Journal of Control Theory and Applications 2007 5 (2) 189–193 DOI 10.1007/s11768-005-5275-5

A novel dynamic terminal sliding mode control of uncertain nonlinear systems

Jinkun LIU [1], Fuchun SUN [2]

(1.School of Automation Science and Electrical Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100083, China;

2.State Key Laboratory of Intelligent Technology and Systems, Tsinghua University, Beijing 100084, China)

Abstract: A new dynamic terminal sliding mode control (DTSMC) technique is proposed for a class of single-input and single-output (SISO) uncertain nonlinear systems. The dynamic terminal sliding mode controller is formulated based on Lyapunov theory such that the existence of the sliding phase of the closed-loop control system can be guaranteed, chattering phenomenon caused by the switching control action can be eliminated, and high precision performance is realized. Moreover, by designing terminal equation, the output tracking error converges to zero in finite time, the reaching phase of DSMC is eliminated and global robustness is obtained. The simulation results for an inverted pendulum are given to demonstrate the properties of the proposed method.

Keywords: Terminal sliding mode control; Dynamic sliding mode; Robust control; Inverted pendulum

1 Introduction

Since the publication of the pioneering paper [1] on sliding mode control (SMC), significant results and many applications have been reported in the literature [2]. In particular, SMC has provided alternative and viable solutions to electro-mechanical control problems [3]. Sliding mode control systems exhibit superb control performance, are applicable to MIMO systems, and most importantly are robust [4]. Generally speaking, a system controlled by SMC is immune to parameter changes or external disturbances. Many different variations of sliding mode control have been developed and reported in the literature [5∼7].

However, before the system gets in the sliding mode, the output performance may be degraded by parameter variations, i.e., the invariance property is not guaranteed during this period and creats a situation known as the reaching phase problem. In general, the sliding surface has been designed as a linear dynamic equation. However, the linear sliding surface can guarantee the asymptotic error convergence in the sliding mode, i.e., the output error will not converge to zero in finite time.

Recently, a novel variation of SMC termed as the terminal sliding mode (TSM) control algorithm has been studied to further alleviate control performance [8∼12]. Compared with linear hyper-plane based sliding modes, TSM offers some superior properties such as fast, finite time convergence. This controller is particularly useful for high precision control as it speeds up the rate of convergence near the equilibrium point, which has been used for second or high nonlinear uncertain systems control [8∼12]. However, just like general sliding mode control, the chattering phenomenon caused by discontinuous control signal (a general problem associated with SMC control) is not addressed sufficiently.

Basically, the control signal of SMC can be divided into two parts: a continuous control signal (usually called equivalent control) which controls the system when its states are on the sliding plane, and a discontinuous control signal which handles uncertainties. Chattering is only caused by the discontinuous control signal. The greater the uncertainties, the larger the discontinuous control signal's amplitude and hence increased chattering effects. A common method to improve chattering is by inserting a boundary layer [13, 14] near the sliding plane such that a continuous control signal replaces the discontinuous one when the system is near the sliding plane. This method eliminates chattering but causes a finite steady-state error, a trade-off between chattering and tracking accuracy is thus desired. Another method is to minimize the amplitude of the discontinuous control signal during the controller design. However, the robustness properties of the controller are affected and the transient performance of the system becomes poor. Vega et al. [15] proposed an alternative approach to reduce the amplitude of the discontinuous input only when the system is near the sliding plane so that the transient response is not affected, but small chattering still exists and the problem is still open.

Received 30 September 2005; revised 23 November 2006.

This work was supported by the National Natural Science Foundation of China (No.60474025, 90405017).

Along this line of argument, one may use the dynamically generated sliding mode control as a means of obtaining a smoother controlled response than those achieved through traditional sliding mode control [16, 17]. All chattering signal can thus be completely cancelled. As a consequence, a sufficiently smooth input signal is generated.

In this paper, a novel dynamic terminal sliding mode control is first developed to eliminate the chattering problem by using dynamic terminal sliding mode surface. By using a function augmented sliding hyper-plane, it is guaranteed that the tracking error converges to zero in finite time. In addition, the reaching phase problem is totally eliminated whenever an initial state is located in the phase space. Therefore, the overall system is always in the sliding mode and shows the invariance property to parameter variations during the entire response time.

