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A New Terminal Sliding Mode Control for Robotic Manipulators

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Abstract: In this paper, a new terminal sliding mode control approach is developed for robotic manipulators. Unlike traditional terminal sliding mode control, the proposed approach can make system states converge to zero in a finite time without requiring explicitly using of system dynamic model. Theoretical analysis and simulation results are presented to illustrate the proposed approach. The controller parameter tuning method is also proposed.

1. INTRODUCTION

Terminal sliding mode control (TSMC) is a finite time stability control approach (Hong, Yang, Cheng, and Spurgeon, 2005; Janardhanan and Bandyopadhyay, 2006). It offers some superior properties such as better tracking precision, fast convergence, unsensitivity to system uncertainty and external disturbance (Feng, Yu, and Man, 2002; Feng, Han, Wang, and Yu, 2007). Recently, some TSMC approaches were developed for robotic manipulators (Barambones, and Etxebarria, 2002; Feng, Yu, and Man, 2002; Man, and Yu, 1997; Tang, 1998; Yu, Yu, Shirinzadeh, and Man, 2005). These methods emphasized different problems for robotic manipulator control with terminal siding mode. The common characteristic of these approach is supposed that the dynamics of robotic manipulator is composed of nominal part (known part) and unknown part. The nominal part can be compensated in controller design. The unknown part is treated as uncertainty. In some situations, it is not an ease job to construct the nominal part of robotic manipulator dynamics. To carry TSMC design out for a robotic manipulator, approach without explicitly using the system dynamics is indeed a challenging and interesting problem. The investigation on this problem is motivated by the following considerations. In terms of application, this study offers an easy TSMC approach for robot control. In terms of theory, TSMC is an important control problem on its own, which has been studied with mode based approach for robotic manipulators. The work of this paper extends the previous results on TSMC. The main results are given on the construction of a new TSMC controller for robotic manipulators without requiring the system dynamic mode explicitly.

The rest of this paper is organized as follows. In Section 2, basic concepts and some preliminary results are given. In Section 3, dynamics of robotic manipulators is formulated. In Section 4, the new TSMC design procedure is developed. Corresponding stability analysis is also presented. In Section 5, an illustrative example is performed to demonstrate the effectiveness of the proposed approach. In Section 6, some concluding remarks and suggestions for further research are presented.

2. PRELIMINARIES

Some notations, definitions and lemmas which will be useful later are introduced in this section.

Definition 1. The fast terminal sliding mode can be described by the following first order nonlinear differential equation (Yu, Yu, Shirinzadeh, and Man, 2005)

$$s = \dot{x} + \Lambda_1 x + \Lambda_2 sig(x)^{\gamma} \tag{1}$$

where $x \in R^n$, $\Lambda_1 = diag(\lambda_{11}, \cdots, \lambda_{1n}) \in R^{n\times n}$, $\Lambda_2 = diag(\lambda_{21}, \cdots, \lambda_{2n}) \in R^{n\times n}$, $\lambda_{1i}, \lambda_{2i} > 0$, $\gamma = q/p$, $q, p > 0$ are positive odd and $q < p < 2q$, $sig(x)^{\gamma} = \left[|x_1|^{\gamma} sign(x_1), \cdots, |x_n|^{\gamma} sign(x_n)\right]^T$.

Remark 1. The *i*th element of s can be written as

$$s_i = \dot{x}_i + \lambda_{1i} x_i + \lambda_{2i} |x_i|^{\gamma} sign(x_i) \tag{2}$$

According to the definition of finite-time stability (Bhat, and Bernstein, 1998, 2000), the equilibrium point $x_i = 0$ of differential equation (2) is globally finite-time sable, i.e., for any given initial condition $x_i(0) = x_0$, the system state x_i converges to 0 in a finite time (Yu, Yu, Shirinzadeh, and Man, 2005)

$$T = \frac{1}{\lambda_{1i}(1-\gamma)} \ln \frac{\lambda_{1i}|x_0|^{1-\gamma} + \lambda_{2i}}{\lambda_{2i}} \tag{3}$$

and stays there forever. The time T is also called as settling time (Bhat, and Bernstein, 1998, 2000), which means $x_i = 0$ for $t \geq T$.

