TOWARD THE IMPLEMENTATION OF A SEEK-CONTROLLER FOR AN OPTICAL PICK-UP HEAD USING A DISCRETE SLIDING-MODE CONTROL SCHEME

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ABSTRACT

Chattering is inevitable in most sliding-mode controllers due to finite and imperfect switching. Most of the discrete-time sliding-mode schemes reported to date fail to alleviate chattering effectively; even under perturbation-free conditions, chattering is still inevitable. This present work proposes a scheme that can guarantee both one-sided behavior and chattering-free performance with uncertainties of the known bounds of the plant. This scheme is applied to the design of a seek-controller for an optical pick-up head to illustrate its feasibility. Both simulation and experimental studies were performed to further validate its effectiveness.

KeyWords: Discrete sliding-mode control, seek-controller, optical pick-up head.

I. INTRODUCTION

The sliding-mode control (SMC) scheme has long been recognized as an effective way to both improve transient response and achieve robust performance [1-7]. However, in most practical applications, digital implementation of continuous-time SMC schemes may worsen performance, inducing chatter or even instability [8-11]. Recently, several studies [7-10] have proposed discrete-time SMC schemes to alleviate this undesirable oscillation. One is based on a varying dead-zone, in which the zone is varied with feedback gain and the portrait of state proportionally [8, 9]. In others, chattering reduction is achieved through continuous approximation using the boundary layer concept, asymptotical state observers that localize the high frequency effect, or so-called post-filtering and pre-filtering processes [7]. Gao et al. [10] proposed a control strategy to make the discrete-time system behave like a quasi-sliding mode, leading to a zigzag trajectory around the sliding surface. Clearly, this design will result in oscillation around the sliding surface and is not at all immune to chattering. A new sliding-mode definition was introduced for discrete-time systems by Utkin et al. [11], in which a dead-beat sliding region can exist around the sliding hyperplane. According to this definition, systems may result in a chattering-free discrete sliding-mode. Nevertheless, the global existence of such a dead-beat sliding region is not easily guaranteed.

In this paper, we will propose a discrete SMC scheme for a class of uncertain systems. A methodology will be provided to guarantee the stability and existence of the sliding-mode as well as to alleviate chatter by adjusting a parameter of the SMC design. It will be seen that the correlation between the pole-zero location in the z-plane and the time domain specifications can be directly specified in the design procedure. An explicit condition to ensure one-sided behavior, which is an inequality constraint on the parameters of the proposed controller, will also be derived. This condition also guarantees that the state trajectory will reach a pre-specified boundary layer of the sliding surface in finite time, and that this time can be pre-calculated. Both simulation and experimental studies on the seek-controller design of an optical pick-up head will be presented to demonstrate its effectiveness.

II. PROBLEM STATEMENT

Consider a discrete-time system defined by

\[ x(k+1) = Ax(k) + Bu(k), \]

where \( x \in \mathbb{R}^n \) is the state vector, \( u(k) \in \mathbb{R} \) is the control.
input, and the nominal linear systems $A$ and $B$ are time-invariant and of appropriate dimensions. Similar to [10], a discrete SMC law is designed to find a sliding function $s(x)$, such that the sliding mode on the sliding plane $s(x) = 0$ is stable. Furthermore a suitable control law, as described by [12], is expressed as

$$ u(k) = u_{eq}(k) + u_a(k), $$

where $u_{eq}$ is the so-called equivalent control [8,10] while the auxiliary control $u_a(k)$ is expressed as

$$ u_a(k) = -(HB)^{-1} \gamma(x) \text{sgn}(s), $$

where $\gamma(x)$ is a positive control gain, and the quantity of $\gamma(x)$ should be a function of the pre-specified sliding function $s(k)$.

It should be noted that $u_{eq}$ determines the dynamics of the sliding-mode, whereas $u_a$ constrains the state trajectory on the sliding surface (5). More specifically, $u_a$ not only corresponds to a switching action so as to ensure the existence of a sliding regime, but also can be utilized to force the state portrait to reach the sliding surface within a specified boundary layer in a finite number of steps. The design procedure and the determination of control parameters are explained in the following subsections.

