AN ASYMPTOTIC SECOND-ORDER SMOOTH SLIDING MODE CONTROL

Yuri B. Shtessel, Ilya A. Shkolnikov, and Mark D.J. Brown

ABSTRACT

Presented is a method of smooth sliding mode control design to provide for an asymptotic second-order sliding mode on the selected sliding surface. The control law is a nonlinear dynamic feedback that in absence of unknown disturbances provides for an asymptotic second-order sliding mode. Application of the second-order disturbance observer in a combination with the proposed continuous control law practically gives the second-order sliding accuracy in presence of unknown disturbances and discrete-time control update. The piecewise constant control feedback is "smooth" in the sense that its derivative numerically taken at sampling rate does not contain high frequency components. A numerical example is presented.

KeyWords: Sliding mode control, second order sliding mode, sliding mode observer.

I. INTRODUCTION

For many control applications, Sliding Mode Control (SMC) [1,2] has been proved efficient technique to provide high-fidelity performance in different control problems for nonlinear systems with uncertainties in system parameters and external disturbances. Ideal sliding modes feature theoretically-infinite-frequency switching, while the real conventional sliding modes feature high, finite frequency switching of the input signal (control) due to imperfections of a switching element, discrete-time implementation of the control or unmodeled dynamics of the plant. Such a mode might be also unacceptable if the control signal has some physical sense like a force, a device angle position, etc. High frequency switching may be destructive for control devices or may cause system resonance via excitation of the omitted higher frequency dynamics of the system under control. The corresponding dangerous vibrations are called the chattering effect [3]. The chattering phenomenon may occur in presence of parasitic unmodeled dynamics in series with the plant, where, in this case, relatively low frequency limit cycles cause destruction of the sliding mode. The methods to compensate for unmodeled dynamics and to restore high frequency switching [4] do not eliminate chattering but save robustness. In case, when any type of switching of control is unadvisable, the methods of chattering elimination are employed. Trading the absolute robustness on the sliding surface for the system convergence to a small domain, the "boundary layer", around it, under a continuous control law, the methods of this group employ the high-gain saturation function [1,5] or the sigmoid function [6]. In the continuous-time control systems with sampled-data measurements and/or discrete-time control action (zero-order hold with digital control), different types of closedloop boundary-layer dynamics are employed to provide for a smooth control, varying from selfadaptive saturation level functions [7] to fixed-gain deadbeat controls with disturbance estimation using delayed-time data [8-10]. Another alternative [11] to the latter approach is to incorporate into the "boundary-layer" dynamics an exosystem model for disturbances [12] avoiding the direct observer-based disturbance estimation.

The idea to hide discontinuity of control in its higher derivatives has been realized using higher order sliding modes [13-16]. The resulting higher-order sliding mode is of enhanced accuracy and robustness to disturbances. However, a drawback of the direct application of this approach to chattering attenuation is that it is very

Manuscript recived January 15, 2003; accepted March 30, 2003.

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sensitive to unmodeled fast dynamics. Therefore, the designed continuous control cannot be, for instance, an outer-loop feedback in a multi-loop control system.

The idea of this paper is to use the disturbance estimation based on higher-order sliding mode techniques [15] to design a continuous sliding mode control that features second-order nonlinear dynamics in the boundary layer. The continuous SMC to be designed will be "smooth" in the sense that its discrete-time implementation will not contain high frequency components in the vicinity of the sampling rate. It means that it can be numerically differentiated at the same rate and be "smooth" as well. This fact, in turn, allows the obtained control to be used in an outer loop of a multi-loop system. The main contribution of this paper is in further development of the approach presented in work [17].

II. PROBLEM DESCRIPTION

In multi-loop, time-scaled backstepping-type control systems, an important issue is to provide a so-called virtual control signal to be smooth in an outer loop, for it has to be tracked by inner cascades of a multi-loop system that involves inherent differentiation. The same issue appears in the control systems with state observers in the feedback loop, where, frequently, the observer designed for one part of the system produces the output, which is a command to be followed by another part of the system that produces a feedback input to the first one, closing the loop. Smoothness of a control signal is not easily achievable in control systems with sliding modes without degrading high precision and robustness.