Lemma 1. Assume $a_1 > 0$, $a_2 > 0$ and $0 < c < 1$, the following inequality holds (Yu, Yu, Shirinzadeh, and Man, 2005)

$$\left(a_1 + a_2\right)^c \le a_1^c + a_2^c \tag{4}$$

Lemma 2. Suppose $a = \left[a_1, \cdots, a_n\right]^T$, $|a| = |a_1| + \cdots + |a_n|$, $\|a\| = \left(a_1^2 + \cdots + a_n^2\right)^{\frac{1}{2}}$ represent the Euclidean norm, then the following inequality holds

$$\|a\| \le |a| \tag{5}$$

Proof. For $n = 1$, it is obvious that expression (5) is satisfied. For $n = 2$, from Lemma 1, the follow inequality can be derived

$$\left(a_1^2 + a_2^2\right)^{\frac{1}{2}} \le \left(a_1^2\right)^{\frac{1}{2}} + \left(a_2^2\right)^{\frac{1}{2}} \tag{6}$$

Therefore

$$\left(a_1^2 + a_2^2\right)^{\frac{1}{2}} \le |a_1| + |a_2| \tag{7}$$

Assume that for $n = k$ the expression (5) holds, i.e.,

$$\left(a_1^2 + \cdots + a_k^2\right)^{\frac{1}{2}} \le |a_1| + \cdots + |a_k| \tag{8}$$

Then for $n = k + 1$

$$\left(a_1^2 + \cdots + a_k^2 + a_{k+1}^2\right)^{\frac{1}{2}} = \left[\left(a_1^2 + \cdots + a_k^2\right) + a_{k+1}^2\right]^{\frac{1}{2}} \tag{9}$$

From Lemma 1, the right hand of equation (9) satisfies the following inequality

$$\left[\left(a_1^2 + \cdots + a_k^2\right) + a_{k+1}^2\right]^{\frac{1}{2}} \le \left(a_1^2 + \cdots + a_k^2\right)^{\frac{1}{2}} + \left(a_{k+1}^2\right)^{\frac{1}{2}} \tag{10}$$

According to the expression (8) and (10), the following inequality can be given

$$\left(a_1^2 + \cdots + a_k^2 + a_{k+1}^2\right)^{\frac{1}{2}} \le |a_1| + \cdots + |a_{k+1}| \tag{11}$$

By the principle of mathematical induction, the conclusion can be drawn that the expression (5) is satisfied for any positive integer n . □

The following results on differential inequalities will be used for the stability analysis (Barambones, and Etxebarria, 2002; Tang, 1998).

Definition 2. If $f(V, t)$ is a scalar function of scalars $V(t)$, t in some open connected set $D \in R^2$, then a function $V(t)$ on $[t_0, t_1)$ is a solution of the differential inequality

$$\dot{V}(t) \le f\left(V(t), t\right) \tag{12}$$

on $[t_0, t_1)$ if $V(t)$ is continuous on $[t_0, t_1)$ and its derivative on $[t_0, t_1)$ satisfies (12).

Lemma 3. Let $f\left(y(t), t\right)$ be continuous on an open connected set $D \in R^2$ and assume that the initial value problem for the scalar equation

$$\dot{y}(t) = f\left(y(t), t\right), \quad y(t_0) = y_0 \tag{13}$$

has a unique solution. If $y(t)$ is a solution of (13) on $[t_0, t_1)$ and $V(t)$ is a solution of (12) on $[t_0, t_1)$ with $V(t_0) \le y(t_0)$, then $V(t) \le y(t)$ for $t_0 \le t < t_1$.

