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불확실 일반 선형 시스템의 레귤레이션 제어를 위한 사전 제어 성능을 갖는 개선된 연속 적분 가변구조 시스템

An Improved Continuous Integral Variable Structure Systems with Prescribed Control Performance for Regulation Controls of Uncertain General Linear Systems

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Abstract –.In this paper, an improved continuous integral variable structure systems(ICIVSS) with the prescribed control performance is designed for simple regulation controls of uncertain general linear systems. An integral sliding surface with an integral state having a special initial condition is adopted for removing the reaching phase and predetermining the ideal sliding trajectory from a given initial state to the origin in the state space. The ideal sliding dynamics of the integral sliding surface is analytically obtained and the solution of the ideal sliding dynamics can predetermine the ideal sliding trajectory(integral sliding surface) from the given initial state to the origin. Provided that the value of the integral sliding surface is bounded by certain value by means of the continuous input, the norm of the state error to the ideal sliding trajectory is analyzed and obtained in Theorem 1. A corresponding discontinuous control input with the exponential stability is proposed to generate the perfect sliding mode on the every point of the pre-selected sliding surface. For practical applications, the discontinuity of the VSS control input is approximated to be continuous based on the proposed modified fixed boundary layer method. The bounded stability by the continuous input is investigated in Theorem 3. With combining the results of Theorem 1 and Theorem 3, as the prescribed control performance, the pre specification on the error to the ideal sliding trajectory is possible by means of the boundary layer continuous input with the integral sliding surface. The suggested algorithm with the continuous input can provide the effective method to increase the control accuracy within the boundary layer by means of the increase of the G_1 gain. Through an illustrative design example and simulation study, the usefulness of the main results is verified.

Key Words : Variable structure system, Sliding mode control, Regulation control, Boundary layer method, Prescribed performance

1. Introduction

A great deal of the researches on the variable structure systems(VSS) or sliding mode control(SMC) has been reported in order to develop the theory of the VSS itself and to extend the application fields of the VSS over last 60 years [1-4]. The objective of the VSS has been greatly extended in a variety control problem such as stabilization, regulation, tracking including the model following, identification, and even fault detection, etc. because of the robustness against the matched uncertainty and disturbance in the sliding mode [5, 6]. In regulation controls, the three fundamental control problems are the simple regulation[7], set-point regulation [8, 19], and point-to-point regulation problems [9]. The simple regulation is so called the controllable problem that is the control of plants from a given initial condition to the zero(origin) in the state space, which is the most simple one among the three regulation problems. The set-point regulation is so called the reachable problem that is the control of plants from the zero(origin) to the set-point. And the point-to-point regulation is the most complex problem that is the control problem from any given initial point to any given set-point. Among them, the simple regulation problem of uncertain general linear systems is the theme of this paper.

The VSS with the SMC can provide the effective means to the control of uncertain linear dynamical systems under parameter variations and external disturbances [1-3]. One of its essential advantages is the robustness of the controlled system to matched parameter uncertainties and external disturbances in the sliding mode on the predetermined sliding surface [4-6]. However the VSS has the two main demerits, those are the reaching phase [3] and chattering problems [5]. The reaching phase is the transient period

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until the controlled system first reaches to the sliding surface for the initial condition far from the sliding surface. During the reaching phase, the sliding mode does not occur so the robustness is not guaranteed [6]. The alleviation of this problem is the use of the high-gain feedback to reduce the effect of the disturbance [10]. This has the drawbacks related to the high-gain feedback sensitive to the unmodeled dynamics and actuator saturation. The adaptive change, rotation, of the sliding surface to reduce the reaching problems is proposed by Itkis in [3]. This method is effectively improved by [11] for second order systems. But the initial condition is limited to some degree in the phase plane. As the similar approaches to Itkis's, the adaptive changing methods, shifting and rotating of the sliding surface, so called moving sliding surfaces are reported also for second order systems in [12] and for n-th order systems in [13] and [14]. The simple integral action without a special initial condition is augmented to the VSS in order to increase the steady state performance by [8] and [27]. But the reaching phase still exists and the overshoot problem may occur because the integral state from the zero must be re-regulated to the zero. So with the special initial condition, the integral state is introduced to the VSS for the first time in [15] and [6], which is applied to tracking controls of motors in [16] and [17] and to simple regulation controls of motors in [18]. The idea of [15] and [6] is applied to set-point regulation controls of robot manipulators in [19], to simple regulation controls of nonlinear systems in [20], and to point-to-point regulation controls of uncertain general linear systems in [9]. The reaching phase is completely removed by means of making the integral sliding surface be zero at $t=0$ with a special initial condition for the integral state in those papers. The performance of the output prediction and predetermination is obtained by using the solution of the ideal sliding dynamics of the integral sliding surface. This ideal of the integral sliding surface with the special initial condition in [15] is adopted in this paper in order to remove the reaching phase completely. A modification of [15] is studied in [21] by Utkin and Shi. The similar results to [21] are obtained in [22] and [23]. But, the algorithms of [21], [22,], and [23] have the drawback of the need of the information of the nominal input u_0 to construct the nonlinear integral-type sliding surface. This demerit is removed in [24] and [25] by means of introducing the closed loop dynamics to the integrand in the nonlinear integral-type sliding manifolds instead of using u_0. Other version of the integral sliding surface is studied in [7] in order to adopt the integral of the sliding surface itself to the conventional sliding surface. The reaching phase is also removed.

On the other hand, the chattering in the VSS is the discontinuously high frequency inherent switching of the control input according to the sign of the sliding surface in the neighborhood of the sliding surface, which is undesirable for practical real plants, may excite the unmodeled high frequency dynamics, reduces the usable life time of actuators, and results in the loss of the asymptotic stability and poor steady state tracking error[26]. Until now, there are many approaches to attenuate the chattering problems, those are the saturation function [17, 27, 28], boundary layer method [29-31], observer-based approach [32, 33], higher-order approach [34-36], adaptive method [37], fuzzy SMC [31, 38-40], neural net SMC [38, 41, 42], filtering technique[43], digital sliding mode scheme[44], fast nonsingular terminal sliding mode [45, 46], and uncertainty and disturbance estimation technique[47], etc[48]. Each method has the advantages and disadvantages at the same time. The first two methods are in which the discontinuous switching function, e.g. sign function in the control input is replaced by continuous approximation functions. Among all the alleviation methods mentioned above, the model-based methods for example the observer-based and uncertainty and disturbance estimation technique are sensitive the mismatches of the parameters between those of models and plants. In [29], the fixed boundary layer method is proposed to alleviate the chattering problems. The variable boundary layer is suggested to effectively cope with chattering problems in [30]. By using the fuzzy control theory, the thickness of the boundary layer is adjusted in [31]. There are the need to compromise between the continuity of the control input and tracking accuracy to the sliding surface including the origin in most forementioned chattering alleviation approaches. The feasible method to increase the tracking accuracy and steady performance is necessary with the implementation of the continuity of control inputs. In this paper, a modified fixed boundary layer method is proposed for removing the chattering problems with providing the means of the increase of the tracking accuracy and steady performance.

