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SHORT PAPER

Sliding Mode Switching Control of Manipulators Based on Disturbance Observer

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Abstract This paper addresses the sliding mode switching control problem based on disturbance observer for an uncertain robot manipulator system. To enhance the robustness and the anti-disturbance capability of the system control algorithm, the manipulator's switching model is composed of two parts: a slide mode controller and a disturbance observer. Based on multiple Lyapunov stability theorem and average dwell-time method, it is proved that the proposed control scheme can guarantee the global stability and robustness of the resulting closed-loop system of robot manipulators system. The application of the proposed switching control scheme with disturbance observer to a robot manipulator shows satisfactory tracking error performance than in the case of switching control strategy without disturbance observer.

Keywords Sliding mode switching control · Average dwell-time method · Disturbance observer · Lyapunov theory

1 Introduction

During the past decades, switching control schemes of complex nonlinear systems have obtained more and more researchers' interest. Main efforts mainly focused on

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the widespread existence of switching characteristic in practical systems, mostly on the analysis of system dynamic control behaviors, such as stability, controllability, reachability, and observability. The aim is to investigate the robust switching control schemes for guaranteeing system stability and optimizing the control performance. Many research results on complex switched nonlinear systems have been reported in the literature [2,5,10,12,16,20,24,26,27,32,37,39]. By multiple Lyapunov functions, stability analysis, and H∞ control for a class of switched nonlinear systems with general point symmetric sector, the conditions were addressed [24]. As we know, robot manipulators can be modeled as switching systems with a large number of practical control applications such as the control of railroad mechanical systems, automotive industry, power plant systems, computer networks, automatic highway systems, industrial process control systems. However, robot manipulator systems are complex nonlinear systems and, more generally, not easier to control. Sliding mode control as a robust control tool is the extremely powerful tool to control uncertain robot manipulators [1,3,6,9,11,14,17,18,23,25,30,31,33–36,38,40]. In Ref. [34], sliding mode control (SMC) scheme for an n-link robot manipulator with actuator dynamics has been investigated to achieve high-precision position tracking with a firm robustness. Nowadays, numerous sliding mode control strategies have been studied to address the tracking control problem for multi-link rigid robot manipulators [1,17,25,30] and single-link flexible robot arms [3,18,19].

Besides the above mentioned advantages, the traditional sliding mode control scheme suffers from significant shortcomings, such as chattering phenomenon and bigger control authority, restricting its practical control performance [3,4,7,8,13,15,18, 21,22,25,33,40]. Therefore, a good way to improve the performance of the controller is to employ a disturbance observer to enhance the robustness and the anti-disturbance capability. To achieve satisfactory tracking control performance, switching control scheme with disturbance observer to a robot manipulator is mainly considered. Moreover, based on the sliding mode methodology [28,31,33,35,40], the switching robust nonlinear observer has been designed. In Ref. [40], a hierarchical sliding mode control scheme with extended state observer has been presented for an under actuated spherical robot. Two robust adaptive nonlinear controllers along with a nonlinear observer has been investigated for controlling the rigid and flexible motions of a single-link robot manipulator [35]. Therefore, as uncertain robot manipulators are widely applied in industries, problems of sliding mode switching control based on disturbance observer become more challenging. To the best of our knowledge, few researches provide a sliding mode switching controller based on disturbance observer for an uncertain robot manipulator system.

This paper investigates the sliding mode switching control problem based on disturbance observer for an uncertain robot manipulator system. A slide mode controller, a disturbance observer, and the average dwell-time method are used to design the switching tracking controller. The contributions of this paper are the following: (1) By designing a sliding mode switching controller with average dwell-time technique, a novel-type multiple switched Lyapunov function is developed to construct a stable robust controller; (2) A sliding mode switching controller based on disturbance observer is designed to enhance system robustness; (3) The tracking error of robotic manipulator system can be reduced as small as desired by choosing appropriate switching controller parameters. Therefore, based on the proposed sliding mode switching control scheme with disturbance observer, this paper can prove that the resulting closed-loop system is asymptotically Lyapunov stable such that the link position of robotic manipulator system can follow the desired output signal.

