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A New Improved Integral Variable Structure Systems for Uncertain Systems

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ABSTRACT

A new improved variable structure controller is designed to drive uncertain linear systems to any given point by using a sliding surface with an integral of state error for removing any reaching phase. Predetermination or prediction of output response is feasible for all the persistent disturbances. The usefulness of the proposed algorithm is verified through an illustrative example.

1. Introduction

The theory of the variable structure system (VSS) or sliding mode control (SMC) can provide the effective means to the problem of controlling uncertain dynamical systems under parameter variations and external disturbances [1-5,23]. Many design algorithms including the linear(optimal control[6,7], eigenstructure assignment[8,9], geometric approach[10], differential geometric approach[11], Lyapunov approach[29]) and nonlinear[12,22] techniques are reported. Moreover, an integral action also had augmented by two groups. One is to improve the steady state performance[7,13,14] against the external disturbances in the digital implementation of the VSS, and the other aims to reduce the chattering problems by filtering the discontinuous input through integral operation[15].

Unfortunately, most of these existing VSS's have the reaching phase, which reduce the robustness of the control systems[18].

Many alleviation methods for the reaching phase problems are reported, high-gain feedback[19], adaptive rotating or shifting of the sliding surface[2,20], segmented sliding surface[21], augmentation of exponential term[22,23], and Park's[30]. However, these methods have merits and disadvantages.

In this paper, a new integral variable structure controller(IVSC) is suggested for the control of uncertain general linear systems to any given point with predetermination/prediction of output response. An example is presented to show the effectiveness of the algorithm compared with the typical VSS having the conventional linear sliding surface.

2. Integral-Augmented Variable Structure Systems

2.1 Description of plants

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

$$\dot{X}(t) = (A+\Delta A)X(t) + (B+\Delta B)u(t) + Df(t), \qquad X(t_0)$$
$$y = EX(t) \tag{1}$$

where $X(\cdot)\in R^n$, $u \in R$, and $f \in R^r$ are the state, control, disturbance, $\Delta A, \Delta B, D$ are the bounded uncertainties and the disturbance matrix and satisfy

$$\Re(\Delta A),\ \Re(\Delta B),\ \text{and}\ \Re(D) \in \Re(B) \tag{2}$$

The purpose of the controller design is to regulate the plant to the output(state) of a plant (1) to any value $y_r\,(x_r,\, y_r = Ex_r)$ for all the uncertainties and disturbances by using the sliding mode control. By state transformation, $z = Px$ a canonical form is obtained as,

$$\dot{Z}(t) = \Lambda Z(t) + \Gamma u(t) + \Gamma h(t), \qquad Z(t_0) \tag{3}$$
$$y = EP^{-1}Z(t)$$

where

$$\Lambda = PAP^{-1} = \begin{bmatrix} 0 & 1 & 1 & \Lambda & 0 \\ 0 & 0 & 1 & \Lambda & 0 \\ M & M & M & M & M \\ -\alpha_1 & -\alpha_2 & -\alpha_3 & \Lambda & -\alpha_n \end{bmatrix} \Gamma = PB = \begin{bmatrix} 0 \\ M \\ 0 \\ 1 \end{bmatrix} \tag{4}$$

$Z(t_0)$ and $h(t)$ are a transformed initial condition and lumped uncertainty, respectively.

2.2 Design of Integral sliding Surfaces

To design the IVSC, the sliding surface in error coordinate system is suggested to the following form having an integral of state as

$$\begin{aligned} S_p(Z,t) &= C_{Z0}[\int_0^t (Z-Z_r)dt + \int_{-\infty}^0 (Z-Z_r)dt] \\ &\quad + c_1(z_1(t)-z_{1r}) + \Lambda + c_n(z_n(t)-z_{nr}) \\ &= C_{Z0}[\int_0^t (Z-Z_r)dt + \int_{-\infty}^0 (Z-Z_r)dt] \\ &\quad + C_{Z1}(Z(t)-Z_r) = 0 \end{aligned} \tag{5}$$

$$\begin{aligned} S_p(X,t) &= C_{X0}[\int_0^t (X-X_r)dt + \int_{-\infty}^0 (X-X_r)dt] \\ &\quad + C_{X1}(X(t)-X_r) = 0 \end{aligned} \tag{6}$$

where coefficient matrices

$$C_{Z1} = [c_1 \quad c_2 \quad \Lambda \quad c_n] \in \aleph^{1\times n}, \quad c_n = 1$$

$$C_{X0} = C_{Z0}P, \qquad C_{X1} = C_{Z1}P \in R^{1\times n} \tag{7}$$

$$C_{Z0}\int_{-\infty}^0 (Z-Z_r)dt] = C_{Z1}(Z_r - Z(t_0)) \quad C_{X0}\int_{-\infty}^0 (X-X_r)dt] = C_{X1}(X_r - X(t_0)) \tag{8}$$