Consider a MIMO plant with n states and m controls, where the $n - m$ dimensional sliding surface has been designed to meet the control objective, and the "diagonalization method" [1] has been applied producing m independent first-order dynamics for each sliding quantity σ. Thus, the one-dimensional dynamics of the n-th order system stabilization on a $n - 1$ dimensional manifold is given as

$$\dot{\sigma} = f(\sigma, t) + u, \tag{1}$$

where $\sigma \in \Re$ is the sliding quantity, such that $\sigma = 0$ defines the system motion on the sliding surface, $u \in \Re$ is a control input that is supposed to be smooth, and $f(\sigma, t)$ is an uncertain smooth nonlinear time-varying function that contributes to the so-called "equivalent control" [1]. Without loss of generality we consider the equivalent control to be fully uncertain within the boundary $|f(\sigma,t)| \le L,\ L > 0,\ |\sigma| \le \sigma_o$. We accept for simulations in this work $f(\sigma, \mathrm{t}) = e^{\sigma} - 1 + \sin t$.

The problem is to establish the sliding mode $\sigma = 0$ given exact measurements of $\sigma(t)$ via discrete-time control $u(t) = u[kT] = const$, $kT \le t < (k + 1)T$, avoiding chattering and making control "smooth" enough (piecewise-constant signal is not smooth, strictly speaking) to tolerate possible differentiation in the unmodeled inner loop.

III. CONTINUOUS SLIDING MODE CONTROL (SMC)

Finite-reaching-time continuous standard-sliding-mode controllers have been studied in many works, for instance, in the work [17]. They provide for the finite-time-convergence first-order closed-loop σ-dynamics. One of the forms in the work [17] is given by

$$\dot{\sigma} + \rho \frac{\sigma}{|\sigma|^{0.5}} = 0. \tag{2}$$

In absence of uncertainty in the function $f(\sigma, t)$, the control law

$$u(\sigma) = -f(\sigma, t) - \rho \frac{\sigma}{|\sigma|^{0.5}}, \tag{3}$$

renders the closed-loop dynamics (1), as a finite time convergent nonlinear manifold. When the function $f(\sigma, t)$ is totally uncertain, the continuous control law

$$u(\sigma) = -\rho \frac{\sigma}{|\sigma|^{0.5}}, \tag{4}$$

provides for convergence to the arbitrarily small domain of attraction, the boundary layer, around the sliding surface $\sigma = 0$ in a standard sliding mode, where the gain ρ and the uncertainty limit L determine the boundary layer thickness. The drawbacks of this controller are that the uncertainty limit defines the boundary layer, and even in absence of uncertainty the domain of attraction to $\sigma = 0$ is proportional to the discrete interval T under the discrete-time control (first-order sliding accuracy).

IV. SECOND-ORDER SLIDING MODE CONTROL

Methods using higher-order sliding modes give better accuracy than that using standard sliding modes. For example, the super-twisting algorithm by Levant [16] producing continuous control provides for accuracy proportional to the square of discrete time. Domain of convergence to the sliding surface does not depend on the disturbance amplitude provided sufficient control authority. The closed-loop σ-dynamics, say

$$\ddot{\sigma} + \frac{3\rho}{2} \frac{\dot{\sigma}}{|\sigma|^{1/2}} + 4\rho\, sign(\sigma) = \dot{f}(\sigma, t) \tag{5}$$

are of the second-order finite-time convergence. For the system (1), the following continuous control,

$$u = \rho_1 \frac{\sigma}{|\sigma|^{1/2}} + \rho_0 \int sign(\sigma) d\tau \tag{6}$$

where ρ_0 and 1 ρ_1 are the design parameters depending on $\max(\dot{f}(\sigma, t))$, provides for the finite-time convergence to the domain $|\sigma| \sim T^2$ in a digital implemetation robustly to any smooth disturbance with a known limit for its derivative. Convergence time does not depend on discrete interval T. The closed-loop system under control (6) featuring a so-called real sliding mode of the second order [13-16].

Providing the accuracy practically comparable to that of the super-twisting algorithm on one hand and smoothness of control derivative and resistance to fast sensor dynamics on the other hand is the problem to be addressed by the control designed in this work.

V. NONLINEAR PROPORTIONAL-INTEGRAL TYPE CONTROL

The proposed control algorithm is formulated in the following Theorem.