2 Problem

The switching model of an uncertain manipulator is expressed in the kinetic equation form:

$$\left(I_{\sigma(t)}+\Delta I_{\sigma(t)}\right)\ddot{\theta}+\left(d_{\sigma(t)}+\Delta d_{\sigma(t)}\right)\dot{\theta}+\delta_{\sigma(t),0}\theta+m_{\sigma(t)}l_{\sigma(t)}g\cos\theta=u-f_c\left(\dot{\theta},u\right) \tag{1}$$

where, θ is angle of system output, $I=\frac{4}{3}ml^2$ is moment of inertia, mg is gravity, u is control input, and $f_c(\dot{\theta},u)$ is unknown nonlinear friction. l is rotation center of centroid from the connecting rod, and d is viscous friction coefficient of the connecting rod movement. ΔI and Δd are uncertainties values of the corresponding parameters respectively, δ_0 is elastic friction coefficient. $\sigma(t):[0,+\infty)$ is piecewise constant switching signal taking value from the finite index set $\Xi\overset{\text{def}}{=}\{1,2,\ldots,n\}$. When $\sigma(t)=i$, the ith subsystem $(I_i+\Delta I_i)\ddot{\theta}+(d_i+\Delta d_i)\dot{\theta}+\delta_{i,0}\theta+m_il_ig\cos\theta=u-f_c(\dot{\theta},u)$ is active and the remaining subsystems are inactive.

3 Design of Sliding Mode Switching Controller of Manipulators Based on Disturbance Observer

System (1) can be rewritten as:

$$\begin{aligned}\ddot{\theta}=\frac{1}{I_{\sigma(t)}}&\left(u-d_{\sigma(t)}\dot{\theta}-\Delta I_{\sigma(t)}\ddot{\theta}-\Delta d_{\sigma(t)}\dot{\theta}-\delta_{\sigma(t),0}\theta\right.\\&\left.-m_{\sigma(t)}l_{\sigma(t)}g\cos\theta-f_c\left(\dot{\theta},u\right)\right)\end{aligned} \tag{2}$$

Then the above equation can be described by second-order differential equations as follows [9,29,34]:

$$\ddot{\theta}=-b_{\sigma(t)}\dot{\theta}+a_{\sigma(t)}u-f_{\sigma(t)} \tag{3}$$

where $b=\frac{d}{I}>0$, $a=\frac{1}{I}>0$. a and b are known, f indicates the sum of the uncertainty term, the gravity term, and the friction term.

$$f_{\sigma(t)}=\frac{1}{I_{\sigma(t)}}\left(\Delta I_{\sigma(t)}\ddot{\theta}+\Delta d_{\sigma(t)}\dot{\theta}+\delta_{\sigma(t),0}\theta+m_{\sigma(t)}l_{\sigma(t)}g\cos\theta+f_c\left(\dot{\theta},u\right)\right) \tag{4}$$

Then the sliding surface of the control systems can be designed as:

$$s=ce+\dot{e},\quad c>0 \tag{5}$$

where $e=r-\theta$, and r is position command.

According to Eqs. (1) and (4), the sliding mode control law is designed as follows:

$$u(t) = \frac{1}{a_{\sigma(t)}}\left(c\dot{e} + \ddot{r} + b_{\sigma(t)}\dot{\theta} + \hat{f}_{\sigma(t)} + k_{\mathrm{f}}\mathrm{sgn}(s)\right) \tag{6}$$

where $\hat{f}$ is estimated value of f by the disturbance observer [33,35], and $\tilde{f}$ is the estimated error of f.

For switching signal $\sigma(t)$, a switching sequence is defined as follows [10,12,20, 26,27,37,39]:

$$\sum := \{(i_0, t_0), (i_1, t_1), \ldots, (i_k, t_k), \ldots, | i_k \in \Xi, k \in N\} \tag{7}$$

where (i_k, t_k) indicates that the i_kth subsystem switches on at t_k, and the i_{k+1}th subsystem switches off at t_{k+1}. t_0 is beginning time, and $t_k > 0$ is kth switching time. If $t \in [t_k, t_{k+1})$, through the i_{k+1}-th subsystem the trajectory of the switched system (1) is produced. Then $\Delta t_k = t_k - t_{k-1}$ is defined as the dwell time of the i_kth subsystem in a period.

