Development of Wearable Wrist Rehabilitation Device using Twisted Wire Type Potentiometer and Built-In Controller with Disturbance Observer

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In the previous study, we developed a flexible pneumatic cylinder. A wrist rehabilitation device using these cylinders was also proposed and tested. To improve the position control performance of the cylinder, a disturbance observer with time-delay compensation and Smith’s compensator were applied into a built-in tiny embedded controller for position control of a single cylinder. As a result, it was confirmed that 40% improvement of the mean absolute error in experiments was achieved by using the proposed control scheme. In the next step, we aim to apply the improved controller into the attitude control system of the whole wrist rehabilitation device using three cylinders in which there exists an interference among three cylinders. To install the control system, it is necessary to measure lengths of bending cylinders. In this paper, we apply the disturbance observer to the attitude control of the device, and we propose a measuring method of bending tube length by using a twisted wire type linear potentiometer and a simple analytical model. Then, the proposed method is applied to the attitude control of the device.

Keywords: Flexible pneumatic cylinder, Rehabilitation device, Built-in controller, Disturbance observer, Wire type linear potentiometer

1. Introduction

Welfare devices are seriously required because of high aging society in Japan for improving Quality of Life. In these devices, soft actuators promise because human friendliness, flexibility, and safety are important. In addition, the requirement for a rehabilitation device without support from physical therapist (PT for short) will also be increased based on the lack of number of PT according to Japanese aging society. Based on this background, Takaiwa developed a wrist rehabilitation equipment using pneumatic parallel manipulator1). In addition, Takaiwa also developed a wrist rehabilitation training simulator for PT using the manipulator2). Taniguchi developed a hand rehabilitation system to prevent contracture for finger joints using a pneumatic soft actuators3). These devices require many control valves and a PC as a controller. Therefore, these devices becomes a little bulky and they are not wearable. In such a situation, “a home rehabilitation device” that the patients can use it by themselves at home is also desired. In ideal, to apply it at home, the device must to be constructed by lower cost so that the users can buy it without official financial support. In this study, we aim to realize such a home rehabilitation device. In our previous study, we developed a flexible pneumatic cylinder4). As an application of the cylinder, a wrist rehabilitation device using three cylinders was proposed and tested5). A wearable wrist rehabilitation device using the cylinders that valves and a controller are mounted on the devices was proposed and tested6). In addition, to improve the position control performance of the single cylinder, a disturbance observer7) with time-delay compensation and Smith’s compensator were applied into a built-in tiny embedded controller. As a result, it was confirmed that the proposed control scheme achieved 40% improvement of the mean absolute error in experiments8).

In the next step, we aim to apply the improved controller into the attitude control system of the wrist rehabilitation device using three cylinders. To install the control system, it is necessary to measure position of bending cylinders. In this paper, we apply the disturbance observer to the attitude control of the device, and we propose a measuring method of bending tube length by using a twisted wire type linear potentiometer and a simple analytical model. Then, the proposed method is applied to the attitude control of the device.
rehabilitation device using three cylinders. Both the attitude controller and the measuring system of three cylinders are installed into the tiny embedded controller.

2. Nomenclature

\[
P_n(s): \text{nominal model} \\
P_d(s): \text{filter of disturbance observer} \\
\hat{d}(t): \text{estimated disturbance} \\
r(t): \text{desired value} \\
e(t): \text{error} \\
u(t): \text{control input} \\
y(t): \text{output} \\
d(t): \text{disturbance} \\
L_d: \text{time-delay} \\
T_n: \text{time constant of the nominal model} \\
T_q: \text{time constant of the filter} \\
l: \text{length from the wire fixed position to the wire contacting point on the cylinder} \\
x_p: \text{wire length} \\
r: \text{radius of the cylinder} \\
w: \text{distance between the wire fixed position and the center of the cylinder} \\
a: \text{length of wire contacted circumference on the cylinder} \\
L: \text{cylinder length}
\]

3. Structure of Rehabilitation Device

Figure 1 shows a structure of the flexible pneumatic cylinder. The cylinder consists of a flexible tube, a steel ball, and a slide stage. The slide stage has two rollers set on the inner bore of the stage to press and deform the tube. These rollers and balls are set on the acrylic plate with a hole by clamping the acrylic plates from both sides. The steel ball is held by the slide stage from both sides of the ball. The operating principle of the cylinder is as follows. When the supply pressure is applied to one side of the cylinder, the inner steel ball is pushed. At the same time, the steel ball pushes the brass rollers and then the slide stage moves toward the opposite side of the pressurized while it deforms the tube. Compared with an ordinal pneumatic cylinder, the frictional force of the tested cylinder is larger. The minimum driving pressure of the cylinder is about 120 kPa.

