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Adaptive Terminal Sliding Mode Control for Rigid Robotic Manipulators

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Abstract: In order to apply the terminal sliding mode control to robot manipulators, prior knowledge of the exact upper bound of parameter uncertainties, and external disturbances is necessary. However, this bound will not be easily determined because of the complexity and unpredictability of the structure of uncertainties in the dynamics of the robot. To resolve this problem in robot control, we propose a new robust adaptive terminal sliding mode control for tracking problems in robotic manipulators. By applying this adaptive controller, prior knowledge is not required because the controller is able to estimate the upper bound of uncertainties and disturbances. Also, the proposed controller can eliminate the chattering effect without losing the robustness property. The stability of the control algorithm can be easily verified by using Lyapunov theory. The proposed controller is tested in simulation on a two-degree-of-freedom robot to prove its effectiveness.

Keywords: Terminal sliding mode, sliding mode control, adaptive control of robot, robust control, Lyapunov method.

1 Introduction

The study of the control of rigid robotic manipulators has attracted growing interest in the last decade both for scientific investigations and industrial needs. In fact, robotic manipulators play an important role in the industry by providing lower production cost, enhanced precision, quality and productivity while having greater flexibility than specialized machines[1].

The control of rigid manipulators faces significant difficulties such as highly nonlinear, highly time-varying, and highly coupled dynamic behavior. Moreover, there always exists uncertainty in the system model such as external disturbances, parameter uncertainty, and so on, which cause unstable performance of the robotic system[2].

So far, sliding mode control is widely applied in the control of rigid robotic manipulators, thanks to its simplicity and robustness properties[3−6]. The sliding mode control is characterized by robustness to parameter variations and insensitivity to disturbance[7−9], and it has been known as a useful strategy to deal with uncertain systems. The basic idea of the sliding mode control is to drive and maintain the system trajectory on a sliding surface designed a priori in the state space. When the sliding mode is achieved, the system dynamics is described by the dynamics of the surface, and then it becomes insensible to uncertainties satisfying the matching condition. However, the sliding mode control guarantees only an asymptotic convergence. The terminal sliding mode control has been proposed to have a fast finite time convergence[10], and it has been applied to robotic manipulators[11−16]. In [11, 12] a robust multi-input multi-output (MIMO) terminal sliding mode controller is proposed for robotic manipulators. A finite time convergence is guaranteed and a reduced gain of the terminal sliding mode controller is obtained with respect to high gain of linear sliding mode controller. To reduce the chattering, the authors used a boundary layer. The proposed controller depends on the upper bound of parameter uncertainties. Unfortunately, due to the complexity of the structure of uncertainties in the dynamics of robotic manipulators, such bound will not be easily obtained. An adaptive terminal sliding mode control is proposed in [13, 14] to estimate the upper bound of uncertainties. However, the controls are discontinuous and in [13] five parameters must be adjusted. Also, an adaptive terminal sliding mode control is proposed in [17], where less parameters are estimated with a finite time convergence. In this paper, we propose a new robust adaptive terminal sliding mode control for tracking problems of rigid robotic manipulators. With this control, a finite time convergence of the error is guaranteed and a prior knowledge of parameter uncertainty and disturbances is not needed because the proposed controller can estimate the upper bound of these uncertainties. Also, the proposed controller eliminates the chattering effect without losing the robustness property and the precision.

This paper is organized as follows. The robot model is presented in Section 2. A continuous terminal sliding mode is exposed in Section 3. In Section 4, the proposed adaptive terminal sliding mode control is elaborated. The stability of this control is proved by the Lyapunov theory. Simulation results are given in Section 5. Finally, conclusions are given in Section 6.

2 Robot model

Consider the dynamics of an n-link rigid robotic manipulator described by the following second-order nonlinear vector differential equation[17]

$$M(q)\ddot{q} + C(q, \dot{q}) + G(q) = u + d(t) \tag{1}$$

where q is an n-dimensional vector of joint angles, $M(q)$ is the $n \times n$ inertia matrix, $C(q, \dot{q})$ is the Coriolis and centrifugal terms, $G(q)$ is the gravitational torque, u is the n-dimensional vector of input torque, and $d(t)$ is the n-dimensional vector of the bounded input disturbance, $\|d(t)\| < d_1$ where $d_1 > 0$.