Lemma 4. Assume that a continuous positive definite function $V(t)$ satisfies the differential inequality

$$\dot{V}(t) \le -\alpha V^\eta(t) \quad \forall t \ge t_0 \quad V(t_0) \ge 0 \tag{14}$$

where $\alpha > 0$, $0 < \eta < 1$ are constants. Then, for any given t_0, $V(t)$ satisfies the inequality

$$V^{1-\eta}(t) \le V^{1-\eta}(t_0) - \alpha(1-\eta)(t - t_0) \quad t_0 \le t \le t_1 \tag{15}$$

and

$$V(t) = 0 , \quad \forall t \ge t_1 \tag{16}$$

with t_1 given by

$$t_1 = t_0 + \frac{V^{1-\eta}(t_0)}{\alpha(1-\eta)} \tag{17}$$

In this paper, $\|\cdot\|$ denotes norm of vector or matrix. The vector norm is Euclidean norm and the matrix norm is corresponding induced norm.

3. DYNAMICS OF ROBOTIC MANIPULATORS

For general *n*-link rigid robotic manipulators, the dynamic equation can be derived in joint space as

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \tau \tag{18}$$

where $q, \dot{q}, \ddot{q} \in R^n$ are the vector of joint angular position, velocity and acceleration, respectively. $M(q) \in R^{n \times n}$ is symmetric and positive definite inertia matrix, $C(q, \dot{q}) \in R^{n \times n}$ and $C(q, \dot{q})\dot{q} \in R^n$ is the vector of centrifugal and Coriolis torques, $G(q) \in R^n$ is the vector of gravitational torques, $\tau \in R^n$ is the vector of applied joint torque. This dynamic model has the following properties that will be used in the controller design (Spong, and Vidyasagar, 1989)

(P1) The matrix $M(q)$ satisfies $\|M(q)\| \le \mu_m$, for constant $\mu_m > 0$.

(P2) The matrix $C(q, \dot{q})$ satisfies $\|C(q, \dot{q})\| \le \mu_c \|\dot{q}\|$, for constant $\mu_c > 0$.

(P3) The vector $G(q)$ satisfies $\|G(q)\| \le \mu_g$, for constant $\mu_g > 0$.

(P4) $\dot{M}(q) - 2C(q, \dot{q})$ is skew-symmetric.

The purpose of this paper is to develop a new TSMC scheme for robotic manipulators such that both position and velocity tracking error converge to zero in a finite time.

4. A NEW TSMC APPROACH WITHOUT REQUIRING SYSTEM DYNAMIC MODEL EXPLICITLY

In this section, a new TSMC control approach is proposed for the tracking control of general *n*-link rigid robotic manipulators. The proposed approach can guarantee the system states to reach the pre-described terminal sliding mode in a finite time, then the states converge to equilibrium point along the terminal sliding mode in a finite time.

Let $q^d(t) \in R^n$ be the desired joint position trajectory of robotic manipulator. The tracking error $e(t) \in R^n$ is defined as

$$e(t) = q(t) - q^d(t) \tag{19}$$

According to expression (1), the fast terminal sliding mode can be written as

$$s = \dot{e} + \Lambda_1 e + \Lambda_2 sig(e)^\gamma \tag{20}$$

The time derivative of ith element of $sig(e)^\gamma$ is $\gamma |e_i|^{\gamma-1} \dot{e}_i$. Because $\gamma - 1 < 0$, the singularity will occur as $e_i = 0$. To avoid the singularity problem, the following definition $e_r \in R^n$ is given as

$$e_{ri} = \begin{cases} \gamma |e_i|^{\gamma-1} \dot{e}_i & e_i \neq 0 \\ 0 & e_i = 0 \end{cases} \quad i = 1, \cdots, n \tag{21}$$

Then the time derivative of s can be written as

$$\dot{s} = \ddot{e} + \Lambda_1 \dot{e} + \Lambda_2 e_r \tag{22}$$

Remark 2. Due to the definition of e_r, the singularity problem will be avoided in the controller design. This will be seen in the following of this section.