The rest of the paper is organized as follows: system description is presented in Section 2. Nonlinear dynamic terminal sliding mode controller design and stability analysis are described in Section 3. Simulation example for inverted pendulum is discussed in Section 4 and the conclusions are drawn in Section 5.

2 System description

It is supposed that the nominal model of the nonlinear system is denoted by $f(x,t)$, $(b(x,t)$. Consider the following SISO uncertain nonlinear system:

$$\begin{cases} \dot{x}_i = x_{i+1}, \\ \dot{x}_n = f(x,t) + \Delta f(x,t) + (b(x,t) \\ \qquad + \Delta b(x,t))u(t) + d_0(x,t), \end{cases} \tag{1}$$

where $i = 1, 2, \cdots, n-1$,

$$x = [x_1, x_2, \cdots, x_n]^{\mathrm{T}} = [x_1, \dot{x}_1, \cdots, x_1^{(n-1)}]^{\mathrm{T}},$$

$f(x,t)$ and b(x, t) are continuous-differential functions of nominal model, $b(x,t) > 0$, $d_0(x,t)$ is external disturbance, and $d_0(x,t)$ is continuous-differential function.

Defining $d(x,t) = \Delta f(x,t) + \Delta b(x,t)u(t) + d_0(x,t)$, we can rewrite the nonlinear system as

$$\begin{cases} \dot{x}_i = x_{i+1}, \\ \dot{x}_n = f(x,t) + b(x,t)u(t) + d(x,t). \end{cases} \tag{2}$$

In this paper, we assume $d(x,t)$ is continuous-differential and limited function, and $\dot{d}(x,t)$ is limited function.

3 Design of dynamic terminal sliding mode control

3.1 Terminal sliding mode surface design

Define tracking error as

$$E = x - x_d = [e, \dot{e}, \cdots, e^{(n-1)}]^{\mathrm{T}}, \tag{3}$$

where $e = x_1 - x_{1d}$.

Define the following terminal sliding mode equation as

$$s(x,t) = CE - W(t), \tag{4}$$

where $C = [c_1, c_2, \cdots, c_n]$, $c_i (i = 1, 2, \cdots, n)$ is positive constant and $c_n = 1$.

Define

$$W(t) = CP(t), \tag{5}$$

where $P(t) = [p(t), \dot{p}(t), \cdots, p^{(n-1)}(t)]^{\mathrm{T}}$.

Define dynamic terminal sliding mode surface as

$$\sigma(x,t) = \dot{s}(x,t) + \lambda s(x,t), \tag{6}$$

where λ is a positive constant value.

Assumption 1 Consider terminal function $p(t)$:$R+ \to \mathbb{R}$, $p(t) \in C^n[0,\infty), \dot{p}, \dot{p}, \cdots, p^{(n)} \in L^\infty$, $p(t)$ is finite in interval $[0,T]$, $E(0) = P(0)$, $\dot{E}(0) = \dot{P}(0)$, that is, $p(0) = e(0)$, $\dot{p}(0) = \dot{e}(0), \cdots, p^{(n)}(0) = e^{(n)}(0)$. Moreover, $p = 0, \dot{p} = 0, \cdots, p^{(n)} = 0$ for $t \geqslant T$. $C^n[0,\infty)$ represents the set of all n rank differentiable continuous functions defined in $[0,\infty)$.

Define terminal function $p(t)$ as

$$p(t) = \begin{cases} \sum\limits_{j=0}^{n} (\sum\limits_{l=0}^{n} (\frac{a_{jl}}{T^{j-l+n+1}} e(0)^{(l)}) t^{j+n+1} \\ \quad + \sum\limits_{k=0}^{n} \frac{1}{k!} e(0)^{(k)} t^k, & \text{if } t \leqslant T, \\ 0, & \text{if } t \geqslant T, \end{cases} \tag{7}$$

where a_{jl} can be obtained by using Assumption 1.