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Because of modeling error, parameter variations and unknown load, it is assumed that the dynamic model of the rigid manipulator (1) presents uncertainty. Therefore, $M(q)$, $C(q,\dot{q})$, and $G(q)$ can be written as

$$M(q) = M_0(q) + \Delta M(q) \tag{2}$$

$$C(q,\dot{q}) = C_0(q,\dot{q}) + \Delta C(q,\dot{q}) \tag{3}$$

$$G(q) = G_0(q) + \Delta G(q). \tag{4}$$

Then, from (2)–(4), (1) can be written in the following form

$$M_0(q)\ddot{q} + C_0(q,\dot{q}) + G_0(q) = u + \rho(t)$$

where $\rho(t)$ is defined as

$$\rho(t) = -\Delta M(q) - \Delta C(q,\dot{q}) - \Delta G(q) + d(t).$$

Some assumptions are used as below:

Assumption 1. The norm of inertia matrix $M(q)$ is upper bounded by a positive number α_0[17]

$$\|M(q)\| < \alpha_0.$$

Assumption 2. The following inequality is verified

$$\|C(q,\dot{q}) + G(q)\| < \beta_0 + \beta_1\|q\| + \beta_2\|\dot{q}\|^2$$

where β_0, β_1, and β_2 are positive numbers. It is shown in [17] that the uncertainty is input related and if the control input does not contain the acceleration signal, the system uncertainty will be bounded by a positive function of the position and velocity measurements in the following form

$$\|\rho(t)\| < b_0 + b_1\|q\| + b_2\|\dot{q}\|^2. \tag{5}$$

This bounded property has been used by some researchers of [15–18].

3 Continuous terminal sliding mode control

The trajectory tracking control of the robot manipulator can be formulated as follows: let $q_d \in \mathbf{R}^n$ be a given twice differentiable desired trajectory, and define the tracking error as $e_1 = q - q_d$; the control objective is to find a feedback control law u such that the manipulator output q tracks the desired trajectory q_d, the tracking error converges to zero in finite time. For this purpose, consider the terminal sliding surface[16−21]

$$S = e_2 + Ce_1^{\frac{a}{b}} \tag{6}$$

where $e_2 = \dot{q} - \dot{q}_d$, $C = \mathrm{diag}\{c_1, \cdots, c_n\}$, and a and b are odd integers satisfying $0 < a < b$.

The dynamic error corresponding to (1) is

$$\begin{cases} \dot{e}_1 = e_2 \\ \dot{e}_2 = -\ddot{q}_d - M_0(q)^{-1}(C_0(q,\dot{q}) + G_0(q)) + \\ \qquad M_0(q)^{-1}u + M_0(q)^{-1}\rho(t). \end{cases} \tag{7}$$

After choosing the sliding surface, the second step is to determine a control law satisfying the sliding condition

$$S^{\mathrm{T}}\dot{S} < 0.$$

We can use the equivalent control method for this goal. The equivalent control method is used to determine the system trajectory on the sliding surface. When the initial condition of the system is not on the sliding surface, the control is the sum of a low-frequency control that is the equivalent control u_{eq} and a high frequency control Δu[22]. The equivalent control is used to maintain the movement of the system on the sliding surface and Δu is a discontinuous control that drives the system trajectory to reach the sliding surface. The equivalent control can be determined, in the absence of disturbances and uncertainties, from

$$\dot{S} = 0.$$

The expression of the equivalent control is then

$$u_{eq} = M_0(q)(\ddot{q}_d - \frac{a}{b}C\mathrm{diag}\{e_1^{\frac{a}{b}-1}\}) + C_0(q,\dot{q}) + G_0(q). \tag{8}$$