The command vector and its time derivative are defined as follows

$$r = \dot{q}^d - \Lambda_1 e - \Lambda_2 sig(e)^\gamma \tag{23}$$

$$\dot{r} = \ddot{q}^d - \Lambda_1 \dot{e} - \Lambda_2 e_r \tag{24}$$

The definitions of s and r lead to the following equation

$$s = \dot{q} - r \tag{25}$$

$$\dot{s} = \ddot{q} - \dot{r} \tag{26}$$

Applying the definitions of s and r to dynamic equation (18) yields

$$M(q)\dot{s} + C(\dot{q},q)s = -M(q)\dot{r} - C(\dot{q},q)r - G(q) + \tau \tag{27}$$

Without loss of generality, two technical assumptions are made to pose the problem in a tractable manner.

(A1) The desired joint position trajectory $q^d(t)$, the time derivatives $\dot{q}^d(t)$ and $\ddot{q}^d(t)$ are bounded and smooth signals.

(A2) The joint angular position and velocity q, $\dot{q}$ are measurable.

The control objective is to design the torque input τ to drive the system states to reach the terminal sliding mode in a finite time and restrict the systems states to converge to equilibrium point along the terminal sliding mode in a finite time.

Now the new TSMC control law which dose not require the explicit use of the system dynamical model is designed as follows

$$\tau = \tau_0 + \tau_1 \tag{28}$$

$$\begin{cases} \tau_0 = K^M \dot{r} + K^C \|\dot{q}\| r + K^G \\ \tau_1 = -Ksig(s)^\rho - sign(s)\left[\Delta^M \|\dot{r}\| + \Delta^C \|\dot{q}\| \|r\| + \Delta^G\right] \end{cases} \tag{29}$$

where the K^M, K^C and K^G are positive definite diagonal feedforward control gain matrices, which are used to compensate the effect caused by $M(q)$, $C(q,\dot{q})$ $G(q)$, respectively. Δ^M, Δ^C and Δ^G are scalars, whose selection will be discussed later. $sign(s) = \left[sign(s_1), \cdots, sign(s_n)\right]^T$ in (29) is for a saturation control used to compensate for the nonlinear effect caused by the error between the feedforward control gains and modelling parameters, which was used in literature (Slotine and Sastry, 1983) The $Ksig(s)^\rho$ is feedback term to guarantee the system states to reach the terminal sliding mode in a finite time. K is positive definite diagonal feedback control gain matrix, the selection of ρ is similar to γ.

A control gain tuning strategy is proposed as follows. First, select the $\Delta^M = 0$, $\Delta^C = 0$ and $\Delta^G = 0$, tune the control gains K, K^M, K^C and K^G using a trial and error method. The controller at this time is a normal feedforward/feedback control. Second, gradually increase Δ^M, Δ^C and Δ^G from zero to introduce the saturation control. Finally, the previous tuned gains may need to be changed slightly, utilizing trail and error method.

Theorem 1. Under assumptions (A1)-(A2), consider the robotic manipulator dynamic equation (27) subject to the new TSMC control law (28)-(29). If the following conditions are satisfied

$$\begin{cases} \Delta^M \geq \|K^M - M(q)\| \\ \Delta^C \|\dot{q}\| \geq \|K^C \|\dot{q}\| - C(\dot{q},q)\| \\ \Delta^G \geq \|K^G - G(q)\| \end{cases} \tag{30}$$

Then the position tracking error $e(t)$ and velocity tracking error $\dot{e}(t)$ will converge to zero in a finite time.

