varepsilon \in R^{n \times 1}$ is the NN approximator error. By applying the results in (5) and (6), we can obtain the derivative of $S(t)$ in the following form

$$\dot{S} = -\frac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1}) K S + \frac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1}) (\tilde{\mathrm{W}}^T \phi + \tilde{K} S + \varepsilon - \tau_d + \tau_r), \tag{7}$$

where $\tilde{K} = K - \hat{K}$, K can be considered as the optimal control gain. Therefore, the ε and τ_d are assumed to be bounded, and they will satisfy the following constraint

$$\|\varepsilon - \tau_d\| \leq R, \tag{8}$$

where R is an uncertain positive parameter. Based on the above analysis, the control performance of the RM control system can be ensured if the robust controller can relax the mentioned uncertainties. Therefore, the robust controller can be designed as the following rule

$$\tau_r = -\hat{R} \frac{\left(K_\alpha^{-1}\right) \mathrm{diag}(\dot{e}^{\frac{a}{b}-1}) S}{\|S\| \left\| \left(K_\alpha^{-1}\right) \mathrm{diag}(\dot{e}^{\frac{a}{b}-1}) \right\|} - c \tanh(S), \tag{9}$$

where $\hat{R}$ will be adaptively updated to relax the requirement of the uncertain R. The tanh(.) is the hyperbolic tangent sigmoid function, $\tanh(S) = \frac{e^S - e^{-S}}{e^S + e^{-S}}$ [10], and c is a designed positive constant. The strategy of the designed fast NTSM control system is shown in Figure 1. With the designed control rules, the adaptive estimating/updating algorithms need to be developed to achieve the aim of the study, such as the improvement of adaptability, robustness, and finite-time convergence. Therefore, based on the Lyapunov theorem, the adaptive online updating/estimating algorithms for the proposed fast NTSM control system are designed as the following rules

$$\begin{aligned} \dot{\hat{\mathrm{W}}} &= \delta_\mathrm{w} \tfrac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1}) \phi S^T, \\ \dot{\hat{K}} &= \delta_k \tfrac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1}) S S^T, \\ \dot{\hat{R}} &= \delta_r \tfrac{a}{b} \|S\| \left\| \left(K_\alpha^{-1}\right) \mathrm{diag}(\dot{e}^{\frac{a}{b}-1}) \right\|, \end{aligned} \tag{10}$$

where $\delta_\mathrm{w}, \delta_k$ are positive diagonal constant matrices, and δ_r is a positive constant parameter.

