Design of Combining Sliding Mode Controller for Overhead Crane Systems

Dianwei Qian[1*] and Jianqiang Yi[2]

[1]*School of Control and Computer Engineering,*
North China Electric Power University, Beijing, 102206, P.R. China
[2]*Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, P.R. China*
dianwei.qian@ncepu.edu.cn

Abstract

In industries, overhead cranes are commonly employed to lift and lower materials or to move them horizontally. A combining sliding mode control method is proposed for overhead crane systems in this paper. The ideas behind the combining sliding mode are as follows. First, an intermediate variable is introduced by dividing the system states into two groups. Then, a sliding surface is defined on basis of the intermediate variable. The control law is deduced from Lyapunonv direct method to asymptotically stabilize the sliding surface. The stability of the system states is also proven. Simulation results demonstrate the feasibility of the presented method through transport control of an overhead crane system.

Keywords: *Sliding mode control, overhead crane system, transport control*

1. Introduction

Overhead cranes are commonly employed in the transport industry for the loading and unloading of freight, in the construction industry for the movement of materials and in the manufacturing industry for the assembling of heavy equipment, because they can move loads far beyond the normal capability of a human. But the performance of this equipment may be constrained by the fact of a pendulum-typemotion of the loads, harmful for industrial security. Although an operator is able to decrease such the harmful motion by moving the trolley in small increments, this will lead to a low efficiency. Thus, automation of operation of this equipment is desirable since high positioning accuracy, small swing angle, short transportation time, and high safety are required [1].

In the last two decades, many papers concerning control problems of overhead crane systems have been published. The varieties of these control approaches are numerous. But in terms of the type of crane models, two classes of the control methods can be seen. One class is for the linearized model of crane systems. The other is for the nonlinear model.

Butler, *et al.*, [2] exploited a model decomposition technique to develop an model reference adaptive controller for a linearized crane system. Yoshida, *et al.*, [3] proposed a saturating control law by using a guaranteed cost control method for a nominal linearized crane dynamics. Giua, *et al.*, [4] considered a linearized parameter-varying model of a planar crane and proposed an observer-based control design via Lyapunov equivalence. Liu, *et al.*, [5] investigated an adaptive sliding mode fuzzy control approach for a linearized two-dimension overhead crane system. However, these methods based on the linearized crane dynamics may lose the sufficient accuracy of information about position and load swing so that some uncertain factors may reduce the performance of these crane control systems.

With the development of nonlinear control technology, many nonlinear methods based on the nonlinear model of crane systems have been presented. Burg, *et al.*, [6] harnessed the saturation control approach to achieve the nonlinear control of a crane system. Yang, *et al.*, [7] developed a nonlinear control scheme incorporating parameter adaptivemechanism to ensure the overall closed-loop system stability. Chang [8] proposed an adaptive fuzzy controller for crane systems, he employed the position error and swing angle only to fulfill the proposed adaptive fuzzy crane controller without any plant information. Yang, *et al.*, [9] presented a robust control approach based on the wave propagation in a crane cable for a gantry crane system with hoisting. Other researches on this field were reported by Yi, *et al.*, [1], Fang, *et al.*, [10], and Toxqui, *et al.*, [11].

As a kind of robust nonlinear feedback control method, sliding mode control (SMC) [12] is able to respond quickly, invariant to systemic parameters and external disturbance. It is a good tool to deal with control problems of overhead crane systems. Some control methods based on the sliding mode technology for overhead crane systems have been presented, *e.g.*, the coupling SMC by Shyu, *et al.*, [13], the secondorder SMC by Bartolini, *et al.*, [14], the high-order SMC by Chen and Saif [16], the incremental hierarchical SMC and the aggregated hierarchical SMC by Wang, *et al.*, [15], the adaptive SMC by Park, *et al.*, [17], Ngo and Hong [20], the discrete time integral SMC by Xi and Hesketh [18], .the input–output decoupling SMC by Choi and Lee [19], nameless to say.

Most of these approaches about SMC for crane systems employ the structure characteristic that an overhead crane system makes up of trolley and load subsystems to achieve their purposes. For instance, Shyu, *et al.*, [13] defined a sliding surface coupling both subsystems. Bartolini, *et al.*, [14] also defined their sliding surface vector as the sliding surfaces of both subsystems. Park, *et al.*, [17] utilized such the divisibility to design a fuzzy sliding surface for trolley subsystem. Wang, *et al.*, [15] split a crane system and rebuilt the system states to construct the aggregated and incremental hierarchical SMC controllers. Even under the condition of discrete time systems, Xi and Hesketh [18] constructed an integral sliding surface by making use of the sliding surfaces of the two subsystems. The divisibility of crane systems were also adopted for control design in Choi and Lee [19], Ngo and Hong [20].

