논 문
59-7-19

부정합조건 불확실성과 외란을 갖는 비선형 시스템을 위한 비선형 적분형 슬라이딩 면을 갖는 새로운 강인한 가변구조제어기

A New Robust Variable Structure Controller With Nonlinear Integral-Type Sliding Surface for Uncertain More Affine Nonlinear Systems with Mismatched Uncertainties and Disturbance

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Abstract - In this note, a systematic general design of a new robust nonlinear variable structure controller based on state dependent nonlinear form is presented for the control of uncertain affine nonlinear systems with mismatched uncertainties and mismatched disturbance. After an affine uncertain nonlinear system is represented in the form of state dependent nonlinear system, a systematic design of a new robust nonlinear variable structure controller is presented. To be linear in the closed loop resultant dynamics, the nonlinear integral-type sliding surface is applied. A corresponding control input is proposed to satisfy the closed loop exponential stability and the existence condition of the sliding mode on the nonlinear integral-type sliding surface, which will be investigated in Theorem 1. Through a design example and simulation studies, the usefulness of the proposed controller is verified.

Key Words : Uncertain nonlinear system, Variable structure system, Sliding mode control, Mismatched uncertainties

1. Introduction

Stability analysis and controller design for uncertain nonlinear systems is open problems now[1]. So far numerous design methodologies exist for the controller design of nonlinear systems[2]. These include any of a huge number of linear design techniques[3][4] used in conjuction with gain scheduling[5]; nonlinear design methodologies such as Lyapunov function approach[1][2][6][7][10][11], feedback linearization method[8][9][10], dynamics inversion[10], backstepping[11], adaptive technique which encompass both linear adaptive[13] and nonlinear adaptive control[14], and sliding mode control[15]-[26] etc[27]-[29].

The sliding mode control(SMC) can provide the effective means to the problem of controlling uncertain nonlinear systems under parameter variations and external disturbances[15][16][17]. One of its essential advantages is the robust of the controlled system to variations of parameters and external disturbances in the sliding mode on the predetermined sliding surface, $s=0$[18]. In [19], for nonlinear output regulator scheme, sliding mode approach is applied. The underlying concept is that of designing sliding submanifold which contains the zero tracking error submanifold. The convergence to a sliding manifold cab be attained relying on a control strategy still based on a simplex of control vectors are identified for multi input uncertain nonlinear systems in [20]. Lu and Spurgeon in 1997 considered the robustness of dynamic sliding mode control of nonlinear system which are in differential input-out form with additive uncertainties in the model[21]. The discrete-time implementation of a second-order sliding mode control scheme is analyzed for uncertain nonlinear system, in [22]. Flemming surveyed so called soft variable structure controls, compared them to other[23]. For 2nd order uncertain nonlinear system with mismatched uncertainties, a switching control law between a first order sliding mode control and a second order sliding mode control is proposed to obtain the globally or locally asymptotic stability[24]. The optimal SMC for nonlinear system with time-delay is suggested in [25]. The nonlinear time varying sliding sector is designed for a single input nonlinear time varying input affine system which can be represented in the form of state dependent linear time variant system with matched uncertainties[26]. In [30], for uncertain affine nonlinear system with mismatched uncertainties and matched disturbance, the systematic design of the SMC was reported. In [31], the integral

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접수일자 : 2009년 12월 4일
최종완료 : 2010년 3월 4일

action is introduced to the nonlinear VSS with mismatched uncertainties and matched disturbance to improve the output performance.

Until now, a nonlinear controller design for uncertain nonlinear systems with mismatched uncertainties and mismatched disturbance is not presented.