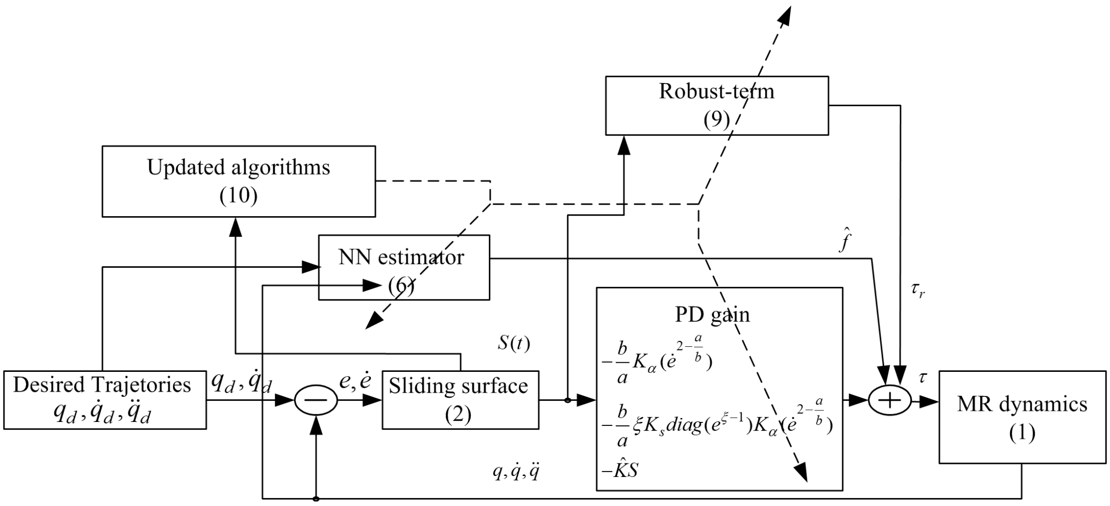

Figure 1: The proposed fast NTSM control strategy

2.2. Stability analysis

Theorem 1. *By considering the RM dynamic system in (1), if the proposed control rules and updating algorithms in (5), (9), and (10) are applied, all assumptions hold, the* $S(t), \tilde{\mathrm{W}}, \tilde{K}$, *and* $\tilde{R}$ *are bounded.*

Proof. The Lyapunov function candidate is defined as the following form

$$V(S(t), \tilde{\mathrm{W}}, \tilde{K}, \tilde{R}) = \frac{1}{2}S^T S + \frac{1}{2}tr(\tilde{\mathrm{W}}^T \delta_{\mathrm{w}}^{-1}\tilde{\mathrm{W}}) + \frac{1}{2}tr(\tilde{K}^T \delta_k^{-1}\tilde{K}) + \frac{1}{2}\tilde{R}\delta_r\tilde{R}, \tag{11}$$

where $\tilde{R} = R - \hat{R}$. By differentiating (11) with respect to time, we can obtain the following result

$$\begin{aligned} \dot{V} &= -S^T K_s S + S^T \frac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1})(\tilde{\mathrm{W}}^T\phi + \tilde{K}S + \varepsilon - \tau_d + \tau_r) \\ &\quad - tr(\tilde{\mathrm{W}}^T\delta_{\mathrm{w}}^{-1}\dot{\mathrm{W}}) - tr(\tilde{K}^T\delta_K^{-1}\dot{K}) - \tilde{R}\delta_r^{-1}\dot{R} \\ &= -S^T K_s S + S^T \frac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1})\tilde{\mathrm{W}}^T\phi \\ &\quad - tr(\tilde{\mathrm{W}}^T\delta_{\mathrm{w}}^{-1}\dot{\mathrm{W}}) + S^T \frac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1})\tilde{K}S - tr(\tilde{K}^T\delta_k^{-1}\dot{K}) \\ &\quad + S^T \frac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1})(\varepsilon - \tau_d) + S^T \frac{a}{b} K_\alpha^{-1} \mathrm{diag}(\dot{e}^{\frac{a}{b}-1})\tau_r - \tilde{R}\delta_r^{-1}\dot{R}, \end{aligned} \tag{12}$$

where $K_s = \frac{a}{b}K_\alpha^{-1}\mathrm{diag}(\dot{e}^{\frac{a}{b}-1})K \geq 0$. When the adaptive online updating algorithms in (10) are used, the (12) can be rewritten as

$$\begin{aligned} \dot{V} &= -S^T K_s S - \tilde{R}\tfrac{a}{b}\left\|S\right\| \left\|\left(K_\alpha^{-1}\right)\mathrm{diag}(\dot{e}^{\frac{a}{b}-1})\right\| \\ &\quad + S^T \tfrac{a}{b} K_\alpha^{-1}\mathrm{diag}(\dot{e}^{\frac{a}{b}-1})(\varepsilon - \tau_d) + S^T \tfrac{a}{b} K_\alpha^{-1}\mathrm{diag}(\dot{e}^{\frac{a}{b}-1})\tau_r. \end{aligned} \tag{13}$$

By applying the robust control rule in (9), from (13), yields

$$\begin{aligned}\dot{V} &= -S^T K_s S - \tilde{R}\tfrac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\| + S^T\tfrac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})(\varepsilon-\tau_d)\\ &\quad -\hat{R}\left\|S\right\|\tfrac{a}{b}\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\| - c\tfrac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})S^T\tanh(S)\\ &\le -S^T K_s S - \tilde{R}\tfrac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\| + R\tfrac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|\\ &\quad -\hat{R}\left\|S\right\|\tfrac{a}{b}\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\| - c\tfrac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})S^T\tanh(S)\\ &\le -S^T K_s S - c\tfrac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})S^T\tanh(S).\end{aligned} \tag{14}$$