Proof Consider the Lyapunov function candidate

$$V = \frac{1}{2} s^T M s \tag{31}$$

The time derivative of V is

$$\dot{V} = s^T M \dot{s} + \frac{1}{2} s^T \dot{M} s \tag{32}$$

Consider closed loop equation (27), one can get

$$\dot{V} = s^T\left(-Cs - M\dot{r} - Cr - G + \tau\right) + \frac{1}{2} s^T \dot{M} s \tag{33}$$

According property (P4), the following expression can be given

$$\dot{V} = s^T\left(-M\dot{r} - Cr - G + \tau\right) \tag{34}$$

Substitute control law τ_0 into expression (34), the following expression can be derived

$$\dot{V} = s^T\left[\left(K^M - M\right)\dot{r} + \left(K^C\|\dot{q}\| - C\right)r + \left(K^G - G\right) + \tau_1\right] \quad (35)$$

$$\begin{aligned}\dot{V} &\le \left\|s^T\left(K^M - M\right)\dot{r}\right\| + \left\|s^T\left(K^C\|\dot{q}\| - C\right)r\right\| + \left\|s^T\left(K^G - G\right)\right\| + s^T\tau_1 \\ &\le \left\|s^T\right\|\left\|K^M - M\right\|\|\dot{r}\| + \left\|s^T\right\|\left\|K^C\|\dot{q}\| - C\right\|\|r\| \\ &\quad + \left\|s^T\right\|\left\|K^G - G\right\| + s^T\tau_1\end{aligned} \quad (36)$$

Using Lemma 2, there must be

$$\begin{aligned}\dot{V} &\le |s|\left\|K^M - M\right\|\|\dot{r}\| \\ &\quad + |s|\left\|K^C\|\dot{q}\| - C\right\|\|r\| + |s|\left\|K^G - G\right\| + s^T\tau_1\end{aligned} \quad (37)$$

Consider control law τ_1

$$\begin{aligned}\dot{V} &\le |s|\left\|K^M - M\right\|\|\dot{r}\| + |s|\left\|K^C\|\dot{q}\| - C\right\|\|r\| + |s|\left\|K^G - G\right\| \\ &\quad - s^T K sig(s)^\rho - |s|\Delta^M\|\dot{r}\| - |s|\Delta^C\|\dot{q}\|\|r\| - |s|\Delta^G\end{aligned} \quad (38)$$

$$\begin{aligned}\dot{V} &\le -|s|\left(\Delta^M - \left\|K^M - M\right\|\right)\|\dot{r}\| \\ &\quad - |s|\left(\Delta^C\|\dot{q}\| - \left\|K^C\|\dot{q}\| - C\right\|\right)\|r\| \\ &\quad - |s|\left(\Delta^G - \left\|K^G - G\right\|\right) - s^T K sig(s)^\rho\end{aligned} \quad (39)$$

According to properties (P1)-(P3), one can get the following inequalities

$$\begin{cases}\left\|K^M - M\right\| \le \delta^M \\ \left\|K^C\|\dot{q}\| - C\right\| \le \delta^C\|\dot{q}\| \\ \left\|K^G - G\right\| \le \delta^G\end{cases} \quad (40)$$

where $\delta^M > 0$, $\delta^C > 0$ and $\delta^G > 0$ are real numbers.

Under condition (30) and inequalities (40), if the Δ^M, Δ^C and Δ^G are chosen as

$$\begin{cases}\delta^M \le \Delta^M \\ \delta^C \le \Delta^C \\ \delta^G \le \Delta^G\end{cases} \quad (41)$$

The following inequality can be given

$$\dot{V} \le -s^T K sig(s)^\rho \quad (42)$$

where

$$\begin{aligned}-s^T K sig(s)^\rho &= -\sum_{i=1}^{n} s_i k_i |s_i|^\rho sign(s_i) \\ &= -\sum_{i=1}^{n} k_i |s_i|^{\rho+1} \le -\alpha\left(\sum_{i=1}^{n}\frac{1}{2}\bar{m}s_i^2\right)^\eta \le -\alpha V^\eta\end{aligned} \quad (43)$$

where $\eta = (1+p)/2$, $\alpha = k_{\min}(2/\bar{m})^\eta$, $k_{\min} = \min\{k_i\}$.