### 3.1 Design of equivalent control law

To find the equivalent control, $u_{eq}$, we first define a difference operator $\Delta$ such that

$$ \Delta s(k+1) = s(k+1) - s(k). $$

Similar notation will be applied to other variables appearing in this article. Should the sliding-mode exist, the discrete-time switching function should satisfy

$$ s(k+1) = s(k), \quad k \in z, $$

which implies that

$$ \Delta s(k+1) = H(A-I)x(k) + HBu(k) = 0. $$

Solving for $u(k)$, the equivalent control law is, thus, obtained as

$$ u_{eq}(k) = -(HB)^{-1} H(A-I)x(k) $$

$$ \equiv -G_{eq}x(k), $$

provided that matrix $H$ is chosen such that $HB$ is non-zero.

Upon substituting $u_{eq}$ into (1), the closed loop dynamics of the system can be found and expressed as
\[ x(k+1) = [A - BG_n]x(k) \equiv Ax(k). \] (12)

Consequently, asymptotically stable sliding dynamics will exist, provided that the matrix \( H \) is chosen such that \( A \) is Hurwitz.

### 3.2 Design of auxiliary control law

In order to fulfill condition (3), consider a Lyapunov function which is described as [8]

\[ v(k) = \frac{1}{2} s^2(k). \] (13)

If the difference

\[ \Delta v(k+1) \equiv v(k+1) - v(k) < 0, \quad \forall s(k) \neq 0, \quad (14) \]

then the discrete Lyapunov stability criterion can be used to exploit the auxiliary control law such that the reaching condition (3) holds.

**Theorem 1.** Consider the discrete-time control system (1) with the SMC law, which is described in (6) and (7). If there exists \( \gamma(x) \) in (7) to satisfy

\[ 0 < \gamma(x) = \alpha |s(k)| < 2|s(k)| \] (15)

with \( 0 < \alpha < 2 \), then reaching condition (3) holds.

**Proof.** The difference \( \Delta v(k+1) \) can be evaluated using (13) and (14), i.e.,

\[ \Delta v(k+1) = s(k) \cdot \Delta s(k+1) + \frac{1}{2} \Delta s^2(k+1). \] (16)

Substituting (7) and (11) into (6), and using (8) will yield

\[ \Delta s(k+1) = -\gamma(x) \text{sgn}(s) \] (17)

with (17), and (16) becomes

\[ \Delta v(k+1) = -\frac{1}{2} \gamma(x) \left[ 2|s(k)| - \gamma(x) \right] < 0, \quad \forall s(k) \neq 0. \] (18)

Hence, the reaching condition will exist, provided that

\[ 0 < \gamma(x) = \alpha |s(k)| < 2|s(k)|, \quad \forall s(k) \neq 0, \]

which implies that

\[ 0 < \alpha < 2. \]

Condition (15) also guarantees the existence of the sliding-mode. Thus, all the state trajectories will move toward the switching surface, or at least stay within its neighborhood. Here, an additional constraint will be given based on which the one-sided behavior sliding-mode can be achieveds conforming to Definition 1.

**Theorem 2.** Suppose that the controller parameter \( \alpha \) in (15) satisfies the following inequality

\[ 0 < \alpha < 1. \] (19)

Then, the proposed SMC law in (6) will guarantee that the sliding-mode exists, and that it has the property of one-sided behavior, as described in Definition 1.

**Proof.** Since \( 0 < \alpha < 1 \), then (15) is satisfied, and the sliding-mode will exist according to Theorem 1. From (17), the sliding dynamics become

\[ s(k+1) = s(k) - \gamma(x) \text{sgn}(s). \] (20)

By Definition 1, it is easy to conclude that to ensure the satisfaction of (4), the inequality

\[ 0 < \gamma(x) = \alpha \cdot |s(k)| < |s(k)|, \quad \forall s(k) \neq 0 \] (21)

must hold. That is,

\[ 0 < \alpha < 1, \]

which is equivalent to (19).