■

Based on the result in (14), we have $\dot{V}(S(t),\ \tilde{\mathrm{W}},\ \tilde{K},\ \tilde{R}) \le 0,\ \forall t \ge 0$. Therefore, the $\dot{V}(S(t),\tilde{\mathrm{W}},\tilde{K},\tilde{R})$ is a negative semi-definite function, so that, $\dot{V}(S(t),\tilde{\mathrm{W}},\tilde{K},\tilde{R}) \le \dot{V}(S(0),\tilde{\mathrm{W}},\tilde{K},\tilde{R})$. Clearly, if the $S(t),\tilde{\mathrm{W}},\tilde{K}$, and $\tilde{R}$ are bounded at the initial time $t=0$, they will stay this bounded state for all $t \ge 0$. Thus, $\hat{\mathrm{W}},\hat{K}$, and $\hat{R}$ are also bounded. By applying the Lyapunov theorem [10, 12], the stability of the proposed control system is guaranteed. Next, the finite-time convergence of the $S(t)$, and $e(t)$ will be addressed by the following lemma.

Lemma 1. *By assuming that* $\left\|\tilde{\mathrm{W}}^T\phi - \hat{K}S\right\| \le c_1, \left\|\tilde{R}\right\| \le c_2, (c_1, c_2 > 0)$, *the* $S(t), e(t)$ *will approach to zero with finite-time.*

Proof. Consider the second Lyapunov candidate function as

$$V_s(S(t)) = \frac{1}{2}S^T S. \tag{15}$$

By differentiating $V_s(t)$ in (15) with respect to time, yields

$$\begin{aligned}\dot{V}_s &= S^T\dot{S} = S^T\frac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})(\tilde{\mathrm{W}}^T\phi - \hat{K}S + \varepsilon - \tau_d)\\ &\quad -\frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|\hat{R} - S^T\frac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})c\tanh(S)\\ &\le \frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|\left\|\tilde{\mathrm{W}}^T\phi - \hat{K}S\right\| + \frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|\left\|\varepsilon-\tau_d\right\|\\ &\quad -\frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|\hat{R} - S^T\frac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})c\tanh(S)\\ &\le \frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|\left\|\tilde{\mathrm{W}}^T\phi - \hat{K}S\right\| + \frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|\left\|\tilde{R}\right\|\\ &\quad -S^T\frac{a}{b}K_\alpha^{-1}\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})c\tanh(S)\\ &\le \frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|(c_1+c_2-c).\end{aligned} \tag{16}$$

From the above proof of theorem, it notes that $S(t),\ \tilde{\mathrm{W}},\ \tilde{K},\ \hat{R}$, and τ_r are bounded. If the designed constant parameter is selected as $c_1 + c_2 < c$, then

$$\dot{V}_s \le \frac{a}{b}\left\|S\right\|\left\|\left(K_\alpha^{-1}\right)\operatorname{diag}(\dot{e}^{\frac{a}{b}-1})\right\|(c_1+c_2-c) \le 0. \tag{17}$$

From the result in (17), if $\dot{e} \ne 0$, $\dot{V}_s < 0$, it can conclude that $S(t)$ converges to zero within finite-time [1, 2]. If $\dot{e} = 0,\ e \ne 0$ then $\ddot{e} = \tilde{\mathrm{W}}^T\phi - \hat{K}S + \varepsilon - \tau_d - c\tanh(S)$. This shows that [1, 2] if $S \ne 0,\ \dot{e} = 0$ then $\ddot{e} \le -c$ for $S > 0$ and $\ddot{e} \ge c$ for $S < 0$. As a result, $\dot{e} = 0$ is not an attractor, and manifold $S(t)$ will converge to zero in finite-time, as well as $e(t)$ will also converge to zero in finite-time [1, 2]. This completes the proof. ■