From $\dot{S}_p(Z,t)=0$, (3), and (4)

$$\begin{aligned} \dot{z}_n(t) &= -C_{Z0}(Z-Z_r) - [0 \quad c_1 \quad \Lambda \quad c_{n-1}]\cdot Z(t) \\ &= -C_Z Z(t) + C_{Z0}Z_r \end{aligned} \tag{9}$$

where

$$C_Z = [c_{z1} \quad c_{z2} \quad \Lambda \quad c_{zn}] = C_{Z0} + [0 \quad c_{z1} \quad \Lambda \quad c_{zn-1}] \tag{10}$$

is obtained. The initial condition for the integral state in (5) and (6) are selected for removing the reaching phase from the beginning as (8). Finally combing (9) with (3) leads to the ideal sliding dynamics:

$$\dot{Z}_s(t) = \Lambda_c Z_s(t) + \Gamma C_{Z0}Z_r, \qquad Z_s(t_0) = Z(t_0) \tag{11}$$

and

$$\dot{X}_s(t) = P^{-1}\Lambda_c P X_s(t) + P^{-1}\Gamma C_{Z0}PX_r, \; X_s(t_0) = X(t_0) \tag{12}$$

where

$$\Lambda_c = \begin{bmatrix} O^{(n-1)\times 1} & I^{(n-1)\times(n-1)} \\ & -C_Z \end{bmatrix} \tag{13}$$

which can be considered as a dynamic representation of the sliding surface (5) or (6). In order to apply the well-studied linear regulator theories to choosing the ideal sliding dynamics, (11) and (12) are transformed to the nominal from of (3)

$$\begin{aligned} \dot{Z}_s(t) &= \Lambda Z_s(t) + \Gamma u_s(Z_s, t) + \Gamma C_{Z0}Z_r \\ u_s(Z_s, t) &= -GZ_s(t) \end{aligned} \tag{14}$$

where

$$\Lambda_c = \Lambda - \Gamma G \tag{15}$$

and

$$\begin{aligned} \dot{X}_s(t) &= AX_s(t) + Bu_s(X_s, t) + BC_{Z0}PX_r \\ u_s(X_s, t) &= -GPX_s(t) = -KX_s(t) \end{aligned} \tag{16}$$

where

$$P^{-1}\Lambda_c P = A - BK$$

In steady state, the condition for the gain

$$\Gamma G = \Lambda + \Gamma C_{Z0} \quad \text{and} \quad BK = A + BC_{Z0}P \tag{17}$$

are satisfied. After determining K or G to have a desired ideal sliding dynamics, the coefficient matrix of the new surface (5) or (6) can be directly determined from the relationship:

$$\begin{aligned} C_Z &= [c_{Z0_1} \quad c_{Z0_2} + c_{Z1} \quad \Lambda \quad c_{Z0_n} + c_{Z1_{n-1}}] \\ &= [\alpha_1 \quad \alpha_2 \quad \Lambda \quad \alpha_n] + G \\ &= [\alpha_1 \quad \alpha_2 \quad \Lambda \quad \alpha_n] + KP^{-1} \end{aligned} \tag{18}$$

$$C_{Z0} = C_Z \tag{19}$$

which is derived from (15) and (17). If one design the desired performance using the nominal plant (14) or (16) based on the previously well developed linear feedback theories, then, the sliding surface having exactly that performance can be effectively chosen using (18) or (19).

2.3 Control Inputs and Stability Analysis

Now, as the second design phase, a following control input to generate the sliding mode on the selected sliding surface is proposed as

$$\begin{aligned} u(t) &= -(C_{X1}B)^{-1}[C_{X0}(X-X_r) + C_{X1}AX(t)] \\ &\quad - (C_{X1}B)^{-1}[\sum_{i=1}^n \rho_{1_i}|x_i - x_{i_r}| + \rho_2\|X\| + \rho_3]\mathrm{sgn}(S_p) \end{aligned} \tag{20}$$

with the positive constant gains satisfying the inequalities:

$$\begin{aligned} \rho_{1_i} &> |c_{X0_i}|\frac{\max\{|C_{X1}\Delta B|\}}{1-\max\{|C_{X1}\Delta B|\}/|C_X B|}, \quad i = 1,2,\ ,n \\ \rho_2 &> \frac{\max\{|C_{X1}\Delta A|\}}{1-\max\{|C_{X1}\Delta B|\}/|C_{X1}B|} \\ \rho_3 &> \frac{\max\{|C_{X1}Df(t)|\}}{1-\max\{|C_{X1}\Delta B|\}/|C_{X1}B|} \end{aligned} \tag{21}$$

and the necessary constraint is imposed on the uncertain bound of $\Delta B(t)$

$$1 > \max\{|C_{X1}\Delta B|\}/|C_{X1}B| \tag{22}$$

This control input (21) can be practically implemented for more general uncertain systems (1). And the obtainable performance can be state in next theorem.

Theorem 1: *The proposed feasible variable structure controller with the input (20) and the modified sliding surface (6) can exhibit the ideal output of the sliding mode dynamics, (14) or (16), defined by the modified sliding surface (6).*

Proof: The real dynamics of the sliding surface by the new control input can be obtained as

$$\begin{aligned} \dot{S}_p(X,t) &= C_{X0}(X-X_r) + C_{X1}\dot{X} = C_0(X-X_r) \\ &\quad + C_{X1}\{(A+\Delta A)X(t) + (B+\Delta B)u(t) + Df(t)\} \end{aligned} \tag{23}$$

Substituting (20) into (23) leads to

$$\begin{aligned} \dot{S}_p(X,t) &= C_{X1}\Delta AX(t) - C_{X1}\Delta B(C_{X1}B)^{-1}[C_0(X-X_r) \\ &\quad + C_{X1}AX(t)] - C_{X1}(B+\Delta B)(C_{X1}B)^{-1}[\sum_{i=1}^n \rho_{1_i}(x_i - x_{i_r}) \\ &\quad + \rho_2\|x\| + \rho_3]\mathrm{sgn}(S_p) + C_{X1}Df(t) \end{aligned}$$

$$\dot{S}_p(X,t) = -C_{X1}\Delta B(C_{X1}B)^{-1}C_0(X-X_r) - C_X\Delta AX(t)$$
$$-C_{X1}(B+\Delta B)(C_{X1}B)^{-1}\sum_{i=1}^{n}\rho_{1_i}(x_i - x_{ir})\operatorname{sgn}(S_p)$$
$$-C_{X1}(B+\Delta B)(C_{X1}B)^{-1}\rho_2\|X\|\operatorname{sgn}(S_p)$$
$$-C_{X1}Df(t) - C_{X1}(B+\Delta B)(C_{X1}B)^{-1}\rho_3\operatorname{sgn}(S_p) \quad (24)$$

To stabilize the dynamics of the sliding surface in (24), the condition (23) is naturally necessary. From the inequalities of gain (22), it can be easily shown that the existence condition of the sliding mode

$$S_p(X,t)\cdot\dot{S}_p(X,t) < 0 \quad (25)$$

is satisfied. Thus the control in this paper can generate the sliding mode at every point on the modified sliding surface with a feasible form. Therefore, the output trajectory of the proposed controller can be identical to that of the ideal sliding mode dynamics from a given initial state to origin defined by the new sliding surface because of the insensitivity of the controlled system to uncertain parameters and disturbances in the sliding mode[31].

3. Design Examples and Simulation Studies

Consider the following plant with uncertainties and disturbance

$$\dot{x}_1(t) = (-2+\Delta a_1)x_1(t) + (1+\Delta b_1(t))u(t) + f(t)$$
$$\dot{x}_2(t) = \Delta a_1 x_1(t) - 3x_2(t) + (1+\Delta b_2(t))u(t) + f(t)$$
$$y = [2 \quad 1][x_1 \quad x_2]^T \quad (26)$$

where

$$\Delta a_1(t) = 3\sin(8t),\ \Delta b_1(t) = \Delta b_2(t) = 0.3\cos(5t),\ f(t) = 0.5\cos(6t)$$
$$|\Delta a_1(t)| \le 3,\ |\Delta b_1(t)| = |\Delta b_2(t)| \le 0.3,\ |f(t)| \le 0.5. \quad (27)$$

The controller is aim to drive the output of the plant (26) to any y_r. In the steady state, the state should be $Z_r = [1 \quad 0]^T y_r$ and $X_r = [3/8 \quad 1/4]^T y_r$ due to the steady state condition. The transformation matrix to a controllable canonical form and the resultant transformed system matrices are

$$P = \begin{bmatrix} 1 & -1 \\ -2 & 3 \end{bmatrix} \quad \Lambda = \begin{bmatrix} 0 & 1 \\ -6 & -5 \end{bmatrix} \quad \Gamma = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (28)$$

