불확실 이산 시스템을 위한 외란관측기와 적분 동특성형 슬라이딩 면을 갖는 새로운 둔감한 이산 적분 정적 출력 궤환 가변구조제어기

논 문
59-7-18

A New Robust Discrete Integral Static Output Feedback Variable Structure Controller with Disturbance Observer and Integral Dynamic-Type Sliding Surface for Uncertain Discrete Systems

이 정 훈*
(Jung-Hoon Lee)

Abstract - In this paper, a new discrete integral static output feedback variable structure controller based on the a new integral dynamic-type sliding surface and output feedback discrete version of the disturbance observer is suggested for the control of uncertain linear systems. The reaching phase is completely removed by introducing a new proposed integral dynamic-type sliding surface. The output feedback discrete version of disturbance observer is presented for effective compensation of uncertainties and disturbance. A corresponding control with disturbance compensation is selected to guarantee the quasi sliding mode on the predetermined integral dynamic-type sliding surface for guaranteeing the designed output in the integral dynamic-type sliding surface from any initial condition for all the parameter variations and disturbances. Using discrete Lyapunov function, the closed loop stability and the existence condition of the quasi sliding mode is proved. Finally, an illustrative example is presented to show the effectiveness of the algorithm.

Key Words : Integral output feedback, Discrete integral variable structure system, Digital sliding mode control, Disturbance observer

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 in case of the continuous[1]-[4] and discrete time system[5]-[18]. One of its essential advantages is the robust of the controlled system to variations of parameters and external disturbances in the quasi sliding mode on the predetermined sliding surface, $s(k)=0$[5][6]. The proper design of the sliding surface can determine the almost output dynamics and its performances. In the SMC for discrete time systems, a few issue is considered in the design of VSS controller, i.e. the stable design of the sliding surface[10][11], reacheability from a given initial state to the fixed sliding surface[12][15][17], proof of existence condition of quasi sliding mode[5][7][8][15] together with closed loop stability[6], robustness analysis against uncertainties and disturbance[6][15][16][18], etc.[19]. In 1985, Milosavljevic defined the quasi sliding mode and presented the condition for the existence of the quasi sliding mode in discrete VSS[5]. The sliding and convergence condition for controlling discrete-time systems is suggested by Sarpturk et. al[7] which is modified from that of Milosavljevic's where an absolute value condition for the reaching and the existence condition of the quasi sliding mode is imposed. Furuta in 1990 proposed the design methodology of discrete VSS by using the transformation matrix, and using Lyapunov function the quasi sliding and convergence condition is proposed and the sliding sector concept is introduced to design sliding mode controller for linear single-input discrete-time systems[8]. In [9], the problems of robust model following control of discrete-time uncertain systems is considered. Using equivalent control of the discrete VSS, the sliding surface is designed in [8] and [13], both are different. Using a candidate Lyapunov function, the coefficient of the sliding surface is designed[10]. By means of optimal theory to minimize the cost function, the optimal sliding surface is chosen with

