Observer-based Adaptive Sliding Mode Control for a Pneumatic Servo System

Kuo-Ming Chang[1] and Tien-Tsai Kung[2]
[1]Department of Mechanical Engineering, National Kaohsiung University of Applied Sciences, 415 Chien-Kung Rd., Kaohsiung, Taiwan
[2]Institute of Mechanical and Precision Engineering, National Kaohsiung University of Applied Sciences, 415 Chien-Kung Rd., Kaohsiung, Taiwan

Keywords: Pneumatic Servo System, Adaptive Sliding Mode Control, Extended State Observer, Dead-Zone.

Abstract: This paper combines an extended state observer (ESO) and adaptive sliding mode control to deal with the problem of nonlinear input dead-zone, unkonw system function, external distrubance and system states unmeasured in a pneumatic servo system. Firstly, an extended state observer is applied to estimate system state variables and uknown system nonlinear function contained the external disturbance, and an adaptive law is used to estimate unknown dead-zone parameters. Then, an observer-based adaptive sliding mode control can be derived for such a uncertain pneumatic servo system. Furturemore, the proposed control scheme in this paper is applied to a pneumatic positioning control experimental equipment and it is shown that the positioning accuracy with less than 0.05 μm can be obtained.

1 INTRODUCTION

In recent year, pneumatic servo system has been widely used in automation industry with low cost, fast, and long stroke, but owing to the compressibility of air, the friction force of the contact surface, and the nonlinear input dead-zone of servo valve, the pneumatic servo system can not reach high precision positioning accuracy. In order to improve the positioning performance of pneumatic servo system, many control methods have been proposed, such as sliding mode control (Song and Ishida, 1997; Korondi and Gyeviki, 2006), neural network control (Gross and Rattan, 1998), fuzzy PWM control (Shih and Ma, 1998) and the control scheme of the pneumatic system combined with piezoelectric actuator (Liu et al., 2004; Chiang et al., 2005).

In this paper, based on the extended state observer, sliding mode control, and adaptive dead-zone inverse techniques, a robust observer-based adaptive sliding mode control scheme is developed to achieve the high positioning performance for a pneumatic servo positioning system. Furthermore, it is proven that the proposed control scheme can obtain the positioning accuracy with less than 0.05 μm in an experimental pneumatic servo control system.

2 PNEUMATIC SERVO SYSTEM

In this paper, the dynamic equation of pneumatic system can be constructed as:

$$m\frac{d^2x_1}{dt^2}+\eta\frac{dx_1}{dt}=F_{applied} \tag{1}$$

where

m : mass of sliding table
η : damping coefficient
$F_{applied}$: force of pneumatic cylinder
$x_1(t)$: displacement of sliding table

Eq. (1) is a second-order linear differential equation, but owing to characteristics of air compression and nonlinear friction, it will be difficult to represent the pneumatic servo system with a linear system actually. Therefore, considering the nonlinear characteristics of pneumatic system, Eq. (1) can be rewritten by

$$\frac{d^2x_1}{dt^2}=\frac{-f_f(\dot{x}_1)-f_P(x_1,\dot{x}_1)}{m}+d(t)+\frac{F_{applied}}{m} \tag{2}$$

Chang K. and Kung T..
Observer-based Adaptive Sliding Mode Control for a Pneumatic Servo System.
DOI: 10.5220/0004032806000604
In *Proceedings of the 9th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2012), pages 600-604
ISBN: 978-989-8565-21-1

where

$f_f(\dot{x}_1)$: nonlinear function of friction

$f_P(x_1, \dot{x}_1)$: nonlinear function of air compression

$d(t)$: external disturbance and system unmodeled error.

In a pneumatic servo system, the nonlinear dead-zone phenomenon is usually caused by proportional valve and nonlinear friction. Concerning about the dead-zone phenomenon, Eq. (2) can be further rewritten in the state-space representation

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x,t) + d(t) + g(t)w(u) = a(t) \end{cases} \tag{3}$$

where $x(t) = [x_1(t) \quad x_2(t)]^{\mathrm{T}}$ is the system state vector, $f(x,t) = \dfrac{-f_f(\dot{x}_1) - f_P(x_1, \dot{x}_1)}{m}$ is the unknown system nonlinear function, $g(t)$ is the unknown control gain, $u(t)$ is the control input, $w(u)$ is the output of unknown dead-zone expressed as

$$w(u) = \begin{cases} m_r(u(t) - b_r) & \text{, if } u > b_r \\ 0 & \text{, if } b_l \le u \le b_r \\ m_l(u(t) - b_l) & \text{, if } u < b_l \end{cases} \tag{4}$$

where $m_l > 0$ and $m_r > 0$ are the slopes of dead-zone on both sides, $b_l < 0$ and $b_r > 0$ are the breaking points of dead-zone on both sides. In addition, regarding to $d(t)$ and $a(t)$ of in Eq. (3) and parameters in Eq. (4), this paper has the following assumptions:

Assumption 1: External disturbance of system is a bounded function, such as $|d(t)| \le \rho$, ρ is positive constant.