Assumption 3.1 [12,26,27]: For $t \in (t_{k-1}, t_k] \in \Omega_m$ $(m \in \Xi)$ and $t \in (t_k, t_{k+1}] \in \Omega_{m+1}$, there is a constant $0 \le \mu \le 1$ such that

$$|s(t_{k+1})| \le \mu \cdot |s(t_k)| \tag{8}$$

where in this paper $\mu = 1$.

The switching signal $\sigma(t)$ belongs to $\Theta_{\mathrm{ave}}[\tau_D\ ,\ N_0] \subset \Theta$ which consists of all switching signals having the same persistent dwell time $\tau_D > 0$ and the same persistent chatter bound N_0, i.e., (i) the number of switching between every two consecutive time intervals of lengths greater than τ_D is less than N_0; (ii) for each $T \ge 0$, there is $i \subset \Xi$ such that $\tau_{\sigma,i} > T$ and $\tau_{\sigma,i+1} - \tau_{\sigma,i+1} > T$. The class of switching signals satisfying the above assumptions is equivalent to the class of switching signals having chatter bound N_0 and average dwell time $\tau_\alpha = \tau_D / (N_0 + 2)$.

To observe the disturbance item f, the observer with switching control scheme has been designed in the following form:

$$\begin{pmatrix} \dot{\hat{f}}_i \\ \dot{\hat{x}}_i \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \hat{f}_i \\ \hat{x}_i \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix}(\ddot{r} + b_i\dot{\theta}) + \begin{pmatrix} 0 \\ -a_i \end{pmatrix} u + \begin{pmatrix} k_1 \\ k_2 \end{pmatrix}[\dot{e} - \hat{x}_i] \tag{9}$$

where $\hat{f}_i$ are estimated values of f, $\hat{x}_i$ are estimated values of $\dot{x}$, $\tilde{x} = \dot{e} - \hat{x}$, k_1 and k_2 are gains by pole placement.

The disturbance observer Eq. (9) can be expressed as:

$$\dot{\hat{f}}_i = k_1\tilde{x}_i \tag{10}$$

$$\dot{\hat{x}}_i = \hat{f}_i - a_i u + k_2\tilde{x} + \ddot{r} + b_i\dot{\theta} \tag{11}$$

In addition, the switching gain coefficient k_{f} is designed as:

$$k_{\mathrm{f}} > \left|\tilde{f}\right| \tag{12}$$

Theorem 1 *Considering the switching model of robot manipulator system represented by (1), the sliding mode switching control law with disturbance observer is designed as (6), and switching signal with average dwell time is given by $\tau_{\alpha} = \tau_{D} / (N_0+2)$. Then, the proposed switching control law can guarantee the global stability and robustness of the resulting switching closed-loop system by Lyapunov control theory and also can achieve good tracking error performance.*

Proof Consider the switched Lyapunov function candidate:

$$\begin{aligned} V &= V_1 + V_2 \\ &= \frac{1}{2}\sum_{i=1}^{n}\theta_i(t)\cdot s^2 + \frac{1}{2k_1}\tilde{f_i}^2 + \frac{1}{2}\tilde{x_i}^2 \end{aligned} \tag{13}$$

where $V_1 = \frac{1}{2}\sum\limits_{i=1}^{n}\theta_i(t)\cdot s^2$, $V_2 = \frac{1}{2k_1}\tilde{f_i}^2 + \frac{1}{2}\tilde{x_i}^2$, $\tilde{f_i} = f_i - \hat{f_i}$ and the characteristic function:

$$\theta_i(t) := \begin{cases} 1 & t \in \Omega_i \\ 0 & t \notin \Omega_i \end{cases}, \quad \Omega_i = \{t|\ \text{the ith subsystem is active at time instant t}\} \tag{14}$$