* 정 회 원 : 공학연구원I, 경상대학교 공대 전기전자공학부 제어계측공학과 교수・공박
E-mail : jhleew@gnu.ac.kr

접수일자 : 2009년 11월 26일
최종완료 : 2010년 2월 22일

selection of the optimal switching gain[11]. Wang[12] designed the a simple sliding mode such that the robust stability of the uncertain system and reduced the chattering along the sliding mode. However a counterexample showing the instability of the control scheme proposed by Wang et al. was given in [13]. The band of the quasi sliding mode is rigorously defined and a new reaching condition is established in [14]. For multivariable system, Koshkouei and Zinober suggested a new condition for the existence of the discrete-time sliding mode and presented a design procedure such that the robust stability of the sliding motion is achieved in [15]. The fixed and adaptive sliding mode control in the presence of an unknown disturbance were in [16]. Hui and Zak compared the difference in the requirements for the sliding mode behavior for continuous- and discrete-time systems and discussed the limitations of discrete-time variable structure sliding mode control[17]. Cheng et al. provided a simple design technique of sliding mode controllers for a class of multi input uncertain discrete-time system with matching conditions[18]. For uncertain nonlinear system, the discrete-time implementation of a second-order sliding mode control scheme is analyzed in [20]. Using the suggested discrete version of the continuous disturbance observer in [22], a full state feedback VSS is proposed in [23]. The integral action is introduced to the discrete full state feedback VSS to remove the reaching phase and improve the output performance[25]. A new robust discrete static output feedback variable structure controller with disturbance observer is presented for uncertain discrete systems in [26].

Until now in most of discrete VSSs, the used sliding surface except [25] and [26] is only the linear combination of the full state $s(k)=c^T x(k)$ and fixed in state space. Because of this, the closed loop system has the reaching phase for the initial state far from the sliding surface and the quasi sliding mode for the robustness is not guaranteed during this phase. The integral action is not introduced to the discrete output feedback VSS.

In this paper, a new discrete integral output feedback variable structure controller based on the a new integral dynamic-type sliding surface and discrete version of the disturbance observer is suggested for the control of uncertain linear systems. The reaching phase is completely removed by introducing a new proposed integral dynamic-type sliding surface which stems from [24] in continuous time and as in [26]. The ideal sliding dynamics is exactly obtained. The output feedback discrete version of disturbance observer is introduced to the effective compensation of uncertainties and disturbance which stems from [22] in continuous time and [23] in full state feedback discrete time. A corresponding control with disturbance compensation is selected to guarantee the quasi sliding mode on the predetermined sliding surface for guaranteeing the designed output in the integral dynamic-type sliding surface from any initial condition for all the parameter variations and disturbances. The advantages obtained after removing the reaching phase are discussed. Finally, an illustrative example is presented to show the effectiveness of the algorithm.

2. A Discrete Integral Variable Structure Systems

2.1 Descriptions of Plants

Let the uncertain linear time invariant discrete plant to be controlled be given in the state space representation by

$$\overline{X_{k+1}}=(\Lambda+\triangle\Lambda)\overline{X_k}+(\Gamma+\triangle\Gamma)u_k+d_k \qquad (1)$$
$$=\Lambda\overline{X_k}+\Gamma U_k+\overline{T_{Lk}}, \quad X_0$$

$$\overline{Y_k}=C_1\overline{X_k}, \qquad \overline{Y_0}=C_1\overline{X_0} \qquad (2)$$

$$\overline{T_{Lk}}=\triangle\Lambda\overline{X_k}+\triangle\Gamma U_k+d_k \qquad (3)$$

where $k\geq 0$ is an integer, $\overline{X_k}\in R^n$ is the state, $\overline{X_0}\in R^n$ is its initial condition of the state, $\overline{Y_k}\in R^q$ $q\leq n$ is the output, $\overline{Y_0}$ is its initial condition of the output, $U_k\in R^1$ is the input control to be determined, nominal matrices $\Lambda\in R^{n\times n}$, $\Gamma\in R^{n\times 1}$ is full rank, and $\overline{T_{Lk}}$ is the unknown lumped uncertainty to be estimated.

Assumption:

A1: (Λ,Γ) is completely controllable and (Λ,C_1) is observable.

A2: The lumped uncertainty $\overline{T_{Lk}}$ is piecewise smooth and, bounded and satisfies the matching conditions[18]

A3: C_1 and $\overline{T_{Lk}}$ satisfy this equation $C_1\overline{T_{Lk}}\neq 0$ for estimation of $\overline{T_{Lk}}$ by using the output feedback..