In this technical note, a systematic general design of a new nonlinear variable structure controller based on state dependent nonlinear form is presented for the control of uncertain affine nonlinear systems with mismatched uncertainties and mismatched disturbance. After an affine uncertain nonlinear system is represented in the form of state dependent nonlinear system, a systematic design of a new nonlinear variable structure controller is presented. To be linear in the closed loop resultant dynamics, a nonlinear integral-type sliding surface is applied[32] in order to remove the reaching phase. A corresponding control input is proposed to satisfy the closed loop exponential stability and the existence condition of the sliding mode on the nonlinear integral-type sliding surface, which will be investigated in Theorem 1. Through a design example and simulation studies, the usefulness of the proposed nonlinear VSS controller is verified.

2. A Nonlinear Variable Structure Systems

2.1 Description of plants

Consider an affine uncertain nonlinear system

$$\dot{x}=f'(x,t)+g(x,t)u+d'(x,t), \quad x(0) \tag{1}$$

where $x\in R^n$ is the state, $x(0)$ is its initial state, $u\in R^1$ is the control, $f'(x,t)\in C^k$ and $g(x,t)\in C^k$, $k\geq 1$, $g(x,t)\neq 0$, for $all\, x\in R^n$ and for $all\, t\geq 0$ are of suitable dimensions, and $d'(x,t)$ implies bounded mismatched external disturbances.

Assumption[26]

A1: $f'(x,t)$ is continuously differentiable and $f'(0,t)=0$ for all $t\geq 0$.

Then, uncertain nonlinear system (1) can be represented in more affine nonlinear system of state dependent coefficient form[26]-[28]

$$\begin{aligned}\dot{x}&=f(x,t)x+g(x,t)u+d'(x,t), \quad x(0)\\ &=\left[f_0(x,t)+\triangle f(x,t)\right]x+\left[g_0(x,t)-\triangle g(x,t)\right]u+d'(x,t)\\ &=f_0(x,t)x+g_0(x,t)u+d(x,t)\end{aligned} \tag{2}$$

$$d(x,t)=\triangle f(x,t)x-\triangle g(x,t)u+d'(x,t) \tag{3}$$

where $f_0(x,t)$ and $g_0(x,t)$ is each nominal value such that $f'(x.t)=\left[f_0(x,t)+\triangle f(x,t)\right]x$ and $g(x,t)=\left[g_0(x,t)-\triangle g(x,t)\right]$, respectively, $\triangle f(x,t)$ and $\triangle g(x,t)$ are matched or mismatched uncertainties, and $d(x,t)$ is the mismatched lumped uncertainties.

Assumption:

A2: The pair $(f_0(x,t),g_0(x,t))$ is controllable for $all\, x\in R^n$ and for $all\, t\geq 0$

A3: The lumped uncertainties $d(x,t)$ is bounded

A4: $\ddot{x}$ is bounded if $\dot{u}$ and $\dot{d}'(x,t)$ is bounded.

2.2 Nonlinear Integral-Type Sliding Surface

To control a mismatched uncertain system (1) or (2) with a linear closed loop dynamics, the nonlinear integral-type sliding surface used in this design is introduced as follows[32]:

$$s=C^T\left[x-\int_{-\infty}^{t}A_c x dt\right](=0) \tag{4}$$

where A_c is the closed loop linear system matrix having a desired performance

$$A_c=f_o(x,t)-g_o(x,t)K(x) \tag{5}$$

where $K(x)$ is the state feedback gain, and the initial condition of the integral in the nonlinear integral-type sliding surface is as follows[16][17]:

$$\int_{-\infty}^{0}A_c x dt=x(0) \tag{6}$$

Therefore, at $t=0$, this nonlinear integral-type sliding surface is zero so that there is no reaching phase[32].

In (4), C is a non zero element as the design parameter such that the following assumption is satisfied.