For $t \in (t_{k-1}, t_k] \in \Omega_m$ $(m \in \Xi)$, and $t \in (t_k, t_{k+1}] \in \Omega_{m+1}$, from (8) and (13), we have:

$$\begin{aligned} \Delta V(t) &= V(t_{k+1}) - V(t_k) \\ &= \frac{1}{2}\left(s(t_{k+1})^2 - s(t_k)^2\right) \\ &= \frac{1}{2}\left(|s(t_{k+1})|^2 - |s(t_k)|^2\right) \\ &< 0 \end{aligned} \tag{15}$$

Then, the time derivative of the switched Lyapunov function V along the solutions of (3)–(6) and (9) has been obtained as follows:

$$\begin{aligned} \dot{V}_1 &= s\dot{s} \\ &= s(c\dot{e} + \ddot{e}) \\ &= s\left(c\dot{e} + \ddot{r} - \ddot{\theta}\right) \\ &= s\left(c\dot{e} + \ddot{r} + b_i\dot{\theta} - a_i u + f_i\right) \\ &= s\left(c\dot{e} + \ddot{r} + b_i\dot{\theta} - \left(c\dot{e} + \ddot{r} + b_i\dot{\theta} + \hat{f_i} + k_{\mathrm{f}}\,\mathrm{sgn}(s)\right) + f_i\right) \\ &= -\left(\hat{f_i}s + k_{\mathrm{f}}s\,\mathrm{sgn}(s)\right) + f_i s \end{aligned}$$

$$= s\left(\tilde{f}_i - k_f \operatorname{sgn}(s)\right)$$
$$= s\tilde{f}_i - k_f |s| < 0 \tag{16}$$

Also,

$$\dot{V}_2 = \frac{1}{k_1}\tilde{f}_i\dot{\tilde{f}}_i + \tilde{x}_i\dot{\tilde{x}}_i = \frac{1}{k_1}\tilde{f}_i\left(\dot{f}_i - \dot{\hat{f}}_i\right) + \tilde{x}_i\left(\ddot{e} - \dot{\hat{x}}_i\right) \tag{17}$$

Assuming disturbance is slow time-varying signal, i.e.,

$$\dot{f}_i = 0 \tag{18}$$

Substituting (10) and (11) into (17):

$$\dot{V}_2 = -\frac{1}{k_1}\tilde{f}_i\dot{\hat{f}}_i + \tilde{x}\left(\ddot{r} - \ddot{\theta} - \left(\hat{f}_i - a_i u + k_2\tilde{x}_i + \ddot{r} + b_i\dot{\theta}\right)\right)$$
$$= -\frac{1}{k_1}\tilde{f}_i k_1\tilde{x}_i + \tilde{x}_i\left(\ddot{r} + b_i\dot{\theta} - a_i u + f_i - \left(\hat{f}_i - a_i u + k_2\tilde{x} + \ddot{r} + b_i\dot{\theta}\right)\right)$$
$$= -\tilde{f}_i\tilde{x}_i + \tilde{x}_i\left(\tilde{f}_i - k_2\tilde{x}_i\right)$$
$$= -k_2\tilde{x}_i^{\,2} \le 0 \tag{19}$$

is obtained. Then: $\dot{V}_1 \le 0$, $\dot{V}_2 \le 0$.
So:

$$\dot{V} = \dot{V}_1 + \dot{V}_2 \le 0 \tag{20}$$

Therefore, the resulting closed-loop switched system is robustly stable. From Barbalat's lemma [12,20,26,27,31,37], we get: $\lim_{t\to\infty} V(t) = 0 \Rightarrow \lim_{t\to\infty} s = 0$, i.e., the sliding surface of the switching control system is reached. Besides, from (3)–(5) and (20) $e \to 0$. Therefore, the assumption that all the signals in the resulting closed-loop switched system keep bounded is verified. In addition, from Assumption 3.1, (3) and (6), control law u is bounded. So far, proof of Theorem 1 and sliding mode switching controller design have been completed.

Remark 1 In this paper, the term f in the controller can be effectively estimated by the disturbance observer which can decrease the sliding mode switching control gain k_1. Then it can effectively decrease the system buffeting. If $\dot{V}_1 < 0$, the condition $k_f > |s|$ needs to be satisfied. If the estimation error $\tilde{f}$ is small enough, switching control gain coefficient k_f should be designed to a very smaller value to effectively decrease the buffeting.