Now, the integral of the output is augmented as follows:

$$Y_{0k+1}=Y_{0k}+T\cdot I\cdot\overline{Y_k}, \ \ Y_{00} \qquad (4)$$

where T is a sampling time, $Y_{0k}\in R^q$ and Y_{00} is the initial condition of the integral state determined later. Let define a new augmented state as

$$X_k=[Y_{0k}^T \ \ \overline{X_k^T}]^T \qquad (5)$$

then the augmented discrete state equation is obtained as

$$X_{k+1}=\begin{bmatrix} I & T^*C_1 \\ 0 & \Lambda+\triangle\Lambda\end{bmatrix}X_k+\begin{bmatrix}0\\ \Gamma+\triangle\Gamma\end{bmatrix}u_k+\begin{bmatrix}0\\1\end{bmatrix}\overline{T_{Lk}} \qquad (6)$$
$$=(A+\triangle A)X_k+(B+\triangle B)u_k+B_1\overline{T_{Lk}}$$
$$=AX_k+Bu_k+\triangle AX_k+\triangle Bu_k+B_1\overline{T_{Lk}}$$
$$=AX_k+Bu_k+T_{Lk} \qquad (7)$$

$$Y_k = \begin{bmatrix} I & 0 \\ 0 & C_1 \end{bmatrix} X_k = CX_k \quad (8)$$

$$T_{Lk} = \triangle A X_k + \triangle B u_k + B_1 \overline{T_{Lk}} \quad (9)$$

2.2 Integral Dynamic-Type Sliding Surface

For the system (6), a integral dynamic-type sliding surface being modified from that of continuous case [24] and as in [26] is proposed as follows

$$S_k = F[\,Y_k - \Lambda_c Y_{k-1}] \quad (10)$$

where a non zero $F \in R^{2q}$ satisfies that FCB has the inverse, the closed loop system matrix $\Lambda_c \in R^{2q \times 2q}$ has also its inverse, and

$$Y_{-1} = \Lambda_c^{-1} Y_0 \quad (11)$$

so that the integral dynamic-type sliding surface is zero at initial time $k=0$ for any initial condition Y_0 in output space. Therefore the reaching phase to the integral dynamic-type sliding surface is removed completely and there is no need of the consideration of the reaching condition in this suggested discrete VSS. The following definitions are introduced.

Definition 1: *Discrete Ideal Sliding Mode*[8][15]

If $S_k = 0, \ \ k \ge 0$ is satisfied, then it is called as an *discrete ideal sliding mode.*

Definition 2: *Quasi Sliding Mode*[5]

For any real number $\epsilon > 0$, if $\|S_k\| < \epsilon$ for all k is satisfied because of the finite sampling time, then it is called as *quasi sliding mode.*

Substituting (6) and (8) in $S_{k+1} = 0$ yields the equivalent control[8][10]

$$\begin{aligned} S_{k+1} &= F[\,Y_{k+1} - \Lambda_c Y_k] = F[\,CX_{k+1} - \Lambda_c CX_k] \\ &= F[\,CAX_k + CBU_k + CT_{Lk} - \Lambda_c CX_k] \end{aligned} \quad (12)$$

$$\begin{aligned} u_{eqk} &= -(FCB)^{-1} FCAX_k + (FCB)^{-1} F\Lambda_c CX_k \\ &\quad -(FCB)^{-1} FCT_{Lk} \end{aligned} \quad (13)$$

which can not be implemented because of the disturbance and function of the state. The closed loop system by equivalent control is obtained as

$$\begin{aligned} X_{k+1} &= \left[A - B(FCB)^{-1} FCA + B(FCB)^{-1} F\Lambda_c C\right] X_k \\ &= A_{cs} \cdot X_k, \quad X_0 \end{aligned} \quad (14)$$

$$Y_k = CX_k \quad (15)$$

where

$$\begin{aligned} A_{cs} &= \left[A - B(FCB)^{-1} FCA + B(FCB)^{-1} F\Lambda_c C\right]. \\ &= A_c = A - BKC \end{aligned} \quad (16)$$