By using (42) and (43), one can get

$$\dot{V} + \alpha V^\eta \le 0 \quad (44)$$

From Lemma 4, it follows that s will be 0 in a finite time. This means that the system states will reach the terminal sliding mode in a finite time T_r

$$T_r = \frac{V^{1-\eta}(s)}{\alpha(1-\eta)} \quad (45)$$

According to the Definition 1, the system states will converge to zero in a finite time along the fast terminal sliding mode. This completes the proof. □

Remark 3 In controller (28)-(29), the sign function $sign(\cdot)$ will cause chattering. To avoid this problem, the function $\tanh(\cdot)$ can be used to instead of $sign(\cdot)$ in a practical controller implementation.

Remark 4 To accelerate the convergence rate when the system state is far away from the terminal sliding mode, the control law τ_1 can be designed as

$$\tau_1 = -K_1 sig(s)^\rho - K_2 s - sign(s)\left[\Delta^M\|\dot{r}\| + \Delta^C\|\dot{q}\|\|r\| + \Delta^G\right] \quad (46)$$

where K_1 and K_2 are positive definite diagonal feedback control gain matrices. $K_2 s$ can guarantee the fast converge rate when the system states are far away from terminal sliding mode.

5. AN ILLUSTRATIVE EXAMPLE

Consider an illustrative example of the two-link rigid robotic manipulator in (Yu, Yu, Shirinzadeh, and Man, 2005)

$$\begin{bmatrix}\alpha_{11}(q_2) & \alpha_{12}(q_2) \\ \alpha_{21}(q_2) & \alpha_{22}\end{bmatrix}\begin{bmatrix}\ddot{q}_1 \\ \ddot{q}_2\end{bmatrix} + \begin{bmatrix}-\beta(q_2)\dot{q}_1 & -2\beta(q_2)\dot{q}_1 \\ 0 & \beta(q_2)\dot{q}_2\end{bmatrix}\begin{bmatrix}\dot{q}_1 \\ \dot{q}_2\end{bmatrix} + \begin{bmatrix}\gamma_1(q_1,q_2) \\ \gamma_2(q_1,q_2)\end{bmatrix}g = \begin{bmatrix}\tau_1 \\ \tau_2\end{bmatrix}$$

where

$$\alpha_{11}(q_2) = (m_1 + m_2)r_1^2 + m_2 r_2^2 + 2m_2 r_1 r_2\cos(q_2) + J_1$$

$$\alpha_{21}(q) = \alpha_{12}(q_2) = m_2 r_2^2 + m_2 r_1 r_2\cos(q_2)$$

$$\alpha_{22} = m_2 r_2^2 + J_2$$

$$\beta(q_2) = m_2 r_1 r_2\sin(q_2)$$

$$\gamma_1(q_1,q_2) = (m_1 + m_2)r_1\cos(q_2) + m_2 r_2\cos(q_1 + q_2)$$

$$\gamma_2(q_1,q_2) = m_2 r_2\cos(q_1 + q_2)$$

The parameter values were $r_1 = 1m$, $r_2 = 0.8m$, $J_1 = 5kgm$, $J_2 = 5km$, $m_1 = 0.5kg$ and $m_2 = 1.5kg$.

The reference signals were given by

$$q_1^d = 1.25 - (7/5)e^{-t} + (7/20)e^{-4t}$$

$$q_2^d = 1.25 + e^{-t} - (1/4)e^{-4t}$$

The initial values of the system were selected as $q_1(0) = 1.0$, $q_2(0) = 1.5$, $\dot{q}_1(0) = 0$ and $\dot{q}_2(0) = 0$.

The control parameters were chosen as $\Lambda_1 = diag([2.5, 2.5])$, $\Lambda_2 = diag([1.5, 1.5])$, $\gamma = \frac{3}{5}$, $K^M = diag([0.014, 0.014])$, $K^C = diag([1.6, 1.6])$, $K^G = [2, 2]^T$, $\Delta^M = 0.13$, $\Delta^C = 1.8$, $\Delta^G = 2.1$, $K_1 = diag([50, 50])$, $K_2 = diag([50, 50])$, $\rho = \frac{9}{11}$.