Assumption 2: $a(t)$ is continuously differentiable with time and its time derivative is bounded.

Assumption 3: m_r, m_l, b_r, and b_l are four unknown positive constants, which are bounded by $m_{r\,\min} \le m_r \le m_{r\,\max}$, $m_{l\,\min} \le m_l \le m_{l\,\max}$, $b_{r\,\min} \le b_r \le b_{r\,\max}$, and $b_{l\,\min} \le b_l \le b_{l\,\max}$.

3 OBSERVER-BASED ADAPTIVE SLIDING MODE CONTROL

Owing to pneumatic servo system is a nonlinear and time-varying system, traditional control methods are usually difficult to achieve a better positioning performance. Among the modern controls, the sliding mode control is less dependent on exact mathematical model of system and has a good robustness with respect to system uncertainty. For designing the sliding mode control, a sliding surface constituted with stage displacement and its derivative with respect to time is firstly constructed, but the derivative of displacement is not easy to measure. Therefore, in this paper, extended state observer will be applied to estimate displacement derivative and system uncertainty. Then, an observer-based adaptive sliding mode control techniques is developed to achieve a high positioning performance for a pneumatic servo system.

3.1 Extended State Observer

Eq. (3) shows that system state variables are x_1 and x_2. Let us expand $x_3 = \ddot{x}_1$ as another system state. Then, we have

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 = a(t) \\ \dot{x}_3 = \dot{a}(t) \end{cases} \tag{5}$$

Follows the work (Han, 1995), the structure of ESO is given as

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 - k_1(\hat{x}_1 - x_1) \\ \dot{\hat{x}}_2 = \hat{x}_3 - k_2(\hat{x}_1 - x_1) \\ \dot{\hat{x}}_3 = -k_3(\hat{x}_1 - x_1) \end{cases} \tag{6}$$

Define the estimated state errors as

$$\begin{cases} \Delta x_1 = \hat{x}_1 - x_1 \\ \Delta x_2 = \hat{x}_2 - x_2 \\ \Delta x_3 = \hat{x}_3 - x_3 = \hat{x}_3 - a(t) \end{cases} \tag{7}$$

Then, from Eq. (7), we can obtain the dynamic equation of estimated state error in the following form:

$$\begin{bmatrix} \Delta\dot{x}_1 \\ \Delta\dot{x}_2 \\ \Delta\dot{x}_3 \end{bmatrix} = \begin{bmatrix} -k_1 & 1 & 0 \\ -k_2 & 0 & 1 \\ -k_3 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \\ \Delta x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\dot{a}(t) \end{bmatrix} \tag{8}$$

Parameters k_1, k_2, and k_3 are chosen such that the dynamical system in Eq. (8) is asymptotic stable.

3.2 Observer-based Adaptive Sliding Mode Control

For designing a sliding mode control, the first step is to construct a sliding surface. The sliding surface is set as

$$s = x_2 + c_1(x_1 - x_d) \tag{9}$$

where c_1 is a positive constant and x_d is a desired reference signal. Then, we have

$$\begin{aligned} s &= x_2 + c_1(x_1 - x_d) \\ &= (\hat{x}_2 - \Delta x_2) + c_1(\hat{x}_1 - \Delta x_1 - x_d) \\ &= \hat{x}_2 + c_1(\hat{x}_1 - x_d) - \Delta x_2 - c_1 \Delta x_1 \end{aligned} \tag{10}$$

where $|\Delta x_2 + c_1 \Delta x_1| \le \eta_1$, $\eta_1 \ge 0$.
Define an almost sliding surface $\hat{s}$ as

$$\hat{s} = \hat{x}_2 + c_1(\hat{x}_1 - x_d) \tag{11}$$

From Eq. (11), Eq. (10) can be expressed as

$$s = \hat{s} - \Delta x_2 - c_1 \Delta x_1 \tag{12}$$

From Eq. (12), we can obtain

$$|\hat{s}| \le |s| + \eta_1 \tag{13}$$

Differentiating $\hat{s}$ with respect to time, we have

$$\dot{\hat{s}} = \Delta \dot{x}_2 + f + d_1 + g_0 w + c_1 \dot{\hat{x}}_1 \tag{14}$$

where $d_1 = d + gw - g_0 w$.