The solution of (14) defines the surface in *discrete ideal sliding mode* of the proposed integral dynamic-type sliding surface. The dynamics of *discrete ideal sliding mode is obtained from* $S_k = 0$ *as*

$$Y_k = \Lambda_c Y_{k-1} \qquad Y_0 \quad (17)$$

The solution of (17) is identical to that of (14) and (15). To design the integral dynamic-type sliding surface to be stable, one chooses the matrix Λ_c to be stable and F is a non zero. From (14) and (15), the following equation is obtained

$$Y_{k+1} = CX_{k+1} = CA_{cs} X_k \quad (18)$$

From (17), the following equation is obtained as

$$Y_{k+1} = \Lambda_c Y_k = \Lambda_c CX_k \quad (19)$$

Therefore, the following relationship is obtained as

$$\Lambda_c C = CA_{cs} = CA_c = C(A - BKC) \quad (20)$$

2.3 Control Input

Now, to estimate the lumped uncertainty (3) for compensation by the output feedback control input, a one step delay nonlinear disturbance observer of discrete version is modified from that in [22] of continuous version, in [23] of full state version, and as in [26] of output feedback version as follows

$$\begin{aligned} \therefore C\widehat{T_{Lk}} &= Y_k - CAX_{k-1} - CBu_{k-1} \\ &= Y_k - CA' C^T CX_{k-1} - CBu_{k-1} \\ &= Y_k - CA' C^T Y_{k-1} - CBu_{k-1} \\ &= CT_{Lk-1} \neq 0 \end{aligned} \quad (21)$$

where

$$CT_{Lk-1} \neq 0 \qquad \text{and} \ \ A = A' C^T C \quad (22)$$

Now to stabilize the (1) with the chosen integral dynamic-type sliding surface and compensation by means of disturbance observer, the following discrete integral static output feedback control input is presented

$$u_k = -KY_k - B^- \widehat{T_{Lk}} + GS_k \quad (23)$$

where K and G are the design parameters in control input and satisfy the following condition

$$\Lambda_c C = C[A - BKC] = CA_c \quad (24)$$

$$Q' < 0, \quad Q' = Q - I, \quad Q = M^T M, \qquad M = FCBG \quad (25)$$

The real sliding dynamics of the integral dynamic-type sliding surface by this control is derived as

$$\begin{aligned} S_{k+1} &= F[\,Y_{k+1} - \Lambda_c Y_k] = F[\,CX_{k+1} - \Lambda_c Y_k] \\ &= F[\,CAX_k + CBu_k + CT_{Lk} - \Lambda_c CX_k] \\ &= F[CAX_k - \Lambda_c CX_k - CBKCX_k - CBB^- \widehat{T_{Lk}} \\ &\qquad + CT_{Lk} + CBGS_k] \\ &= F[CBGS_k + \epsilon] \end{aligned} \quad (26)$$

Using the control input (17) with the integral dynamic-type sliding surface (4) and disturbance observer (14), the existence of the quasi sliding mode and closed loop stability is investigated in text theorem.

Theorem 1: If the integral dynamic-type sliding surface is designed in the stable i,e, stable Λ_c and A_{cs}, the proposed input with disturbance observer satisfies the quasi sliding mode on the predetermined integral dynamic-type sliding surface from the initial state and stability in the sense of Lyapunov.