For example, for a second system, $n = 2$, $p(t)$ can be written as

$$p(t) = \begin{cases} e_0 + \dot{e}_0 t + \frac{1}{2}\ddot{e}_0 t^2 + (\frac{a_{00}}{T^3} e_0 + \frac{a_{01}}{T^2} \dot{e}_0 + \frac{a_{02}}{T} \ddot{e}_0) t^3 \\ \quad + (\frac{a_{10}}{T^4} e_0 + \frac{a_{11}}{T^3} \dot{e}_0 + \frac{a_{12}}{T^2} \ddot{e}_0)) t^4 \\ \quad + (\frac{a_{20}}{T^5} e_0 + \frac{a_{21}}{T^4} \dot{e}_0 + \frac{a_{22}}{T^3} \ddot{e}_0) t^5, & \text{if } t \leqslant T, \\ 0, & \text{if } t \geqslant T. \end{cases} \tag{8}$$

According to Assumption 1, function $p(t)$ and $\dot{p}(t)$, $\ddot{p}(t)$ can be equal to zero at time $t = T$ by designing $a_{jl}(j = 0, 1, 2, l = 0, 1, 2)$. That is, if we design $a_{jl}(j = 0, 1, 2, l = 0, 1, 2)$ according to the following equations, $p(t), \dot{p}(t), \ddot{p}(t)$ can all be equal to zero at time $t = T$.

$$\begin{cases} a_{00} + a_{10} + a_{20} = -1, \\ 3a_{00} + 4a_{10} + 5a_{20} = 0, \\ 6a_{00} + 12a_{10} + 20a_{20} = 0, \end{cases} \tag{9}$$

$$\begin{cases} a_{01} + a_{11} + a_{21} = -1, \\ 3a_{01} + 4a_{11} + 5a_{21} = -1, \\ 6a_{01} + 12a_{11} + 20a_{21} = 0, \end{cases} \tag{10}$$

$$\begin{cases} a_{02} + a_{12} + a_{22} = -\dfrac{1}{2}, \\ 3a_{02} + 4a_{12} + 5a_{22} = -1, \\ 6a_{02} + 12a_{12} + 20a_{22} = -1. \end{cases} \quad (11)$$

Based on the three groups of equations above, parameters $a_{jl}(j = 0, 1, 2; l = 0, 1, 2)$ can be solved as

$$a_{00} = -10, a_{10} = 15, a_{20} = -6,$$
$$a_{01} = -6, a_{11} = 8, a_{21} = -3,$$
$$a_{02} = -1.5, a_{12} = 1.5, a_{22} = -0.5.$$

For the same reason, parameters a_{jl} in Equation (7) can be obtained for n rank system.

3.2 Terminal sliding mode controller design

Theorem 1 For system (1), if the dynamic control law is designed by

$$\dot{u}(t) = -\frac{1}{c_n b(x,t)}(I_1 u(t) + I_2 + I_3 + (c_{n-1} + \lambda c_n)(D + \eta)\mathrm{sign}(\sigma)), \quad (12)$$

where $\eta > 0$, then $\sigma(x,t)$ will reach zero in finite time T. Furthermore, the states x will converge to zero in finite time T, D is a positive constant value designed as below.

Proof Consider a Lyapunov function candidate as follows:

$$V(t) = \frac{1}{2}\sigma^{\mathrm{T}}\sigma, \quad (13)$$

$$s(x,t) = C(E - P) = \sum_{l=0}^{n} c_l(e^{(l-1)} - p^{(l-1)}). \quad (14)$$

The derivative of $s(x,t)$ is

$$\begin{aligned} \dot{s}(x,t) &= C(\dot{E} - \dot{P}) \\ &= C[\dot{e}, \ddot{e}, \cdots, e^{(n)}] - C[\dot{p}, \ddot{p}, \cdots, p^{(n)}] \\ &= c_n(e^{(n)} - p^{(n)}) + \sum_{k=1}^{n-1} c_k(e^{(k)} - p^{(k)}), \end{aligned} \quad (15)$$

$$\begin{aligned} \sigma &= \dot{s} + \lambda s \\ &= c_n(e^{(n)} - p^{(n)}) + \sum_{k=1}^{n-1} c_k(e^{(k)} - p^{(k)}) \\ &\quad + \lambda\sum_{l=1}^{n} c_l(e^{(l-1)} - p^{(l-1)}), \end{aligned} \quad (16)$$

$$\begin{aligned} \dot{\sigma} &= c_n(e^{(n+1)} - p^{(n+1)}) + \sum_{k=1}^{n-1} c_k(e^{(k+1)} - p^{(k+1)}) \\ &\quad + \lambda\sum_{l=1}^{n} c_l(e^{(l)} - p^{(l)}). \end{aligned} \quad (17)$$