The discontinuous term Δu is[23]

$$\Delta u = -\frac{\left(S^{\mathrm{T}}M_0(q)^{-1}\right)^{\mathrm{T}}}{\|S^{\mathrm{T}}M_0(q)^{-1}\|^2} \times \left[\|S\|\|M_0(q)^{-1}\|\left(b_0 + b_1\|q\| + b_2\|\dot{q}\|^2\right)\right].$$

However, the discontinuous control Δu can result in the chattering problem, and to overcome this undesirable effect Δu can be replaced by the following expression[23]

$$\Delta u_1 = \begin{cases} -\dfrac{(S^{\mathrm{T}}M_0(q)^{-1})^{\mathrm{T}}}{\|S^{\mathrm{T}}M_0(q)^{-1}\|^2}[\|S\|\|M_0(q)^{-1}\|\times \\ \quad (b_0 + b_1\|q\| + b_2\|\dot{q}\|^2)], \quad \text{if } \|S^{\mathrm{T}}M_0(q)^{-1}\| \geqslant \delta \\ -\dfrac{(S^{\mathrm{T}}M_0(q)^{-1})^{\mathrm{T}}}{\delta^2}[\|S\|\|M_0(q)^{-1}\|\times \\ \quad (b_0 + b_1\|q\| + b_2\|\dot{q}\|^2)], \quad \text{if } \|S^{\mathrm{T}}M_0(q)^{-1}\| < \delta \end{cases}$$

where $\delta > 0$.

The control applied to the rigid robotic manipulator is

$$u = u_{eq} + \Delta u_1.$$

The continuous terminal sliding mode control eliminates the chattering phenomenon at the cost of robustness property, and this controller depends on the upper bound of the uncertainties and disturbances which is difficult to determine.

4 Robust adaptive terminal sliding mode control

Applying the terminal sliding mode control for rigid robotic manipulators needs the knowledge of the upper bound of uncertainties and disturbances in advance. However, in the case of manipulators, the complexity and unpredictability of the structure of uncertainties may particularly cause certain difficulties in determining this bound. Besides, to eliminate the chattering effect, an increase of the parameter δ will generate the loss in robustness. To overcome these problems, we propose a new robust adaptive terminal sliding mode controller for the robotic manipulators described by (1), where the disturbance and the uncertainty satisfy (2)–(4), in order to estimate the bound of uncertainties and external disturbances online. Using the sliding surface (6), the adaptive terminal sliding mode control is proposed as follows

$$u = u_{eq} + \Delta u_2 \tag{9}$$

where u_{eq} is defined in (8) and Δu_2 has the following expression

$$\Delta u_2 = \begin{cases} -\dfrac{(S^{\mathrm{T}} M_0(q)^{-1})^{\mathrm{T}}}{\|S^{\mathrm{T}} M_0(q)^{-1}\|^2}[\|S\|\|M_0(q)^{-1}\|\times \\ \quad (\hat{b}_0 + \hat{b}_1\|q\| + \hat{b}_2\|\dot{q}\|^2)], \quad \text{if } \|S^{\mathrm{T}} M_0(q)^{-1}\| \geqslant \delta \\ -\dfrac{(S^{\mathrm{T}} M_0(q)^{-1})^{\mathrm{T}}}{\delta^2}[\|S\|\|M_0(q)^{-1}\|\times \\ \quad (\hat{b}_0 + \hat{b}_1\|q\| + \hat{b}_2\|\dot{q}\|^2)], \quad \text{if } \|S^{\mathrm{T}} M_0(q)^{-1}\| < \delta \end{cases}$$

where $\hat{b}_0$, $\hat{b}_1$, and $\hat{b}_2$ are the adaptive variables for b_0, b_1, and b_2 defined in (5). The adaptation laws are

$$\begin{aligned} \dot{\hat{b}}_0 &= x_0\|S\|\|M_0(q)^{-1}\| \\ \dot{\hat{b}}_1 &= x_1\|S\|\|M_0(q)^{-1}\|\|q\| \\ \dot{\hat{b}}_2 &= x_2\|S\|\|M_0(q)^{-1}\|\|\dot{q}\|^2 \end{aligned} \tag{10}$$

where x_0, x_1, and x_2 are arbitrary positive constants.