By means of Ackermanns formula, the gain is obtained as

$$K = [0.75 \quad 0.25] \text{ and } G = [1.75 \quad 1.00] \quad (29)$$

for desired poles in Λ_c are located at −2.5 and -3.5. By the relationship (18) and (19), the coefficient of the new sliding surface directly becomes such that the closed loop eigenvalues of

$$C_n = [\alpha_1 \quad \alpha_2] + G = [6 \quad 5] + [1.75 \quad 1.00]$$
$$= [8.75 \quad 6.00] = C_{z0} \quad (30)$$
$$C_{Z0} = [8.75 \quad 6],\quad C_{z1} = [0 \quad 1],$$
$$C_{X0} = C_{Z0}P = [-3.25 \quad 9.25],\quad C_{X1} = C_{Z1}P = [-2 \quad 3] \quad (31)$$

and finally the new sliding surface become

$$S(X,t) = -3.25[\int_0^t (x_1 - x_{1r})dt + (2/3.25)(x_{1r} - x_1(0))]$$
$$+9.25[\int_0^t (x_2 - x_{2r})dt + (3/9.25)(x_{2r} - x_2(0))]$$
$$-2(x_1 - x_{1r}) + 3(x_2 - x_{r2}) \quad (32)$$

For the second design phase of the IVSC,

$$C_{X1}B = 1,\quad C_{X1}\Delta B = 0.3\cos(5t)$$
$$1 - \max\{C_{X1}\Delta B\}/|C_{X1}B| = 0.7 \quad (33)$$

are obtained. The condition (22) is satisfied in this design. The inequalities for the gains in discontinuous input term, (25) become that the constraint on

$$\rho_{11} > |c_{X0_1}|\frac{\max\{|C_{X1_1}\Delta B|\}}{1-\max\{|C_{X1}\Delta B|\}/|C_{X1}B|} = 3.25\frac{0.3}{0.7} = 1.393$$
$$\rho_{12} > |c_{X0_2}|\frac{\max\{|C_{X1}\Delta B|\}}{1-\max\{|C_{X1}\Delta B|\}/|C_{X1}B|} = 9.25\frac{0.3}{0.7} = 3.964$$
$$\rho_2 > \frac{\max\{|C_{X1}\Delta A|\}}{1-\max\{|C_{X1}\Delta B|\}/|C_{X1}B|} = \frac{3}{0.7} = 4.286 \quad (34)$$
$$\rho_3 > \frac{\max\{|C_X Df(t)|\}}{1-\max\{C_X\Delta B|\}/|C_XB|} = \frac{0.5}{0.7} = 0.714$$

The control gains are selected as

$$\rho_{11} = 2 \quad \rho_{12} = 5 \quad \rho_2 = 7 \text{ and } \rho_3 = 4 \quad (35)$$

and finally, the following control input is obtained to satisfy the existence condition of the sliding mode as

$$u(t) = -[-3.25(x_1 - x_{1r}) + 9.25(x_2 - x_{2r}) + 4x_1 - 9x_2]$$
$$-[2|x_1 - x_{1r}| + 5|x_2 - x_{2r}| + 7\|X\| + 4]\operatorname{sgn}(S_p) \quad (36)$$

Fig. 1 shows the ideal output and real output from $y(0) = -2 = [2 \quad 1][-0.5 \quad -1]^T$ to $y_r = 2$. The ideal and real state responses by the proposed SMC are shown in Fig. 2. As can be seen, the trajectories identically equal to those of the ideal sliding output. The phase portrait is presented in Fig. 3. There is no reaching phase. The integral state of output error is depicted in Fig. 4. The fact of no reaching phase can be also found in Fig. 5 showing that the value of the new simple sliding surface chatters from the initial time without any reaching action. And this is fundamentally resulted from the switching of the implemented control input from the initial time as shown in Fig. 6 as designed. Fig.7 shows the output responses to the two different commnads, $y_r = 5$ and 10

