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A New Robust Integral Variable Structure Controller for Uncertain More Affine Nonlinear Systems with Mismatched Uncertainties

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Abstract - In this note, a systematic design of a new robust nonlinear integral variable structure controller based on state dependent nonlinear form is presented for the control of uncertain more affine nonlinear systems with mismatched uncertainties and matched 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 integral variable structure controller is presented. To be linear in the closed loop resultant dynamics and remove the reaching phase problems, the linear integral sliding surface is suggested. A corresponding control input is proposed to satisfy the closed loop exponential stability and the existence condition of the sliding mode on the linear integral 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, Integral 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 swichting 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]. For uncertain affine nonlinear system with mismatched uncertainties and matched disturbance, the systematic design of the SMC is reported[30]. In [31], using a nonlinear integral of the system dynamics composing the nonlinear system vector and nominal input, a nonlinear integral type sliding surface was proposed by Cao and Xu for both matched and unmatched uncertainty. However to construct that sliding surface, the nominal input is needed. The same type sliding surface was used in [32], the same demerit exists. Chang modified that sliding surface with a dynamic output integral type[33], which is more complex to implement it.

In this technical note, a systematic design of a new nonlinear integral variable structure controller based on

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state dependent nonlinear form is presented for the control of uncertain affine nonlinear systems with mismatched uncertainties and matched disturbance. After an affine uncertain nonlinear system is represented in the form of state dependent nonlinear system, a systematic design of a new nonlinear integral variable structure controller is presented. In order to be linear in the closed loop resultant dynamics and to remove the reaching phase problems, the linear integral sliding surface is suggested without the problems mentioned above, which originally stem from [34]. The merit of the integral sliding surface is that the integral is most simple and there does not need the nominal input to implement. A corresponding control input is proposed to satisfy the closed loop exponential stability and the existence condition of the sliding mode on the linear integral sliding surface, which will be investigated in Theorem 1. Through a design example and simulation studies, the usefulness of the proposed 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 matched 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]

$$\begin{aligned}\dot{X}&=f(X,t)X+g(X,t)U+d'(X,t), \quad X(0) \qquad (2)\\ &=[f_0(X,t)+\triangle f(X,t)]X+[g_0(X,t)+\triangle g(X,t)]U+d'(X,t)\\ &=f_0(X,t)X+g_0(X,t)U+d(X,t)\end{aligned}$$

$$d(X,t)=\triangle f(X,t)X+\triangle g(X,t)U+d'(X,t) \tag{3}$$

where $f_0(X,t)$ and $g_0(X,t)$ is each nominal value such that $f'(X.t)=[f_0(X,t)+\triangle f(X,t)]X$ and $g(X,t)=[g_0(X,t)-\triangle g(X,t)]$, respectively, $\triangle f(X,t)$ and $\triangle g(X,t)$ are matched or mismatched uncertainties, and $d(X,t)$ is the 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 $\dot{U}$ is bounded.

For the use later, the simple integral term $X_0\in R^r$, $r\leq n$ is augmented as

$$X_0=\int_0^t X(\tau)d\tau+\int_{-\infty}^0 X(\tau)d\tau=\int_0^t X(\tau)d\tau+X_0(0) \tag{4}$$

2.2 Integral Sliding Surface

To control uncertain nonlinear system (1) or (2) with a linear closed loop dynamics and without reaching phase, the integral sliding surface used in this design is as follows[34]:

$$S=C^TX+C_0^TX_0=\left[C^T \;\; C_0^T\right]\left[X^T \;\; X_0^T\right]^T(=0) \tag{5}$$

where $X_0(0)=-C_0^{T-}C^TX(0)$. In [31] and [32], there need the nominal input to implement and in [33] the form is more complex. However the sliding surface (5) is most simple and does not need the nominal input to implement. At $t=0$, the integral sliding surface is zero, Hence, there is no reaching phase. In (5), C^T is a nonzero element as the design parameter such that the following assumption is satisfied.