From Eq. (14), let $\dot{\hat{s}} = 0$ and $\Delta \dot{x}_2 = 0$, an equivalent nonlinear control input can be obtained as

$$w_{eq} = \frac{-(f + d_1) - c_1 \dot{\hat{x}}_1}{g_0} \tag{15}$$

In addition to the equivalent nonlinear control input, a nonlinear switching control input is given as

$$w_s = -k_d \hat{s} - k \cdot sat(\frac{\hat{s}}{\varepsilon}) \tag{16}$$

where ε is a sufficiently small positive constant, k_d and k are two positive constants which must satisfy the condition $\eta_2 \le k_d \varepsilon + k$, $\eta_2 > 0$.

From Eqs. (7) and (16), nonliner control input w_d can be obtained as

$$\begin{aligned} w_d &= w_{eq} + w_s \\ &= \frac{-(f + d_1) - c_1 \dot{\hat{x}}_1}{g_0} - k_d \hat{s} - ksat(\frac{\hat{s}}{\varepsilon}) \end{aligned} \tag{17}$$

Considering Eqs. (3) and (10), $-(f + d_1)$ can be repla ced by $-\dot{\hat{x}}_2 + g_0 w$ and then w is replaced by a filter signal $\hat{w}_d$ given from the following equation

$$\dot{\hat{w}}_d = -\delta \, \hat{w}_d + \delta \, w_d$$

where δ is a positive constant and the filter can let $\hat{w}_d$ have the property, $\lim_{t \to \infty} \lim_{\delta \to \infty} \hat{w}_d = w$.
Therefore, Eq. (17) can be rewritten as

$$w_d = \frac{-\dot{\hat{x}}_2 + g_0 \hat{w}_d - c_1 \dot{\hat{x}}_1}{g_0} - k_d \hat{s} - ksat(\frac{\hat{s}}{\varepsilon}) \tag{18}$$

Because function w and dead-zone parameters are unknown, the control input is given by

$$u = \begin{cases} \dfrac{w_d + \widehat{m_r b_r}}{\hat{m}_r} & , \text{if } e_1 < -e_d \\ 0 & , \text{if } |e_1| \le e_d \\ \dfrac{w_d + \widehat{m_l b_l}}{\hat{m}_l} & , \text{if } e_1 > e_d \end{cases} \tag{19}$$

Define parameter vectors as

$$N = [n_r \quad n_l] \tag{20}$$

$$M = [m_r \quad m_l]^{\mathrm{T}} \tag{21}$$

$$\theta = [m_r b_r \quad m_l b_l]^{\mathrm{T}} \tag{22}$$

With

$$n_r = \begin{cases} 1 & , \text{if } e_1 < -e_d \\ 0 & , \text{otherwise} \end{cases} \tag{23}$$

$$n_l = \begin{cases} 1 & , \text{if } e_1 > e_d \\ 0 & , \text{otherwise} \end{cases} \tag{24}$$

It follows that estimated paramter vectors as

$$\hat{M} = [\hat{m}_r \quad \hat{m}_l]^{\mathrm{T}} \tag{25}$$

$$\hat{\theta} = [\hat{\theta}_r \quad \hat{\theta}_l]^{\mathrm{T}} = [\widehat{m_r b_r} \quad \widehat{m_l b_l}]^{\mathrm{T}} \tag{26}$$

and the paramter error vector as

$$\tilde{\theta} = \hat{\theta} - \theta \tag{27}$$

Define the dead-zone and the estimated dead-zone slope ratios as

$$\phi = [\phi_r \quad \phi_l]^{\mathrm{T}} = \begin{bmatrix} \dfrac{m_r}{m_r} & \dfrac{m_l}{m_l} \end{bmatrix}^{\mathrm{T}} = [1 \quad 1]^{\mathrm{T}} \tag{28}$$

and

$$\hat{\phi} = [\hat{\phi}_r \quad \hat{\phi}_l]^{\mathrm{T}} = \begin{bmatrix} \dfrac{m_r}{\hat{m}_r} & \dfrac{m_l}{\hat{m}_l} \end{bmatrix}^{\mathrm{T}} \tag{29}$$

Define

$$\tilde{\phi} = \hat{\phi} - \phi \tag{30}$$

Finally, the control input can be designed in the following form

$$u = \frac{1}{N\hat{M}}(w_d + N\hat{\theta}) \tag{31}$$

$\hat{\theta}$ can be obtained from the following adaptive law

$$\dot{\hat{\theta}} = -s_{\varepsilon}\alpha N^{\mathrm{T}} \tag{32}$$

where $s_{\varepsilon} = \hat{s} - \varepsilon \cdot sat(\frac{\hat{s}}{\varepsilon})$ and α is a positive constant. $\hat{M}$ can be obtained from the following equations

$$\hat{m}_{j,n+1} = \hat{\phi}_{j,n}\,\hat{m}_{j,n} \tag{33}$$

$$\dot{\hat{\phi}} = -s_{\varepsilon}\mu N^{\mathrm{T}}\beta \tag{34}$$

where $\beta = w_d + N\hat{\theta}$ and μ is a positive constant.