Proof; Take the discrete candidate Lyapunov function as

$$V_k = S_k^T S_k \tag{27}$$

then

$$\begin{aligned} V_{k+1} &= S_{k+1}^T S_{k+1} \\ &= S_{k+1}^T F[CBGS_k + \epsilon] \\ &\simeq S_{k+1}^T FCBGS_k \\ &= S_k^T G^T (CB)^T F^T FCBGS_k \\ &= S_k^T M^T M S_k \\ &= S_k^T Q S_k \end{aligned} \tag{28}$$

then

$$\begin{aligned} \triangle V_k = V_{k+1} - V_k &= S_{k+1}^T S_{k+1} - S_k^T S_k \\ &= S_k^T [Q - I] S_k \\ &= S_k^T Q' S_k < 0 \end{aligned} \tag{29}$$

which implies that

$$(i) \|S_{k+1}\| < \|S_k\| \tag{30}$$

$$(ii) S_k^T \triangle S_{K+1} < -\frac{1}{2} \|\triangle S_{k+1}\|^2, \quad \triangle S_{k+1} = S_{k+1} - S_k \tag{31}$$

$$(iii) |S_k^T S_{k+1}| < \|S_k\|^2 \tag{32}$$

are satisfied[15] which completes the proof of Theorem 1.

By the results of Theorem 1, the quasi sliding mode on the integral dynamic-type sliding surface for all $k \geq 0$ is guaranteed. the performance designed in the integral dynamic-type sliding surface is almost also guaranteed.

3. Design Example and Simulation Studies

Consider 3rd order discrete system as

$$X_{k+1} = \begin{bmatrix} 1 & 0.01 & 0 \\ 0 & 1 & 0.01 \\ 0 & 0 & 0.4575 \end{bmatrix} X_k + \begin{bmatrix} 0 \\ 0 \\ 12.246 \end{bmatrix} u_k + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} T_{LK} \tag{33}$$

$$Y_k = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} X_k \tag{34}$$

which satisfy the assumption A1-A3. The sampling time is selected as $T = 10[mSec]$. An integral state of the output is as follows

$$Y_{0k+1} = Y_{ok} + TY_k \tag{35}$$

Then, the augmented state equation is obtained as

$$X_{k+1} = \begin{bmatrix} 1 & 0 & 0 & 0.01 & 0 \\ 0 & 1 & 0 & 0 & 0.01 \\ 0 & 0 & 1 & 0.01 & 0 \\ 0 & 0 & 0 & 1 & 0.01 \\ 0 & 0 & 0 & 0 & 0.4575 \end{bmatrix} X_k + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 12.246 \end{bmatrix} u_{k+} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} T_{LK} \tag{36}$$

To design the dynamic-type sliding surface, the closed loop system matrix in (10) and (17) Λ_c is selected as

$$\Lambda_c = \begin{bmatrix} 1 & 0 & 0.01 & 0 \\ 0 & 1 & 0 & 0.01 \\ 0 & 0 & 1 & 0.01 \\ 0 & 0 & -1.9998 & 0.0571 \end{bmatrix} \tag{37}$$

in order to assign the stable poles at 1, 0.9783, and 0.0788. And a non zero F in (10) is determined as

$$F = [5 \ -0.01 \ 5.0 \ -1.0] \tag{38}$$

Hence, the closed loop matrix A_{cs} in (16) of the ideal sliding dynamics of (14) becomes

$$A_{cs} = \begin{bmatrix} 1 & 0 & 0 & 0.01 & 0 \\ 0 & 1 & 0 & 0 & 0.01 \\ 0 & 0 & 1 & 0.01 & 0 \\ 0 & 0 & 0 & 1.0 & 0.01 \\ 0 & 0 & 0 & -1.998 & 0.0571 \end{bmatrix} = A_c = (A - BKC) \tag{39}$$

in order to assign the stable poles at 1.0, 0.9933, and 0.0709. Then, the integral output feedback constant gain K is

$$K = [0 \quad 0 \quad 0.1633 \ \ 0.0327] \tag{40}$$

The disturbance observer (21) based on the output feedback is implemented as

$$\widehat{T_{Lk}} = y_{2k} - 0.4575 y_{2k-1} - 12.246 u_{k-1} \tag{41}$$

The G in (23) is chosen as $G = 0.001$ which satisfy the relationship (25). As a results of the systematic design, M, and Q' are as follows:

$$M = -0.6123 \tag{42}$$

$$Q' = -0.6251 < 0 \tag{43}$$

The Q' satisfies the relationship of (25) and the stability condition (29). An initial condition for (33) is given as $X_0 = [0 \quad 180 \quad 0]^T \ [degree{*}\sec \quad degree \ degree/\sec]^T$ and $Y_{-1} = [-0.664 \ -23.3577 \ 66.6423 \ 2.3358 \times 10^3]^T$ by (11). The simulation is carried out under $T_{Lk} = 0.2544$ load variation of disturbance from 0.1[sec] to 1[sec]. Fig. 1 shows three output responses (i) ideal sliding output, i.e. solution of (17), (ii) without disturbance, (iii) with disturbance. As can be seen, the three outputs are almost identical. The phase trajectories for the three cases (i) ideal sliding trajectory, (ii) without disturbance, (iii) with disturbance are depicted in Fig. 2. The ideal sliding trajectory is slightly different from others because of the quasi sliding mode. The phase trajectory under disturbance is disturbed at the changed time because of one step delay estimation of disturbance observer and the quasi sliding mode of the discrete VSS, however fastly recovered by the suggested control input. Fig. 3 shows the two integral dynamic-type sliding surfaces for the two cases (i) without disturbance and (ii) with disturbance. The load variation of disturbance from 0.1[sec] to 1[sec] and its estimated value by means of the discrete one step delay disturbance observer are shown in Fig. 4. The control inputs for the two cases (i) without disturbance and (ii) with disturbance are depicted in Fig. 5. From the simulation studies, the usefulness of the proposed discrete VSS is proven.

4. Conclusions

In this paper, a systematic design of a new robust discrete integral output feedback VSS with disturbance observer is presented for control of uncertain linear discrete systems under lumped uncertainties.

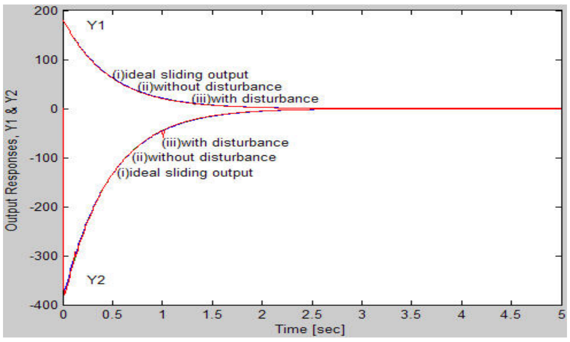

Fig. 1 Three output responses (i) ideal sliding output (ii) without disturbance, and (iii) with disturbance

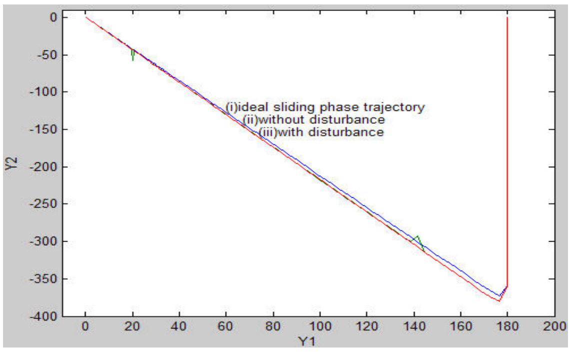

Fig. 2 Phase trajectories for the three cases (i) ideal sliding trajectory (ii) without disturbance, and (iii) with disturbance.

