Position Control of Flexible Pneumatic Cylinder Using Tiny Embedded Controller with Disturbance Observer

Wataru Kobayashi, Naoki Kato, Shujiro Dohta, and Tetsuya Akagi
Department of Intelligent Mechanical Engineering, Okayama University of Science, Okayama, Japan
Email: {kobayashi, dohta, akagi}@are.ous.ac.jp, t16rm02kn@ous.jp

Kazuhisa Ito
Department of Machinery and Control Systems, College of Systems Engineering and Science, Shibaura Institute of Technology, Saitama, Japan
Email: kazu-ito@shibaura-it.ac.jp

***Abstract*—In the previous study, the flexible pneumatic cylinder was proposed and tested as a wearable actuator. The flexible robot arm using the cylinder for human wrist rehabilitation was also developed. In the next step, it is necessary to improve the control performance affected by disturbance such as a friction in a cylinder. In this paper, to realize a wearable, low-cost and robust control system, the position control system of the cylinder using a disturbance observer applied into the tiny embedded controller is proposed and tested. The position tracking control using the proposed system is carried out. As a result, it was confirmed that the proposed control scheme achieved 40% improvement of the mean absolute error in experiments.**

***Index Terms*—flexible pneumatic cylinder, embedded controller, disturbance observer, position control**

I. Introduction

Welfare devices are seriously required because of high aging society in Japan for improving Quality of Life (QOL). In these devices, soft actuators are promising because human friendliness, flexibility, and safety are important. We developed a flexible pneumatic cylinder [1] which is a kind of rodless-type cylinders. As an application of the developed actuator, a wrist rehabilitation device using the cylinders was proposed and tested [2]-[4].

The tested device is wearable type and consists of three flexible pneumatic cylinders, an embedded controller, an accelerometer, six quasi-servo valves, and two acrylic stages. Conventional PID control scheme was applied to the device. Although the device can trace the desired position, there exist vibrations which is not suitable for rehabilitation devices. The vibration mainly comes from a time-delay depending on friction of the cylinder and valves.

In this paper, we apply disturbance observer [5] with time-delay compensation and Smith's compensator into a tiny embedded controller in order to attenuate vibrations of the device. The disturbance observer was applied to various applications, such as force control of robots [6], [7] and then its effectiveness has been confirmed. However, the disturbance observer has not been used to the tiny embedded controller because of low memory, low ability for calculation, and its complex hardware setting such as timers, A/D converters and serial communications.

To reduce the amount of calculation, a nominal model in the disturbance observer is simplified. From preliminary experiments, it can be seen that the cylinder has relatively large time-delay. To compensate the time-delay, we propose a novel control system which is a two-degrees of freedom control system [8] that it combines the disturbance observer with consideration of the time-delay and the Smith's compensator for the controller.

II. Flexible Pneumatic Cylinder

The construction and movement of the flexible pneumatic cylinder which is a primary component in the proposed rehabilitation device are shown in Fig. 1 and Fig. 2, respectively. The cylinder consists of these main parts; a flexible tube as a cylinder, the steel ball as a cylinder head, and a slide stage. The slide stage has two rollers set on the inner bore of the stage to press and deform the tube. The steel ball is held by two slide stages from both sides of the ball. When the pressure is supplied to one side of the cylinder, the tube is moved forward or backward while holding the slide stage. This is a kind of rodless-type cylinder. The slide stage can move smoothly on the curved cylinder tube. The minimum driving pressure of the flexible pneumatic cylinder is 120kPa. The frictional force of the cylinder is relatively large, and time-delay is longer compared with a typical pneumatic cylinder. Therefore, it is necessary to apply a control scheme with compensation for frictional force and time-delay.

III. Design of Control System with Time-Deley

As a control scheme, we apply the two-degrees of freedom control system including the disturbance

Manuscript received January 20, 2017; revised April 17, 2017.

doi: 10.18178/ijmerr.6.4.318-321

observer with time-delay compensation and the Smith's compensator.

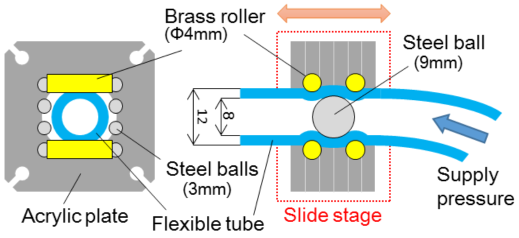

Figure 1. Construction of flexible pneumatic cylinder.

Figure 2. Movement of flexible pneumatic cylinder.