4 Simulation

In this section, the proposed sliding mode switching control strategy with disturbance observer is applied to control the robot systems to verify its feasibility and effectiveness. A switching model of robot manipulator is used in the simulation. The robot

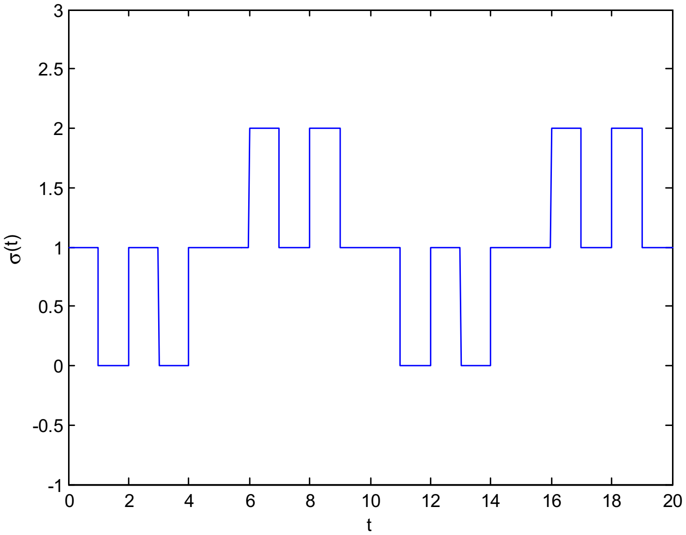

Fig. 1 The switching signal

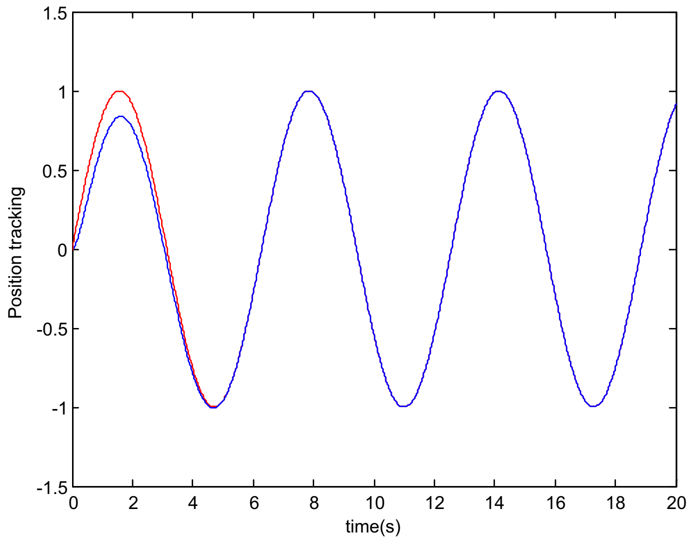

Fig. 2 Position tracking performance with disturbance observer

manipulator system can be expressed in the dynamic equation form of system (1) as follows:

$$\begin{cases} \ddot{\theta}_1 = -b_1\dot{\theta}_1 + a_1 u - f_1 \\ \ddot{\theta}_2 = -b_2\dot{\theta}_2 + a_2 u - f_2 \end{cases} \tag{21}$$

