ISA Transactions 53 (2014) 1661–1669

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Second-order integral sliding-mode control with experimental application

Murat Furat [a,*], İlyas Eker [b,1]

[a] Mustafa Kemal University, Department of Electrical & Electronic Engineering, 31200 Hatay, Turkey
[b] Çukurova University, Department of Electrical & Electronic Engineering, 01330 Adana, Turkey

ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form
16 May 2014
Accepted 31 May 2014
Available online 5 July 2014
This paper was recommended for publication by Jeff Pieper

Keywords:
Integral sliding-mode
Stability
Adaptive gain

ABSTRACT

In the present study, a second-order sliding-mode controller is proposed for single-input single-output (SISO) uncertain real systems. The proposed controller successively overcomes the variations caused by the uncertainties and external load disturbances although an approximate model of the system is used in the design procedure. An integral type sliding surface is used and the stability and robustness properties of the proposed controller are proved by means of Lyapunov stability theorem. The chattering phenomenon is significantly reduced adopting the switching gain with the known parameters of the system. Thus, the proposed controller is suitable for long-term application to the real systems. The performance of the proposed control scheme is validated by a real system experiments and the results are compared with the similar controllers presented in the literature.

1. Introduction

Control of uncertain systems affected by external disturbances has been one of the main applications of sliding-mode control (SMC) since it was introduced in the international literature which was previously developed in Russia [1]. Several types of sliding-mode theories can be found in the literature. The initial studies were concentrated on conventional sliding-mode. The conventional SMC provides a systematic design procedure using an approximate model of the system [2]. Therefore, it has been applied a wide area in the industry such as in motion control and robotics, in aerospace applications, power converters [3]. The reasons of the popularity of the conventional SMC are the robustness of the modeling errors as well as its insensitivity of the parameter variations and external disturbances [4]. Nevertheless, in practical applications, a purely design SMC suffers from chattering problem which is high-frequency (theoretically, at infinite frequency) variation of the control input due to presence of unmodelled dynamics of the system. Chattering is highly dangerous, especially, for the mechanical part of systems which results in undesired wear and tear of the actuators. Furthermore, it may lead to instability [5].

In the design procedure of conventional SMC, the first stage is to define an appropriate sliding surface such that the system states moves toward the sliding surface and stays on it [5]. One of the main objectives of the SMC is to bring sliding surface to zero [6]. The defined sliding surface provides the desired asymptotic behavior in the steady state [7].

It is worth nothing that conventional SMC is a robust control technique to attenuate uncertainties at a price of sacrificing its control performance [8]. The main drawback is the chattering phenomenon. In an ideal conventional SMC, the switching control switches from one value to another infinitely fast due to the presence of uncertainties and external load disturbances. Such control action produces the chattering. The secondary stage of the design procedure is to construct an appropriate switching control. In the literature, several solutions were proposed to attenuate chattering effect on the control signal. The main approaches to chattering attenuation or elimination can be classified in some main categories. In the very first implementation of the SMC, the chattering was produced the switching control which was a signum function with constant gain [1]. Instead of discontinuous signum function, saturation or tangent hyperbolic functions were preferred in some studies with a positive constant gain [4,9–11]. In addition, sigmoid functions were also used with a positive constant gain [2]. In these functions, the thickness of the boundary layer was also defined to avoid chattering and to achieve exponential stability. Another solution is the observer-based approach which allows for bypassing the plant dynamics by the chattering loop. This approach may reduce the robustness with respect to plant uncertainties [9].

Furthermore, a novel idea has been developed in the last two decades to overcome chattering problem keeping the robustness of the conventional SMC, called higher-order SMC. Since the control input appears in the first-time derivative of the sliding surface and it allows to finite-time convergence of sliding surface

* Corresponding author. Tel.: +90 326 6135600; fax: +90 326 6137080.
E-mail address: mfurat@mku.edu.tr (M. Furat).
[1] Tel.: +90 322 3386868x124; fax: +90 322 3386326.

http://dx.doi.org/10.1016/j.isatra.2014.05.030
0019-0578/

to zero, the conventional SMC is designated as first-order SMC. In the theory of new idea, it allows finite-time convergence of not only the sliding surface but also its successful derivatives. For an *rth-order sliding mode*, the condition, $\sigma(t)=\dot{\sigma}(t)=\ldots=\sigma^{(r-1)}(t)=0$ is satisfied where $\sigma(t)$ is the sliding surface and $\sigma^{(r)}(t)$ is generally supposed to be discontinuous [12]. A large number of studies can be found in the literature. The well-known second-order SMC (SOSMC) algorithms are twisting and super-twisting [13], drift [14], quasi-continuous [12] and sub-optimal [15]. Similar to the conventional sliding mode, a proportional-integral-derivative (PID) sliding surface based second-order SMC was proposed in [16] to control linear uncertain systems. Moreover, a number of studies focused on the chattering analysis and reduction algorithms can be found in the literature [17–20].

Although SOSMC algorithms were successfully applied to the real systems, the higher-order SMC algorithms were generally studied theoretically [21]. Nevertheless, the conventional SMC is generally applied to practical systems because of its simple design procedure. For this purpose, several sliding surface functions were defined in the literature for the conventional SMC. Typical choices of the sliding surface were introduced as a function of system states, i.e. $\sigma(t)=cx(t)+\dot{x}(t)$ in [1], $\sigma(t)=\lambda e(t)+\dot{e}(t)$ in [11] where $e(t)$ is the error. A PID surface, $\sigma(t)=k_1e(t)+k_2\int_0^t e(\tau)d\tau+k_3\dot{e}(t)$, was adopted to control of an electromechanical plant [10]. A PI-PD type sliding surface, $\sigma(t)=k_1e(t)+k_2\int_0^t e(\tau)d\,\tau-k_3y(t)-k_4\dot{y}(t)$, was designed to control stable processes where $y(t)$ is the output of the process [4]. An integral term was augmented to the typical sliding surface, $\sigma(t)=(\lambda+d/dt)^{n-1}e(t)+\int_0^t e(\tau)d\,\tau$ in [22] where n is the order of the system.