Assumption

A5: $C^Tg(x,t)$ and $C^Tg_0(x,t)$ have the full rank, i,e are invertible

A6: $C^T\triangle g(x,t)\left[C^Tg_0(x,t)\right]^{-1}=\triangle I$ and $|\triangle I|<\delta\leq 1,\ 0<\delta<1.$

In (5), the design parameters C^T and C_0^T are satisfy the following relationship

$$C^T[f_0(X,t)-g_0(X,t)K(X)]+C_0=0 \tag{6a}$$

$$C_0=-C^T[f_0(X,t)-g_0(X,t)K(X)]=-C^Tf_c(X,t) \tag{6b}$$

$$f_c(X,t)=f_0(X,t)-g_0(X,t)K(X) \tag{6c}$$

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

$$\begin{aligned}U_{eq}=&-\left[C^Tg(X,t)\right]^{-1}[C^Tf_0(X,t)+C_0]X\\&-\left[C^Tg(X,t)\right]^{-1}C^T\triangle f(X,t)X-\left[C^Tg(X,t)\right]^{-1}d'(X,t)\end{aligned} \tag{7}$$

This control input can not be implemented because of the uncertainties, but used to obtaining the ideal sliding dynamics. The ideal sliding mode dynamics of the sliding surface (5) can be derived by the equivalent control approach[16] as

$$\dot{X}_s=\left[f_0(X_s,t)-g_0(X_s,t)(C^Tg_0(X_s,t))^{-1}\left\{C^Tf_0(X_s,t)+C_0\right\}\right]X_s \tag{8}$$

$$\dot{X}_s=\left[f_0(X_s,t)-g_0(X_s,t)K(X_s)\right]X_s=f_c(X_s,t)X_s, \tag{9}$$

$$K(X_s)=\left[C^Tg_0(X_s,t)\right]^{-1}\left\{C^Tf_0(X_s,t)+C_0\right\} \tag{10}$$

The solution of (8) or (9) identically defines the integral sliding surface. Hence to design the sliding surface as stable, this ideal sliding dynamics is designed to be stable, the reverse argument also holds. 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

$$\dot{x}=f_0(X,t)X+g_0(X,t)U, \qquad U=-K(X)X \tag{11}$$

$$=f_c(X,t)X, \quad f_c(X,t)=f_0(X,t)-g_0(X.t)K(X) \tag{12}$$

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

$$V(X) = \frac{1}{2}X^T PX, \qquad P > 0 \tag{13}$$

The derivative of (10) becomes

$$\begin{aligned}\dot{V}(X) &= X^T\left[f_0(X,t)^T P + Pf_0(X,t)\right]X \\ &\quad + U^T g_0^T(X,t)PX + X^T Pg_0(X,t)U\end{aligned} \tag{14}$$

If take the control input as

$$U = -g_0^T(X,t)PX \tag{15}$$

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

$$f_0(X,t)^T P + Pf_0(X,t) = -Q(X,t) \tag{16}$$

then

$$\begin{aligned}\dot{V}(X) &= -X^T Q(X,t)X - 2X^T Pg_0(X,t)g_0^T(X,t)PX \\ &= -X^T\left[Q(X,t) + 2Pg_0(X,t)g_0^T(X,t)P\right]X \\ &= -X^T\left[f_c^T(X,t)P + Pf_c(X,t)\right]X \\ &= -X^T Q_c(X,t)X, \ \ Q_c(X,t) = f_c^T(X,t)P + Pf_c(X,t) \\ &\leq -\lambda_{\min}\{Q_c(X,t)\}X^2 \\ &\leq 0\end{aligned} \tag{17}$$

Therefore the stable gain is chosen as

$$K(X) = g_0^T(X,t)P \ \ \text{or} = \left[C^T g_0(X_s,t)\right]^{-1}\left\{C^T f_0(X_s,t) + C_0\right\} \tag{18}$$

2.3 Stabilizing Control Input

The corresponding control input is proposed as follows:

$$U = -K(X)X - \triangle KX - K_1 S - K_2 sign(S) \tag{19}$$

where $K(X)$ is a nonlinear feedback gain, $\triangle K$ is a switching gain, K_1 is a feedback gain of the sliding surface, and K_2 is a switching gain, respectively as

$$K(X) = \left[C^T g_0(X,t)\right]^{-1}\left\{C^T f_0(X,t) + C_0\right\} \ \text{or} = g_0^T(X,t)P \tag{20}$$

$$\triangle K = \left[C^T g_0(X,t)\right]^{-1}\triangle K' \tag{21}$$

$$\triangle k'_j = \begin{cases} \geq \dfrac{\max\left\{C^T\triangle f(X,t) - C^T\triangle gK(X)\right\}_j}{\min\{I - \triangle I\}} & sign(SX_j) > 0 \\ \leq \dfrac{\min\left\{C^T\triangle f(X,t) - C^T\triangle gK(X)\right\}_j}{\min\{I - \triangle I\}} & sign(SX_j) < 0 \end{cases}$$

$$j = 1, \ldots, n \tag{22}$$

$$K_1 = \left[C^T g_0(X,t)\right]^{-1}K_1', \qquad K_1' > 0 \tag{23}$$

$$K_2 = \left[C^T g_0(X,t)\right]^{-1}K_2' \tag{24}$$

$$K'_2 = \frac{\max\left\{C^T d'(X,t)\right\}}{\min\{I - \triangle I\}} \tag{25}$$