Theorem. Let $\alpha_0 > 0$, $\alpha_1 > 0$ and uncertain term $f(\sigma, t) = 0$ in (1) then the smooth control

$$u = -\alpha_1 |\sigma|^{1/2} sign(\sigma) - \alpha_0 \int |\sigma|^{1/3} sign(\sigma) d\tau \tag{7}$$

provides for the asymptotic convergence of the sliding surface compensated dynamics (1) into 2-sliding mode $\dot{\sigma} = \sigma = 0$.

Proof. The system (1) and (7) can be equivalently presented by the system of two first-order equations

$$\begin{cases} \dot{x}_1 = x_2 - \alpha_1 |x_1|^{1/2} sign(x_1), \\ \dot{x}_2 = -\alpha_0 |x_1|^{1/3} sign(x_1), \end{cases} \tag{8}$$

where $x_1 = \sigma$, and $x_2 = -\alpha_0 \int |\sigma|^{1/3} sign(\sigma) d\tau$.

Let a Lyapunov function candidate be

$$V(x_1, x_2) = \frac{x_2^2}{2} + \int_0^{x_1} \alpha_0 |z|^{1/3} sign(z) dz, \tag{9}$$

$V(x) > 0$, if $x \in \Re^2 \backslash \{0\}$, then the Liapunov function derivative will be

$$\dot{V} = \frac{\partial V}{\partial x} \cdot \begin{bmatrix} x_2 - \alpha_1 |x_1|^{1/2} sign(x_1) \\ -\alpha_0 |x_1|^{1/3} sign(x_1) \end{bmatrix} = -\alpha_0 \alpha_1 |x_1|^{5/6} < 0, \tag{10}$$

if $x \in \Re^2 \backslash \{0\}$.

Next, applying La Salle theorem [6] we can prove $x \to 0$ as time increases. A set $x : \{\dot{V}(x) = 0\}$ consists of $x_1 = 0$ and x_2 equal to any real value. Substituting these values into (8) we obtain $\dot{x}_1 = x_2$, $\dot{x}_2 = 0$. It is easy to show that the only invariant set inside $x_1 = 0$ is the origin, since $x_1 = 0$ immediately implies $x_2 = 0$. So, we proved asymptotic convergence x_1 and x_2 to zero. In the other words $\sigma \to 0$ and $\dot{s} \to 0$ as time increases, and we have smooth asymptotic 2nd order sliding that is achieved without a disturbance term. ■

Remark. The proven theorem provides for an asymptotic 2nd order sliding mode via smooth control using measurement of σ only.

VI. NONLINEAR PROPOTIONAL-INTEGRAL TYPE CONTROL WITH DISTURBANCE ESTIMATION

The sliding surface compensated dynamics under the proposed control law (7) is sensitive to the unknown bounded term $f(\sigma, t)$ that is assumed to be smooth, hence, $|f(\sigma, t)| \leq L$, $L > 0$. In order to compensate for this term we propose to use the control law (7) that includes a smooth disturbance estimator $\hat{f}_{smooth}(\sigma, t)$ based on the super-twisting algorithm and a nonlinear proportional-integral type term

$$u = -\alpha_1 \frac{\sigma}{|\sigma|^{1/2}} - \alpha_0 \int |\sigma|^{1/3} sign(\sigma) d\tau - \hat{f}_{smooth}(\sigma, t), \tag{11}$$

where

$$\begin{aligned} \hat{f} &= \rho_1 \frac{(\sigma - \hat{\sigma})}{|\sigma - \hat{\sigma}|^{1/2}} + \rho_0 \int sign(\sigma - \hat{\sigma}) d\tau \\ \hat{\sigma} &= \int (\hat{f} + u) d\tau \end{aligned} \tag{12}$$

and

$$\hat{f}_{smooth} = \text{LowPassFilter}\{\hat{f}\} \tag{13}$$

The super-twist base observer (12) provides for a finite time convergence, i. e. $\hat{f} = f$ for all time larger than some finite time instant. On the other hand, $\hat{f}$ is not smooth, and its use in the control law (11) makes the control law continuous only. In order to retain smoothness of the control law (11) a smooth Low Pass Filter (13) should be used. The Low-Pass Filter (13) is to be implemented as a second-order observer with finite time converegnce (for instance, using another super-twisting algorithm in a cascade). Then, provided sufficiently smooth uncertainty $f(\sigma, t)$, the estimate $\hat{f}$ in (13), low-pass filtered before entering control as $\hat{f}_{smooth}$, converges to $f(\sigma, t)$ in a finite time. Considering $\hat{f}_{smooth}$ ≈

$f(\cdot)$, when $\sigma << 1$ and the bandwidth of $f(\sigma, t)$ is far to the right from the low-pass filter cut-off frequency, in the vicinity of the origin we have the closed-loop asymptotic 2nd order dynamics (8). Under the discrete control law const $u(t) = u[kT] = const$, $kT \le t < (k + 1)T$, the convergence is achievable to the domain $|\sigma| \sim T^2$.