Next, we will proceed to derive the number of steps that are required to reach the vicinity of a prescribed sliding surface. For \( 0 < \alpha < 1 \), given any \( \delta > 0 \) and \( n > 0 \), we can assume that \( |s(k)| < \delta \) for all \( k \geq n \), where \( n \) is a finite number that guarantees that the trajectory of (5) will reach the boundary layer \( L \) (i.e., \( L = \{x : |s(x)| < \delta\} \) ) in finite time and stay within \( \delta \) thereafter. According to Theorem 2 and using (20), we have

\[ s(k+1) = (1-\alpha) \cdot s(k). \] (22)

Subsequently, \( n \) can be obtained as

\[ n = \text{int} \left[ \frac{\ln(\delta/s(0))}{\ln(1-\alpha)} \right], \] (23)

where \( \text{int}[\chi] \) is the round-off of the argument \( \chi \) to the nearest integer toward infinity. Note that in this case, the roots of the sliding equation are located on the real axis within the unit circle. The performance of the time-response characteristics of the sliding dynamics can, thus, be determined by means of a first-order continuous-time control system.
Remark 1. Based on Theorem 1 and (22), it can be easily verified that if

$$|\lambda - \alpha| < 1$$

holds, then the sliding dynamics are asymptotically stable. Thus, the results of Theorem 1 can also be used to establish a correlation between the pole-zero location in the $z$-plane and the time domain response characteristics.

Remark 2. Equation (22) shows that if $\alpha = 1$, then we have

$$s(k + 1) = 0,$$

and the discrete SMC law may yield a deadbeat sliding-mode. The sliding surface at any initial state $s(x(0))$ can be moved to $s(k) = 0$ in one step [13].

Remark 3. From Theorems 1 and 2, we can conclude that if

$$1 < \alpha < 2,$$

then the SMC law may produce chattering. Consequently, one-sided behavior will not hold, and only alleviation of chattering is expected.

### 3.3 Consideration of robustness

Previously, the system was assumed to be known exactly. However, uncertainties and disturbances will inevitably cause the system performance to deviate from expectations. Thus, we will next consider a perturbed system of the form

$$x(k + 1) = Ax(k) + \Delta Ax(k) + Bu(k) + d(k).$$

To ensure the existence of a sliding-mode under perturbation of $\Delta A$ and $d(k)$, we further assume that $\Delta A$ and $d(k)$ lie within the span of input matrix $B$ (i.e., $\Delta A \in \text{span} \{B\}$ and $d(k) \in \text{span} \{B\}$). Moreover, the variation ranges of the uncertainty and external disturbance are unknown but lie within known bounds, and the following assumption is satisfied as described in [14].

**Assumption.** There exists a constant $0 < \beta < 1$ and a known positive function $\tilde{\lambda}(x, k)$ such that

$$\|H \cdot \Delta Ax(k) + H \cdot d(k)\| \leq \beta \tilde{\lambda}(x, k),$$

where $H$ is selected so that the closed-loop feedback system (24) is asymptotically stable.

The above assumption is satisfied for a certain class of systems, for example, an optical pick-up head positioning system, in which the tolerance bounds of the system parts and the external disturbances due to the side loading, windage, and media defect are exceeding the predetermined value. In addition, the maximum moving distance of the pick-up head is known exactly.

**Theorem 3.** Let $\delta = 1 - \beta$, which is the thickness of the boundary layer $L = \{x : |s(x)| < \delta \}$. The control law is

$$u(k) = \begin{cases} u_s(k) + u_d(k), & \text{if } |s(k)| < \delta \\ u_s(k) + u_d(k), & \text{if } |s(k)| > \delta, \end{cases}$$

in which

$$u_d(k) = -\frac{1}{\delta} F(x(k))\psi(s) \text{sgn}(s),$$

where $F(x, k) \geq \lambda(x, k)$ and $\psi(s)$ is a smoothed function of the form

$$\psi(s) = \eta - \exp(-\tau \cdot |s|)$$

with $\eta \geq 1$ and $\tau \geq \frac{1}{\delta}$. That guarantees that the trajectory of the system (24) will reach the boundary layer in a finite number of steps and stay within $L$ thereafter.