The real sliding dynamics by the proposed control with the linear integral sliding surface is obtained as follows:

$$\begin{aligned}\dot{S} &= C^T\dot{X} + C_0^T X \\ &= C^T\left[f_0(X,t)X + \triangle f(X,t)X + g(X,t)U + d'(X,t)\right] + C_0^T X \\ &= C^T\left[\begin{matrix} f_0(X,t)X + \triangle f(X,t)X \\ + g(X,t)\left\{\begin{matrix} -K(X)X - \triangle KX \\ -K_1 S - K_2 sign(S)\end{matrix}\right\} + d'(X,t)\end{matrix}\right] + C_0^T X \\ &= C^T f_0(X,t)X - C^T g_0(X,t)K(X)X + C_0^T X + C^T\triangle f(X,t)X \\ &\quad - C^T\triangle g(X,t)K(X)X - C^T g(X,t)\triangle KX - C^T g(X,t)K_1 S \\ &\quad + C^T d'(X,t) - C^T g(X,t)K_2 sign(S) \\ &= C^T\triangle f(X,t)X - C^T\triangle g(X,t)K(X)X \\ &\quad - [I - \triangle I]\,C^T g_0(X,t)\triangle KX - [I - \triangle I]\,C^T g_0(X,t)K_1 S \\ &\quad + C^T d'(X,t) - [I - \triangle I]\,C^T g_0(X,t)K_2 sign(S)\end{aligned} \tag{26}$$

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

Theorem 1: *If the sliding surface is designed in the stable, i.e. stable design of $K(X)$, the proposed input with Assumption A1-A6 satisfies the existence condition of the sliding mode on the integral sliding surface and exponential stability.*

Proof; Take a Lyapunov function candidate as

$$V(X) = (1/2)S^T S \tag{27}$$

Differentiating (27) with respect to time leads to and substituting (26) into (28)

$$\begin{aligned}\dot{V}(X) &= S^T\dot{S} \\ &= S^T C^T\triangle f(X,t)X - S^T C^T\triangle g(X,t)K(X)X \\ &\quad - S^T[I - \triangle I]\,C^T g_0(X,t)\triangle KX \\ &\quad - S^T[I - \triangle I]\,C^T g_0(X,t)K_1 S + S^T C^T d'(X,t) \\ &\quad - S^T[I - \triangle I]\,C^T g_0(X,t)K_2 sign(S) \\ &\leq -\epsilon K_1'\|S\|^2, \qquad \epsilon = \|(I - \triangle I)\| \\ &= -\epsilon K_1' S^T S \\ &= -2\epsilon K_1' V(X)\end{aligned} \tag{28}$$

From (25), the following equation is obtained as

$$\dot{V}(X) + 2\epsilon K_1' V(X) \leq 0 \tag{29}$$

$$V(t) \leq V(0)e^{-2\epsilon K_1' t} \tag{30}$$

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

$$\ddot{V}(X) = \dot{S}\cdot\dot{S} + S\cdot\ddot{S} = (\dot{S})^2 + S(C^T\ddot{X} + C_0^T\dot{X}) < \infty \tag{31}$$

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 matched disturbance

$$\dot{X}_1 = -X_1 + 0.1X_1\sin^2(X_1)) + X_2 + 0.02\sin(2X_1)U$$

$$\dot{X}_2 = X_2 + X_2\sin^2(X_2) + (2 + 0.5\sin(2t))U + d(X,t) \tag{32}$$

$$\begin{aligned}d(X,t) &= 0.7\sin(X_1) - 0.8\sin(X_2) \\ &\quad + 0.2(X_1^2 + X_2^2) + 2\sin(5t) + 3.0\end{aligned} \tag{33}$$