In this paper, an ICIVSS with the prescribed control performance is presented for simple regulation controls of uncertain general linear systems. With the results in [19] of regulation controls to robot manipulators, this suggested algorithm is applied and extended to simple regulation controls of the uncertain general linear systems. In the proposed algorithm, the two main disadvantages of the VSS, ie. the reaching phase and chattering problems are addressed to by means of the integral sliding surface with a special initial condition and modified fixed boundary layer method. The reaching phase is completely removed and the chattering is dramatically improved. The ideal sliding dynamics of the integral sliding surface is analytically obtained in advance after the state transformation. By using the solution of the ideal sliding dynamics, the output is predictable and predetermined. The norm of the error of tracking to the sliding surface is analyzed analytically as a specification on tracking to the integral sliding surface. Theoretically a discontinuous input with the exponential stability is proposed and practically by means of the modified fixed boundary layer method, a continuous input is suggested with providing the tool of the increase of the tracking accuracy to the integral sliding surface even better tracking accuracy than that of the discontinuous input. With the continuous input, the exponential stability is lost and the bounded stability is obtained but the tracking accuracy is even improved with the prescribed control performance. The proposed algorithm with the continuous input can provide the efficient means to increase the accuracy of tracking to the sliding surface and steady state performance. A design example and simulation study shows the usefulness of the main results.

2. An Continuous Integral Variable Structure Systems

2.1 Descriptions of plants

An n-th order uncertain general linear plant is described by

$$\dot{z}=(A_0+\Delta A)\cdot z(t)+(B_0+\Delta B)\cdot u(t)+Df(t) \qquad z(0) \tag{1}$$

where $z(\cdot)\in R^n$ is the original state, $u(\cdot)\in R^1$ is the control input, $f\in R^r$ is the external disturbance, respectively, A_0 and B_0 is the nominal parameter matrices, ΔA, ΔB, and D are the bounded matrix uncertainties and those satisfy the matching condition as follows

$$\begin{aligned} &R(\Delta A)\subset R(B_0)\\ &R(\Delta B)\subset R(B_0)\\ &R(D)\subset R(B_0)\end{aligned} \tag{2}$$

Moreover the assumption on ΔB is made.

Assumption

A1:It is assumed the following equation is satisfied for a non zero element coefficient vector $C_{z1}\in R^{1\times n}$

$$|C_{z1}\Delta B(C_{z1}B_0)^{-1}|=|\Delta I|\le \eta<1 \tag{3}$$

where η is a positive constant less than 1.

The assumption 1 means that the value of uncertainty ΔB is less than the nominal value B_0, which is acceptable in practical situations.

The purpose of the controller design is to control of the state of (1) to follow the predetermined intermediate sliding dynamics(trajectory) from a given initial state to the origin. By the state transformation, $x=Pz$, a weak canonical form[9] of (1) is obtained as

$$\dot{x}=\Lambda x(t)+\Gamma u(t)+\Gamma d(t), \qquad x(0) \tag{4}$$

where

$$\Lambda=PA_0P^{-1}=\begin{bmatrix}0&1&0&\cdots&0\\0&0&1&\cdots&0\\ \vdots&\vdots&\vdots&\cdots&\vdots\\ -a_1&-a_2&-a_3&\cdots&-a_n\end{bmatrix} \text{ and } \Gamma=PB_0=\begin{bmatrix}0\\ \vdots\\ 0\\ b\end{bmatrix} \tag{5}$$

where $x(0)$ is the initial condition transformed from $z(0)$ and $d(t)$ is the lumped uncertainty in the transformed system as

$$d(t)=\Delta A'P^{-1}x(t)+\Delta B'u(t)+D'f(t) \tag{6}$$

In (5), b is 1, then the system (4) is the standard canonical form, otherwise, then the (4) is the weak canonical one[9].

2.2 Design of Integral sliding Surfaces

To design the ICIVSS, the integral sliding surfaces [6, 15, 16] are suggested to the following form having an integral of the state as

$$\begin{aligned} s(z,t)&=C_{z0}\cdot\left[\int_0^t zdt+\int_{-\infty}^0 zdt\right]+C_{z1}\cdot z\\ &=C_{z0}\cdot z_0+C_{z1}\cdot z\end{aligned} \tag{7}$$

$$\begin{aligned} s(x,t)&=C_{x0}\cdot\left[\int_0^t xdt+\int_{-\infty}^0 xdt\right]+C_{x1}\cdot x\\ &=C_{x0}\cdot x_0+C_{x1}\cdot x\end{aligned} \tag{8}$$

where the coefficient matrices and the initial conditions for the integral states are expressed as shown

$$C_{x1}=[c_1 \quad c_2 \quad \dots \quad c_n]\in R^{1\times n}, \quad c_n=1$$
$$C_{z1}B_0=C_{x1}\Gamma, \quad C_{z0}=C_{x0}P, \quad C_{z1}=C_{x1}P\in R^{1\times n} \tag{9}$$
$$\int_{-\infty}^{0} x_i dt=-c_i x_i(0)/C_{x0i}, \quad i=1,2,\dots,n \tag{10a}$$
$$\int_{-\infty}^{0} z_i dt=-c_{z1i} z_i(0)/C_{z0i}, \quad i=1,2,\dots,n \tag{10b}$$

The initial conditions (10a) and (10b) for the integral states in (7) and (8) are selected so that the integral sliding surfaces are zeros at $t=0$ for removing the reaching phase [6, 16], which is stemmed from the idea in [15]. Without these initial conditions, the reaching phase still exists and the overshoot problem maybe exist because the integral state starting from the zero will be re-regulated to the zero [6, 8, 27]. From

$$\dot{s}(x,t)=C_{x0}\cdot x+C_{x1}\cdot \dot{x}=0 \tag{11}$$

the differential equation for x_n is obtained as

$$\begin{aligned}\dot{x}_n(t)&=-C_{x0}\cdot x-[0 \ c_1 \ c_2 \ \dots \ c_{n-1}]\cdot x \\ &=-C_x\cdot x\end{aligned} \tag{12}$$

where

$$C_x=[c_{x1} \ c_{x2} \ \dots \ c_{xn}]=C_{x0}+[0 \ c_1 \ c_2 \ \dots \ c_{n-1}] \tag{13}$$

Combining (12) with the first n-1 differential equations in the system (4) leads to the ideal sliding dynamics

$$\dot{x}_s^*=\Lambda_c x_s^* \qquad x_s^*(0)=x(0) \tag{14}$$

and

$$\dot{z}_s^*=P^{-1}\Lambda_c P z_s^* \qquad z_s^*(0)=z(0) \tag{15}$$

where

$$\Lambda_c=\begin{bmatrix}0^{(n-1)\times 1} & I^{(n-1)\times(n-1)} \\ & -C_x\end{bmatrix} \tag{16}$$

which is considered as a dynamic representation of the integral sliding surfaces (7) or (8)[6]. The solutions of (14) and (15), x_s^* and z_s^* coincide with and predetermine the integral sliding surfaces (7) and (8)(the sliding trajectories) from a given initial condition to the origin [15]. By using the solutions of (14) and (15), the output is predetermined and predicted. To design the integral sliding surfaces (7) and (8), the system matrix Λ_c is to be stable or Hurwitz, that is all the eignvalues of Λ_c have the negative real parts. To choose the coefficient vectors of the integral sliding surfaces by means of the well known linear regulator theories, (14) and (15) are transformed to the each nominal system form of (1) and (4)

$$\begin{aligned}&\dot{x}_s^*=\Lambda\cdot x_s^*+\Gamma u_s(x_s^*,t) \\ &u_s(x_s^*,t)=-Gx_s^*(t)\end{aligned} \tag{17}$$