Theorem 1. If the control law (9), with the sliding surface (6) and the adaptation law (10), is applied to the nonlinear uncertain system defined by (7), the error converges to zero in finite time.

Proof. Let us consider the following positive definite function as a Lyapunov function candidate

$$V = \frac{1}{2}S^{\mathrm{T}}S + \frac{1}{2}\sum_{i=0}^{2} x_i^{-1}\tilde{b}_i^2$$

where $\tilde{b}_i = b_i - \hat{b}_i$, $i \in \{0, 1, 2\}$.

Differentiating V with respect to time and using the control law (9) for $\|S^{\mathrm{T}} M_0(q)^{-1}\| \geqslant \delta$ yields

$$\begin{aligned} \dot{V} =& S^{\mathrm{T}}[-\ddot{q}_d - M_0(q)^{-1}(C_0(q,\dot{q}) + G_0(q)) + \\ & M_0(q)^{-1}(u_{eq} + \Delta u_2) + M_0(q)^{-1}\rho(t) + \\ & \frac{a}{b}C\mathrm{diag}\{e_1^{\frac{a}{b}-1}\}e_2] - \sum_{i=0}^{2} x_i^{-1}\tilde{b}_i\dot{\hat{b}}_i \end{aligned}$$

$$\begin{aligned} \dot{V} =& S^{\mathrm{T}} M_0(q)^{-1}\rho(t) - [S^{\mathrm{T}} M_0(q)^{-1}\frac{(S^{\mathrm{T}} M_0(q)^{-1})^{\mathrm{T}}}{\|S^{\mathrm{T}} M_0(q)^{-1}\|^2}\times \\ & \|S\|\|M_0(q)^{-1}\|(\hat{b}_0 + \hat{b}_1\|q\| + \hat{b}_2\|\dot{q}\|^2)] - \sum_{i=0}^{2} x_i^{-1}\tilde{b}_i\dot{\hat{b}}_i \end{aligned}$$

Simplifying and substituting $\dot{\hat{b}}_i$ by the expression defined by (10), we obtain

$$\begin{aligned} \dot{V} =& S^{\mathrm{T}} M_0(q)^{-1}\rho(t) - \\ & \|S\|\|M_0(q)^{-1}\|(\hat{b}_0 + \hat{b}_1\|q\| + \hat{b}_2\|\dot{q}\|^2) - \\ & \|S\|\|M_0(q)^{-1}\|(\tilde{b}_0 + \tilde{b}_1\|q\| + \tilde{b}_2\|\dot{q}\|^2) = \\ & S^{\mathrm{T}} M_0(q)^{-1}\rho(t) - \\ & \|S\|\|M_0(q)^{-1}\|(b_0 + b_1\|q\| + b_2\|\dot{q}\|^2) \leqslant \\ & \|S\|\|M_0(q)^{-1}\|(\|\rho(t)\| - (b_0 + b_1\|q\| + b_2\|\dot{q}\|^2) < 0 \\ & . \end{aligned}$$

□

5 Simulation results

The performance of the proposed controller is tested via simulation on a two-degrees-of-freedom robot described by the following model[17]

$$\begin{pmatrix} M_{11}(q) & M_{12}(q) \\ M_{12}(q) & M_{22}(q) \end{pmatrix}\begin{pmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{pmatrix} + \begin{pmatrix} C_1(q,\dot{q}) \\ C_2(q,\dot{q}) \end{pmatrix} + \begin{pmatrix} G_1(q) \\ G_2(q) \end{pmatrix} = \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} + \begin{pmatrix} d_1(t) \\ d_2(t) \end{pmatrix}$$