Assumption

A5: $C^T g(x,t)$ and $C^T g_0(x,t)$ have the full rank and are invertible

A6: $C^T\triangle g(x,t)\left[C^T g_0(x,t)\right]^{-1}=\triangle I$ and $|\triangle I|<\delta<1,\ 0<\delta<1.$

The equivalent control input is obtained using $\dot{s}=0$[15] as

$$\begin{aligned}u_{eq}=&-\left[C^T g(x,t)\right]^{-1}C^T f(x,t)x-\left[C^T g(x,t)\right]^{-1}d'(x,t)\\ &+\left[C^T g(x,t)\right]^{-1}C^T A_c x\end{aligned} \tag{7}$$

This control input can not be implemented because of the uncertainties and disturbances. The ideal sliding mode dynamics of the nonlinear integral-type sliding surface (4) can be derived by the equivalent control approach[16] as

$$\begin{aligned}\dot{x}_s=&[f_0(x,t)-g_0(x,t)(C^T g_0(x,t))^{-1}C^T f_0(x,t)]x_s\\ &+g_0(x,t)(C^T g_0(x,t))^{-1}C^T A_c x_s, \quad x_s(0)=x(0)\end{aligned} \tag{8}$$

and from $\dot{s}=0$, the another ideal sliding mode dynamics is obtained as[30]

$$\begin{aligned}\dot{x}_s=A_c x_s&=[f_0(x_s,t)-g_0(x_s,t)K(x_s)]x_s\\ &=f_c(x,t)x, \qquad x_s(0)\end{aligned} \tag{9}$$

The solution of (8) or (9) identically defines the nonlinear integral-type sliding surface. Hence to design the nonlinear integral-type sliding surface as stable, this ideal sliding dynamics (9) is designed to be stable. To choose the stable gain based on the Lyapunov stability theory, the ideal sliding dynamics (9) is represented by the nominal plant of (2) as

$$\begin{aligned}\dot{x}&=f_0(x,t)x+g_0(x,t)u, \qquad u=-K(x)x\\ &=f_c(x,t)x, \quad f_c(x,t)=A_c=f_0(x,t)-g_0(x.t)K(x)\end{aligned} \tag{10}$$

To select the stable gain, take a Lyapunov function candidate as

$$V(x)=\frac{1}{2}x^{T}Px, \qquad P>0 \tag{11}$$

The derivative of (11) becomes

$$\begin{aligned}\dot{V}(x)&=x^{T}\left[f_0(x,t)^{T}P+Pf_0(x,t)\right]x\\&\quad+u^{T}g_0^{T}(x,t)Px+x^{T}Pg_0(x,t)u\end{aligned} \tag{12}$$

If take the control input as

$$u=-g_0^{T}(x,t)Px \tag{13}$$

and $Q(x,t)>0$ for all $x\in R^{n}$ and for all $t\geq 0$ is

$$f_0(x,t)^{T}P+Pf_0(x,t)=-Q(x,t) \tag{14}$$

then

$$\begin{aligned}\dot{V}(x)&=-x^{T}Q(x,t)x-2x^{T}Pg_0(x,t)g_0^{T}(x,t)Px\\&=-x^{T}\left[Q(x,t)+2Pg_0(x,t)g_0^{T}(x,t)P\right]x\\&=-x^{T}\left[f_c^{T}(x,t)P+Pf_c(x,t)\right]x\\&=-x^{T}Q_c(x,t)x, \quad Q_c(x,t)=f_c^{T}(x,t)P+Pf_c(x,t)\\&\leq-\lambda_{\min}\{Q_c(x,t)\}x^{2}\\&\leq 0\end{aligned} \tag{15}$$

Therefore the stable gain is chosen as

$$K(x)=g_0^{T}(x,t)P \text{ or }=\left[C^{T}g_0(x_s,t)\right]^{-1}C^{T}f_0(x_s,t) \tag{16}$$