where

$$\Lambda_c=\Lambda-\Gamma G \tag{18}$$

and expressed with the original state as

$$\begin{aligned}&\dot{z}_s^*=A_0 z_s^*+B_0 u_s(z_s^*,t) \\ &u_s(z_s^*,t)=-GPz_s^*(t)=-Kz_s^*(t)\end{aligned} \tag{19}$$

where

$$P^{-1}\Lambda_c P=A_0-B_0K \tag{20}$$

After determining K or G to have the desired ideal sliding dynamics, the coefficient vectors of the integral sliding surfaces (7) or (8) can be directly chosen from the relationship

$$\begin{aligned}C_x&=[c_{x1} \ c_{x2} \ \dots \ c_{xn}]=C_{x0}+[0 \ c_1 \ c_2 \ \dots \ c_{n-1}] \\ &=[a_1 \ a_2 \ \dots \ a_n]+bG \\ &=[a_1 \ a_2 \ \dots \ a_n]+bKP^{-1} \\ c_{x1}&=c_{x01}\end{aligned} \tag{21}$$

which is derived from (18). If this regulation control problem is designed by using the nominal plants (17) or (19), then the integral sliding surface having exactly the same performance can be effectively chosen by using (21). If Λ_c is designed to be Hurwitz, then which guarantees the exponential stability of the system (14) and there exist the positive scalar constants K_1 and κ such that

$$\|e^{\Lambda_c t}\|\leq K_1\cdot e^{-\kappa t} \tag{22}$$

where $\|\cdot\|$ is the induced Euclidean norm as $\sqrt{trace(e^{\Lambda_c t^T}\cdot e^{\Lambda_c t})}$.

Now, define $\overline{E_0}(t)$ and $\overline{E_1}(t)$ are the modified error vector from the ideal sliding trajectory and its derivative, ie. the error vector, respectively as

$$\overline{E_0}(t)=[e_0\ e_1\ e_2\ \cdots\ e_{n-1}]^T \qquad (23)$$
$$\overline{E_1}(t)=\dot{\overline{E_0}}(t)=[e_1\ e_2\ e_3\ \cdots\ e_n]^T$$

where

$$e_0(t)=\int_0^t x_1-x_{s1}^* dt+e_0(0) \qquad (24)$$
$$e_i(t)=x_i-x_{si}^*, \quad i=1,2,...,n$$

If the integral sliding surface is the zero for all time, naturally this defined error and its derivative are also the zeros. The integral sliding surfaces may be not exactly zeros if the control input of the ICIVSS is continuously implemented. Hence the effect of the non-zero value of the integral sliding surface to the error to the sliding trajectory is analyzed in the following Theorem 1[19] as a prerequisite to the main theorem.

Theorem 1: *If the integral sliding surfaces defined by equation (7) or (8) satisfy $\|s(t)\|\leqq\gamma$ for any $t\geqq 0$ and $\|\overline{E_0}(0)\|\leqq\gamma/\kappa$ is satisfied at the initial time, then*

$$\|\overline{E_0}(t)\|\leqq\epsilon_1 \qquad (25)$$
$$\|\overline{E_1}(t)\|\leqq\epsilon_2$$

is satisfied for all $t\geqq 0$ where ϵ_1 and ϵ_2 are the positive constants defined as follows:

$$\epsilon_1=\frac{K}{\kappa}\cdot\gamma, \quad \epsilon_2=\gamma\cdot\left[1+\|\Lambda_c\|\cdot\frac{K}{\kappa}\right] \qquad (26)$$

Proof: The integral sliding surface can be re-written as

$$\begin{aligned} s(x,t) &= C_{x0}\cdot x_0+C_{x1}\cdot x-\left\{C_{x0}\cdot x_{0s}^*+C_{x1}\cdot x_s^*\right\} \qquad (27)\\ &= C_{x0}\cdot[x_0-x_{0s}^*]+C_{x1}\cdot[x-x_s^*]\\ &= C_{x0}\cdot\overline{E_0}+C_{x1}\cdot\overline{E_1}\end{aligned}$$

and can be re-expressed in a differential matrix from as

$$\dot{\overline{E_0}}=\Lambda_c\cdot\overline{E_0}+\begin{bmatrix}0\\ \vdots\\ 0\\ 1\end{bmatrix}\cdot s(x,t) \qquad (28)$$

In (28), the integral sliding surface may be considered as the bounded disturbance input, $\|s(t)\|\leqq\gamma$. The solution of (28) is expressed as

$$\overline{E_0}(t)=e^{\Lambda_c t}\cdot\overline{E_0}(0)+\int_0^t\left\{e^{\Lambda_c t}\cdot\begin{bmatrix}0\\ \vdots\\ 0\\ 1\end{bmatrix}\cdot s(x,t-\tau)\right\}d\tau \qquad (29)$$

From the boundness of the sliding surface and (22), the Euclidean norm of the vector $\overline{E_0}$ become

$$\begin{aligned}\|\overline{E_0}(t)\| &= \|e^{\Lambda_c t}\|\cdot\|\overline{E_0}(0)\|+\int_0^t\left\|\left\{e^{\Lambda_c t}\cdot\begin{bmatrix}0\\ \vdots\\ 0\\ 1\end{bmatrix}\cdot s(x,t-\tau)\right\}\right\|d\tau\\ &\leqq K_1\cdot e^{-\kappa t}\cdot\|\overline{E_0}(0)\|+\int_0^t\|e^{\Lambda_c t}\|\cdot\left\|\begin{bmatrix}0\\ \vdots\\ 0\\ 1\end{bmatrix}\right\|\cdot\|s(x,t-\tau)\|d\tau\\ &\leqq \frac{K_1}{\kappa}\cdot\gamma+\left(\|\overline{E_0}(0)\|-\frac{\gamma}{\kappa}\right)\cdot K_1\cdot e^{-\kappa t}\\ &\leqq \frac{K_1}{\kappa}\cdot\gamma \qquad (30)\\ &=\epsilon_1\end{aligned}$$

for all time, $t\geqq 0$. From (28), the following equation is obtained

$$\begin{aligned}\|\overline{E_1}\| &= \|\Lambda_{d}\|\cdot\|\overline{E_0}\|+\left\|\begin{bmatrix}0\\ \vdots\\ 0\\ 1\end{bmatrix}\right\|\cdot\|s(x,t)\| \qquad (31)\\ &\leqq\epsilon_2\end{aligned}$$

which completes the proof of Theorem 1.

The above Theorem 1 implies that the modified error vector and error vector from the ideal sliding trajectory are uniformly bounded, provided that the integral sliding surface is bounded for all time $t\geqq 0$. Using this result of Theorem 1, we can give the specifications on the norm of the error vector from the ideal sliding trajectory being dependent upon the value of the integral sliding surface, (7). In the next section, we will design the discontinuous and continuous variable structure regulation controllers which can guarantee the boundedness of s(t), i.e., $\|s(t)\|\leqq\gamma$ for a given γ, then the error vector to the ideal sliding trajectory is bounded by ϵ_2 in virtue of Theorem 1.