Since (29) satisfy the Assumption A1, (29) is represented in state dependent coefficient form as

$$\begin{aligned}\begin{bmatrix}\dot{X}_1 \\ \dot{X}_2\end{bmatrix} &= \begin{bmatrix}-1 + 0.1\sin^2(X_1) & 1 \\ 0 & 1 + \sin^2(X_2)\end{bmatrix}X \\ &\quad + \begin{bmatrix}0.02\sin(X_1) \\ 2 + 0.5\sin(2t)\end{bmatrix}U + \begin{bmatrix}0 \\ d(X,t)\end{bmatrix}\end{aligned} \tag{31}$$

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

$$f_0(X,t)=\begin{bmatrix}-1 & 1\\ 0 & 1\end{bmatrix},\ g_0(X,t)=\begin{bmatrix}0\\2\end{bmatrix}, \triangle g(X,t)=\begin{bmatrix}0.02\sin(X_1)\\ 0.5\sin(2t)\end{bmatrix}$$

$$\triangle f(X,t)=\begin{bmatrix}0.1\sin^2(X_1) & 0\\ 0 & \sin^2(X_2)\end{bmatrix}, \tag{32}$$

To design the integral sliding surface, $f_c(X,t)$ is selected as

$$f_c(X,t)=f_0(X,t)-g_0(X,t)K(X)=\begin{bmatrix}-1 & 1\\ -30 & -21\end{bmatrix} \tag{33}$$

in order to have the two poles at -19.3666 and -2.6334. Hence, the feedback gain $K(X)$ becomes

$$K(X)=[15 \quad 11] \tag{34}$$

The P in (13) is chosen as

$$P=\begin{bmatrix}15 & 7.5\\ 7.5 & 5.5\end{bmatrix}>0 \tag{34}$$

so as to be

$$f_c(X,t)^T P+Pf_c(X,t)=\begin{bmatrix}-480 & -315\\ -315 & -216\end{bmatrix}<0 \tag{35}$$

Hence, the continuous feedback gain is chosen as

$$K(X)=g_0^T(X,t)P=[15 \quad 11] \tag{36}$$

Therefore, the coefficient of the sliding surface is determined as

$$C=[2 \quad 1]^T \tag{37}$$

Then, to satisfy the relationship (6), C_0 is selected as

$$C_0=-C^T f_c(X)=\begin{bmatrix}C_1+30C_2\\ -C_1+21C_2\end{bmatrix}=\begin{bmatrix}32\\19\end{bmatrix} \tag{38}$$

The selected gains in the control input are as follows:

$$\triangle k_1=\begin{cases}27 & \text{if } SX_1>0\\ -27 & \text{if } SX_1<0\end{cases},\quad \triangle k_2=\begin{cases}9 & \text{if } SX_2>0\\ -9 & \text{if } SX_2<0\end{cases} \tag{39}$$

$$K_1=6,\ K_2=1.8+0.1(X_1^2+X_2^2) \tag{40}$$

The simulation is carried out under 1[msec] sampling time and with $X(0)=[5 \quad 1]^T$ initial state. Fig. 1 shows four case X_1 and X_2 time trajectories (i) ideal sliding

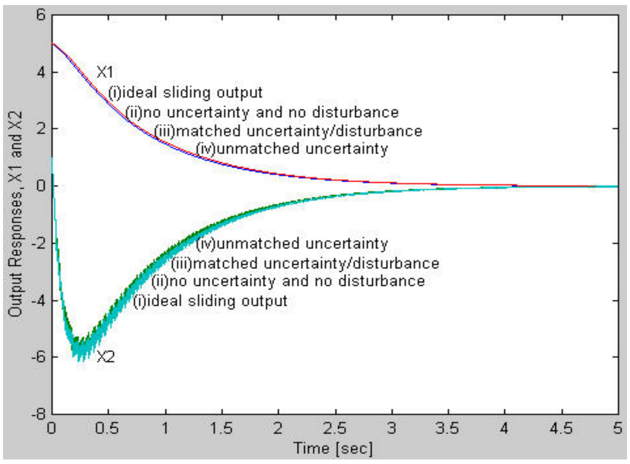

Fig. 1 X_1 and X_2 time trajectories (i) ideal sliding output, (ii) no uncertainty and nodisturbance (iii)matched uncertainty/disturbance, and (iv) unmatched uncertainty and matched disturbance