Since

$$e^{(n+1)} = \dot{e}^{(n)} = \dot{x}_1^{(n)} - \dot{x}_{1d}^{(n)} = \ddot{x}_n - \ddot{x}_{nd},$$

$$\begin{aligned} & c_n(e^{(n+1)} - p^{(n+1)}) \\ &= c_n(\ddot{x}_n - \ddot{x}_{nd} - p^{(n+1)}) \\ &= c_n(\dot{f}(x,t) + \dot{b}(x,t)u(t) + b(x,t)\dot{u}(t) \\ &\quad + \dot{d}(x,t) - \ddot{x}_{nd} - p^{(n+1)}), \end{aligned}$$

$$\begin{aligned} & \sum_{k=1}^{n-1} c_k(e^{(k+1)} - p^{(k+1)}) \\ &= c_{n-1}(e^{(n)} - p^{(n)}) + \sum_{k=1}^{n-2} c_k(e^{(k+1)} - p^{(k+1)}) \\ &= c_{n-1}(f(x,t) + b(x,t)u(t) + d(x,t) - \dot{x}_{nd} - p^{(n)}) \\ &\quad + \sum_{k=1}^{n-2} c_k(e^{(k+1)} - p^{(k+1)}), \end{aligned}$$

$$\begin{aligned} & \lambda\sum_{l=1}^{n} c_l(e^{(l)} - p^{(l)}) \\ &= \lambda c_n(e^{(n)} - p^{(n)}) + \lambda\sum_{l=1}^{n-1} c_l(e^{(l)} - p^{(l)}) \\ &= \lambda c_n(f(x,t) + b(x,t)u(t) \\ &\quad + d(x,t) - \dot{x}_{nd} - p^{(n)}) + \lambda\sum_{l=1}^{n-1} c_l(e^{(l)} - p^{(l)}). \end{aligned}$$

Therefore

$$\begin{aligned} \dot{\sigma} &= (c_n\dot{b}(x,t) + (c_{n-1} + \lambda c_n)b(x,t))u(t) \\ &\quad + (c_{n-1} + \lambda c_n)d(x,t) + c_n(b(x,t)\dot{u}(t) \\ &\quad + \dot{d}(x,t)) + c_n(\dot{f}(x,t) - \ddot{x}_{nd} - p^{(n+1)}) \\ &\quad + (c_{n-1} + \lambda c_n)(f(x,t) - \dot{x}_{nd} - p^{(n)}) \\ &\quad + \sum_{k=1}^{n-2} c_k(e^{(k+1)} - p^{(k+1)}) + \lambda\sum_{l=1}^{n-1} c_l(e^{(l)} - p^{(l)}) \\ &= I_1 u(t) + (c_{n-1} + \lambda c_n)(d(x,t) + \frac{c_n}{c_{n-1} + \lambda c_n}\dot{d}(x,t)) \\ &\quad + c_n b(x,t)\dot{u}(t) + I_2 + I_3, \end{aligned} \quad (18)$$

where

$$\begin{aligned} I_1 &= c_n\dot{b}(x,t) + (c_{n-1} + \lambda c_n)b(x,t), \\ I_2 &= c_n(\dot{f}(x,t) - \ddot{x}_{nd} - p^{(n+1)}) \\ &\quad + (c_{n-1} + \lambda c_n)(f(x,t) - \dot{x}_{nd} - p^{(n)}), \\ I_3 &= \sum_{k=1}^{n-2} c_k(e^{(k+1)} - p^{(k+1)}) + \lambda\sum_{l=1}^{n-1} c_l(e^{(l)} - p^{(l)}). \end{aligned}$$

Since $d(x,t)$ is a continuous-differential and limited function, and $\dot{d}(x,t)$ is a limited function, then we can get

$$d(x,t) + \frac{c_n}{c_{n-1} + \lambda c_n}\dot{d}(x,t) = d'(x,t) \leqslant D. \quad (19)$$

Substituting the dynamic control law (12) into (18) yields

$$\dot{\sigma} = (c_{n-1} + \lambda c_n)(d'(x,t) - (D + \eta)\mathrm{sign}(\sigma)), \quad (20)$$

$$\begin{aligned} \sigma\dot{\sigma} &= (c_{n-1} + \lambda c_n)(d'(x,t)\sigma - (D + \eta)|\sigma|) \\ &\leqslant -(c_{n-1} + \lambda c_n)\eta|\sigma|. \end{aligned} \quad (21)$$

If $\sigma \neq 0$, then $\dot{V} < 0$. That means this Lyapunov function will decrease gradually and the sliding surface, $\sigma(x,t)$ will converge to zero.