2.3 Transformed Discontinuous and Continuous Control Inputs

As the second design phase of the ICIVSS, a following corresponding discontinuous transformed[49] control input to generate the perfect sliding mode on the every point of the pre-selected integral sliding surface from a given initial state to the origin is proposed as composing of the continuous terms and discontinuously switching terms as

$$u(t) = -(C_{z1}B_0)^{-1}\{K_z \cdot z + G_1 \cdot s\} - (C_{z1}B_0)^{-1}\{\Delta K_z \cdot z + G_2 sign(s)\} \quad (32)$$

where

$$K_z = C_{z0} + C_{z1}A_0 \quad (33)$$

$$G_1 > 0 \quad (34)$$

$$\triangle k_{zi} = \begin{cases} \geq \dfrac{\max\{C_{z1}\triangle A - \triangle IK_z\}_i}{\min\{I+\triangle I\}_i} & sign(sz_i) > 0 \\ \leq \dfrac{\min\{C_{z1}\triangle A - \triangle IK_z\}_i}{\min\{I+\triangle I\}_i} & sign(sz_i) < 0 \end{cases}$$
$$i = 1,2,...,n \quad (35)$$

$$G_2 = \begin{cases} \geq \dfrac{\max\{C_{z1}Df(t)\}}{\min\{I+\triangle I\}} & sign(s) > 0 \\ \leq \dfrac{\min\{C_{z1}Df(t)\}}{\min\{I+\triangle I\}} & sign(s) < 0 \end{cases} \quad (36)$$

The $G_1 \cdot s$ in the continuous feedback term can reinforce the controlled systems in more closer tracking to the pre-selected ideal integral sliding surface from a given initial condition to the origin[6][15][27] in order to increase the control accuracy and steady state performance. By this discontinuous control input, the real dynamics of s, i.e. the time derivative of s becomes

$$\begin{aligned} \dot{s}(z,t) &= C_{z0}z + C_{z1}\dot{z} \\ &= C_{z0}z + C_{z1}(A_0 + \Delta A)z \\ &\quad + C_{z1}(B_0 + \Delta B)u + C_{z1}Df(t) \\ &= (C_{z0} + C_{z1}A_0)z + C_{z1}\Delta A z \\ &\quad - C_{z1}(B_0 + \Delta B)(C_{z1}B_0)^{-1}(K_z \\ &\quad + G_1 s + \Delta Kz + G_2 sign(s)) + C_{z1}Df(t) \\ &= (C_{z0} + C_{z1}A_0)z - K_z z + C_{z1}\Delta Az - \Delta IK_z z \\ &\quad - (I + \Delta I)\Delta Kz - (I + \Delta I)G_1 s \\ &\quad + C_{z1}Df(t) - (I + \Delta I)G_2 sign(s) \\ &= C_{z1}\Delta Az - \Delta IK_z z - (I + \Delta I)\Delta Kz \\ &\quad - (I + \Delta I)G_1 s + C_{z1}Df(t) - (I + \Delta I)G_2 sign(s) \end{aligned} \quad (37)$$

The closed loop stability and existence of the sliding mode on the preselected integral sliding surface by the proposed transformed discontinuous control input will be investigated in the next theorem.

Theorem 2: The proposed integral variable structure controller with the discontinuous input (32) and the integral sliding surface (7) can exhibit the exponential stability to the ideal sliding surface and the ideal output of the sliding dynamics for all the uncertainties exactly defined by the integral sliding surface (7).

Proof: Take a Lyapunov candidate function as

$$V(t) = \frac{1}{2}s^2(z,t) \quad (38)$$

Differentiating (38) with time leads to

$$\dot{V}(t) = s(z,t) \cdot \dot{s}(z,t) \quad (39)$$

Substituting (37) into (39) and by (33)-(36), one can obtain the following equation

$$\begin{aligned} \dot{V}(t) = s(z,t) \cdot \dot{s}(z,t) &< -(1-\eta)G_1 s^2(z,t) \\ &= -2(1-\eta)G_1 V(t) \end{aligned} \quad (40)$$

From (40), the following equation is obtained as

$$\begin{aligned} &\dot{V}(t) + 2(1-\eta)G_1 V(t) \leqq 0 \\ &V(t) \leqq V(0)e^{-2(1-\eta)G_1 t} \end{aligned} \quad (41)$$

which completes the proof.

As can be seen in (40) and (41), because G_1 is included in the decay rate parameter, the larger G_1, the closer tracking to the integral sliding surface. The $G_1 \cdot s$ term can increase the control accuracy to the ideal sliding surface including the zero(origin) within the boundary layer and steady state performance. The exponential stability to the integral sliding surface and the existence condition of the sliding mode on the every point of the integral sliding surface is proved, while in the previous works on the VSS, only the asymptotic stability is guaranteed [1, 7, 8, 22, 47]. The sliding mode on the every point of the integral sliding surface from a given initial state to the origin is guaranteed. Hence the sliding output from a given initial state to the origin is insensitive to the matched uncertainties and external disturbances by the proposed discontinuous VSS input (32). By using the solution of the ideal sliding dynamics (15), the controlled output from a given initial state to the origin can be predicted and predetermined, as an attractive performance in the theoretic aspect, because the reaching phase is removed. The discontinuous input (32) can regulate the integral sliding surface to be zero theoretically. However, the control input is discontinuous which results in the chattering problems [5, 26]. So for practical applications, the discontinuous input term is essentially approximated to be continuous. By using the modified boundary layer method, the discontinuous input (32) has changed to the following form

$$u_c(t) = -(C_{z1}B_0)^{-1}\{K_z \cdot z + G_1 \cdot s\} - (C_{z1}B_0)^{-1}\{\Delta K_z \cdot z + G_2 sign(s)\} \cdot MBLF(s) \tag{42}$$

where $MBLF(s)$ is defined as a modified boundary layer function proposed in this paper as follows:

$$MBLF(s) = \begin{cases} 1 & \text{for} \quad s \geqq l_+ \\ s/l_+ & \text{for} \quad 0 \leqq s < l_+ \\ |s|/l_- & \text{for} \quad -l_- < s \leqq 0 \\ 1 & \text{for} \quad s \leqq -l_- \end{cases} \tag{43}$$

Because the switching terms in (42) are stable shown through Theorem 2, the $MBLF(s)$ function can not influence on the closed loop stability and only can modify the magnitude of the switching terms within the boundary layer instead of the sign function when s is positive as well as negative. If $l_+ = l_-$, then the $MBLF(s)$ function is symmetric, otherwise it is asymmetric, which is suitable in case of unbalanced uncertainty and disturbance and unbalanced chattering inputs.

Theorem 3: The proposed integral variable structure controller with the suggested continuous input (42) and the integral sliding surface (7) can exhibit the bounded stability for all the uncertainties and external disturbances.

Proof: Take a Lyapunov candidate function as

$$V(t) = \frac{1}{2}s^2(z,t) \tag{44}$$

From the proof of Theorem 2, we can obtain the following equation

$$\dot{V}(t) = s(z,t) \cdot \dot{s}(z,t) < -(1-\eta)G_1 s^2(z,t) = -2(1-\eta)G_1 V(t) \tag{45}$$

as long as $|s(z,t)| \geqq l = \max(l_+, l_-)$. From (45), the following equation is obtained as

$$\dot{V}(t) + 2(1-\eta)G_1 V(t) \leqq 0 \qquad V(t) \leqq V(0)e^{-2(1-\eta)G_1 t} \tag{46}$$

as long as $|s(z,t)| \geqq l$, which completes the proof.