In this paper, the disturbance observer is applied because it is not necessary to estimate all state variables and it is enough to estimate disturbance. The frictional force between the flexible tube and the slide stage is large due to a sealing mechanism for preventing leakage flow. Thereby, improvement of the control performance can be expected by using the disturbance observer. The estimated disturbance $\hat{d}(t)$ is obtained from a following equation.

$$\hat{d}(t) = Q(s)P_n^{-1}(s)y(t) - Q(s)e^{-Ls}u(t) \tag{1}$$

where $Q(s)$ is a transfer function of a filter of the disturbance observer which will be designed later, $P_n(s)$ a transfer function of a nominal model of the system, $u(t)$ a control input, $y(t)$ an output, and L a time-delay. Fig. 3 shows the block diagram of the disturbance observer where $d(t)$ and $u'(t)$ mean disturbance and an external input, respectively.

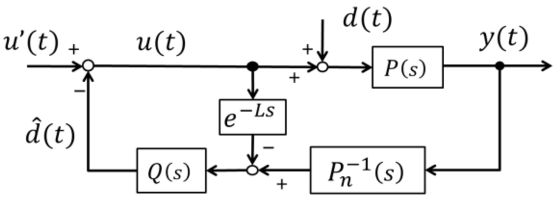

Figure 3. Block diagram of the disturbance observer.

From (1), the transfer function from $u'(t)$ to $y(t)$ coincides with the transfer function of the nominal model $P_n(s)$.

On the other hand, the Smith's compensator can be widely used to compensate the time-delay. To make the compensator work well, the transfer function of the system must be known. However, we can use the compensator because the transfer function of the system is $P_n(s)$ as described above. Fig. 4 shows a block diagram of a feedback control system with the Smith's compensator. Notice that $r(t)$ is a desired value, $C(s)$ a transfer function of a controller, $S(s)$ a transfer function of the Smith's compensator.

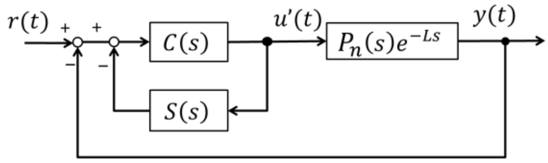

Figure 4. Block diagram of the Smith's compensator.

Choosing

$$S(s) = P_n(s)\left(1 - e^{-Ls}\right) \tag{2}$$

leads to

$$\frac{Y(s)}{R(s)} = \frac{C(s)P_n(s)}{1 + C(s)P_n(s)} e^{-Ls} \tag{3}$$

From (3), it is confirmed that the time-delay can be removed from the characteristic polynomial.

Thus, the control system with the disturbance observer and the Smith's compensator can be obtained. Fig. 5 shows a block diagram of whole feedback control system. The control system is used a PID control as a controller.

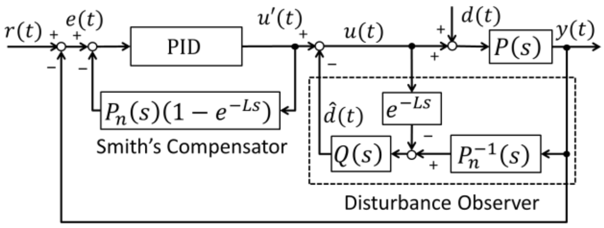

Figure 1. Block diagram of the proposed control system.

In a design of a control system using an embedded controller, these hardware setting and programming for the controller are required to execute by using in tiny memory of controller. In the control system, to reduce memory and amount of calculation, the following first order transfer function of the nominal model $P_n(s)$, the transfer function of the filter $Q(s)$, and the external input $u'(t)$ were used.

$$P_n(s) = \frac{1}{1 + T_n s} \tag{4}$$

$$Q(s) = \frac{1}{1 + T_q s} \tag{5}$$

$$u'(t) = K_p e(t) + K_d \dot{e}(t) + K_i \int_0^t e(\tau)d\tau \tag{6}$$

where T_n is a time constant of the nominal model, T_q a time constant of the filter. T_n is 1s and T_q is 0.0025s. These discretized equations with sampling period of 5ms are given as follows.

$$P_n(z) = \frac{0.004988}{z - 0.995} \tag{7}$$

$$Q(z) = \frac{0.1813}{z - 0.8187} \tag{8}$$

$$\hat{d}(k) = 0.819\hat{d}(k-1) + 40.0y(k) - 39.8y(k-1) - 0.181u(k - L_d), \tag{9}$$

$$u'(k) = K_p e(k) + K_d \left(e(k) - e(k-1)\right) + K_i \sum_{j=1}^{k} e(j) \tag{10}$$

IV. Position Control of Cylinder

Fig. 6 and Fig. 7 show the schematic diagram of control system of the flexible pneumatic cylinder and the view of the experimental setup of the position control system, respectively. The system consists of the flexible pneumatic cylinder, an embedded controller (Renesas Electronics Corporation, SH7125), a function-generator (Teledyne LeCroy Japan Corporation, wave station 2012), a wire-type linear potentiometer [9], and four quasi-servo valves [10]. The quasi-servo valve consists of two on/off type control valve: one is a switching valve for supply/ exhaust and the other is a PWM controlled valve for adjusting flow rate. The operation of these valves are based on the control input $u(t)$. The absolute value of the control input $u(t)$ is input duty ratio of the PWM control valve, and the sign of the control input $u(t)$ is used to drive the switching valve for supply or exhaust. The sampling period and PWM period are controlled by using integrated timers in the embedded controller. Both are set as 5ms. The output $y(t)$ is detected as A/D value through the potentiometer and built-in 10 bit A/D converter.