2.3 Stabilizing Control Input

A corresponding control input is proposed as follows:

$$u=-K(x)x-\triangle Kx-K_1s-K_2sign(s) \tag{17}$$

where $K(x)$ is a nonlinear feedback gain satisfying the relationship (5), $\triangle K$ is a switching gain of the state, K_1 is a feedback gain of the nonlinear integral-type sliding surface, and K_2 is a switching gain, respectively as

$$K(x)=\left[C^{T}g_0(x,t)\right]^{-1}C^{T}f_0(x,t) \text{ or }=g_0^{T}(x,t)P \tag{18}$$

$$\triangle K=\left[C^{T}g_0(x,t)\right]^{-1}\triangle K' \tag{19}$$

$$\triangle k'_j=\begin{cases}\geq\dfrac{\max\left\{C^{T}\triangle f(x,t)+\triangle IC^{T}f_0(x,t)\right\}_j}{\min\{I-\triangle I\}} & sign(sx_j)>0\\[2ex] \leq\dfrac{\min\left\{C^{T}\triangle f(x,t)+\triangle IC^{T}f_0(x,t)\right\}_j}{\min\{I-\triangle I\}} & sign(sx_j)<0\end{cases}$$

$$j=1,\ldots,n \tag{20}$$

$$K_1=\left[C^{T}g_0(x,t)\right]^{-1}K_1', \qquad K_1'>0 \tag{21}$$

$$K_2=\left[C^{T}g_0(x,t)\right]^{-1}K_2' \tag{22}$$

$$K'_2=\frac{\max\{|C^{T}d'(x,t)|\}}{\min\{I-\triangle I\}} \tag{23}$$

The real sliding dynamics by the proposed control (17) with the nonlinear integral-type sliding surface (4) is obtained as follows:

$$\begin{aligned}\dot{s}&=C^{T}(\dot{x}-A_c x)\\&=C^{T}\left[f_0(x,t)x+\triangle f(x,t)x+g(x,t)u+d'(x,t)-A_c x\right]\\&=C^{T}\Big[f_0(x,t)x+\triangle f(x,t)x\\&\quad+g(x,t)\{-K(x)x-\triangle Kx-K_1s-K_2sign(s)\}\\&\quad+d'(x,t)-A_c x\Big]\\&=C^{T}[f_0(x,t)-g_0(x,t)K(x)-A_c]x+C^{T}\triangle f(x,t)x\\&\quad+C^{T}\triangle g(x,t)K(x)x-C^{T}g(x,t)\triangle Kx-C^{T}g(x,t)K_1s\\&\quad+C^{T}d'(x,t)-C^{T}g(x,t)K_2sign(s)\\&=C^{T}\triangle f(x,t)x+C^{T}\triangle g(x,t)K(x)x\\&\quad-[I-\triangle I]C^{T}g_0(x,t)\triangle Kx-[I-\triangle I]C^{T}g_0(x,t)K_1s\\&\quad+C^{T}d'(x,t)-[I-\triangle I]C^{T}g_0(x,t)K_2sign(s)\end{aligned} \tag{24}$$

The closed loop stability by the proposed control input with nonlinear integral-type sliding surface together with the existence condition of the sliding mode will be investigated in next Theorem 1.

Theorem 1: If the nonlinear integral-type sliding surface is designed to be stable, i.e. stable design of $K(x)$ (A_c), the proposed control input with Assumption A1-A6 satisfies the existence condition of the sliding mode on the nonlinear integral-type sliding surface and closed loop exponential stability.

Proof; Take a Lyapunov function candidate as

$$V(x)=\frac{1}{2}s^{T}s \tag{25}$$

Differentiating (25) with respect to time leads to and Substituting (24) into (26)

$$\begin{aligned}\dot{V}(x)&=s^{T}\dot{s}\\&=s^{T}C^{T}\triangle f(x,t)x+s^{T}C^{T}\triangle g(x,t)K(x)x\\&\quad-s^{T}[I-\triangle I]C^{T}g_0(x,t)\triangle Kx\\&\quad-s^{T}[I-\triangle I]C^{T}g_0(x,t)K_1s+s^{T}C^{T}d'(x,t)\\&\quad-s^{T}[I-\triangle I]C^{T}g_0(x,t)K_2sign(s)\\&\leq-\epsilon K_1'\|s\|^{2}, \qquad \epsilon=\|(I-\triangle I)\|\\&=-\epsilon K_1's^{T}s\\&=-2\epsilon K_1'V(x)\end{aligned} \tag{26}$$