Figure 2 shows a structure of the wearable wrist rehabilitation device using the cylinders. The device consists of three cylinders and two round stages. Each cylinder is arranged on the round stage with radius of 87.5 mm every 120 deg. from the center and the end of each cylinder is fixed to the base stage. The end stage has a hole so that a human arm can insert into it. The slide stage of each cylinder is fixed to the end stage with a handle. In rehabilitation, the device can serve passive exercise to the human wrist. The attitude control system that consists of an embedded controller (Renesas Electronics Corporation, SH7125), an accelerometer and six quasi-servo valves\textsuperscript{10} is mounted on the device. The device has the outer diameter of 200 mm and the length of 420 mm. The total mass of the device is 1.14 kg. The accelerometer is mounted on the end stage to measure the length of the flexible pneumatic cylinder between the end and base stages of the device based on the analytical model\textsuperscript{3}. The attitude tracking control of the device using the accelerometer and the model was successfully carried out for sequential desired position\textsuperscript{7}. However, in the control, the device must be set toward the horizontal direction because of the attitude measurement by measuring the direction of a gravity. This measuring method using the accelerometer prevents from changing the setting position of the device freely. Therefore, a novel direct measuring method of cylinder displacement will be required. In addition, the position control performance of the flexible pneumatic cylinder is not proper, because the cylinder has relatively large frictional force that is more than 10 N. The large friction causes a time delay until the actuator starts to move. Therefore, in the position control of the flexible pneumatic cylinder, it is necessary to apply a control scheme that can compensate the friction and time delay.
4. Proposed Controller and Measuring System

From above background, we applied the two-degrees-of-freedom control system including the disturbance observer with time-delay compensation and the Smith’s compensator. 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. Figure 3 shows a block diagram of whole feedback control system, where $Q(s)$ is a filter transfer function of the disturbance observer, $P_n(s)$ a transfer function of a nominal model of the system, $R(s)$ a reference, $U(s)$ a control input, $Y(s)$ an output, $D(s)$ disturbance, $U'(s)$ an external input, $\hat{D}(s)$ the estimated disturbance and $L_t$ a time-delay.

$$P_n(s) = \frac{1}{1 + T_n s}, \quad (1)$$

$$Q(s) = \frac{1}{1 + T_q s}, \quad (2)$$

$$u'(t) = K_p e(t) + K_d \dot{e}(t) + K_i \int_0^t e(\tau) d\tau, \quad (3)$$

where $T_n$ is a time constant of the nominal model, $T_q$ a time constant of the filter, $e(t)$ an error. $T_n$ and $T_q$ are 1 s and 0.0025 s, respectively. The time-delay $L_t$ is caused by friction of the flexible pneumatic cylinder. From the preliminary experiments, the time-delay of 0.5 s was identified. This time-delay can’t be ignored because the value of 0.5 s is relatively large compared with that of typical pneumatic cylinder. These discretized equations by using the zero-order hold method with sampling period of 5 ms are given as follows.

$$P_n(z) = \frac{0.004988}{z - 0.995}, \quad (4)$$

$$Q(z) = \frac{0.1813}{z - 0.8187}, \quad (5)$$

$$u'(k) = K_p e(k) + K_d (e(k) - e(k - 1)) + K_i \sum_{j=1}^{k} e(j), \quad (6)$$

where $z$ and $k$ mean a forward shift operator and a sampling count.

In order to apply the control scheme to the system, it is needed to measure the length of the cylinder. However, it is difficult to measure a length of the bending cylinder between the end and base stage. Therefore, a novel measuring method well, the transfer function of the system must be precisely known. In this device, however, the transfer function $P(s)$ is unknown. The transfer function from $U'(s)$ to $Y(s)$ coincides with the transfer function of the nominal model $P_n(s)$ by using the disturbance observer as shown in Fig. 3. It means that the transfer function of the nominal model $P_n(s)$ can be used as a known transfer function. Therefore, we can design the Smith’s compensator correctly by using $P_n(s)$. In addition, to improve the dynamic characteristics, the PID control law is applied. In design of the control system using an embedded controller, these hardware setting and programming for the controller are required to execute by using in tiny memory of the controller. In the control system, to reduce memory and amount of calculation, the following first order transfer functions of the nominal model $P_n(s)$, the transfer function of the filter $Q(s)$, and the external input $u(t)$ are used.

$$P_n(s) = \frac{1}{1 + T_n s}, \quad (1)$$

$$Q(s) = \frac{1}{1 + T_q s}, \quad (2)$$

$$u'(t) = K_p e(t) + K_d \dot{e}(t) + K_i \int_0^t e(\tau) d\tau, \quad (3)$$

where $T_n$ is a time constant of the nominal model, $T_q$ a time constant of the filter, $e(t)$ an error. $T_n$ and $T_q$ are 1 s and 0.0025 s, respectively. The time-delay $L_t$ is caused by friction of the flexible pneumatic cylinder. From the preliminary experiments, the time-delay of 0.5 s was identified. This time-delay can’t be ignored because the value of 0.5 s is relatively large compared with that of typical pneumatic cylinder. These discretized equations by using the zero-order hold method with sampling period of 5 ms are given as follows.