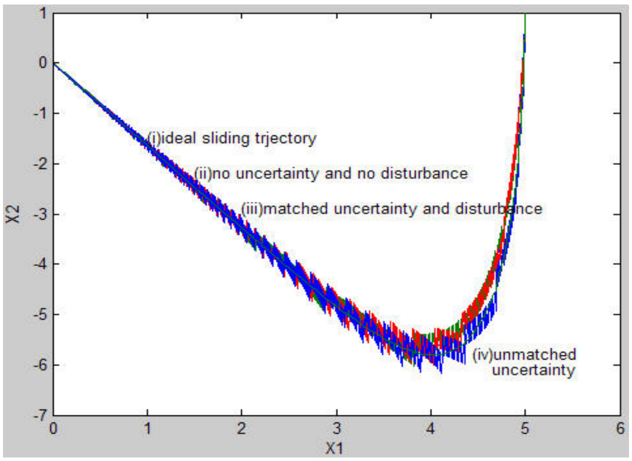

Fig. 2 Four phase trajectories (i) ideal sliding trajectory, (ii) no uncertainty and no disturbance (iii) matched uncertainty/disturbance, and (iv) unmatched uncertainty and matched disturbance

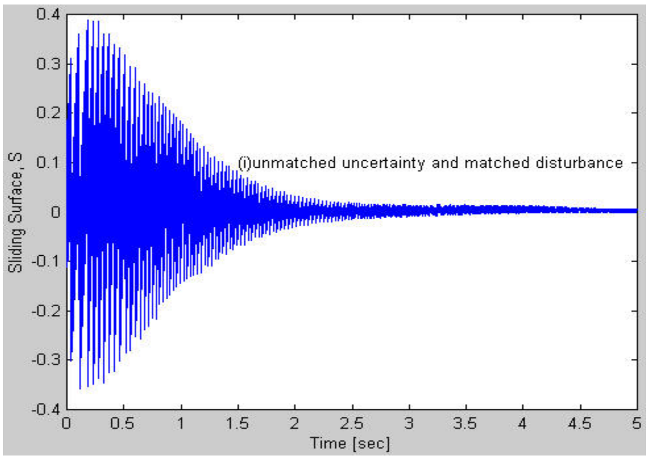

Fig. 3 Sliding surface (i) unmatched uncertainty and matched disturbance

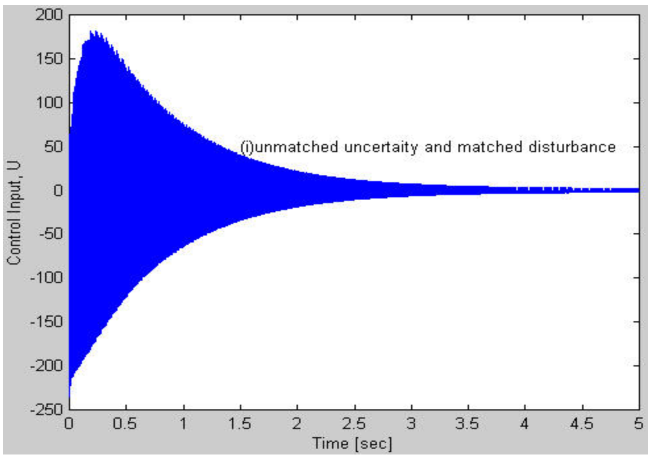

Fig. 4 Control input (i) unmatched uncertainty and matched disturbance

output, (ii) no uncertainty and no disturbance (iii)matched uncertainty/disturbance, and (iv) unmatched uncertainty and matched disturbance. The four case outputs are almost identical to each other. The four phase trajectories (i) ideal sliding trajectory, (ii) no uncertainty and no disturbance (iii)matched uncertainty/disturbance, and (iv) unmatched uncertainty and matched disturbance are depicted in Fig. 2. As can be seen, there is no reaching phase, only sliding from the initial condition. The unmatched uncertainties influence on the ideal sliding dynamics as in the case (iv). The sliding surface $S(t)$ (i) unmatched uncertainty and matched disturbance is shown in Fig. 3. The control input (i) unmatched uncertainty and matched disturbance is depicted in Fig. 4. From the simulation studies, the usefulness of the proposed SMC is proven.

4. Conclusions

In this note, a systematic design of a new robust nonlinear integral variable structure controller based on state dependent nonlinear form is presented for the control of uncertain more affine nonlinear systems with mismatched uncertainties and matched 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 integral variable structure controller with the linear integral sliding surface is suggested for removing reaching phase problems. A corresponding control input is proposed. The closed loop exponential stability by the proposed control input with linear integral sliding surface together with the existence condition of the sliding mode on the selected integral sliding surface is investigated in Theorem 1 for all mismatched uncertainties and matched disturbance. Through a design example and simulation studies, the usefulness of the proposed controller is verified.

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