VII. NUMERICAL SIMULATIONS

To test the designed sliding mode smooth control with the second-order SMC disturbance observer, the plant (1) with the control $u(t) = u[kT] = const$, $kT \le t < (k + 1)T$, $T = 0.001$ sec, is simulated using Euler method with integration step $\tau = 10^{-5}$ sec. The feedback control is designed

$$u = -10\sigma - 0.05\frac{\sigma}{|\sigma|^{1/2}} - 5\int |\sigma|^{1/3} sign(\sigma)d\tau - \hat{f}_{smooth}, \quad (14)$$

where the first term -10σ is to compensate mostly for the initial condition, and $\hat{f}_{smooth}$ is the lowpass filtered estimate of $\hat{f}$, which is given

$$\begin{aligned} \hat{f} &= 3|\sigma - \hat{\sigma}|^{1/2} sign(\sigma - \hat{\sigma}) + 4\int sign(\sigma - \hat{\sigma})d\tau, \\ \hat{\sigma} &= \int (\hat{f} + u)d\tau \end{aligned} \quad (15)$$

and the filter equations are the superposition of the supertwisting [15,16] low-pass filter and the filter based on a nonlinear dynamic sliding manifold, J, [18]

$$\begin{aligned} \dot{z}_1 &= z_2 \\ \dot{z}_2 &= 5sign(J) \\ J &= (z_3 - z_1) + \int (0.2|z_3 - z_1|^{1/2} sign(z_3 - z_1) \\ &\quad -10|J|^{2/3} sign(J))d\tau \\ \dot{z}_3 &= 1.5\left|\hat{f} - z_3\right|^{1/2} sign(\hat{f} - z_3) + 2\int sign(\hat{f} - z_3)d\tau \\ \hat{f}_{smooth} &= z_1 \end{aligned} \quad (16)$$

Both filters connected in cascade have finite-time-convergent estimation error dynamics. The results of a simulation are presented in Figs. 1-3.

To test the system robustness to the unmodeled series dynamics,

$$u_{actual}(s) = \frac{1}{(0.001s + 1)^2}u(s), \quad (17)$$

the plant (1) is simulated with an actuator after the Sample&Hold element in the loop, $u(t) = u[kT]$, $kT \le t < (k + 1)T$, where the control u is described

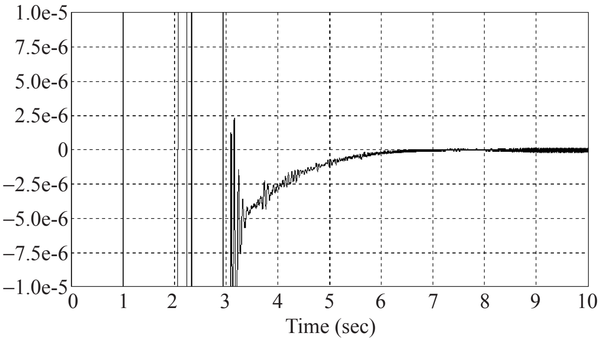

Fig. 1. Smooth asymptotic second order SMC: σ versus time (high resolution)

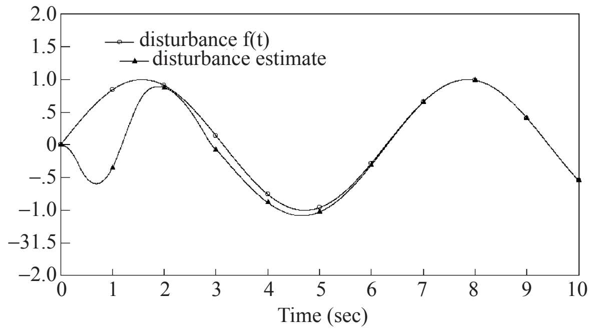

Fig. 2. Smooth asymptotic second order SMC: $f(\sigma, t)$, and $\hat{f}_{smooth}$ versus time.