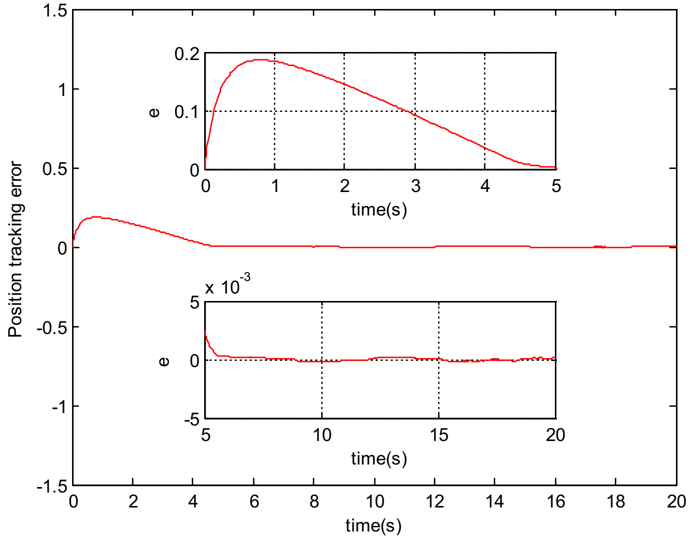

Fig. 3 Position tracking error performance with disturbance observer

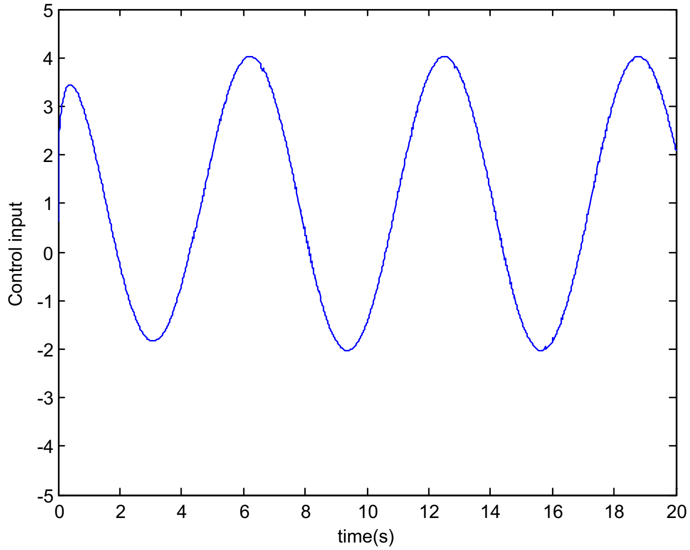

Fig. 4 Control input with disturbance observer

where, $a_1 = 6$, $a_2 = 8$, $b_1 = 12$, $b_2 = 15$, $f = [f_1 \quad f_2]^T = [3 + 0.3 \sin t \quad 2 + 0.2 \sin t]^T$. In addition, according to design procedures described in Sect. 3, the proper parameters are designed: $c = 2.5$, $k_f = 0.25$, $k_1 = 1200$, $k_2 = 250$, $\tau_D = 2$. The control objective is designed to make the link position following the desired output signal $r = \sin(t)$. Matlab/Simulink was used to display the tracking performance of the controller, and the results with the proposed sliding mode switching control