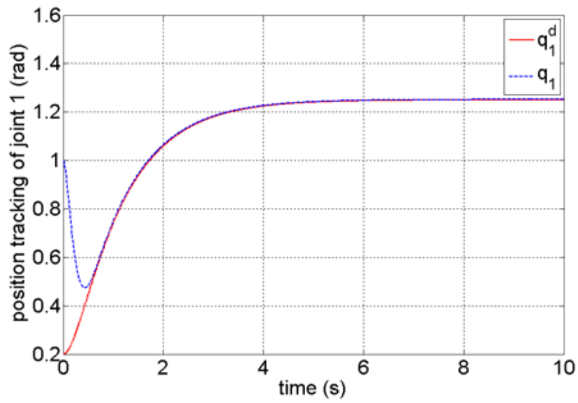

Fig. 1. The angle position tracking of joint 1

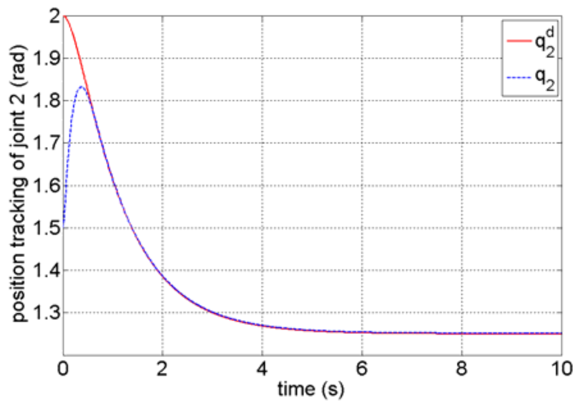

Fig. 2. The angle position tracking of joint 2

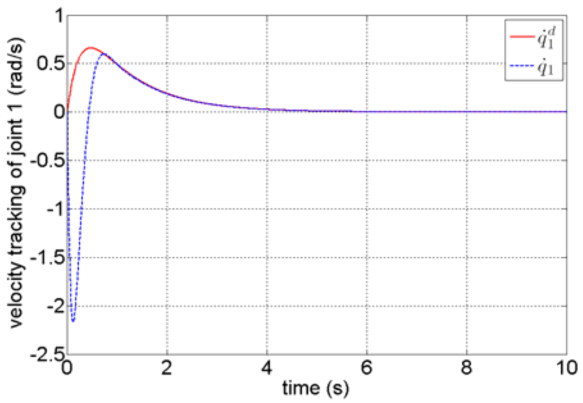

Fig. 3. The angle velocity tracking of joint 1

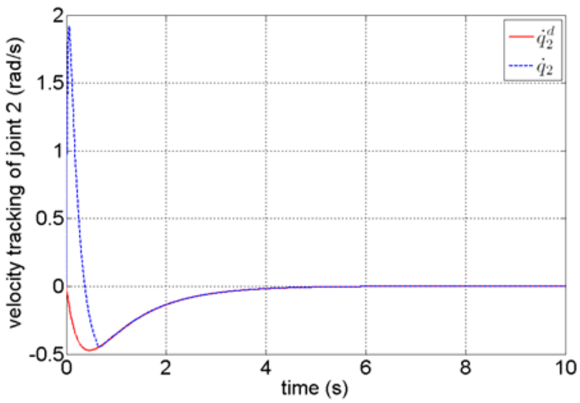

Fig. 4. The angle velocity tracking of joint 2

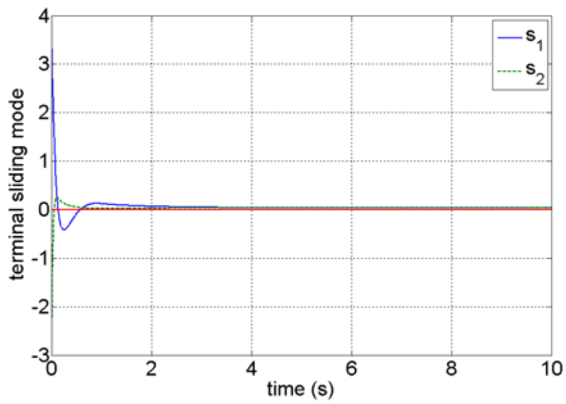

Fig. 5. The terminal sliding mode of joint 1 and joint 2

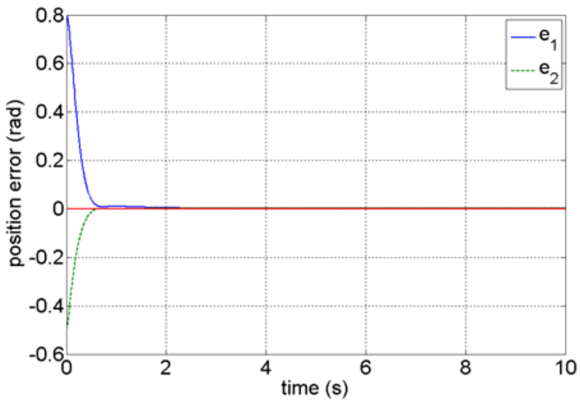

Fig. 6. The angle position error of joint 1 and joint 2

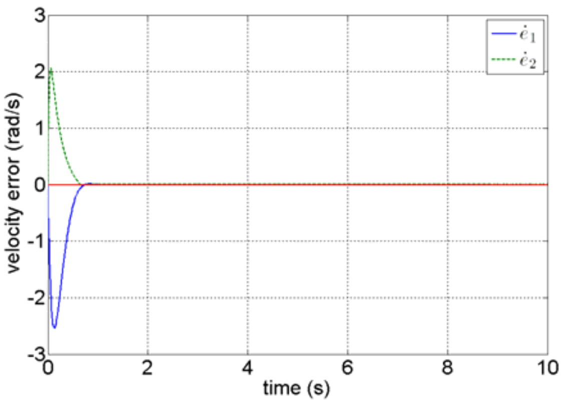

Fig. 7. The angle velocity error of joint 1 and joint 2

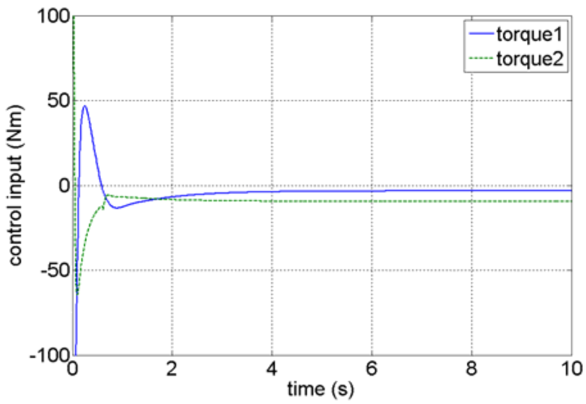

Fig. 8. The control input of joint 1 and joint 2

Fig. 1-4 show the position tracking and velocity tracking of joint 1 and joint 2. These figures show that the good tracking performance is achieved. Fig. 5 shows that the terminal sliding modes converge to zero in a finite time. Fig. 6 and 7 show that the position error and velocity error converge to zero in a finite time. From Fig. 5-7, it can be seen that system states reach terminal sliding mode in a finite time, then, converge to equilibrium along terminal sliding mode in a finite time. Fig. 8 denotes the control inputs. Since the new definition of non-singular terminal sliding mode and saturation technique are employed in controller design, the control inputs are bounded and chattering free.

6. CONCLUSIONS

This paper presents a new TSMC approach for robotic manipulators without requiring system dynamic mode explicitly. The proposed approach can guarantee the system states reach to the terminal sliding mode in a finite time. Then the system states converge to zero along the terminal sliding mode in a finite time. A novel non-singular terminal sliding mode is employed in controller design. The singularity problem can be avoided. Because this method does not require the explicit use of the robotic manipulator dynamic model, it can be implemented easily. It should mentioned that sound bench tests need to be conducted by simulations and lab demonstrations before applying the approach to control of real robotic manipulators. A fully adaptive TSMC for robotic manipulators is under the authors' research.

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