Remark 1 It follows from Assumption 1 that

$$\begin{aligned} s(x,0) &= CE(0) - W(0) = C(E(0) - P(0)) = 0, \\ \dot{s}(x,0) &= C\dot{E}(0) - \dot{W}(0) = C(\dot{E}(0) - \dot{P}(0)) = 0. \end{aligned} \quad (22)$$

From Equation (6), we can get $\sigma(x,0) = 0$. According to Lyapunov analysis, $\sigma(x,t) = 0$ can be achieved all the time. This indicates that the reaching phase in dynamic sliding mode control can be eliminated, and global robustness can be guaranteed.

Remark 2 Consider $\sigma(x,t) = 0$ and (6), we have $s(x,t) = 0$ for all the time.

Remark 3 Let $\xi(t) = E(t) - P(t)$, we have

$$\begin{aligned} s(x,t) &= CE(t) - W(t) = CE(t) - CP(t)) \\ &= C(t)\xi(t). \end{aligned} \tag{23}$$

According to Remark 2, if we choose $P(t)(\forall t \geqslant T)$, the tracking error $E(t)(\forall t \geqslant T)$ will converge to zero in finite time T.

In summary, if we choose the dynamic control law (12) and design terminal equation $p(t)$, the output tracking error will converge to zero in finite time T, the reaching phase could be eliminated, and global robustness can be obtained.

4 Simulation and results

Consider an inverted pendulum, the dynamics of the system can be expressed as equations:

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= \frac{g\sin x_1 - mlx_2^2\cos x_1 \sin x_1/(m_c+m)}{l(4/3 - m\cos^2 x_1/(m_c+m))} \\ &\quad + \frac{\cos x_1/(m_c+m)}{l(4/3 - m\cos^2 x_1/(m_c+m))}u(t) + d(x,t). \end{aligned} \tag{24}$$

where $x = [x_1, x_2]$, x_1 and x_2 are the angular position and velocity of the pole, $g = 9.8\text{m/s}^2$ is the acceleration due to gravity, $m_c = 1$kg is the mass of cart, $m = 0.1$kg is the mass of pole, $l = 0.5$m is the half-length of pole, u is the applied force. The external disturbance is assumed as $d(x,t) = 3\sin(\pi t)$.

From the equation (24), we have

$$f(x,t) = \frac{g\sin x_1 - mlx_2^2\cos x_1 \sin x_1/(m_c+m)}{l(4/3 - m\cos^2 x_1/(m_c+m))},$$

$$b(x,t) = \frac{\cos x_1/(m_c+m)}{l(4/3 - m\cos^2 x_1/(m_c+m))}.$$

According to (19), we set $D = 3.5$. We choose control parameters as $c_1 = 5, c_2 = 1, \lambda = 15, \eta = 1.5$, and choose the desired trajectory as $x_d(t) = 0.5\sin(t)$. The initial state is assumed as $x = [0.6, 0]$, and the terminal time is chosen as $T = 0.80$s.

The position tracking and its error are shown in Figs. 1 and 2, respectively. The time of tracking error converging to zero is shown in Fig. 2. The dynamic control input and practical control input are shown in Figs. 3 and 4, respectively. Comparing the results shown in Figs. 1∼4, we can see that the superior position tracking performance and high robustness with respect to big external disturbance can be obtained by using the proposed controller. The position tracking error converges to zero at finite time $T = 0.8$s exactly, and smooth control input signal is realized. The results look promising.

In addition, the simulation Matlab program of the proposed sliding mode controller is given in the book [18].