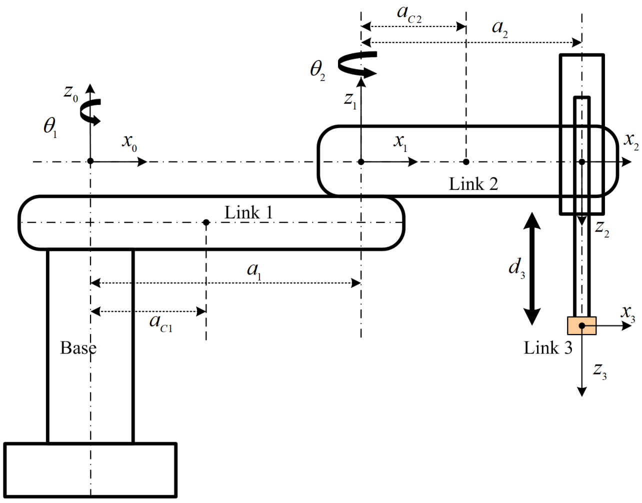

Figure 2: The MR 3 – DOF model

Remark 1. In the proposed NTSM scheme, the NTSM sliding surface has been modified by adding the part, $K_\xi e^\xi$, that is different from our previous study. This part causes the proposed main NTSM controller to be changed with the added term, $-\frac{b}{a}\xi K_s \text{diag}(e^{\xi-1})K_\alpha(\dot{e}^{2-\frac{a}{b}})$. Thus, this improvement first leads to a faster time convergence of the tracking errors.

Remark 2. For the sliding mode control techniques, the part, $\hat{K}S$, is usually used to reduce the convergence time and tracking error. However, if the PD control gain, $\hat{K}$, is not selected properly, the stability of the control system will be seriously affected. This drawback has been solved in our study by the online self-tuning algorithm for the PD control gain.

Remark 3. In the proposed robust controller in (9), the first part, $\hat{R}\frac{\left(K_\alpha^{-1}\right)\text{diag}(\dot{e}^{\frac{a}{b}-1})S}{\|S\|\left\|\left(K_\alpha^{-1}\right)\text{diag}(\dot{e}^{\frac{a}{b}-1})\right\|}$, play a role in compensating for the inevitable uncertainties, such as the unknown disturbances and estimating errors, in order to ensure the robustness of the NTSM control system. However, the structure of this part can lead to chattering phenomena or discontinuity of the control signals. This disadvantage has been relaxed by the second part of the proposed robust controller,$c\tanh(S)$. This second part, as a smooth function, can assist in minimizing the chattering phenomena and discontinuity for the control signals. In general, the proposed NSTM strategy has some advantages in increasing the finite-time convergence of tracking errors, adaptability, and robustness of the RM control system. In addition, the proposed controller is a type of full-form model-free adaptive robust controller, in which the uncertainties of the control system are solved thoroughly. Moreover, by applying the online adaptive updating algorithms based on the Lyapunov stability theorem, the stability and the finite-time convergence of the proposed NTSM are guaranteed.

3. NUMERICAL SIMULATION RESULTS

The MR 3 – DOF model, as shown in Figure 2, is used in the simulation process. All the dynamic parameters of the MR are provided by [10]. To verify the effectiveness of the proposed control method (AFNSM), the NTSM1, NTSM2, and the proposed NTSM controllers are applied to