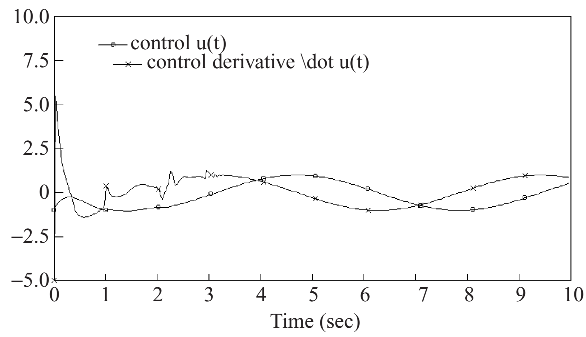

Fig. 3. Smooth asymptotic second order SMC: control $u[kT]$ and control derivative $\frac{u[(k+1)T] - u[kT]}{T}$.

$$\begin{aligned} u &= -10\sigma - u_1 - \hat{f}_{smooth} \\ u_1 &= 0.01|\sigma|^{1/2} sign(\sigma) + 1\int |\sigma|^{1/3} sign(\sigma)d\tau \end{aligned} \quad (18)$$

Aslo a deadband of $2.5 \cdot 10^{-6}$ has been introduced to the σ feedback in u_1, and smooth $\hat{f}_{smooth}$ is the same as in (16).

The simulation results are in Figs. 4 and 5.

For comparison, the plant (1) is simulated with the super-twisting control in the form $u(t) = u[kT]$, $kT \le t < (k + 1)T$, $T = 0.001$sec

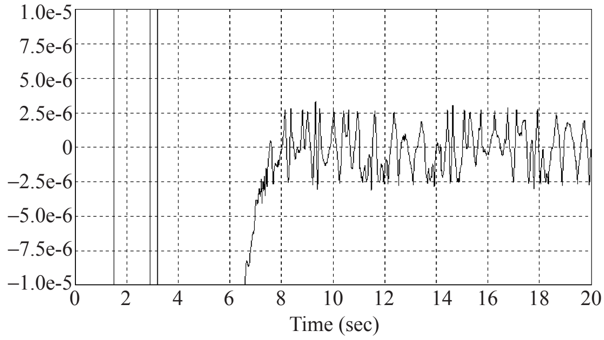

Fig. 4. Smooth asymptotic second order SMC with unmodeled dynamics: σ versus time (high resolution).

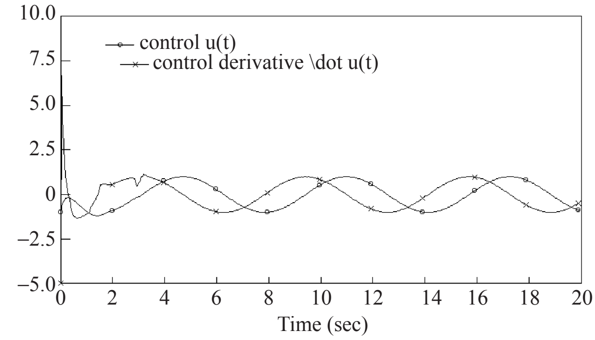

Fig. 5. Smooth asymptotic second order SMC with unmodeled dynamics: control $u[kT]$ and control derivative $\frac{u[(k+1)T]-u[kT]}{T}$.

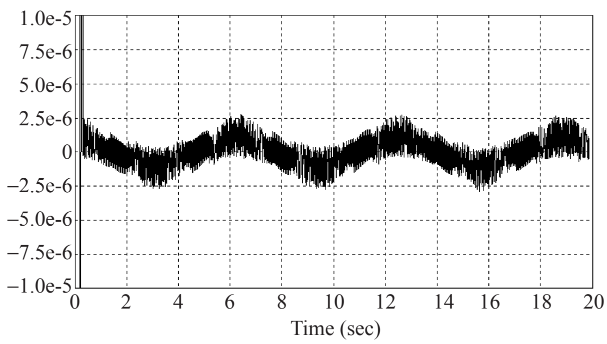

Fig. 6. Super-twist SMC: σ versus time (high resolution)

$$u = -10\sigma - 1.05|\sigma|^{1/2}\, sign(\sigma) - 1.4\int sign(\sigma)d\tau \quad (19)$$

without unmodeled dynamics, Figs. 6 and 7, and with actuator (17) engaged, Figs. 8 and 9.