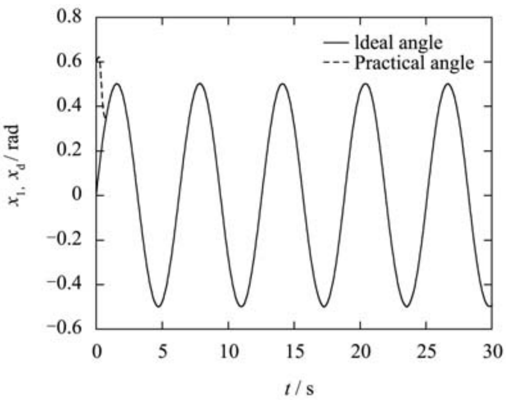

Fig. 1 Sinusoidal position tracking with DTSMC.

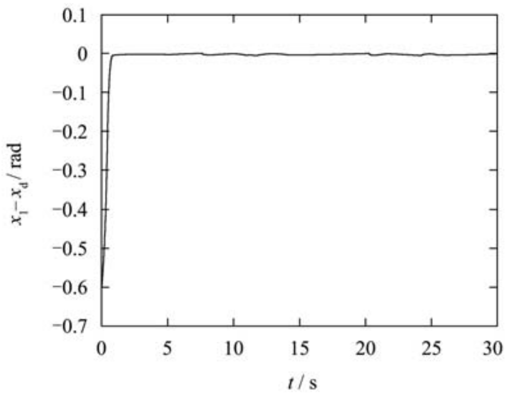

Fig. 2 Sinusoidal position tracking error with DTSMC.

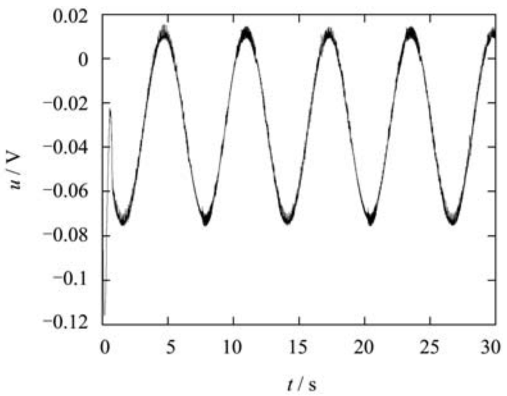

Fig. 3 Practical control input.

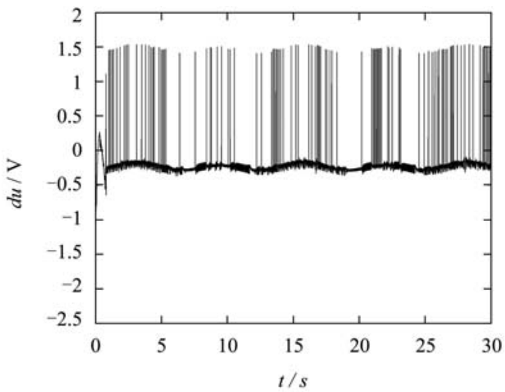

Fig. 4 Dynamic control input.

5 Conclusions

A novel dynamic terminal sliding mode control (DSMC) technique was put forward and successfully designed for a class of SISO nonlinear uncertain systems. From the analysis and design above, we demonstrated that the proposed dynamic can eliminate the chattering phenomenon caused by the switching term of the conventional sliding mode control. In addition, the proposed controller can guarantee that the system reaches the sliding manifolds at all times and the terminal sliding modes further take the tracking error to zero in finite time T. Moreover, the finite time T can be adjusted to the desired values in the design. Simulation results for inverted pendulum have shown that superior tracking performance can be achieved by using the proposed controller. The control input signal become smooth, and the chattering phenomenon can be eliminated effectively.

References

[1] V. I. Utkin. Variable structure systems with sliding modes[J]. *IEEE Transactions on Automatic Control*, 1977, 22(2): 212 – 222.

[2] K. D. Young, V. I. Utkin, U. Ozguner. A control engineer's guide to sliding mode control[J]. *IEEE Transactions Control Systems Technology*, 1999, 7(3): 328 – 342.

[3] V. I. Utkin. *Sliding Mode Control in Electromechanical Systems*[M]. London: Taylor Francis, 1999.

[4] H. Elmali, N. Olgac. Robust output tracking control of nonlinear MIMO systems via sliding mode technique[J]. *Automatica*, 1992, 28(1): 145 – 151.