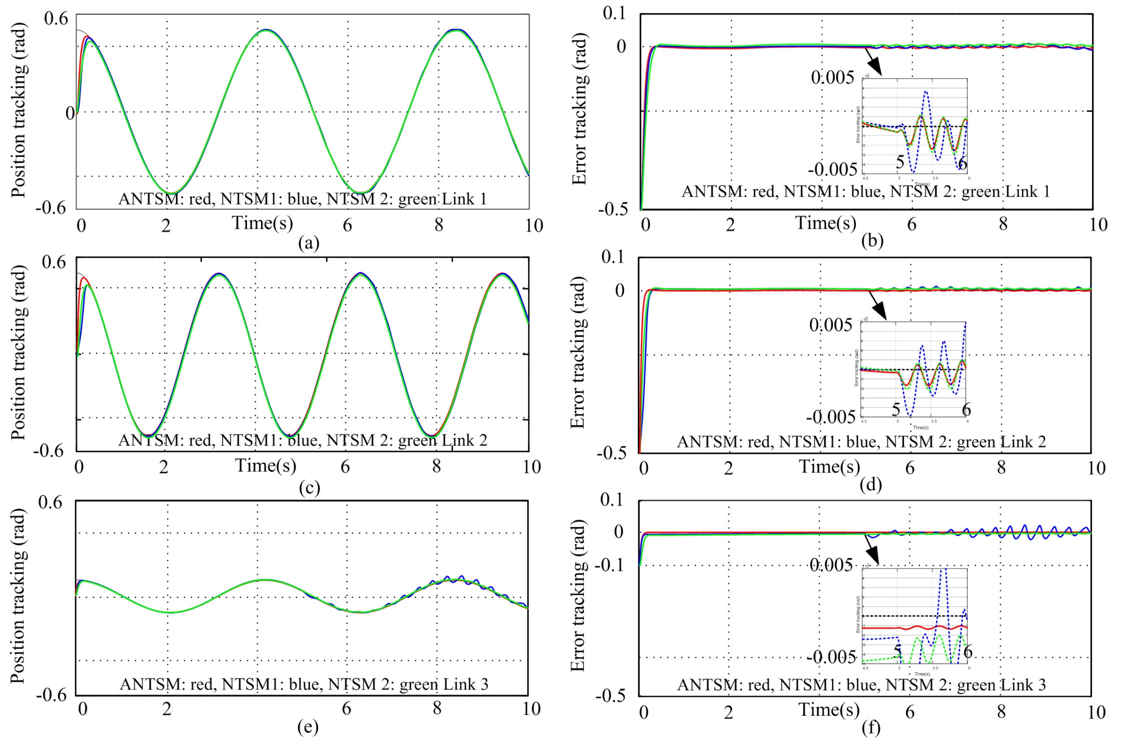

Figure 3: Tracking control simulation results

provide the compared simulation results. For more details, the control strategies of the NTSM1 and NTSM2 controllers are considered as follows:

- The NTSM1 controller: With fixed proportional control gains and sat (.) function (1)–(8), the control rules of the NTSM1 controller are

$$\tau = \tau_r - \hat{f} - \frac{b}{a} K_\alpha(\dot{e}^{2-\frac{a}{b}}) - \frac{b}{a}\xi K_s \mathrm{diag}(e^{\xi-1}) K_\alpha(\dot{e}^{2-\frac{a}{b}}) - KS,$$

and

$$[\tau_r = -\hat{R}\frac{S\left(K_\alpha^{-1}\right)\mathrm{diag}(\dot{e}^{\frac{a}{b}-1})}{\|S\|\left\|\left(K_\alpha^{-1}\right)\mathrm{diag}(\dot{e}^{\frac{a}{b}-1})\right\|} - c\mathrm{sat}(S),$$

its updating algorithms are the same as the proposed NTSM controller.

- The NTSM2 controller: Similar to the proposed controller, except the NTSM sliding surface and the control inputs do not contain the terms, $K_\xi e^\xi$ and $\frac{b}{a}\xi K_s \mathrm{diag}(e^{\xi-1})K_\alpha(\dot{e}^{2-\frac{a}{b}})$, respectively.

The control parameters of considered methods in the simulation process are provided as $a = 11$, $b = 9$, $\xi = 1.5$, $K_\xi = \mathrm{diag}(4)$, $K_\alpha = \mathrm{diag}(2)$, $K = \mathrm{diag}(50)$, $c = 0.3$, $\delta_{\mathrm{w}} = \delta_k = \delta_r = \mathrm{diag}(50)$. The desired trajectories are defined as $q_d = [0.5\cos(1.5t), 0.5\cos(2t), 0.1\cos(1.5t)]$, the friction and disturbances considered as

$$F(\dot{q}) = 0.1[0.5\dot{q}_1 + 0.2\mathrm{sign}(\dot{q}_1); 0.5\dot{q}_2 + 0.2\mathrm{sign}(\dot{q}_2); 0.5\dot{q}_3 + 0.2\mathrm{sign}(\dot{q}_3)],$$