**Proof.** If (7) and (11) are substituted into (26), (17) can be rewritten as

$$\Delta s(k + 1) = H[\Delta Ax(k) + d(k)] - F(x(k))\psi(s) \text{sgn}(s), \quad \forall |s(k)| > \delta.$$  

Since $\tau \geq \frac{1}{\delta}$, the following inequalities hold; hence,

$$\psi(s) \geq \eta - \delta \geq 1 - \delta = \beta, \quad \forall |s| > \delta$$

Using $F(x, k) \geq \lambda(x, k)$, we have

$$\Delta s(k + 1) = -F(x, k)\psi(s) \text{sgn}(s) + H \Delta Ax(k) + Hd(k)$$

$$\leq -F(x, k)(\eta - 1) < 0, \quad \forall s > \delta, \eta \neq 1$$

and

$$\Delta s(k + 1) = -F(x, k)\psi(s) \text{sgn}(s) + H \Delta Ax(k) + Hd(k)$$

$$\geq F(x, k)(\eta - 1) > 0, \quad \forall s < -\delta, \eta \neq 1.$$  

According to (32), condition (3) is easily verified. $\blacksquare$
Remark 4. The smoothing function $\psi(s)$ is used to obviate the chattering phenomenon. By simply adjusting the parameter $\delta$, the discontinuous control law can be arbitrarily approximated to achieve satisfactory robustness.

Remark 5. For $\eta \neq 1$, an upper bound of the reaching time can be obtained according to (32) and (23), i.e.,

$$n = \text{int} \left[ \frac{\psi(0) - \delta}{F_m(\eta - 1)} \right],$$

where $F_m \equiv \min \{F(x, k)\}$.

IV. SIMULATION AND EXPERIMENTAL VALIDATION

Simulation and experimental studies were performed to demonstrate the validity of the proposed scheme by implementing this design on an optical pick-up head servo system for a 40x CD-ROM drive system. The configuration of a typical optical pick-up head servo system is shown in Fig. 1. It is a typical dual-stage system, in which a dc motor is adopted as the actuator for the coarse stage or the long-seek (or the so-called sledge) stage, while a voice-coil motor is used for the fine stage or the track-seeking and track-following stage. In combination, this dual-stage servo system will move the objective lens to the target track of the optical disk to read data. Normally, to improve the access time (one-third of the stroke, or nearly 6000 tracks for a CD-ROM), the long-seek task must move the objective lens and the fine-stage actuator as quickly as possible to a position as close to the target as possible without overshoot. Since the coarse stage is driven by a low-cost dc motor and a rack-gear, non-linearities, such as backlash, dead zones and friction, are encountered. For most CD-ROM drives, the maximal range of actuation for the fine-actuator is $\pm 300$ tracks; thus, the steady-state error for the coarse-stage should be less than 200 track-counts, and the settling time must be less than 80 msec.

To meet the above requirements in a conventional seek control system, the profile following method with an electronic damper has been widely applied. If the number of tracks to be crossed is given, the reference velocity profile can be generated via an approximate time optimal control method. The difference between the reference velocity profile and the measured velocity (estimated head velocity) is, then, fed into a feedback compensator which utilizes the coarse stage to force the measurable velocity to follow the reference velocity profile. In this case, minimum power consumption of the control system can be achieved. However, when the disk rotates at high speed, the beam spot can not be moved to the target track through a long-seek operation.

4.1 System modeling

The continuous-time state space representation of a time invariant control system can be expressed as

$$\dot{x}(t) = A_c x(t) + \Delta A_x x(t) + B_c u(t) + d(t),$$

where $A_c$ and $B_c$ are the nominal linear system, and $\Delta A_x$ represents the system parameter variations. $d(t)$ represents a certain class of external disturbance. For a CD-ROM positioning system, only the typical values of the system parameters $M$ and $m$, and the resonance peak of the actuator can be obtained from the manufacturer’s data sheet [16]. However, the equivalent stiffness $c$ and damping of suspension $b$ are not presented, and are difficult to measure. For the long seek operating condition, the CD-ROM’s firmware produces a control signals, $f_a$, to provide critical damping (a so-called electronic damper) between the dual-stage systems, while the sledge mechanism control input, $f_c$, is designed to achieve the desired performance. Hence, the nominal plant transfer function, including a driver circuit with an electronic damper operating at a spindle speed of 16x, was obtained here via a Laser Doppler Vibrometer and/or a digital signal analyzer HP DSA-3563. The Bode-plot of the experimental system is shown in Fig. 2. For simplicity, a reduced order nominal plant model,