3 EXPERIMENTAL RESULTS

To illustrate and validate the positioning control performance, the proposed control scheme is applied in a pneumatic servo sytem shown in Fig. 1. Fig. 2 illustrates the positioning control experimental results of pneumatic servo system. From Fig 2 (b), it is shown that the positioning error is less than 0.05 μm when sliding table moves forward or backward.

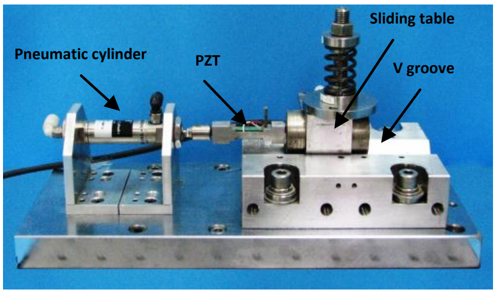

Figure 1: Photograph of the experimental equipment.

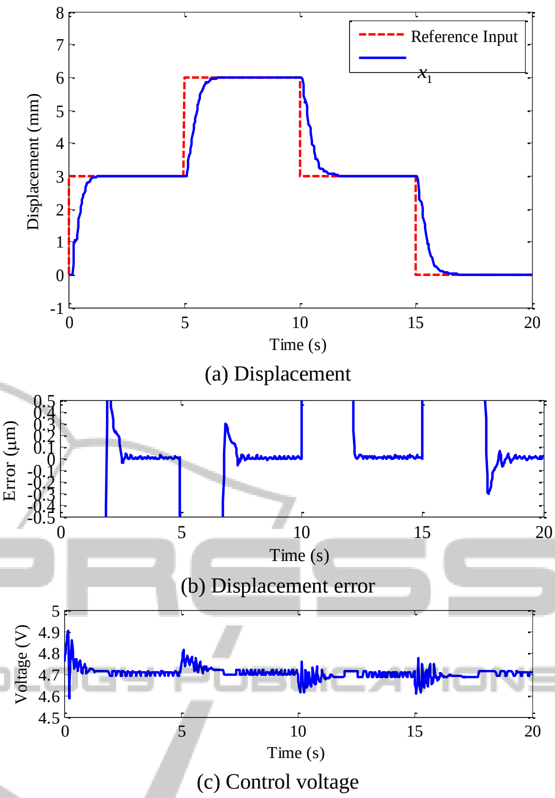

Figure 2: Pneumatic positioning control.

4 CONCLUSIONS

In this paper, an observer-based adaptive sliding mode control is developed for a pneumatic servo control system with nonlinear dead-zone and system uncertainty according to extended state observer, sliding mode control, and adaptive dead-zone inverse techniques. The proposed control scheme is also applied to a pneumatic positioning control experiment and from experimental results, it is shown that the positioning accuracy with less than 0.05 can be obtained.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support from National Science Council, Taiwan, Republic of China for this work, under Grant NSC 100-2221-E-151-006.

REFERENCES

Chiang, M. H., Chen, C. C., Tsou, T. N., 2005. Large Stroke and High Precision Pneumatic-Piezoelectric Hybrid Positioning Control Using Adaptive Discrete Variable Structure Control. *Mechatronics*, Vol. 15, pp. 523-545.

Gross, D. C, Rattan, K. S., 1998. An Adaptive Multilayer Neural Network for Trajectory Tracking Control of A Pneumatic Cylinder. *Proceedings of IEEE International Conference on Systems, Man, and Cybernetics*, Vol. 2, pp. 1662–1667.

Han, J., 1995. Extended State Observer for A Class of Uncertain Plants. *Control Decis.*, Vol. 10, No. 1, pp 85-88.

Korondi, P., Gyeviki, J., 2006. Robust Position Control for a Pneumatic Cylinder. *12th Power Electronics and Motion Control Conference*, pp. 513-518.

Liu, Y. T., Lee, C. H., Fung, R. F., 2004. A Pneumatic Positioning Device Coupled with Piezoelectric Self-Moving Mechanism. *Asian Journal of Control*, Vol. 6, No. 2, pp. 199-207, 2004.
Shih, M. C., Ma, M. A., 1998. Position Control of A Pneumatic Cylinder Using Fuzzy PWM Control Method. *Journal of Mechatronics*, Vol. 8, No. 3, pp. 241-253.
Song, J., Ishida, Y., 1997. A Roboust Sliding Mode Control for Pneumatic Servo Systems. *International Journal of Engineering Science*, Vol. 35, No. 8, pp. 711-723.