As can be seen in (45) and (46), outside the boundary layer, the exponential stability is still guaranteed and inside the boundary layer the $G_1 \cdot s$ term can increase the control accuracy and steady state performance. The larger G_1, the closer tracking to the ideal sliding surface from a given initial condition to the origin. By Theorem 3, the continuously implemented control input (42) can guarantee that the integral sliding surface (7) is bounded by l. Hence it is possible to design that l is less than γ, that is $l \leqq \gamma$. Thus the integral sliding surface is bounded by γ which satisfies the condition of Theorem 1. Then by Theorem 1, the fact that the norm of the error vector to the ideal sliding surface is bounded by ϵ_2 is possible as the prescribed control performance.

3. Design Examples and Simulation Studies

Consider a following plant with uncertainties and disturbances [9]

$$\begin{aligned} \dot{z}_1 &= (-2+\Delta a_1)z_1(t) + (2+\Delta b_1)u(t) + f(t) \\ \dot{z}_2 &= \Delta a_1 z_1(t) - 3z_2(t) + (2+\Delta b_2)u(t) + f(t) \end{aligned} \tag{47}$$

where

$$\begin{aligned} &A_0 = \begin{bmatrix} -2 & 0 \\ 0 & -3 \end{bmatrix}, \quad B_0 = \begin{bmatrix} 2 \\ 2 \end{bmatrix} \\ &\Delta a_1 = 0.15\cos(7t), \quad \Delta b_1 = \Delta b_2 = 0.3\sin(5t) \\ &f(t) = 0.5\cos(8t) \\ &|\Delta a_1| \le 0.15, \quad |\Delta b_1| = |\Delta b_2| \le 0.3, \quad |f(t)| \le 0.5. \end{aligned} \tag{48}$$

The ICIVSS controller aims to drive the output of the plant (47) to the ideal sliding surface from any given initial state to the origin. The transformation matrix to a controllable weak canonical form and the resultant transformed system matrices are

$$P = \begin{bmatrix} 1 & -1 \\ -2 & 3 \end{bmatrix}, \; \Lambda = \begin{bmatrix} 0 & 1 \\ -6 & -5 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} 0 \\ 2 \end{bmatrix} \tag{49}$$

By means of Ackermanns formula, the continuous static gain is obtained

$$K = [0.5 \quad 0] \text{ and } G = [1.5 \quad 0.5] \tag{50}$$

so that the closed loop double eigenvalues of Λ_c are located at -3. Hence, the Λ_c in (14) and (18) and $P^{-1}\Lambda_c P$ in (15) and (20) become

$$\Lambda_c = \begin{bmatrix} 0 & 1 \\ -9 & -6 \end{bmatrix}, \quad P^{-1}\Lambda_c P = \begin{bmatrix} -3 & 0 \\ -1 & -3 \end{bmatrix} \tag{51}$$

By using the solution (14) or (15), the regulated output from a given initial state to the origin can be predicted and predetermined. By the relationship (21), the coefficient matrices of the integral sliding surface directly becomes

$$\begin{aligned} C_x &= [\alpha_1 \quad \alpha_2] + bG = [6 \quad 5] + 2[1.5 \quad 0.5] \\ &= [9 \quad 6] \\ C_{x0} &= [9 \quad 0], \quad C_{x1} = [6 \quad 1] \qquad (52) \\ C_{z0} &= C_{x0}P = [9 \ -9], \quad C_{z1} = C_{x1}P = [4 \ -3], \qquad (53) \\ C_{z1}B_0 &= C_{x1}\Gamma = 2 \end{aligned}$$

As a result, the integral sliding surface becomes

$$\begin{aligned} s(z,t) = 9&\left\{\int_0^t z_1 d\tau - 4/9 z_1(0)\right\} \\ -9&\left\{\int_0^t z_2 d\tau - 3/9 z_2(0)\right\} + 4z_1 - 3z_2 \end{aligned} \tag{54}$$

The constants K_1 and κ in the equation (22) are selected as $K_1 = 3.8$ and $\kappa = 1.0$, hence the constants ϵ_1 and ϵ_2 in (25) and (26) are determined as $\epsilon_1 = 3.8\gamma$ and $\epsilon_2 = 42.28\gamma$. The specification on the norms of the error vector to the ideal sliding surface and the modified error vector, ϵ_2 and ϵ_1 are given as $\epsilon_2 = 5$ and $\epsilon_1 = 0.45$ for an example. Then the γ is determined as $\gamma = 0.1184$. The discontinuous input automatically and theoretically satisfy that the norm value of the integral sliding surface is bounded by $\gamma = 0.1184$. For practical applications, the continuous input essentially adapted with little performance degradation as expected in the design stage. Therefore, l is determined less than $\gamma = 0.1184$ that is $l = l_+ = l_- = 0.1$. For the second design phase of the ICIVSS, the equation (3) in the Assumption A1 is calculated

$$(C_{z1}B_0)^{-1}C_{z1}\Delta B = \Delta I \leq 0.15 \tag{55}$$

Thus the Assumption A1 is satisfied in this design. The K_z of (33) becomes

$$K_z = C_{z0} + C_{z1}A_0 = [1 \quad 0] \tag{56}$$

The inequalities for the switching gains in discontinuous input terms, (34)-(36) become

$$\begin{aligned} &G_1 > 0, \\ &k_{z1} = \begin{cases} > \dfrac{0.30}{0.85} = 0.3529 & \text{for } (sz_1) > 0 \\ < -\dfrac{0.30}{0.85} = -0.3529 & \text{for } (sz_1) < 0 \end{cases} \\ &k_{z2} = \begin{cases} > \dfrac{1.2}{0.85} = 1.412 & \text{for } (sz_2) > 0 \\ < -\dfrac{1.2}{0.85} = 1.412 & \text{for } (sz_2) < 0 \end{cases} \\ &G_2 > \frac{0.5}{0.85} = 0.5882 \end{aligned} \tag{57}$$

Finally the selected control gains ar

$$\begin{aligned} &G_1 = 3000 \\ &k_{z1} = \begin{cases} 20.5 & \text{for } (sz_1) > 0 \\ -20.5 & \text{for } (sz_1) < 0 \end{cases} \\ &k_{z2} = \begin{cases} 28.5 & \text{for } (sz_2) > 0 \\ -28.5 & \text{for } (sz_2) < 0 \end{cases} \\ &G_2 = 10.0 \end{aligned} \tag{58}$$