In the experiment, the initial position of the cylinder is set on the center of the cylinder. In the control, the control parameter of PID gains of K_p = 6.0%/mm, K_d = 2.5%/mm, and K_i = 0.1%/mm were used. These values were determined by trial and error.

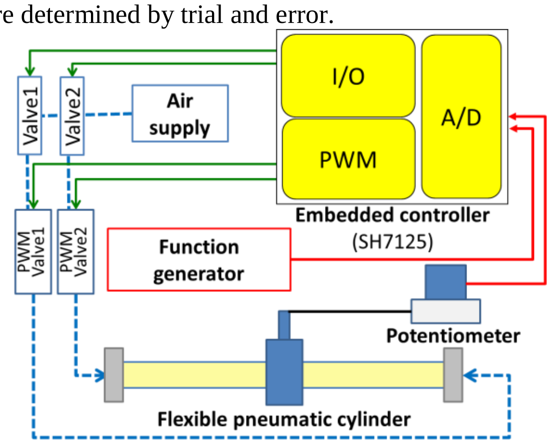

Figure 2. Schematic diagram of control system.

Fig. 8 shows experimental result of position control of the cylinder displacement. The desired position with frequency of 0.1Hz and the amplitude of 50mm was applied. The displacement was measured through serial communication port with sampling period of 5ms. In Fig. 8, broken line and solid line show the reference and the output, respectively. From the figure, it can be seen that the cylinder displacement can trace the reference very well. In order to confirm the effectiveness of the disturbance observer, the position control using typical PD control scheme was also executed and Fig. 9 shows the result. In the experiment, the control parameter of K_p = 3.5%/mm and K_d = 2.5%/mm were used. It can be found that a lager oscillation was occurred compared with the case using the proposed controller. As a result, it was confirmed that the disturbance could be compensated by the proposed controller. The mean absolute error was improved 40% compared with the result using the typical PD controller.

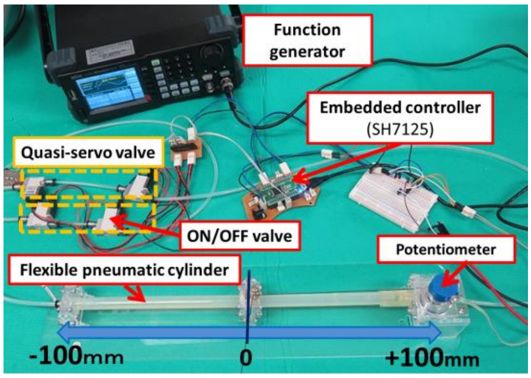

Figure 1. Experimental setup of position control.

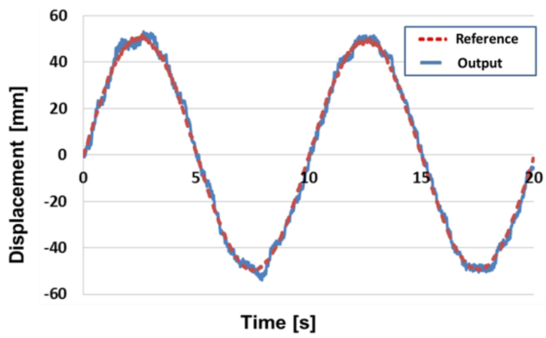

Figure 2. Position control of cylinder using proposed controller.

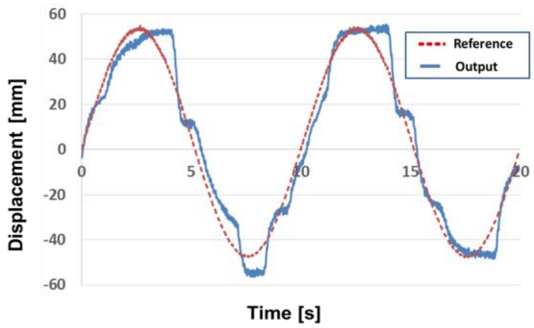

Figure 3. Position control using typical PD control scheme.