$$\tau_d = [0.5\sin(2t); 0.5\sin(2t); 0.5\sin(2t)].$$

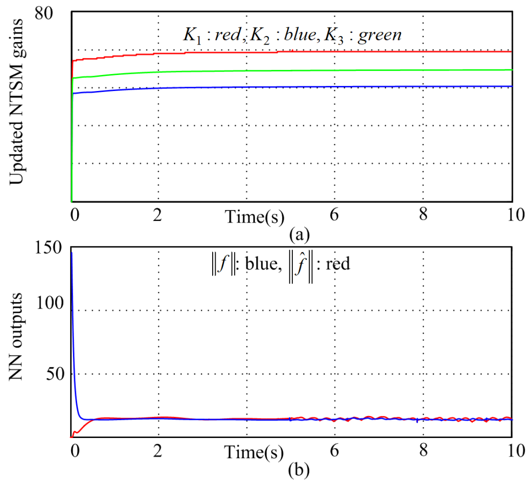

Figure 4: The simulation results: Adaptive updated parameters

The Matlab/Simulink software with a sample time of 0.001 (s) is done for the simulations. The simulation procedures are suggested that the simulation time is 5 (s), $\tau_d = 2.0[\sin(20t)\sin(20t); \sin(20t)]$, the time-varying tip loads will add to links 2 and 3 of the RM control system as $(2\sin(2t)$ kg and $1.5\cos(2t)$ kg on links 1 and 2), and the friction is changed to

$$F(\dot{q}) = 1.0[0.5\dot{q}_1 + 0.2\text{sign}(\dot{q}_1);\ 0.5\dot{q}_2 + 0.2\text{sign}(\dot{q}_2);\ 0.5\dot{q}_3 + 0.2\text{sign}(\dot{q}_3)].$$

First, Figure 3 shows the compared simulation results of the tracking positions and errors with the proposed ANTSM, NTSM1, and NTSM2 methods. For the NTSM1 method, with the fixed PD control parameters, the tracking performance is not good as that of the ANTSM and NTSM2 methods. Especially at the time when abrupt time-uncertainties with higher amplitude and frequency appears (disturbances, frictions, and loads), the NTSM1 tracking positions and errors appear deviation with large fluctuation and amplitude (in Figures. 3 (e) and (f)). Although the PD gains of the NTSM1 controller are selected based on the prior knowledge and simulation results of the proposed method (with the adaptive self-turned PD gains), the NTSM1 controller still has not met the operating requirements in the presence of abrupt uncertainties. For the NTSM2 method, the tracking control performance is good except the finite-time convergence speed of tracking errors is slower than those of the proposed ANTSM and NTSM1 methods. This can be explained that the NTSM2 controller has no convergence speed-up part $(\frac{b}{a}\xi K_s\text{diag}(e^{\xi-1})K_\alpha(\dot{e}^{2-\frac{a}{b}}))$ as the ANTSM and NTSM1 methods. Based on the simulation results in Figure 4, the PD gains of the proposed method have been adaptively updated to deal with abrupt uncertainties and achieved better tracking performances when compared with the NTSM1 and NTSM1 methods (Figure 3). And with the simulation results of the NN estimator (in Figure 4 (b)), these results have guaranteed the bounded properties of the adaptive updated parameters in the theory. Next, Figure 5 shows the simulation results of the control inputs with the proposed ANTSM, NTSM1, and NTSM2 methods. By observing in Figure 5, for the NTSM1 method, the chattering phenomenon has gradually appeared when the control conditions are impacted by the highly time-frequency uncertainties. In addition, when compared with the proposed ANTSM and NTSM2 methods, the robust term of the NTSM1 method does not support the control signals well in signal smoothing and chattering phenomena suppression.