The simulation is carried out using a Fortran software under 0.1[msec] sampling time and with $z(0) = [3 \ -1.5]^T$ initial condition. Fig. 1 shows the control results of the designed ICIVSS by the proposed discontinuous control input (32) with the integral sliding surface (54) in the upper figure the two output responses, z_1 and z_2 for the three cases (i) the ideal sliding outputs that is the solution of (15), (ii) the outputs without the uncertainty and disturbance, and (iii) the outputs with the uncertainty and disturbance, in the middle figure, the discontinuous sliding surface with the uncertainty and disturbance, in the bottom figure the discontinuous control input with the uncertainty and disturbance. As can be seen in the upper figure, the three case outputs are almost equal, which means that Fig. 1 shows the strong and complete robustness against uncertainty and disturbance because of removing the reaching phase, prediction of the output by using the solution of (15), and predetermination of the output directly according to the pre-chosen of the integral sliding surface, as the attractive features in the theoretical point of view. As can be seen in the middle and bottom figures, the controlled system chatters and slides from $t = 0$ without the reaching phase. Since the integral sliding surface is naturally defined from any given initial condition to the origin, there is no need of consideration of the reaching mode. The value of the integral sliding surface is no more decreased as increase of the switching gains and G_1 of the input because of the finite sampling frequency, discontinuous chattering of the switching input, and digital implementation of the VSS. The integral sliding surface and the control input (32) is discontinuous because of the switching of the sign function in the control input (32), which is undesirable for practical applications. Therefore, the continuous approximation of the discontinuous input is essentially necessary. Based on the modified boundary layer function (43), the control input is continuously implemented as (42). The positive(negative) thickness of the boundary layer is not smaller than the positive(negative) maximum magnitude of the chattering of the integral sliding surface in the middle figure of Fig. 1. Thus the positive(negative) maximum magnitude of the chattering of the integral sliding surface must be smaller than $l_+(l_-)$. If not, re-design with larger ϵ_2. Fig. 2 shows the control results of the designed ICIVSS by the proposed continuous control input (42) with the integral sliding surface (54) in the upper figure the two output responses, z_1 and z_2 for the three cases (i) the ideal sliding outputs that is the solution of (15), (ii) the outputs without the uncertainty and disturbance, and (iii) the outputs with the uncertainty and disturbance, in the middle figure, the continuous sliding surface with the uncertainty and disturbance, in the bottom figure the continuous control input with the uncertainty and disturbance. As can be seen in the upper figure, the three outputs are almost identical to each other by the continuous input with the better performance than that of the discontinuous input. The integral sliding surface is continuous, is bounded by $l=0.1$, and much smaller than that of the discontinuous input because of the large G_1. The control input in the bottom figure is dramatically improved from the bottom figure of Fig. 1. There exists the tool to increase the tracking accuracy and steady state performance by means of increase of G_1 gain. But, the increase over $G_1=16930.0$ makes the chattering and more increase does unstable in the closed

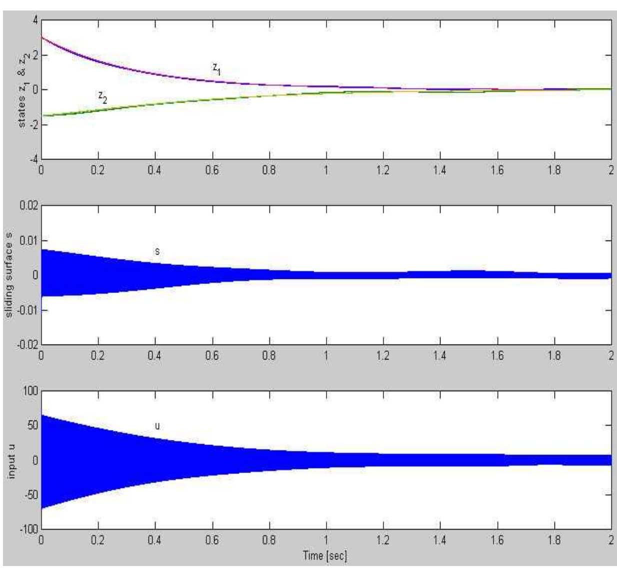

그림 1 적분 슬라이딩면 (54)와 제안된 불연속 제어입력 (32)에 의한 설계된 ICIVSS의 제어결과

Fig. 1 Control results of the designed ICIVSS by the proposed discontinuous control input (32) with the integral sliding surface (54) in the upper figure the two output responses, z_1 and z_2 for the three cases (i) the ideal sliding outputs that is the solution of (15), (ii) the outputs without the uncertainty and disturbance, and (iii) the outputs with the uncertainty and disturbance, in the middle figure the discontinuous sliding surface with the uncertainty and disturbance, in the bottom figure the discontinuous control input with the uncertainty and disturbance

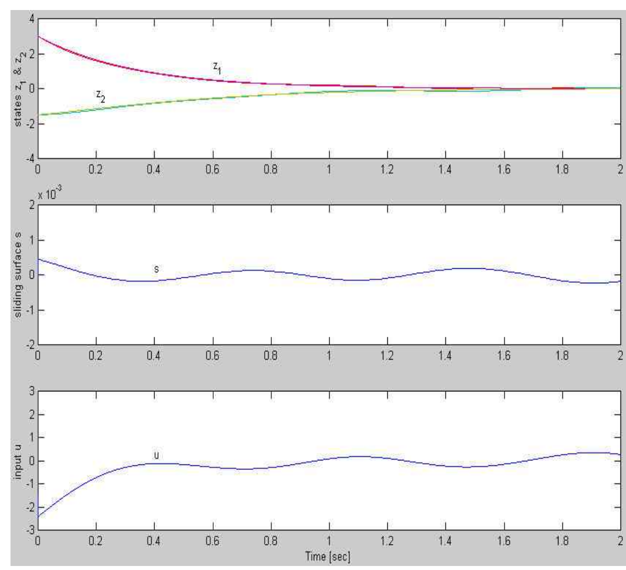

그림 2 적분 슬라이딩면 (54)와 제안된 연속 제어입력 (42)에 의한 설계된 ICIVSS의 제어결과

Fig. 2 Control results of the designed ICIVSS by the proposed continuous control input (42) with the integral sliding surface (54) in the upper figure the two output responses, z_1 and z_2 for the three cases (i) the ideal sliding outputs that is the solution of (15), (ii) the outputs without the uncertainty and disturbance, and (iii) the outputs with the uncertainty and disturbance, in the middle figure, the continuous sliding surface with the uncertainty and disturbance, in the bottom figure the continuous control input with the uncertainty and disturbance

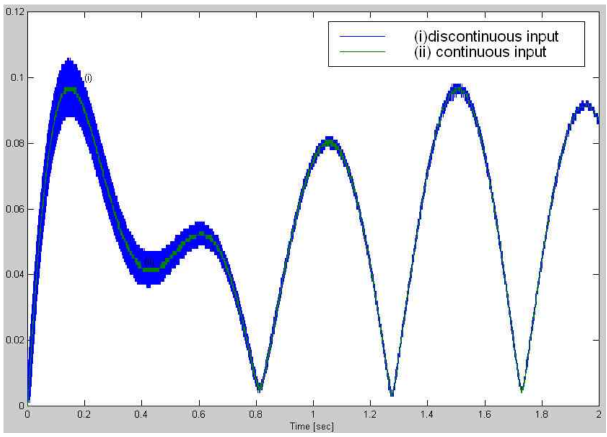

그림 3 적분 슬라이딩 면 추적 오차 벡터의 노옴 (i) 불연속 제어입력 경우 (ii) 연속 제어입력 경우

Fig. 3 Norm of the tracking error vectors to the integral sliding surface (i) for the discontinuous input with uncertainty and disturbance and (ii) for the continuous input with uncertainty and disturbance.

loop system due to the high gain effect. Fig. 3 shows the norm of the tracking error vectors to the integral sliding surface (i) for the discontinuous input with uncertainty and disturbance and (ii) for the continuous input with uncertainty and disturbance. Both the norms of the tracking error vectors to the integral sliding surface are smaller than $\epsilon_2' = \|P^{-1}\|\epsilon_2 = 19.3640$, which means that the specification on the tracking error to the integral sliding surface is satisfied. The integrals of both the norms of the tracking error vectors to the integral sliding surface in Fig. 3 are 0.1129883 for the discontinuous case and 0.1129564 for the continuous case, which means that the tracking error of the continuous case is smaller than that of the discontinuous case but both the tracking errors are similar. By comparing the simulation figures of the discontinuous and continuous inputs, it is concluded that the performance of the continuous input is better than that of the discontinuous input in view of the accuracy of the integral sliding surface and the continuity and magnitude of the control input. While in the theoretical point of view, one can use the discontinuous input directly, in practical aspects, one can use the continuous input based on the modified boundary layer method proposed in this paper with the prescribed and better control performance.