Along the route of the divisibility methodology in [13-20], this paper presents a combining sliding mode method for overhead crane systems. The remainder of this paper is organized as follows. In Section 2, the dynamic model of an overhead crane system is depicted. By introducing an intermediate variable, the control law is deduced from Lyapunov direct method in Section 3. In Section 4, stability analysis of the system states is proven. Validity of the proposed method in Section 5 is illustrated through simulation results. Finally, conclusions are drawn in Section 6.

2. Dynamic Model

Figure 1 shows the coordinate system of an overhead crane system with its load. Apparently, this system consists of trolley and load subsystems. The former is with the trolley driven by a force f. The latter is with the load suspended from the trolley by a rope. For simplicity, we have the following assumptions: *1)* the load is regarded as a material particle; *2)* the rope is considered as an inflexible rod; *3)* compared with the load mass, the rope mass is ignored. *4)* the trolley moves in the x–direction; *5)* the load moves on the x–y surface. 6) no friction exists in the system.

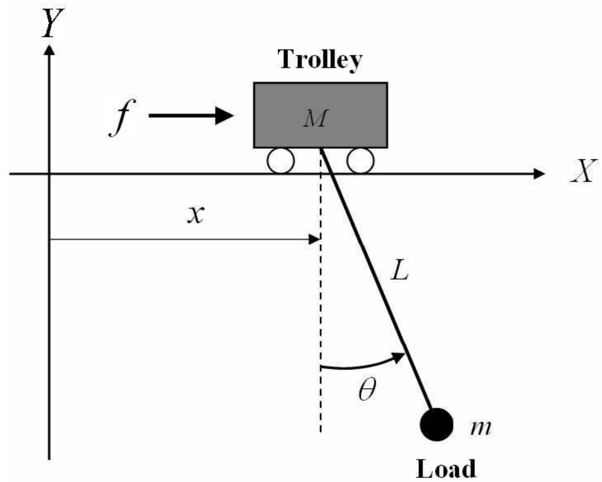

Figure 1. Structure of an Overhead Crane System

The symbols in Figure 1 are described as the trolley mass *M*, the load mass *m*, the rope length *L*, the swing angle of the load with respect to the vertical line *q*, the trolley position with respect to the origin *x*, the force applied to the trolley *f*. Using Lagrange's method, we can obtain the following Lagrangian equation related to the generalized coordinates *x*, *q* as

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial La}{\partial \dot{q}_i}\right)-\frac{\partial La}{\partial q_i}=T_i \tag{1}$$

where i = 1, 2, $La = K-P$ (K is system kinetic energy, P is system potential energy.), q_i is generalized coordination (here are x and θ , respectively), and T_i is external force. The dynamic model of the overhead crane system can be obtained with respect to x and θ as

$$(m+M)\ddot{x}+mL(\ddot{\theta}\cos\theta-\dot{\theta}^2\sin\theta)=f \tag{2}$$

$$\ddot{x}\cos\theta+L\ddot{\theta}+g\sin\theta=0 \tag{3}$$

Here g is gravitational acceleration. Further, the above dynamic model can be transformed to the state space expression as

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=f_1(\mathbf{x})+b_1(\mathbf{x})\cdot u\\ \dot{x}_3=x_4\\ \dot{x}_4=f_2(\mathbf{x})+b_2(\mathbf{x})\cdot u\end{cases} \tag{4}$$

Here $\mathbf{x}$ = [x_1, x_2, x_3, x_4]T ; $x_1 = x$; $x_3 = \theta$; x_2 is trolley velocity; x_4 is angular velocity of the load; u is control input; f_i and b_i (i = 1,2) can be gotten as

$$f_1(\mathbf{x})=\frac{mLx_4^2\sin x_3+mg\sin x_3\cos x_3}{M+m\cdot\sin x_3\cdot\sin x_3}$$

$$b_1(\mathbf{x})=\frac{1}{M+m\cdot\sin x_3\cdot\sin x_3}$$

$$f_2(\mathbf{x}) = \frac{(M+m)g\sin x_3 + mLx_4^2 \sin x_3 \cos x_3}{(M+m\cdot\sin x_3\cdot\sin x_3)L}$$

$$b_2(\mathbf{x}) = \frac{\cos x_3}{(M+m\cdot\sin x_3\cdot\sin x_3)L}$$

3. Control Design

Here, we capture the physical nature of the overhead crane system in (4) that x_2 and x_4 are equal to the derivative of x_1 and x_3 with respect to time t, respectively. So the state vector $\mathbf{x} = [x1, x_2, x_3, x_4]^T$ can be divided into two groups, i.e., (x_1, x_3) and (x_2, x_4). For the first group, we define an intermediate variable z as the linear combination of the two states.