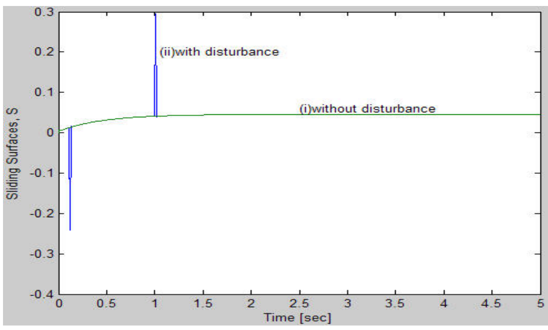

Fig. 3 Two integral dynamic-type sliding surfaces for the two cases (i)without disturbance and (ii)with disturbance

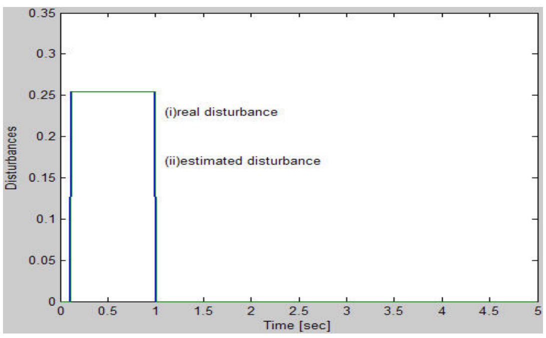

Fig. 4 Load variation of disturbance from 1[sec] to 5[sec] and its estimated value by means of the discrete one step delay disturbance observer

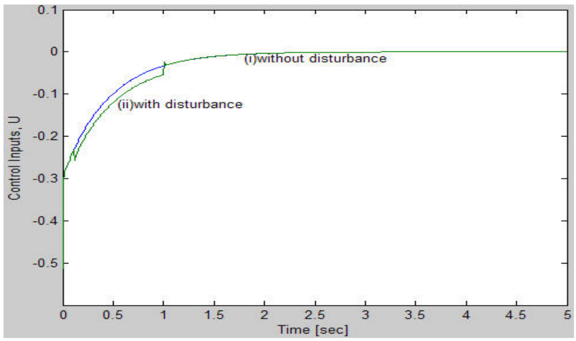

Fig. 5 Control inputs for the two cases (i) without disturbance and (ii) with disturbance

To successfully remove the reaching phase problems, a discrete integral dynamic-type sliding surface is suggested to define the hyper plane from any given initial condition. For the design of its integral dynamic-type sliding surface, the ideal sliding dynamics is obtained. The integral dynamic-type sliding surface is determined to have almostly that performance of the ideal sliding mode dynamics from a given initial condition to the origin. The output feedback discrete version of disturbance observer is presented to effectively estimate the lumped uncertainties. A corresponding control input with disturbance observer is also designed to almost guarantee the performance pre-determined in the integral dynamic-type sliding surface. The robustness of the pre-determined output for all the lumped uncertainties is investigated in Theorem 1 together with the existence condition of the quasi sliding mode of the discrete VSS and the stability of the closed loop system in the sense of Lyapunov. Through simulation studies, the usefulness of the proposed controller is verified.