4. Conclusions

In this paper, the simple regulation control of uncertain general linear systems is handled by means of a discontinuous and continuous improved integral variable structure systems with the prescribed control performance. The general linear plant under consideration is transformed to the weak canonical system. To remove the reaching phase, an integral sliding surface with an integral state having a special initial condition is defined from a given initial state to the origin. The ideal sliding dynamics of the integral sliding surface is obtained analytically in the transformed and original systems. The solution of the ideal sliding dynamics coincides with the integral sliding surface from a given initial condition to the origin. Also by using the solution of the ideal sliding dynamics of the integral sliding surface, the controlled output can be predicted and predetermined in advance as an attractive property in the theoretical aspect. The design of the integral sliding surface can be done by the well known linear regulator feedback theories. The relationship between the norm of the error vector to the ideal integral sliding surface and the non-zero value of the sliding surface due to the continuous control input is analyzed and obtained analytically in Theorem 1, provided that the value of the integral sliding surface is bounded by γ for all t. In the theoretical aspect, a transformed discontinuous input with a feedback of the sliding surface itself is proposed to generate the sliding mode on the every point of the integral sliding surface from g given initial condition to the origin. The exponential stability to the integral sliding surface including the origin is investigated in Theorem 2. For the high potential of practical applications, the continuous modification of the discontinuous input is made based on the modified boundary layer method proposed in this paper. The bounded stability of the continuous input is studied in Theorem 3. Outside the boundary layer, the exponential stability is still guaranteed inside the boundary layer the $G_1 \cdot s$ term increase the control accuracy and steady state performance. If one can design that l is smaller than γ, then it is possible that the value of the integral sliding surface is bounded by γ, and thus the norm of the error vector to the ideal sliding surface is bounded by ϵ_2 with the continuous input proposed in this paper as the prescribed control performance. The algorithm with the continuous input can provide the effective mean to increase the tracking accuracy to the sliding surface from a given initial state to the origin and the steady state performance by means of the increase of G_1. In fact, because of the large G_1, the performance of the continuous input is better than that of the discontinuous input, while the performance of the discontinuous input is no more improved as the increase of the control gains because of the finite sampling frequency, chattering of the input, and digital implementation of the VSS. The continuity of the input is dramatically improved based on the suggested modified boundary layer method. Through an illustrative example and simulation study, the effectiveness of the proposed main results is verified. In the theoretical point of view, one can use the discontinuous input for the attractive performance of output prediction and predetermination and exponential stability to the integral sliding surface including the origin, however in the aspect of practical applications, one can use the proposed continuous input with not the performance degradation but the better performance. If one can design that l is smaller than the resolution or equal to the resolution, then the bounded stability has the practical meaning.

References

[1] V.I. Utkin, “Variable Structure Systems with Sliding Mode,” IEEE Trans. on Automatic Control, vol. 22, no. 2 pp. 212-222, 1977.

[2] V.I. Utkin,, Sliding Modes and Their Application in Variable Structure Systems. Moscow, 1978.

[3] U, Itkis, Control Systems of Variable Structure. New York; John Wiley & Sons, 1976.

[4] Decarlo, R.A., Zak, S.H., and Mattews, G.P., "Variable Structure Control of Nonlinear Multivariable Systems: A Tutorial," Proc. IEEE, vol. 76, pp. 212-232, 1988

[5] Young, K.D., Utkin, V.I., Ozguner, U, "A Control Engineer's Guide to Sliding Mode Control," 1996 IEEE Workshop on Variable Structure Systems, pp. 1-14, 1996

[6] J. H. Lee, Design of Integral-Augmented Optimal Variable Structure Controllers, Ph. D. Dissertation, KAIST, 1995.

[7] H. H. Choi, “LMI-Based Sliding Surface Design for Integral Sliding Mode Control of Mismatched Uncertain Systems,” IEEE T. Automatic Control, vol. 52, no. 2 pp. 736-742, 2007.

[8] T. L. Chern and Y. C. Wu, “An Optimal Variable Structure Control with Integral Compensation for Electrohydraulic postion Servo Control Systems," IEEE T. Industrial Electronics, vol. 39, no. 5 pp460-463, 1992.

[9] J. H. Lee, "A Variable Structure Point-to-Point Regulation Controller for Uncertain General Systems, KIEE(The Korean Institute of Electrical Engineers), vol. 63, no. 4, pp. 519-525, 2014.

[10] K. K. D. Young, P. V. Kokotovic, and V. I. Utkin, “A Singular Perturbation Analysis of High-Gain Feedback Systems,” IEEE Trans. Autom. Contr., vol. AC-22, no. 6, pp. 931-938, 1977.

[11] F. Harashima, H. Hashimoto, and S. Kondo, “MOSFET Converter-Fed Position Servo System with Sliding Mode Control,” IEEE Trans. Ind. Electron. vol. I.E.-32 no. 3, 1985.

[12] S. B. Choi, C. C. Cheong, and D. W. Park, “Moving Switching Surface for Robust Control of Second-Order Variable Structure System,” Int. J. Control, vol. 58, no. 1, pp. 229-245, 1993.

[13] R. Roy and N. Olgac, “Robust Nonlinear Control via Moving Sliding Surfaces-nth Order Case,” Proceedings of 36th Conference on Decision and Control, San Diego, CA, USA, pp. 943-948, 1997.

[14] P. Husek, “Adaptive Sliding Mode Control with Moving Sliding Surface,” Applied Soft Computing, vol. 42, pp. 178-183, 2016.

[15] J. H. Lee and M. J. Youn, "An Integral-Augmented Optimal Variable Structure control for Uncertain dynamical SISO System, KIEE(The Korean Institute of Electrical Engineers), vol. 43, no. 8, pp. 1333-1351, 1994.

[16] J. H. Lee and W. B. Shin, “Continuous Variable Structure System for Tracking Control of BLDDSM,” IEEE Int. Workshop on Variable Structure Systems, VSS’96, Tokyo, pp. 84-90, 1996.

[17] J. H. Lee and M. J. Youn, “A New Improved Continuous Variable Structure Controller for Accurately Prescribed Tracking Control of BLDD Servo Motors,” Automatica, vol. 40, pp. 2069-2074, 2004.

[18] J. H. Lee, “Highly Robust Position Control of BLDDSM Using an Improved Integral Variable Structure System,” Automatica, vol. 42, pp. 929-935, 2006.

[19] J. H. Youn and M. J. Youn, “A New Integral Variable Structure Regulation controller for Robot Manipulators with Accurately Predetermined Output,” Proceedings of the IEEE Int. Symposium on Industrial Electronics (ISIE’99), vol. 1 pp. 336-341, 1999.

[20] J. H. Lee, “New Practical Integral Variable Structure Controllers for Uncertain Nonlinear Systems,” Chapter 10 in Recent Advances in Robust Control-Novel Approaches and Design Methods Edited by Andreas Mueller Intech Open Access Pub. www,intechopen.com, 2011.