Discussion of the simulation results. In Fig. 1, one can observe that the trajectory of the plant (1) under control (14) enters the domain $|\sigma| \sim 1\cdot 10^{-6}$ and stays there in presence of the time-varying uncertainty $f(\sigma, t) = e^{\sigma} - 1 + \sin t$, which estimation is shown in Fig. 2. The smooth control $u(t)$ and its derivative are presented in Fig. 3. Figures 4 and 5 confirm robustness of the closed-loop

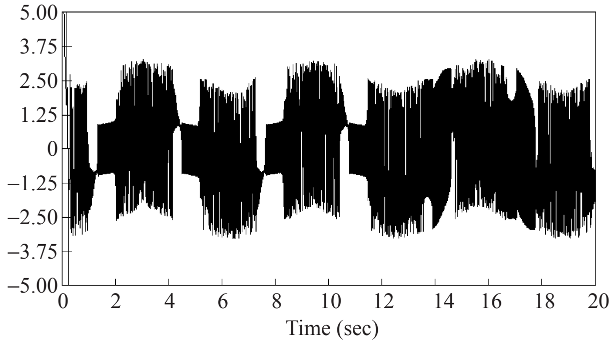

Fig. 7. Super-twist SMC: control derivative $\frac{u[(k+1)T]-u[kT]}{T}$.

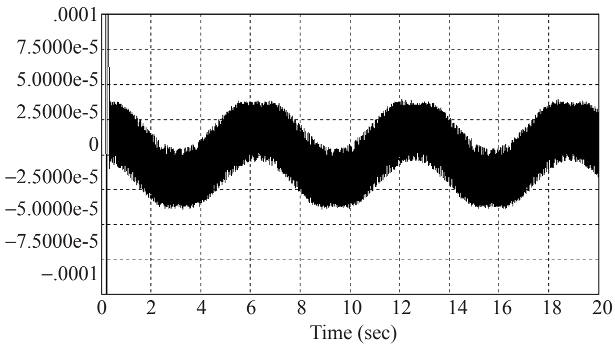

Fig. 8. Super-twist SMC with unmodeled dynamics: σ versus time (high resolution).

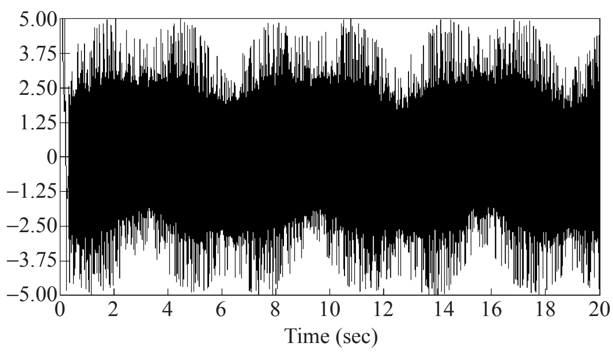

Fig. 9. Super-twist SMC with unmodeled dynamics: control derivative $\frac{u[(k+1)T]-u[kT]}{T}$.

system to unmodeled dynamics (16). Control (18) does not exhibit chattering.

On the other hand, one can see chattering at the rate close to Nyquist rate in Figs. 6-9 for supertwisting control (19) with a discrete-time update. Accuracy of σ stabilization, Fig. 6, is of the second order real sliding $\sim 10^{-6}$, however, chattering due to unmodeled dynamics destroys this accuracy, Fig. 8, after the actuator (17) being engaged.

VIII. CONCLUSIONS

A new smooth nonlinear proportional-integral type control in a combination with the known super-twisting disturbance observer and a low-pass finite-time convergent post-filter is proposed to stabilize a sliding hyper-surface in the sliding mode controlled plant. Under the assumption that the observer captures the uncertainty and cancels its effect on the closed-loop dynamics, the system motion in the vicinity of the sliding surface is governed by a second-order asymptotic dynamics that practically has shown a second-order sliding accuracy on the sliding surface in simulations. Thus, practically both parts of the control law (feedback PI-type control and disturbance observer) are the second order SMC's, meaning that under the discrete-time control with a zero-order hold, the accuracy of holding the trajectories on the sliding surface is of the second-order real sliding, $O(T^2)$. Robustness of the proposed control law to a second order unmodeled dynamics was demonstrated on the simulation.

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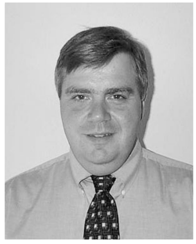

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