[5] Y. Niu, J. Lam, X. Wang, D. Ho. Sliding mode control for nonlinear state-delayed systems using neural network approximation[J]. *IEE Proceeding D*, 2003, 150(3): 233 – 239.

[6] Y. Niu, J. Lam, X. Y. Wang, D. Ho. Observer-based sliding mode control for nonlinear state-delay systems[J]. *International Journal of Systems Science*, 2004, 35(2): 139 – 150.

[7] Y. Niu, D. Ho, J. Lam. Robust integral sliding mode control for uncertain stochastic systems with time-varying delay[J]. *Automatica*, 2005, 41(5): 873 – 880.

[8] Z. Man, A. P. Paplinski, H. Wu. A robust MIMO terminal sliding mode control scheme for rigid robot manipulators[J]. *IEEE Transactions on Automatic Control*, 1994, 39: 2464 – 2469.

[9] K. B. Park, J. Lee. Comments on 'A robust MIMO terminal sliding mode control scheme for rigid robot manipulators'[J]. *IEEE Transactions on Automatic Control*, 1996, 41(5): 761 – 762.

[10] Y. Feng, X. Yu, Z. Man. Non-singlar terminal sliding mode control of rigid robot manipulators[J]. *Automatica*, 2002, 38 (12): 2159 – 2167.

[11] K. B. Park, T. Tsuiji. Terminal sliding mode control of second-order nonlinear uncertain systems[J]. *International Journal of Robust and Nonlinear Control*, 1999, 9(11): 769 – 780.

[12] K. Y. Zhuang, H. Y. Su, K. Q. Zhuang, J. Chu. Adaptive terminal sliding mode control for high order nonlinear dynamic systems[J]. *Journal of Zhejiang University*, 2003, 4: 58 – 63.

[13] J. J. E. Slotine, W. Li. *Applied Nonlinear Control*[M]. Englewood Cliffs, NJ: Prentice – Hall, 1991.

[14] R. A. Decarlo, S. H. Zak, G. P. Matthews. Variable structure control of nonlinear multivariable systems: a tutorial[J]. *Proceedings of the IEEE*, 1998, 76(3): 212 – 232.

[15] P. V. Vrga, Y. Liu, S.Arimoto. Variable structure robot control undergoing chattering attenuation: adaptive and nonadaptive cases[C] *//Proceedings of IEEE International Conference on Robotics and Automation*. San Diego: IEEE Press, 1994, 5: 1824 – 1829.

[16] R. H. Sira. On the dynamical sliding mode control of nonlinear systems[J]. *International Journal of Control*, 1993, 57: 1039 – 1061.

[17] M. Hamerlain, T. Youssef, M. Belhocine. Switching on the derivative of control to reduce chatter[J]. *IEE Proceedings on Control Theory and Applications*, 2001, 148: 88 – 96.

[18] J. Liu. *Matlab Simulation For Sliding Mode Control*[M]. Beijing: Tsinghua University Press, 2005.

Jinkun LIU was born in Heilongjiang Province, 1965. He received his Ph.D. degree in automatic control from Northeastern University, China, in 1997. After a two-year post-doctoral position at the Automatic Control Department in Zhejiang University from 1997 to 1999, he joined the Department of Automatic Control, Beijing University of Aeronautics and Astronautics, as an associate professor. His research concerns motion control, intelligent control and robust control. E-mail: ljk@buaa.edu.cn.

Fuchun SUN received the B.S., M.S. degrees from Naval Aeronautical Engineering Academy, Yantai, China, in 1986 and 1989, respectively, and the Ph.D. degree from the Department of Computer Science and Technology, Tsinghua University, Beijing, China, in 1998. He worked for over four years for the Department of Automatic Control at Naval Aeronautical Engineering Academy. From 1998 to 2000 he was a Postdoctoral Fellow of the Department of Automation at Tsinghua University, Beijing, China. Now he is a professor in the Department of Computer Science and Technology, Tsinghua University, Beijing, China. His research interests include intelligent control, network control and management, neural networks, fuzzy systems, variable structure control, nonlinear systems and robotics. Dr. Sun is a member of the IEEE Control System Society. He is the recipient of the excellent Doctoral Dissertation Prize of China in 2000. E-mail: fcsun@mail.tsinghua.edu.cn.