$$z = x_1 + cx_3 \tag{5}$$

Here c is a positive constant. It is the source that we call the novel SMC method as the combining SMC. Further, the sliding surface s of the combining SMC is defined as

$$s = \alpha z + \dot{z} \tag{6}$$

Here α is positive.

As Utkin [12] has pointed out, the SMC law includes two parts: switching control law and equivalent control law. The switching control law is employed to drive the system states moving towards a specific sliding surface. The equivalent control law guarantees the system states to keep sliding on the sliding surface and converge to zero along the sliding surface. To design the combining SMC, we still adopt such the approach and define the total control law u as

$$u = u_{eq} + u_{sw} \tag{7}$$

here u_{eq} is the equivalent control and u_{sw} is the switching control. By differentiating s with respect to time t in (6), letting $\dot{s} = 0$, and substituting (4) into it, the equivalent control on the surface s is gotten as

$$u_{eq} = \frac{cf_2 + f_1 + \alpha c x_4 + \alpha x_2}{cb_2 + b_1} \tag{8}$$

Define a Lyapunov function as

$$V = \frac{1}{2}s^2 \tag{9}$$

Differentiate V with respect to time t and substitute (4), (6), (7), and (8) into it. Then, there exists

$$\dot{V} = s\dot{s} = s(\alpha\dot{z} + \ddot{z}) = s[\alpha x_2 + \alpha c x_4 + f_1 + cf_2 + (b_1 + cb_2)u] = s(b_1 + cb_2)u_{sw} \tag{10}$$

Let

$$u_{sw} = -\overline{k}s - \overline{\eta}\,\mathrm{sgn}(s) \tag{11}$$

where $\overline{k} = k/(cb_2 + b_1)$, $\overline{\eta} = \eta/(cb_2 + b_1)$, sgn(•) is the sign function, k and η are positive, so we have

$$\dot{V} = s[-ks - \eta\,\mathrm{sgn}(s)] = -ks^2 - \eta|s| \le 0 \tag{12}$$

(12) ensures the sliding mode is reachable in finite time. We assume the sliding mode takes place at t_f. In the subsequent time interval, the system trajectory moves along the sliding

surface and converges to the coordinate origin constructed by the intermediate variable z and its derivative $\dot{z}$.

Comment 1: From the viewpoint of mathematics, this combining SMC is a subset of conventional SMC, with a fixed ratio of $x_1/x_2 = x_3/x_4$. Further, the combining SMC reveals the inherent relationship between the state variables, so that this combining methodology can illustrate the system sliding mode in phase plane, which will facilitate our design and analysis. But such the transformation will arouse a new problem about the system stability. In light of Lyapunov method, the control law (7) can ensure the sliding surface is reachable in finite time, which means only the intermediate variable z is asymptotically stable rather than the system states. Thus, we have to analyze the stability of the system states to lead to an asymptotically stable control system.

4. Stability Analysis

Lemma 1. Consider an overhead crane system as (4) under the control law (7), then all the system states are bounded.

Proof: Define a set

$$\Omega = \{s \in \Re^2 \mid V(s) \le \varepsilon\} \tag{13}$$

here ε is positive. Since $\mathrm{d}V/\mathrm{d}t \le 0$, we have that Ω is a positively invariant and compact set. By LaSalle's principle, s approaches the largest invariant set in

$$E = \{s \mid \frac{\mathrm{d}V}{\mathrm{d}t} = 0\} \tag{14}$$

As we have pointed out, the intermediate variable z achieves the sliding mode at t_f. Thus, the system trajectory converges to the coordinate origin by the axes z and $\dot{z}$ along the surface s in $(t_f,\ \infty)$. So, we have

$$E = \{s \mid s = 0 \cap \dot{s} = 0\} = \{z \mid \alpha z + \dot{z} = 0 \cap \alpha\dot{z} + \ddot{z} = 0\} = \{z \mid z = \dot{z} = \ddot{z} = 0\} \tag{15}$$

We already know E is attracting. This case indicates the largest invariant set in E contains no sets other than the coordinate origin constructed by z and $\dot{z}$. Thus, we have the sliding surface s and the intermediate variable z are asymptotically stable as $t \to \infty$ in terms of Lasalle's principle.