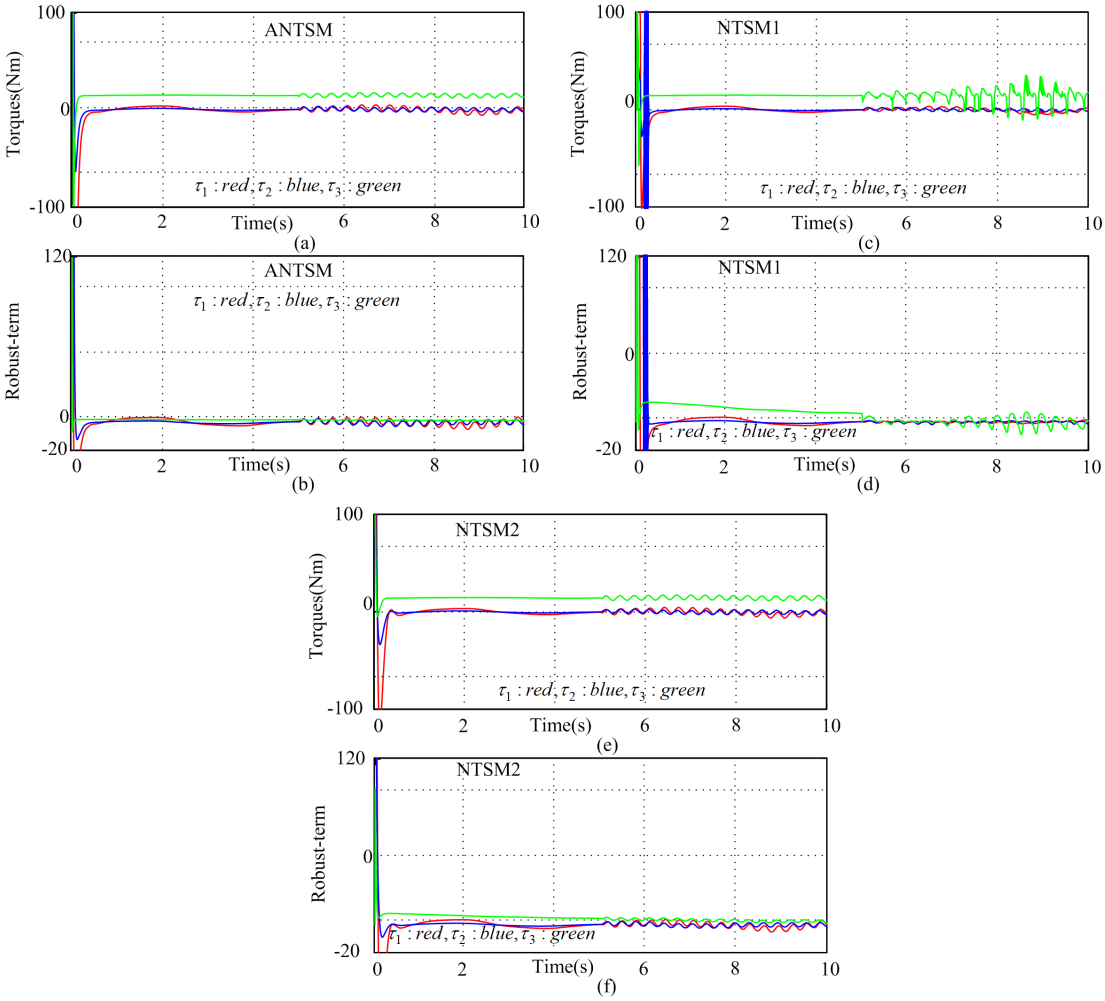

Figure 5: The simulation results: Control inputs

4. CONCLUSIONS

This study has proposed an improved fast NSTM control strategy, which has been applied successfully for the RM control system in theory and simulation works. The enhancement is first shown with the proposed self-tuning mechanism to achieve the adaptive PD control gains for the main NTSM controller. In addition, the NTSM sliding surface has been developed to achieve faster finite-time convergence of the tracking errors. In the designed robust controller, by adding the tanh(.) function, the drawbacks of applying the sign(.) function in the traditional NSTM controllers have also been solved. This robust controller has performed well in eliminating the chattering phenomenon and reducing the discontinuity of the control signals. Therefore, based on the proven stability theorem and comparative simulation results, the proposed fast NSTM strategy can be considered a good alternative method to the existing NSTM controllers in the RM control applications.

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