From (26), the following equation is obtained as

$$\dot{V}(x)+2\epsilon K_1'V(x)\leq 0 \tag{27}$$

$$V(t)\leq V(0)e^{-2\epsilon K_1't} \tag{28}$$

And the second order derivative of $V(x)$ becomes

$$\ddot{V}(x)=\dot{s}\dot{s}+s\ddot{s}=(\dot{s})^{2}+sC^{T}(\ddot{x}-A_c\dot{x})<\infty \tag{29}$$

and by Assumption A4 $\ddot{V}(x)$ is bounded, which completes the proof of Theorem 1.

3. Design Example and Simulation Studies

Consider a second order affine uncertain nonlinear system with mismatched uncertainties and mismatched disturbance

$$\begin{aligned}\dot{x}_1&=-x_1+x_1\sin^{2}(x_1))+x_2+0.02\sin(2x_1)u+d'_1(x,t)\\\dot{x}_2&=x_2+x_2\sin^{2}(x_2)+(2+0.5\sin(2t))u+d'_2(x,t)\end{aligned} \tag{30}$$

$$d'_1(x,t)=-0.5\sin(x_1)+0.9\sin(x_2)-0.02(x_1^{2}+x_2^{2})-1.5\sin(10t) \tag{31}$$

$$d'_2(x,t)=0.7\sin(x_1)-0.8\sin(x_2)+0.2(x_1^{2}+x_2^{2})+2\sin(5t)+3.0 \tag{32}$$

Since (30) satisfy the Assumption A1, (30) is represented in state dependent coefficient form as

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix}=\begin{bmatrix}-1+\sin^2(x_1) & 1\\ 0 & 1+\sin^2(x_2)\end{bmatrix}x+\begin{bmatrix}0.02\sin(x_1)\\ 2+0.5\sin(2t)\end{bmatrix}u+\begin{bmatrix}d'_1(x,t)\\ d'_2(x,t)\end{bmatrix} \quad (33)$$

where the nominal parameter $f_0(x,t)$ and $g_0(x,t)$ and mismatched uncertainties $\triangle f(x,t)$ and $\triangle g(x,t)$ are

$$f_0(x,t)=\begin{bmatrix}-1 & 1\\ 0 & 1\end{bmatrix},\quad g_0(x,t)=\begin{bmatrix}0\\ 2\end{bmatrix},$$

$$\triangle f(x,t)=\begin{bmatrix}\sin^2(x_1) & 0\\ 0 & \sin^2(x_2)\end{bmatrix},\triangle g(x,t)=\begin{bmatrix}0.02\sin(x_1)\\ 0.5\sin(2t)\end{bmatrix} \quad (34)$$

To design the nonlinear integral-type sliding surface, $A_c=f_c(x,t)$ is selected as

$$A_c=f_c(x,t)=f_0(x,t)-g_0(x.t)K(x)=\begin{bmatrix}-1 & 1\\ -80 & -21\end{bmatrix} \quad (35)$$

in order to have the two stable poles at -15.4721 and -6.5279. The P in (11) is chosen as

$$P=\begin{bmatrix}170 & 20\\ 20 & 5.5\end{bmatrix}>0 \quad (36)$$

so as to be

$$f_c(x,t)^TP+Pf_c(x,t)=\begin{bmatrix}-3540 & -710\\ -710 & -191\end{bmatrix}<0 \quad (37)$$