V. Conclusions

In order to realize a wearable, low-cost and robust control system, the position control system of the cylinder using a disturbance observer applied into the tiny embedded controller was proposed and tested. To compensate the time-delay of the system, PID controller that combines the disturbance observer with consideration of the time-delay and the Smith's compensator was also applied to the system. The design that includes both proposed control scheme and hardware setting of the tiny embedded controller was executed. The position tracking control using the proposed system was also carried out. As a result, it can be confirmed that the proposed control scheme improved the control performance of 40% of the mean absolute error compared with typical PD control scheme.

ACKNOWLEDGMENT

This research was supported by the MEXT in Japan through a Financial Assistance Program for QOL Innovative Research (2012-2016) and a Grant-in-Aid for Scientific Research (C) (Subject No. 24560315 & 16K06202).

REFERENCES

[1] T. Akagi and S. Dohta, "Development of a rodless type flexible pneumatic cylinder and its application," *Transactions on Robotics and Automation of the JSME (C)*, vol. 73, no. 731, pp. 2108-2114, 2007.

[2] M. Aiff, *et al*., "Control and analysis of robot arm using flexible pneumatic cylinder," *Mechanical Engineering Journal*, vol. 1, no. 5, pp. 1-13, 2014.

[3] T. Morimoto, *et al.*, "Development of flexible haptic robot arm using flexible pneumatic cylinders with backdrivability for bilateral control," *Lecture Notes in Electrical Engineering*, vol. 345, pp. 231-237, 2016.

[4] N. Kato, *et al.*, "Development of wearable wrist rehabilitation device using flexible pneumatic cylinders," in *MATEC Web of Conferences*, vol. 51, no. 02003, pp. 1-5, 2016.

[5] K. Kubo, *et al*., "Disturbance torque compensated speed observer for digital servo drives," in *Proc. 16th Annual Conference of Industrial Electronics Society*, 1990, pp. 1182-1187.

[6] S. Katsura, M. Yuichi, and O. Kouhei, "Modeling of force sensing and validation of disturbance observer for force control," *IEEE Transactions on Industrial Electronics*, vol. 54, no.1, pp. 530-538, 2007.

[7] K. Kong, J. Bae, and M. Tomizuka, "A compact rotary series elastic actuator for human assistive systems," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 2, pp. 288-297, 2012.

[8] K. Ito, *et al*., "Robust control of water hydraulic servo motor system using sliding mode control with disturbance observer," *in Proc. SICE-ICASE International Joint Conference*, 2006.

[9] Y. Matsui, *et al*., "Development of low-cost wire type linear potentiometer for flexible spherical actuator," Proc. AIM2016, 2016.

[10] F. Zhao, T. Akagi, and S. Dohta, "Development of small-sized quasi-servo valve for flexible bending actuator," in *Proc. CACS Int. Automatic Control Conference*, 2009, pp. 558-562.

Wataru Kobayashi is currently an assistant professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Shibaura Institute of Technology in 2015. His research interests are robust control theory and aqua drive system; especially rehabilitation and life support systems.
He is a member of The Japan Society of Mechanical Engineers, The Society of Instrument and Control Engineers, The Japan Fluid Power System Society, and The Society of Life Support Engineering.

Naoki Kato master student, studies in Okayama University of Science since 2016. His research topics are focused on development of wearable rehabilitation device using soft pneumatic actuator.

Shujiro Dohta is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He is also currently a Vice-president of Okayama University of Science.
He joined Okayama University of Science as a research associate on 1974. Then, he became an Exchange Faculty of Wright State University, U.S.A. from 1984 to 1985. He received his doctor degree in Engineering from Kobe University in 1990. His major in mechatronics is focusing on the development of robotics, wearable devices for rehabilitation purpose.
Prof. Shujiro Dohta is currently a member of The Japan Society of Mechanical Engineers (JSME), The Society of Instrument and Control Engineers (SICE), The Robotics Society of Japan (RSJ), and The Japan Fluid Power System Society (JFPS).

Tetsuya Akagi is currently a professor of Department of Intelligent Mechanical Engineering, Okayama University of Science, Japan. He received his doctor degree in Engineering from Okayama University of Science in 1998.
He started at Tsuyama National College of Technology, Japan as a research associate on 1998. Then, he joined Okayama University of Science as a lecturer from 2005. He received Young Scientists' Prize from Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan. His research interests include mechatronics and robotics; especially wearable control systems using microcomputers and wearable control devices such as flexible pneumatic actuator, soft sensor and wearable control valve.

Kazuhisa Ito is currently a full professor at the Department of Machinery and Control Systems, Shibaura Institute of Technology. He received his B.E. (1993), M.E. (1995), and D.E. (2001) degrees in Mechanical Engineering from Sophia University, JAPAN.
His current research interests include controller design for nonlinear systems and its application to mechanical systems; especially control/ energy saving performance improvement of aqua drive system, and agriculture engineering.
He is a member of The Japan Fluid Power System Society, The Society of Instrument and Control Engineers, and Japanese Society of Agricultural, Biological and Environment Engineers and Scientists.