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -107 \end{bmatrix} \begin{bmatrix} x(t) \\ u(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 3.75e6 \end{bmatrix} u(t).$$

was adopted in the design, in which $u \in \mathbb{R}^1$ is the control input of the sledge (shown in Fig. 4 and referred to as FMSO). The poles of the system were 0 and $-107$. Moreover, the upper bound of the external disturbance due to runout, $d(t)$, was measured and found to be 30 track-pitch, as shown in Fig. 3. Furthermore, we as-
sumed that the variation ranges of all the components were bounded within ±10% of their nominal values. The ZOH equivalent model for a sampling period of 1 msec can be obtained as

\[
x(k + 1) = \begin{bmatrix} 1 & 0.0009 \\ 0 & 0.8958 \end{bmatrix} x(k) + \Delta x(k) \\
+ \begin{bmatrix} 0.0018e3 \\ 3.5563e3 \end{bmatrix} u(k) + d(k)
\]

(36)

\[
x(k) = A x(k) + \Delta A x(k) + B u(k) + d(k).
\]

4.2 Experimental setup

The test bench for a 40x CD-ROM drive system is shown in Fig. 4 [16]. In practical applications, only the pickup head tracking signals (RFZC and TEZC) are available from the chipset. Since the embedded track-count circuit inside the chipset can not be accessed directly, a high-speed counter was developed and implemented on an FPGA (FLEX 10K-100GC503-3) development board. Also, to reduce the number of miscounts, an impulse-deglitch scheme [17] was implemented to improve the precision, and the resolution could, thus, be upgraded to 1/4 track for short-seek and 1/2 track for long-seek (1 track-pitch = 1.6 µm), respectively. Furthermore, the proposed DSMC scheme with a discrete reduced-order observer for the long-seek control stages was implemented on a dSPACE DS1103 running at 400MHz.

4.3 Long-seek controller design

To provide a discrete SMC long-seek controller with available states, a reduced-order observer was adopted to estimate the velocity of the sledge. The block diagram of the proposed seek-controller with the reduced-order observer is shown in Fig. 5. Referring to [18], the structure of the reduced-order observer is given by

\[
z(k + 1) = F_o z(k) + G_o y_m(k) + H_o u(k)
\]

\[
\hat{x}(k) = z(k) + L_o y_m(k),
\]

(37a)

where \(\hat{x}(k)\) is the estimated state vector, and the inputs are \(u(k)\) and \(y_m(k)\), where \(y_m(k)\) is the measured vector. Accordingly, the settling time of the observer was set to be 15 msec, and the corresponding reduced-order observer matrices for the plant given in (36) were calculated using pole-placement formula and found to be

\[
F_o = 0.7349, \quad G_o = -46.418, \quad H_o = 3.24e3,
\]

\[
L_o = 175.108.
\]

(37b)
We let $x_e(k)$ be the tracking error vector

$$x_e(k) = \hat{x}(k) - x_d(k),$$

(38)

where $x_d$ denotes the desired output of the seek-controller. In addition, the desired error dynamics were defined by the sliding function as

$$s(k) = Hx_e(k).$$

(39)

Due to the limitation of the power driver, BA 5937 (c.f. to Fig. 4), the DSMC law in (26) as modified as

$$u(k) = \begin{cases} u_{\text{eq}}(k) + u_{\text{a}}(k), & \text{if } |s(k)| < \delta \\ u_{\text{limit}}, & \text{if } |s(k)| > \delta, \end{cases}$$

(40)

where $u_{\text{limit}}$ is the maximum input signal. Hence, maximum power was delivered to the sledge in the reaching phase, which means that the objective lens driven by the actuator was moved as quickly as possible to a position close to the target track.