Hence, the continuous feedback gain is designed as

$$K(x)=g_0^T(x,t)P=[40 \quad 11] \quad (38)$$

The non zero coefficient of the nonlinear integral-type sliding surface is determined as

$$C=[10 \quad 1]^T \quad (39)$$

The selected gains in the control input are as follows:

$$\triangle k_1=\begin{cases}13.25 & \text{if } sx_1>0\\ -13.25 & \text{if } sx_1<0\end{cases},\ \triangle k_2=\begin{cases}11.0 & \text{if } sx_2>0\\ -11.0 & \text{if } sx_2<0\end{cases} \quad (40)$$

$$K_1=10,\ K_2=32.25+0.2(x_1^2+x_2^2) \quad (41)$$

The simulation is carried out under 1[msec] sampling time and with $x(0)=[10 \quad 5]^T$ initial state. Fig. 1 shows the three case output responses of x_1 and x_2 (i) with no uncertainty and no disturbance, (ii) with matched uncertainty and matched disturbance, and (iii) ideal sliding output. The each three output is insensitive to the matched uncertainty and disturbance hence is almost equal, so the output can be predicted by using the ideal sliding output. The three case phase trajectory (i) with no uncertainty and no disturbance, (ii) with matched uncertainty and matched disturbance, (iii) ideal sliding trajectory are shown in Fig. 2. There is no reaching phase and the each phase trajectory is almost identical also. The two case nonlinear integral-type sliding surfaces (i) with no uncertainty and no disturbance and (ii) with matched uncertainty and matched disturbance are depicted in Fig. 3. Fig. 4 shows the two control inputs (i) with no uncertainty and no disturbance and (ii) with matched uncertainty and matched disturbance. The four case output responses of x_1 and x_2 are depicted in Fig. 5 (i) with no uncertainty and no disturbance, (ii) with matched uncertainty and matched disturbance, (iii) ideal sliding output, and (iv) mismatched uncertainty and mismatched disturbance. The output with mismatched uncertainty and disturbance is disturbed by the mismatched uncertainty and disturbance. Fig. 6 shows the four case phase trajectories (i) with no uncertainty and no disturbance, (ii) with matched uncertainty and matched disturbance, (iii) ideal sliding output, and (iv) mismatched uncertainty and mismatched disturbance. The nonlinear integral-type sliding surface (i) mismatched uncertainty and mismatched disturbance are shown in Fig. 7. And Fig. 8 shows the control input (i) mismatched uncertainty and mismatched disturbance. For all (mis)matched uncertainties and (mis)matched disturbance, the controlled system by the proposed control input with the nonlinear integral-type sliding surface possess the good performances in view of no reaching phase and the output prediction as designed(and exponential stability). From the simulation studies, the effectiveness of the proposed nonlinear SMC is proven.

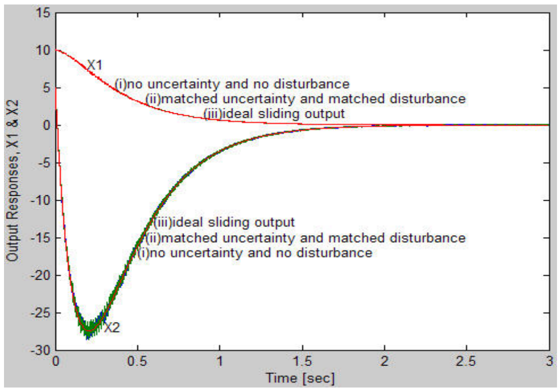

Fig. 1 The three case output responses of x_1 and (ii) x_2 (i) with no uncertainty and no disturbance, (ii) with matched uncertainty and matched disturbance, and (iii) ideal sliding output.

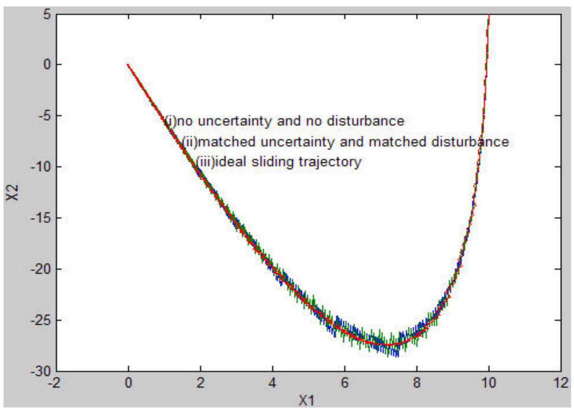

Fig. 2 The three case phase trajectories (i) with no uncertainty and no disturbance, (ii) with matched uncertainty and matched disturbance, and (iii) ideal sliding trajectory.