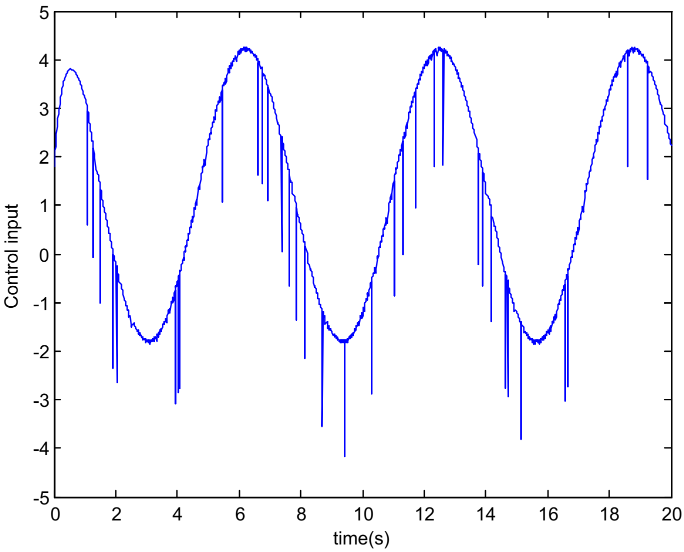

Fig. 5 Control input without disturbance observer

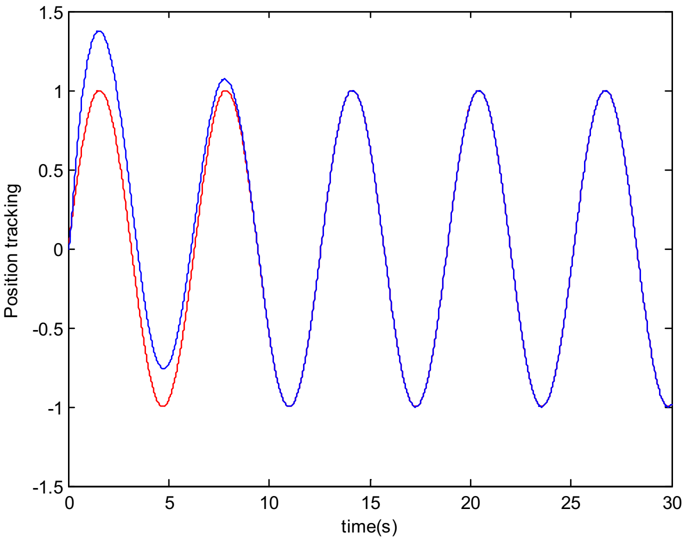

Fig. 6 Position tracking performance without disturbance observer

approach with disturbance observer are shown in Figs. 1, 2, 3 and 4. Switching signal using average dwell time is shown in Fig. 1, tracking performance results are shown in Fig. 2, and detailed tracking error is given in Fig. 3. In addition, control input is shown in Fig. 4. All the figures obviously show that both of the two robotic links can follow the desired trajectory precisely.

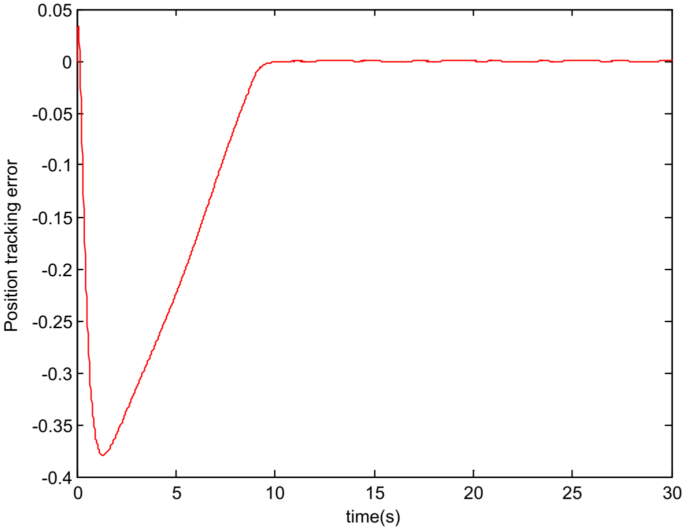

Fig. 7 Position tracking error performance without disturbance observer

To show the effectiveness of the proposed robustly stable sliding mode switching control with disturbance observer method, detailed experiments were carried out without the disturbance observer using average dwell-time method and the control parameters for the same switching model of robot manipulator could be designed as: $c = 2.85$, $k_{\mathrm{f}} = 5$. The desired output signal $r = [r_1 \quad r_2]^T$ is the same as the above control scheme. For this simulation, Fig. 5 shows the control input, while the position tracking performance and the position tracking error performance are shown in Figs. 6 and 7, respectively.

According to the simulations, from the comparison and analysis of the two switching control approaches, in terms of performance indices, the performance without disturbance observer method is poorer in the two controllers with larger tracking errors while the proposed sliding mode switching control scheme in this paper has indicated better tracking control performance. The key reason for this result is that disturbance observer can overcome the unmodeled factors and disturbances.

5 Conclusions

In this paper, a robust switching control strategy with disturbance observer for the trajectory's tracking problem of robot manipulators is proposed. A sliding mode switching controller based on disturbance observer is designed to enhance system robustness, and an admissible switching signal with average dwell-time approach is given. With the proposed robust switching control scheme of robot manipulators, the resulting sliding mode closed-loop control system is asymptotically Lyapunov stable such that the position tracking error performance of robotic manipulators is well obtained. Finally, simulation results on the switching robot manipulators have verified the feasibility and validity of the presented control algorithms. Future research will focus on the extension of the sliding control method based on disturbance observer to the switching model of robot manipulators including uncertain kinematics, dynamics, and actuator model.

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