From (4), (5) and (15), we have

$$\begin{aligned} \lim_{t\to\infty} z &= \lim_{t\to\infty}(x_1 + cx_3) = 0 \\ \lim_{t\to\infty} \dot{z} &= \lim_{t\to\infty}(x_2 + cx_4) = 0 \end{aligned} \tag{16}$$

$\forall t_0 \in (t_f, \infty)$, we have $\lim_{t\to t_0} x_1 = -\lim_{t\to t_0} cx_3$ and $\lim_{t\to t_0} x_2 = -\lim_{t\to t_0} cx_4$. If any state were divergent, there would exist

$$\lim_{t\to t_0} x_1 = -\lim_{t\to t_0} cx_3 = \infty \quad \text{or} \quad \lim_{t\to t_0} x_2 = -\lim_{t\to t_0} cx_4 = \infty \tag{17}$$

Either in (17) will contradict (15). (If either in (17) were satisfied, we would have $\lim_{t\to t_0} z = \infty$.) Thus, there exist

$$\lim_{t\to t_0} x_1 = -\lim_{t\to t_0} cx_3 = Const. \text{ and } \lim_{t\to t_0} x_2 = -\lim_{t\to t_0} cx_4 = Const. \tag{18}$$

Compared with the asymptotically stable s and z, we have all the state variables x_1, x_2, x_3 and x_4 are just bounded in the time interval $[0,\infty)$ on account of the mathematic transformation of the conventional SMC as (5) and (6). ■

Theorem 1. Consider an overhead crane system as (4) under the control law (7), then all the system states are asymptotically stable if (19) is satisfied in the time interval (t_f, ∞), where t_f is the reached time of the sliding surface s.

$$c = \begin{cases} c & if \;\; x_1 x_3 \ge 0 \\ -c & if \;\; x_1 x_3 < 0 \end{cases} \tag{19}$$

Proof: t_f splits the time interval into two parts, $[0, t_f]$ and (t_f, ∞). From Lemma 1, We have known that the system states are bounded in $[0, t_f]$. Let us analyze the system stability in (t_f, ∞). According to Lemma 1, it is obvious that all the states are bounded in (t_f, ∞), i.e.,

$$\sup_{t>t_f} |x_i| = \| x_i \|_\infty < \infty \tag{20}$$

Here $i = 1, \dots, 4$. So we have

$$\sup_{t>t_f} |x_j| = \| x_j \|_\infty < \infty \quad \text{and} \quad \sup_{t>t_f} |\dot{x}_j| = \| \dot{x}_j \|_\infty < \infty \tag{21}$$

here $j = 1, 3$. We can obtain

$$x_j \in L_\infty \quad \text{and} \quad \dot{x}_j \in L_\infty \tag{22}$$

Further, we have $z \in L_2$ in (t_f, ∞) on account of the asymptotically stable z in $[0, t_f]$. Thus, there exists

$$\int_{t_f}^{\infty} z^2 \, \mathrm{d}t = \int_{t_f}^{\infty} (x_1 + c x_3)^2 \, \mathrm{d}t = \int_{t_f}^{\infty} (x_1^2 + c^2 x_3^2 + 2c x_1 x_3) \, \mathrm{d}t < \infty \tag{23}$$

It is obvious that

$$\int_{t_f}^{\infty} 2c x_1 x_3 \, \mathrm{d}t \le \int_{t_f}^{\infty} (x_1^2 + c^2 x_3^2) \, \mathrm{d}t \tag{24}$$

From (23) and (24), we have

$$\int_{t_f}^{\infty} 4c x_1 x_3 \, \mathrm{d}t \le \int_{t_f}^{\infty} z^2 \, \mathrm{d}t < \infty \tag{25}$$

(25) will come into existence so long as $\int_{t_f}^{\infty} 4c x_1 x_3 \, \mathrm{d}t > 0$ by choosing the sign of c as (19). Further, from (23), we can obtain

$$\int_{t_f}^{\infty} x_j^2 \, \mathrm{d}t < \infty \tag{26}$$

i.e. $x_j \in L_2$ (j=1, 3).