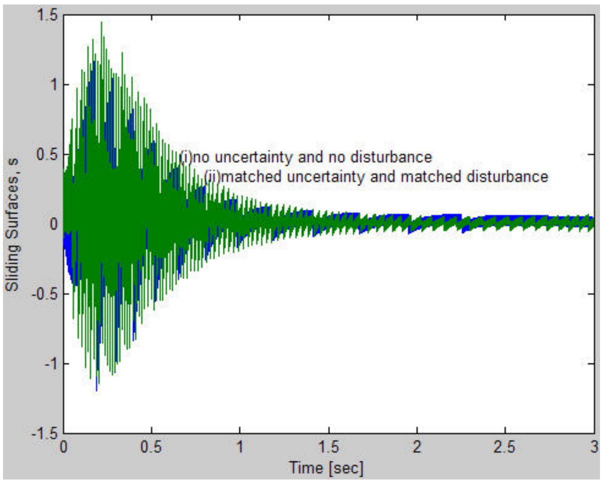

Fig. 3 Two case nonlinear integral-type sliding surfaces (i) no uncertainty and no disturbance and (ii) matched uncertainty and matched disturbance

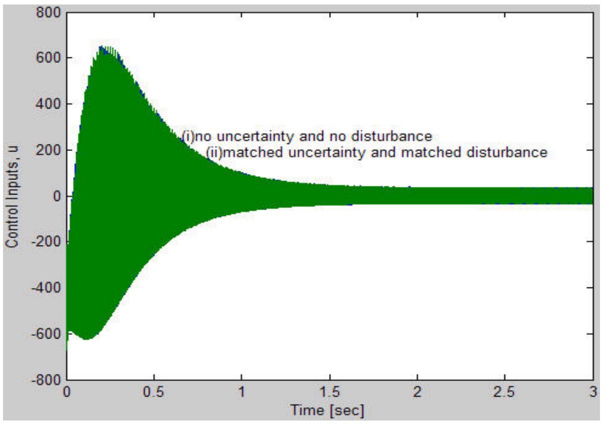

Fig. 4 Two control inputs (i) no uncertainty and no disturbance and (ii) matched uncertainty and matched disturbance

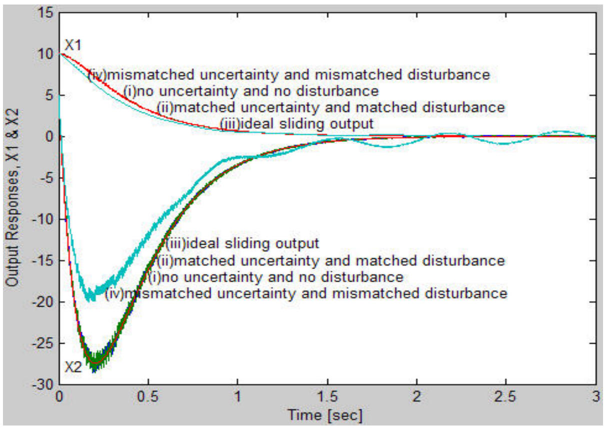

Fig. 5 Four output responses of x_1 and x_2 (iv) mismatched uncertainty and mismatched disturbance