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

References

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

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

[3] 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
[4] Drazenovic, B.,"The Invariance Conditions in Variable Structure Systems, Automatica, 1969, (5), pp.287-295.
[5] Milosavljevic, C, "General Conditions for the Existence of a Quasi Sliding Mode on the Switching Hyper Plane in Discrete Variable Structure Systems," Automat. Remote Control, vol. 46, pp.307-314, 1985
[6] Opitz, H. P., "Robustness Properties of Discrete-Variable Structure controllers." Int. J. Control, 1986 vol. 43, no.3 pp. 1003-1014.
[7] Sarpturk , A. Z., Istefanopulos Y. and Kaynak O., " On the Stability of Discrete-Time Sliding Mode Control Systems," IEEE Trans. Autom. Contr, 1987, AC-32, no. 10, pp.930-932
[8] Furuta, K., "Sliding Mode Control of a Discrete System," System and Control Letter, vol.14, pp.145-152, 1990
[9] W. Chai, N. K. Loh and C. F. Lim, "Unified Design of Robust Discrete-Time Control Systems, 1992 ACC, pp.1091-1095.
[10] S. K. Spurgeon, "Hyperplane Design Technique for Discrete-Time Variable Structure Control Systems." Int. J. Control 1991, vol.55 no.2 pp.445-456.
[11] J. K. Pieper and B. W. Surgenor, "Discrete Sliding control of a Coupled-Drives Apparatus with Optimal Sliding Surface and Switching Gain," IEE Proc.-D Vol. 140 no.2 March,1993, pp.70-78
[12] W. J. Wang, G. H. Wu, and D. C. Yang, "Variable Structure Control Design for Uncertain Discrete-Time Systems," IEEE Trans. Autom. Contr, 1994, vol.AC-39, no. 1, pp.99-102.
[13] P. Myszkorowski and U. Holmberg, "Comments on" Variable Structure Control Design for Uncertain Discrete-Time System"", IEEE Trans. Autom. Contr, 1994, vol.AC-39, no. 11, pp.2366-2367.
[14] W. Gao, Y. Wang, and A. Homaifa, "Discrete-Time Variable Structure Control Systems," IEEE T. Indust. Electronics, vol.42, no.2 1995, pp117-122.
[15] A. J. Koshkouei and A. S. I. Zinober, "Sliding Lattice Design for Discrete-time Linear Multivariable Systems," 1996 CDC pp.1497-1502.
[16] C. Y. Chan, "Discrete Adaptive Sliding Mode control of a State-Space System with Bounded Disturbance," Automatic, vol.34, no.12pp1631-1635, 1998.
[17] S. Hui and S H Zak, "On Discrete-Time Variable Structure Sliding Mode," System & Control Letters vol.38 pp.283-288, 1999.
[18] C. C. Cheng M. M. lin, and J. M. Hsiao, " Sliding Mode Controllers Design for Linear Discrete-time Systems with Matching Perturbations," Automatica vol.36 pp1205-1211, 2000.
[19] G. Golo and C. Milosavljevic, "Robust Discrete-Time Chattering Free Sliding Mode Control" System & Control Letters vol. 41, pp.19-28, 2000.
[20] G. Bartolini A. Pisano, E. Usai, " Digital Second-Order Sliding Mode Control for Uncertain Nonlinear Systems," Automatica, vol.37 pp.1371-1377, 2001.
[21] W. J. Cao and J. X. Xu, "Nonlinear Integral-Type Sliding Mode Surface for Both Matched and Unmatched Uncertain Systems, IEEE T. Automatic Control, vol.49,no.8, pp.1355-1360, 2004.
[22] J. H. Lee, at el, Continuous Variable Structure Controller for BLDDSM Position Control with Prescribed Tracking Performance," IEEE T. Industrial Electronics, vol.41,no.5 pp.483491, 1994
[23] J. H. Lee, "A New Robust Digital Sliding Mode Control with Disturbance Observer for Uncertain Discrete Systems," KIEE(To be appear)
[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,(to be appear)
[25] J. H. Lee, "A New Robust Discrete Integral Variable Structure Controller with Nonlinear Disturbance Observer for Uncertain Discrete Systems," KIEE,(to be appear)
[26] J. H. Lee, "A New Robust Discrete Static Output Feedback Variable Structure Controller with Disturbance Observer for Uncertain Discrete Systems," KIEE(to be appear)

저 자 소 개

이 정 훈 (李 政 勳)
1966년 2월 1일생. 1988년 경북대학교 전자공학과 졸업(공학사), 1990년 한국과학기술원 전기 및 전자공학과 졸업(석사). 1995년 한국과학기술원 전기 및 전자공학과 졸업(공박). 현재 2010년 현재 경상대학교 제어계측공학과 교수. 1997-1999 경상대학교 제어계측공학과 학과장. 마르퀘스사의 Who's Who in the world 2000년 판에 등재. American Biograhpical Institute(ABI)의 500 Leaders of Influence에 선정.
Tel : +82-55-751-5368, Fax : +82-55-757-3974
E-mail : jhleew@gnu.ac.kr