According to (22) and (26), we have both x_1 and x_3 possess the asymptotic stability in terms of Barbalat's lemma in (t_f, ∞). Further, we have $x_2 = \dot{x}_1$ and $x_4 = \dot{x}_2$ in (4). Thus, x_2 and x_4 are asymptotically stable in (t_f, ∞) as well. ■

5. Simulation Results

In this section, the validity of the combining SMC is demonstrated by the transport control problem of an overhead crane system. The control objective of the transport control is to transport the load to the required position as fast and as accurately as possible with no free swings. In our simulations, the physical parameters of the overhead crane system in Figure 1 are determined as M = 1 kg, m = 0.8 kg, and L = 0.305 m, and gravitational acceleration g = 9.81 $m\ s^{-2}$ (See [15]). The parameters of the combining SMC controller is selected as c = 0.24, a = 0.487, k = 7 and η = 0.04. Here, the initial state vector $\mathbf{x}^0$ and the desired state vector $\mathbf{x}^d$ are $[2, 0, 0, 0]^T$ and $[0, 0, 0, 0]^T$, respectively.

Figure 2 illustrates the system performance under the combining SMC control law (7) without the sufficient condition (19). As we have proven in Lemma 1, the combining SMC, as a special case of the conventional SMC with the fixed ratio $x_1/x_2= x_3/x_4$, only makes the sliding surface and the intermediate variable asymptotically stable, but it leads to the simple harmonic motions of the system states. Apparently, all the states are bounded. Further, we have the sliding mode takes place at about 2.4 s in Figure 2.

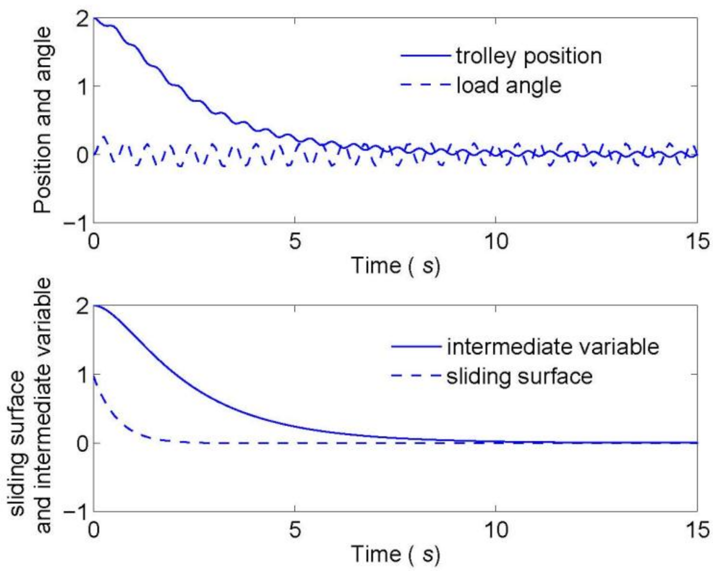

Figure 2. System Performance without the Switch Process of c_1

Figure 3 displays the system performance under the control law (7) with (19) at 2.4 s after the sliding mode is reached. As long as the sufficient condition (19) in Figure 3 is satisfied, not only the sliding surface and the intermediate variable are asymptotically stable, but also the system states, trolley position and load angle, are of the asymptotic stability. Figure 4 shows the switch process of the parameter c_1 and the control input applied to the trolley. Figure 5 demonstrates the phase plane of the sliding surface with the switch of c_1. From the phase curve in Figure 5, the phase trajectory pierces the sliding surface when (19) acts at the first time, and it moves away before intercepting the surface again. Such switch is more frequent as the system states converge to the origin. From the viewpoint of energy, the control energy without (19) can only main the sliding motion on the surface. There is no extra energy to derive the system states stable. With (19), the switch action increases the control energy to simultaneously stabilize the whole control system rather than a part of the system variables.