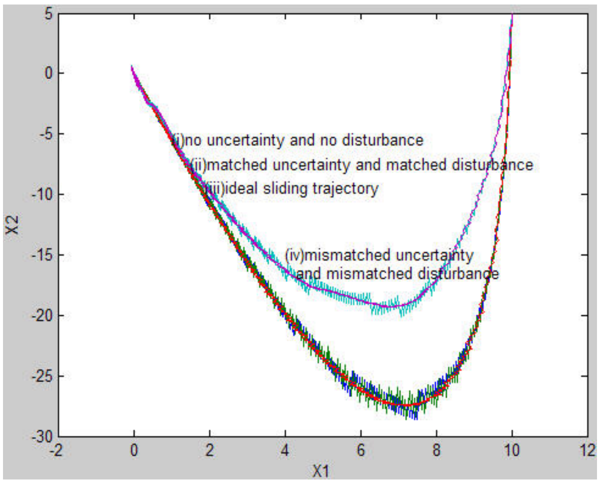

Fig. 6 Four case phase trajectories (iv) mismatched uncertainty and mismatched disturbance

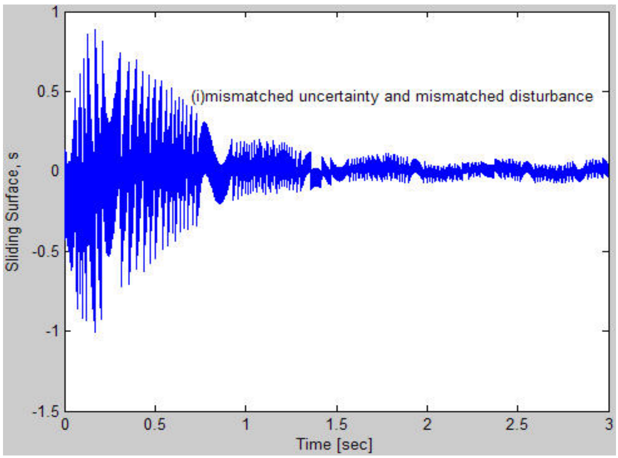

Fig. 7 nonlinear integral-type sliding surface (i) mismatched uncertainty and mismatched disturbance

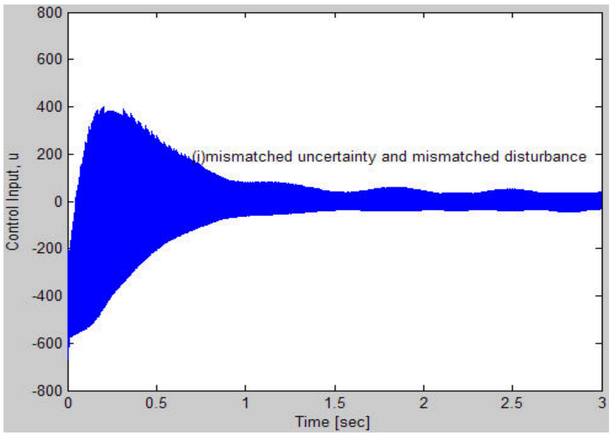

Fig. 8 Control input (i) mismatched uncertainty and mismatched disturbance

4. Conclusions

In this note, a new robust nonlinear variable structure controller with a new nonlinear integral-type sliding surface is presented based on state dependent nonlinear form for the control of uncertain more affine nonlinear systems with mismatched uncertainties and mismatched disturbance. After an affine uncertain nonlinear system is represented in the form of state dependent nonlinear system, a systematic design of a new robust nonlinear variable structure controller with the nonlinear integral-type sliding surface is suggested for removing the reaching phase. A corresponding control input is proposed. The closed loop stability by the proposed control input with nonlinear integral-type sliding surface together with the existence condition of the sliding mode on the selected sliding surface will be investigated in Theorem 1 for all mismatched uncertainties and mismatched disturbance. Through a design example and simulation studies, the usefulness of the proposed controller is verified. The output with matched uncertainty and disturbance is insensitive to the matched uncertainty and disturbance, but the output with mismatched uncertainty and disturbance is disturbed but only robust to the mismatched uncertainty and disturbance.

Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology

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