Once the settling time of the system was determined based on the prototype Bessel function, these pole locations were mapped onto the z-plane using the ZOH pole-mapping formula. The sliding function matrix $H$ was then obtained using the transformation matrix scheme [15] and Ackermann’s pole assignment formula. Thus, the equivalent control law could be calculated from (11) with $H = [0.0306 \ 0.0003]$, i.e.,

$$u_{\text{eq}}(k) = -(HB)^{-1} H(A - I)\dot{x}(k)$$

$$= [0 \ 3.716e-6] \dot{x}(k).$$

(41)

Next, to meet the requirement that the tracking error must be less than 200 tracks at the end of the seek operation for seeking one-third of a stroke, the boundary layer $\delta$ was chosen such that $\delta < 350 \mu\text{m}$. To improve the access time, we set $\delta = 0.03$. It should be noted that the sliding surface of the seek controller was selected to be the weighted sum of the velocity and the position. Hence, the formula for accurately determining a boundary layer that satisfied the requirement for the tracking error is difficult to derive. For simplicity, a suitable estimating boundary layer $\delta$ could be calculated by assuming that the seek operation was finished, that is $\dot{x}_e = 0$. Also, according to the specifications of the sledge driver, we have

$$u_{\text{limit}} = 2 + 2 \cdot \text{sgn}(\sigma),$$

(42)

where $\text{sgn}(\sigma)$ is the desired moving direction of the sledge. The $\text{sgn}$ function was used to determine whether the pick-up head was moving inward or outward on the disk.

Finally, to provide a one-sided behavior sliding-mode, the parameter $\alpha$ was chosen, as described in Theorem 2 and Remark 3, to be 0.3. Consequently, the poles of the controlled system were 0.9117 and 0.7. Moreover, the control guaranteed that the system trajectory would moved from $\delta$ to the vicinity of the switching surface $s$. Also, according to (23), the reaching time could be calculated as $t_r = 14.7\text{msec}$. Thus, from the experimental results, the total settling time of the long-seek stage was 64.7 msec. In addition, it should be noted that the settling time of the short-seek control stage was always designed to be less than 20 msec, so that the total settling time in the track-seeking stage was less than 85 msec.
The simulation results obtained under external disturbances due to the runout effect, such as side loading, windage, and media defects, are shown in Figs. 6(a) and 6(b), respectively. The results shown in Fig. 6 reveal that the system response exhibited a sufficiently small steady-state error without overshoot, and was robust against the external disturbances even under the condition that the upper bound on the total eccentricity was 350 µm, which met the design specification. Also, the chattering phenomenon was suppressed.

In addition, the experimental results obtained with the spindle motor running in the CAV mode are shown in Figs. 7 and 8, respectively. Figure 7 displays the response achieved when the spindle speed was 16x (5000 rpm). The results indicate that there was no overshoot, and that the settling time was close to 70 msec, as desired. Figure 8 shows the response achieved when the spindle speed was 20x (6000 rpm). Here, the response was also well-behaved, and the desired settling time could be ensured, but there was a small amount of oscillation at the end of transient response, which occurred because the system (fine stage) had a resonant frequency of 80 Hz due to the runout effect and an unsuitable electronic damper. Moreover, when the spindle speed was 16x or 20x, the track-count errors percentages were all within 0.45%. The track-count errors are also shown in the sub-windows of Figs. 7 and 8, which further show that the proposed method provided good robustness and disturbance rejection. From these results, the proposed scheme has shown its effectiveness in handling the track-seeking task of an optical pick-up head servo system. Finally, it should be noted that by increasing α, the settling time can be drastically reduced. However, in a CD-ROM drive positioning system, this will excite the high frequency dynamics, which in turn will probably lead to oscillation that will cause the performance of the next stage (the short-seek or the fine stage) to deteriorate due to the coupling effect between these two stages.

**V. CONCLUDING REMARKS**

A novel discrete sliding-mode control scheme has been proposed to guarantee the existence of a sliding-mode as well as to alleviate chattering. Conditions for stability have been given and analyzed. The explicit condition needed to ensure one-sided behavior have been derived as an inequality constraint on the controller parameters. This condition also guarantees that the state trajectory, starting from any initial condition, will reach the boundary layer of the switching surface in a finite number of steps. Also, the estimated reaching time can be pre-calculated. Both simulation and experimental studies on our design of a seek-controller for an optical pick-up head servo system were performed to further demonstrate its effectiveness.

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