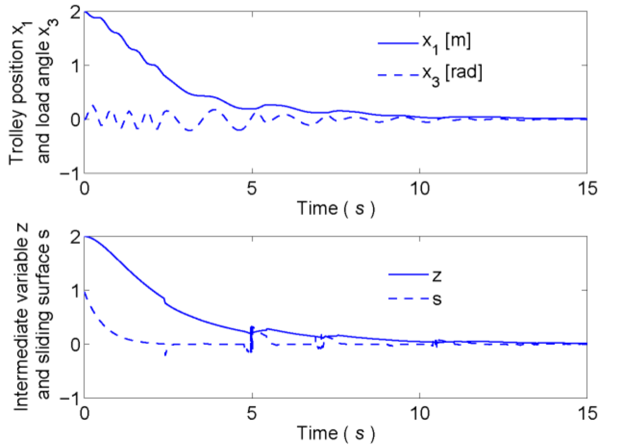

Figure 3. System Performance with the Switch Process of c_1

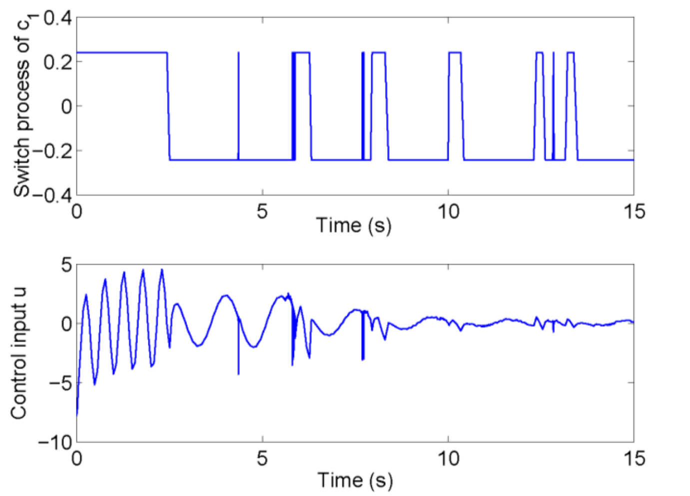

Figure 4. Switch Process of c_1 and Control Input u with Respect to Time t

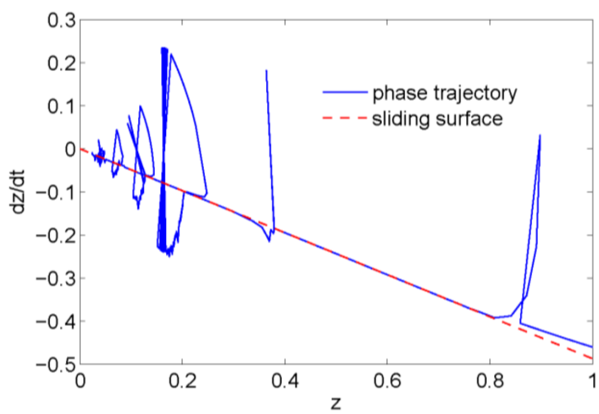

Figure 5. Phase Plane of the Sliding Surface s

7. Conclusions

This paper has presented a combining sliding mode design approach for overhead crane systems. Here the so-called "combining sliding mode" means that we introduce an intermediate variable that is the linear combination of a part of the system states after investigating the physical nature of overhead crane systems. On basis of the intermediate variable, the sliding surface is defined and the control law is deduced from Lyapunov direct method. The sufficient condition to ensure the stability of the system states is proven. Simulation results show the controller's validity through the transport control problem of an overhead crane system.

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Authors

Dianwei Qian received the B.E. degree from the Hohai University, Nanjing, Jiangsu, China, in 2003. In 2005 and 2008, He received the M.E. degree from the Northeastern University, Shenyang, Liaoning, China, and the Ph.D. degree from the Institute of Automation, Chinese Academy of Sciences, Beijing, China, respectively. Currently, he is an Associate Professor at the School of Control and Computer Engineering, North China Electric Power University, Beijing, P.R. China. His research interests include theories and applications of intelligent control, under-actuated system control, sliding-mode control, process control, etc.

Jianqiang Yi received the B.E. degree from the Beijing Institute of Technology, Beijing, China, in 1985 and the M.E. and Ph.D. degrees from the Kyushu Institute of Technology, Kitakyushu, Japan, in 1989 and 1992, respectively. He worked as a Research Fellow with Computer Software Design, Inc., Tokyo, Japan, from 1992 to 1994. From 1992 to 1994, he was with the Computer Software Development Company, Tokyo. From 1994 to 2001, he was a Chief Researcher and Chief Engineer with MYCOM, Inc., Kyoto, Japan. Currently, he is a Full Professor with the Key Laboratory of Complex Systems and Intelligence Science, Institute of Automation, Chinese Academy of Sciences, Beijing. His research interests include theories and applications of intelligent control, intelligent robotics, underactuated system control, sliding-mode control, flight control, etc. Dr. Yi is an Associate Editor for the Journal of Advanced Computational Intelligence and Intelligent Informatics, and Journal of Innovative Computing, Information and Control.