where

$$\begin{gathered} M_{11}(q) = (m_1 + m_2)L_1^2 + m_2L_2^2 + 2m_2L_1L_2\cos(q_2) + J_1 \\ M_{12}(q) = m_2L_2^2 + m_2L_1L_2\cos(q_2) \\ M_{22}(q) = m_2L_2^2 + J_2 \\ C_1(q,\dot{q}) = -m_2L_1L_2\sin(q_2)\dot{q}_1^2 - 2m_2L_1L_2\sin(q_2)\dot{q}_1\dot{q}_2 \\ C_2(q,\dot{q}) = m_2L_1L_2\sin(q_2)\dot{q}_2 \\ G_1(q) = (m_1 + m_2)L_1\cos(q_2) + m_2L_2\cos(q_1 + q_2) \\ G_2(q) = m_2L_2\cos(q_1 + q_2). \end{gathered}$$

The nominal values of m_1 and m_2 are assumed to be[17]

$$m_{10} = 0.4\,\mathrm{kg}, \quad m_{20} = 1.2\,\mathrm{kg}$$

and we suppose that we have an uncertainty on masses of the order ±10% (see Figs. 1 and 2). The other system parameters are assumed to be known[17]:

$$\begin{gathered} L_1 = 1\,\mathrm{m}, \quad L_2 = 0.8\,\mathrm{m} \\ J_1 = 5\,\mathrm{kg{\cdot}m}, \quad J_2 = 5\,\mathrm{kg}. \end{gathered}$$

The disturbance vector is $d(t) = [d_1(t) \quad d_2(t)]^{\mathrm{T}}$, where

$$\begin{gathered} d_1(t) = 0.2\sin(3t) + 0.02\sin(26\pi t) \\ d_2(t) = 0.1\sin(2t) + 0.01\sin(26\pi t). \end{gathered}$$

In this example, the initial values of the system are selected as

$$\begin{gathered} [q_1(0) \quad q_2(0)]^{\mathrm{T}} = [0.8 \quad 0.9]^{\mathrm{T}} \\ [\dot{q}_1(0) \quad \dot{q}_2(0)]^{\mathrm{T}} = [0 \quad 0]^{\mathrm{T}}. \end{gathered}$$

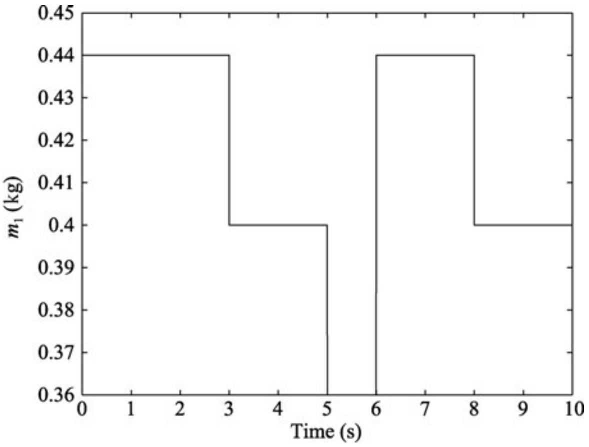

Fig. 1 Variation of mass m_1

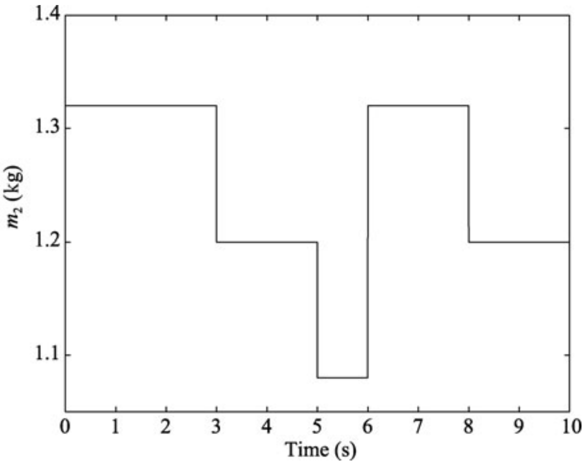

Fig. 2 Variation of mass m_2

We desire the two articulations track, respectively, the following desired angular positions[17]