In addition, an "*Integral Sliding Mode*" (I-SMC) was defined in [23]. Since then, several types of integral sliding surfaces were introduced in the literature. A linear combination of state variables, $\sigma(t)=e(t)-c\int_0^t e(\tau)d\tau$, was used in the controller configuration of a grid-connected photovoltaic system to transfer maximum solar energy in to the grid [24]. A different type $\sigma(t)=(\lambda+d/dt)^n\int_0^t e(\tau)d\,\tau$ was proposed to regulate nonlinear chemical processes in [2] and similar one was in [25] for faster tracking.

The idea behind the I-SMC was presented so that the integral action in the sliding surface drives the system states to the desired equilibrium point in the presence of mismatched uncertainties. Although it is as simple and robust as conventional SMC to apply various systems, some drawbacks, such as overshoot and long settling time, were always seen on the control systems [4,8]. Therefore, defining the appropriate sliding surface is one of the major tasks. The other major task is to select an appropriate switching control to guarantee the stability of the sliding motion at the desired point.

Since the real systems always suffer from uncertainties, the sliding surface converges to the equilibrium point, $\sigma(t)=0$, in a finite time and varies arbitrarily within small region around it. On the other hand, the stability may not be achieved by a real system because of the presence of uncertainty which must be solved by carefully designed switching control [26]. For example, it was stated in [2] that the sliding surface, $\sigma(t)$, reaches a constant value when the error and its derivative is zero. The experiments were performed on a simulation of a chemical process without uncertainty.

In the present study, a new second-order I-SMC algorithm is proposed for SISO uncertain systems. The stability of the controller is proved in the sense of Lyapunov stability theorem. In the proposed algorithm, the control input appears in the second-order time derivative of the sliding surface. Both $\sigma(t)$ and $\dot{\sigma}(t)$ converge to the desired point under uncertain conditions. The experimental procedure is performed on a real electromechanical system. Two conventional SMC algorithms and a super-twisting algorithm are also applied to the system for comparison. The robustness and performance of the controllers is analyzed with both graphical and statistical results.

The main contribution of the present study is that the cited drawbacks of the I-SMC algorithms are removed with the proposed controller. The new sliding surface and new switching control provide a high accurate control input which is useful for long-term application to uncertain real systems. The long settling-time is also reduced with small magnitudes of variations around the desired point.

The organization of the present paper is as follows. In the next section, the experimental system described and modeled. The proposed I-SMC was derived in Section 3. Then, real system applications and discussion on the results were given in Section 4. Finally, concluding remarks are provided in Section 5.

2. Description of the experimental system and modeling

An approximate mathematical model of the experimental system can be used in the proposed I-SMC. The experimental system consists of a dc motor and some loads on the shaft of the motor. The dc motors are widely used in the industrial applications since the useful property of easy adjustability of the position and speed control under load disturbance [16]. The feedback is provided with a tachogenerator directly connected to the shaft. The tachogenerator produces output voltage proportional to the shaft speed. The system can be modeled using first-order plus dead-time model (FOPDT) since its effective way for the real systems where dead-time is relatively small [4]. The procedure is based on the process reaction curve method which is simple to understand so that any operator can easily apply [22,27]. The FOPDT model of the system is obtained as follows:

$$G(s)=\frac{Y(s)}{U(s)}=\frac{Ke^{-t_ds}}{\tau s+1} \tag{1}$$

where τ is the time constant, t_d is the time delay and K is the steady-state gain. If the time delay is so small compared with τ, the system model can be approximated as follows:

$$G(s)\cong\frac{K}{(\tau s+1)(t_ds+1)}=\frac{C_n}{s^2+A_ns+B_n} \tag{2}$$

In order to obtain the parameters of the transfer function in (2), a step input was applied to the armature of the motor with amplitude of 5.52 V corresponding to 1200 rpm shaft speed. The output of the open-loop response of the system was measured with a computer via a data acquisition card (DAQ) as shown in Fig. 1.

The output voltage produced by the tachogenerator was measured to be 4.48 V at 1200 rpm shaft speed. The modeling error, the difference between the measured output of the system

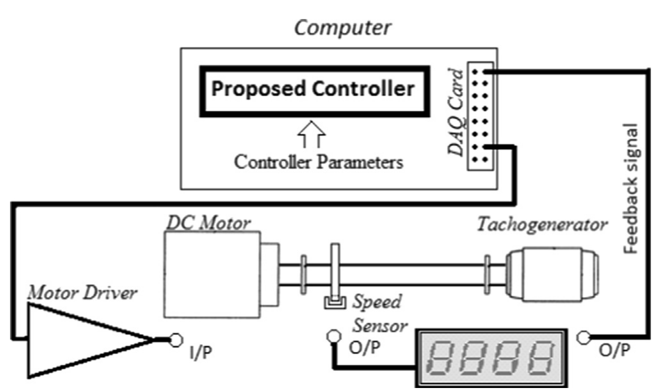

Fig. 1. Diagram of experimental setup.