[21] V. I. Utkin and J. Shi, “Integral Sliding Mode in Systems Operating under Uncertainty Conditions,” Proceedings of the 35th Conference on Decision and Control, Kobe, Japan, Dec. pp. 4591-4596, 1996.

[22] W. J. Cao and J. X. Xu, "Nonlinear Integral-Type Sliding

Surface for Both Matched and Unmatched Uncertain Systems," IEEE T. Automatic Control, vol. 49, no. 83 pp. 1355-1360,2004.
[23] J. H. Zhang, X. W. Liu, Y. Q. Xia, Z. Q. Zuo, and Y. J. Wang, "Disturbance Observer-Based Integral Siding-Mode Conrtol for Systems with Mismatched Disturbance," IEEE Trans. Industr. Electron. vol. 63, no. 11, pp. 7040-7048, 2016.
[24] J. H. Lee, "A New Robust Variable Structure Controller with Nonlinear Integral-Type Sliding Surface for Uncertain Systems with Mismatched Uncertainties and Disturbance,", KIEE, vol. 59, no. 3, pp. 623-629, 2010.
[25] J. H. Lee, "A New Robust Variable Structure Controller with Nonlinear Integral-Type Sliding Surface for Uncertain More Affine Nonlinear Systems with Mismatched Uncertainties and Disturbance,", KIEE, vol. 59, no. 7, pp. 1295-1301, 2010.
[26] I. Boiko, L. Fridman, A. Pisano, and E. Usai, "Analysis of Chattering in systems with Second-Order Sliding Mode," IEEE Trans. on Automatic Conrtol, vol. 52, no. 11, pp. 2085-2102, 2007.
[27] M. S, Chen, Y. R. Hwang, and M. Tomizuka, "A State-Dependent Boundary Layer Design for Sliding Mode Conrtol," IEEE Trans. on Automatic Conrtol, vol. 47, no. 10, pp. 1677-1681, 2002.
[28] J. H. Lee, "A Continuous Sliding Surface Transformed VSS by Saturation Function for MIMO Uncertain Linear Plants," Journal of The Institute of Electronics and Information Engineers(IEIE), vol. 52, no. 7, pp. 127-134, 2115.
[29] J. J. Slotine and S. S. Sastry, "Tracking Control of Nonlinear Systems Using Sliding Surfaces with Aapplication to Robot Manipulators," Int. J. Control, vol. 38, pp. 465-492, 1983.
[30] J. J. Slotine and W. Li, Applied Nonliear Control, Englewood Cliffs, NJ:Prentice-Hall, 1991.
[31] H. J. Lee, E. T. Kim, H. J. Kang, and M. N. Park, "A New Slding Mode Control with Fuzzy Boundary Layer," Fuzzy Sets and Systems, vol. 120, pp135-143, 2001.
[32] A. G. Bondarev, S. A. Bondarev, N. E. Kostyleva, and V. I. Utkin, "Sliding Modes in Systems with Asymptotic State Observers, Automat. Rem. Control, vol. 46, no. 5, pp. 679-684, 1985.
[33] V. I. Utkin, J. Guldner, and J. Shi, Sliding Modes in Electromechanical Systems, London, U.K.:Taylor & Francis, 1999.
[34] G. Bartolini and P. Pydynowski, "An Improved, Chattering Free, V.S.C. Scheme for Uncertain Dynamical Systems," IEEE T. Automatic Control, vol. 41, no. 8, pp. 1220-1226, 1996
[35] G. Bartolini and A. Ferrara, and E. Usai, "Chattering Avoidance by Second-Order Sliding Mode Control," IEEE T. Automatic Control, vol. 43, no. 2, pp. 241-246, 1998.
[36] G. Bartolini and A. Ferrara, E. Usai, and V. I. Utkin, "On Multi-Input Chattering Free Second-Order Sliding Mode Control," IEEE T. Automatic Control, vol. 45, no. 9, pp. 1711-1717, 2000.
[37] X. Zhang and X, Liu, "Chattering Free Adaptive Sliding Mode Control for Attitude Tracking pf Spacecraft with External disturbance," Proceedings of the 33rd Chinese Control Conference, Nanjing China, pp. 2224-2228, 2014.
[38] O. Kaynak, K. Erbatur, and M. Ertugrul, "The Fusion of Computationally Intelligent Methodologies and Sliding Mode Control-A Survey," IEEE Trans. on Industrial Electronics, vol. 48, no. 1, pp. 4-17, 2001.
[39] M. H. Khooban, T. Niknam, F. Blaabjerg, and M. Dehgni, "Free Chattering Hybrid Sliding Mode Control of a Class of Non-Linear Systems:Electric Vehicles as a Case Study," IET Science, Measurement & Technology, vol. 10, no. 7 pp. 776-785, 2016.
[40] Y. Yang, Y. Yan, Z. Zhu, and X. Huang, "Chattering-Free Sliding Mode Control for Strict-Feedback Nonlinear System Using Back Stepping Technique," 2017 Int. Conference on Mechanical, System and Control Engineering, pp. 53-57, 2017.
[41] H. Morioka, K. Wada, A. Sabanovic, and K. Jezernik, "Neural Network Based Chattering Free Sliding Mode Control," Proceedings of the 34th SICE'95 Annual Conference: Int. Session papers, pp. 1303-1308, 1995.
[42] M. Yasser, M. Arifin, and T. Yahagi, "Sliding Mode Control Using Neural Networks," Chapter 17 in Sliding Mode Control Edited by Andrzej Bantoszewicz, Intech Open Access Pub. www,intechopen.com, 2011.
[43] H. J. Shieh and P. K. Huang, "Precise Tracking of a Piezoelectric Positioning Stage via Filtering-Type Sliding Surface Control with Chattering Alleviation," IET Conrtol Theory Applications, vol. 1 no. 3, pp. 586-594, 2007.
[44] V. Acary, B. Brogliato, and Y. Orlov, "Chattering-Free Digital Sliding Mode Control with State Observer and Disturbance Rejection," IEEE Trans. on Automatic Conrtol, vol. 57, no. 5, pp. 1087-1101, 2012.
[45] J. Zheng, H. Wang, Z. Man, J. Jin, and M. Fu, "Robust Motion Control of a Linear Motor Positioner Using Fast Nonsingular Terminal Sliding Mode," IEEE/ASME Trans. Mechatronics, vol. 20, no. 4, pp. 1743-1752, 2015.
[46] S. Lyu, Z. H. Zhu, S. Tang, and X. Yan, "Fast Nonsingular Terminal Sliding Mode to Attenuate the Chattering for Missile Interception with Finite Time

Convergence," IFAC-PapersOnLine, vol. 49, Issue 17, pp. 34-39, 2016.
[47] Q. S. Xu, "Precision Motion Control of Piezoelectric Nanopositioning Stage with Chattering_Free Adaptive Sliding Mode Control," IEEE Trans. on Automation Science and Engineering, vol. 14, no. 1, pp. 238-248, 2017.
[48] Y. J. Xu, "Chattering Free Robust Control of Nonlinear Systems," IEEE Trans. on Control Systems Technology, vol. 16, no. 6, pp1352-1359, 2008.
[49] J. H. Lee, "A Proof of Utkin's Theorem for a MI Uncertain Linear Case", KIEE, vol. 59, no. 9, pp. 1680-11685, 2010.

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