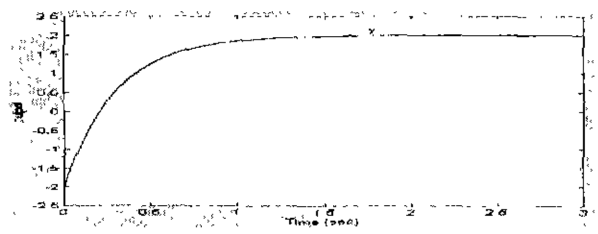

Fig. 1 Ideal and real output responses

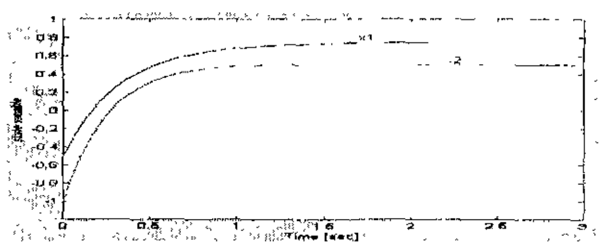

Fig. 2 Ideal and real state responses

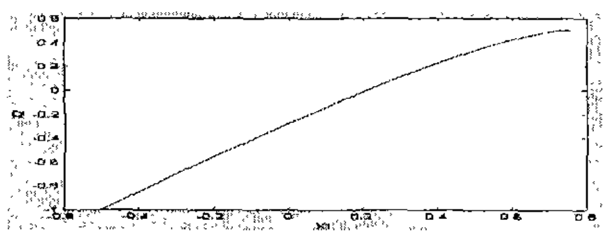

Fig. 3 Phase portrait

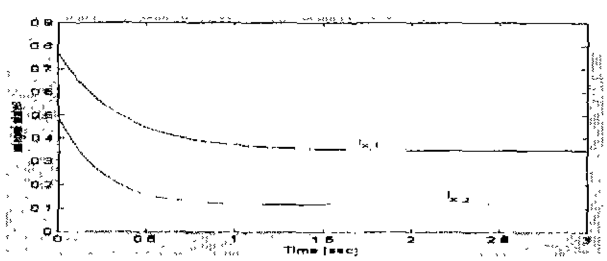

Fig. 4 Integral states

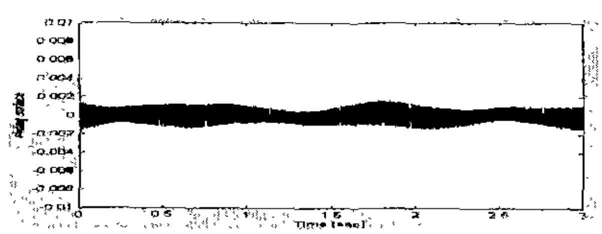

Fig. 5 Sliding surface

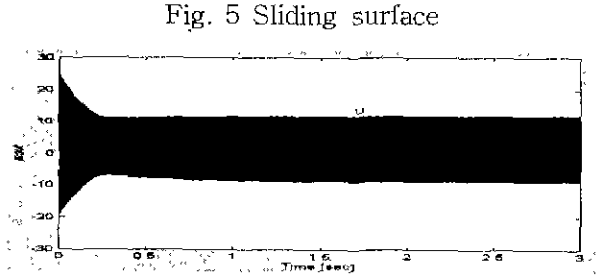

Fig. 6 Control input

4. Conclusions

In this paper, a design of an IVSC is

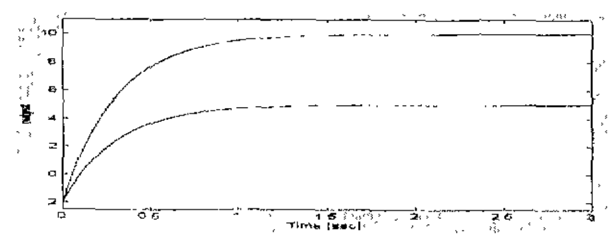

Fig. 7 Two outputs for different commands

presented to control uncertain linear systems under persistent disturbances to a given desired output. This algorithm basically concerns with removing the reaching phase and application to *uncertain non-canonical linear systems*. To successfully remove the reaching phase problems, a sliding surface augmented by an integral of state is suggested to define the hyper plane from any given initial condition to a given desired output. For the design of its sliding dynamics, the system is transformed to a canonical domain and the ideal sliding dynamics is obtained. After choosing the desired performance by means of any well developed linear regulator theories, the integral sliding surface is determined to have exactly that performance from a given initial condition. A corresponding control input is also designed to completely guarantee the performance pre-determined in the sliding surface from any initial condition to an arbitrary desired output. *The complete robustness of the pre-determined* performance for all the persistent disturbances is investigated in Theorem 1 together with the existence condition of the sliding mode of the IVSC and the asymptotic stability of the closed *loop system because the reaching phase* is removed perfectly. Through studies, the usefulness of the proposed controller is verified.

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