$$q_{d1} = 1.25 - \frac{7}{5}\exp(-t) + \frac{7}{20}\exp(-4t)$$

$$q_{d2} = 1.4 - \frac{7}{5}\exp(-t) + \frac{7}{20}\exp(-4t).$$

The chosen surface parameters are $a = 5$, $b = 7$, and $c_1 = c_2 = 2$, and the initial conditions of the upper bound of the uncertainty are $b_{00} = 5$, $b_{10} = 14$, and $b_{20} = 2$. The results obtained for the continuous terminal sliding mode control and the adaptive terminal sliding mode control are given by Figs. 3 and 4. In order to have a small boundary layer around the sliding surface to have a more robust system, we have chosen small δ equal to 0.0005. However, the control law is not totally continuous, and it presents a high frequency commutation at the instant 1 s which is undesirable in practice. Besides, the controller depends on the upper bound of uncertainties and disturbances. By the application of the new adaptive terminal sliding mode control, these problems are solved conserving the same parameter δ. In fact, the proposed control is continuous without losing the robustness property, and the parameters of the upper bound are estimated online. Figs. 5–7 present these parameters. These results show a finite time convergence of the upper bound parameters. In the presence of large uncertainty, the terminal sliding mode control can give large tracking error which is not the case in adaptive terminal sliding mode control. In fact, according to the adaptive laws (10), the control is adjusted to have a very small tracking error. Therefore, the effect of the uncertainty can be eliminated. The obtained results present some improvements in convergence time of the error and control amplitude compared to the results of [17].

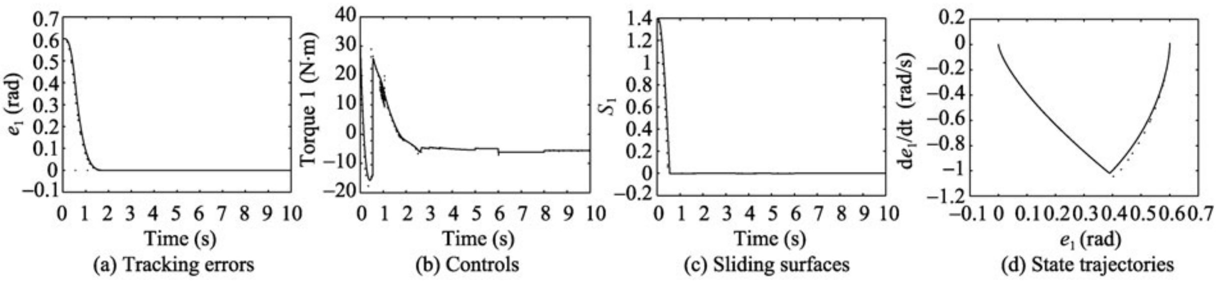

Fig. 3 Tracking of the first joint with terminal sliding mode control (dotted line) and adaptive terminal sliding mode control (solid line)

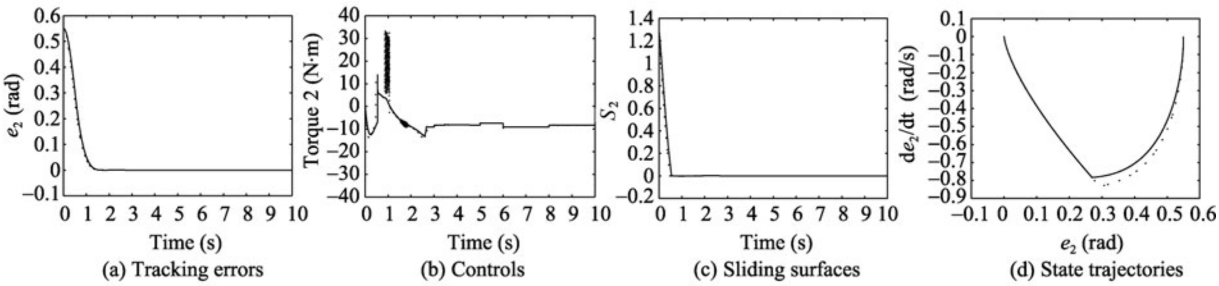

Fig. 4 Tracking of the second joint with terminal sliding mode control (dotted line) and adaptive terminal sliding mode control (solid line)

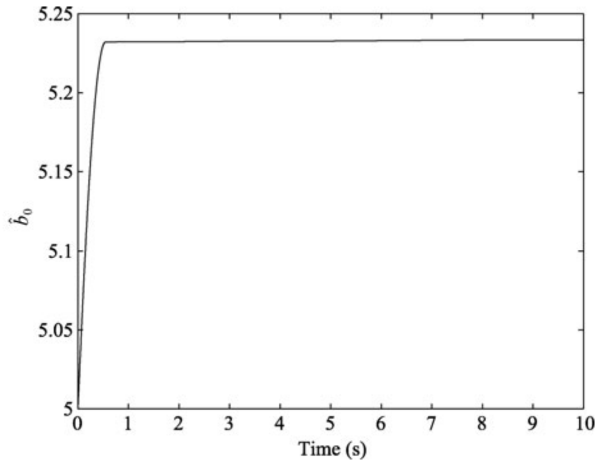

Fig. 5 Estimated parameter $\hat{b}_0$

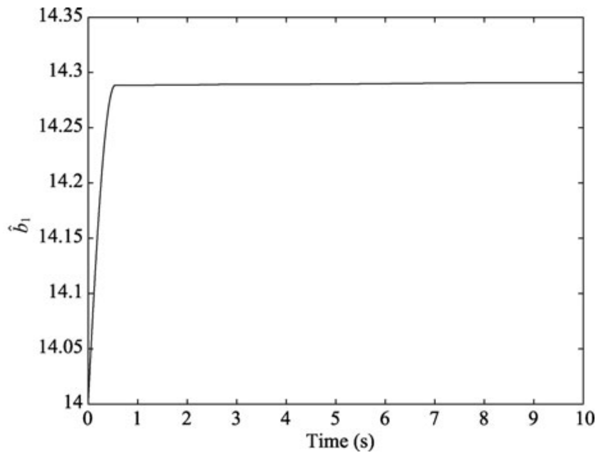

Fig. 6 Estimated parameter $\hat{b}_1$

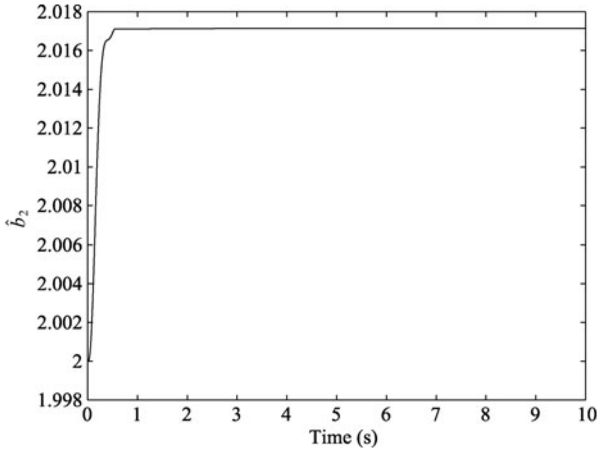

Fig. 7 Estimated parameter $\hat{b}_2$

6 Conclusions

In this paper, we have described the design of a new robust adaptive terminal sliding mode controller for the tracking problem of the rigid robotic manipulators. The main feature of this design is that it combines the terminal sliding mode control with a boundary layer and the adaptive approach. This adaptive algorithm is used to estimate the bounds of uncertainties and external disturbances. With this controller, a finite time convergence of the error is guaranteed and the knowledge of the upper bound of the disturbances and uncertainties is not necessary. The simulation results show that the algorithm can estimate this bound online and can assure a good performance. In fact, the error converges to zero in finite time and the proposed control is robust to uncertainties and disturbances. Also, the proposed control has eliminated the chattering phenomenon without losing the robustness property and precision.

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