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where $z$ and $k$ mean a forward shift operator and a sampling count.

In order to apply the control scheme to the system, it is needed to measure the length of the cylinder. However, it is difficult to measure a length of the bending cylinder between the end and base stage. Therefore, a novel measuring method.

Fig.2 Construction of wearable wrist rehabilitation device using flexible pneumatic cylinders

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using a twisted wire type linear potentiometer is proposed and tested. Figure 4 (a) shows the measuring method of bending cylinder length. For convenience, we call “cylinder length” for the arc distance between the end of cylinder and the slide stage as shown in Fig. 4. To measure the cylinder length when the cylinder bends, the wire of the displacement sensor is wound into a 360-degree roll around the cylinder helically. We assume that the wire is always wound at the middle position of the cylinder length. According to the change of the cylinder length, the wire length is changed. We also propose a simple analytical model for measuring the tube length from the twisted wire length.

Figure 4 (b) shows a model of cylinder length under the condition that the tube is straight. From the geometric relationship, the following equations about cylinder length \( L \) can be obtained.

\[
L = \sqrt{X_p^2 - (2l + a)^2}, \quad (7)
\]
\[
l = \sqrt{w^2 - r^2}, \quad (8)
\]
\[
a = 2r \left( \pi - \cos^{-1} \frac{r}{w} \right), \quad (9)
\]

where \( x_p, l, a, r, \) and \( w \) mean a wire length, a length from the wire fixed position to the wire contacting point on the cylinder, a length of wire contacted circumference on the cylinder, a radius of the cylinder, and a distance between the wire fixed position and the center of the cylinder, respectively. \( L \) means the arc length of the cylinder between the base stage and the end stage connected to the slide stage. In the experiment, we used the radius \( r \) of 6 mm and the distance \( w \) of 20 mm.

![Helical potentiometer](image)

**Fig. 5 Low-cost wire type linear potentiometer**

Figure 6 shows a result of measured length of the cylinder using the proposed method and the analytical model as shown in Fig. 4 (b) for various attitudes of the cylinder. In experiments, as an initial length of cylinder, length of three cylinders in the rehabilitation device are set to 150 mm. In the case when the length of cylinder 2 as shown in Fig. 2 was changed between 60 to 270 mm every 30 mm, the calculated length and measured length using a scale of the cylinder were observed. The measured length using a scale was measured by using the string along to bending shape of the cylinder. In Fig. 6, the solid line shows the result using the proposed method. The broken line shows the case when measured length using a scale of the cylinder meets the result using proposed method. From Fig. 6, it can be found that there are relatively larger error in the case of shorter length of less than 90 mm and longer length of more than 210 mm of the cylinder. The error is caused by modeling error that the trajectory of the wire of the potentiometer does not meet the proposed model. However, it can be seen that the measured length agrees well with the measured length using a scale of the bending cylinder in the range from 90 to 210 mm. We can confirm that the proposed method is useful to
apply the displacement measurement of the flexible pneumatic cylinder in the rehabilitation device because the range from 90 to 210 mm is covered a typical moving range for rehabilitation motion using the tested device.

**5. Attitude Control of Device**

Figure 7 shows the whole view of the wearable wrist rehabilitation device that has three wire type linear potentiometers. The geometric configuration of a wire fixed position is designed by the model as shown in Fig.4 (b). Figure 8 shows the schematic diagram of the proposed control system of the tested rehabilitation device. The system consists of the flexible robot arm using three flexible pneumatic cylinders, an embedded controller (Renesas Electronics Corporation, SH7125), a function-generator (Teledyne LeCroy Japan Corporation, wave station 2012) for desired position, three wire-type linear potentiometers, and four quasi-servo valves. Each quasi-servo valve consists of two on/off type control valves: one is a switching valve for supply/ exhaust and another 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 5 ms. The output $y(t)$ is A/D value through the potentiometer and built-in 10 bit A/D converter. In the controller, the control parameter of PID gains of $K_p = 6.0 \ [%/\text{mm}]$, $K_d = 1.5 \ [%/\text{mm}]$, and $K_i = 0.0025 \ [%/\text{mm}]$ were used. These values were determined by trial and error so as to get less tracking error.

Figures 9 (a) and (b) show the experimental result of attitude control of the wearable wrist rehabilitation device of each cylinder length using the proposed controller and the typical PD controller, respectively. In the experiment, when a subject wears the wearable wrist rehabilitation device, the desired position with frequency of 0.1 Hz and amplitude of 50 mm from the neutral position of the cylinder were applied. The measured lengths of three cylinders were sent from the embedded controller to the personal computer through serial communication port with sampling period of 5 ms. In Fig. 9, the broken and solid lines show the desired length of the cylinder and the controlled length of cylinder, respectively. From Fig.9 (a), it can be seen that the cylinder displacement can track the desired length well. Compared with the result using the typical PD controller as shown in Fig.9 (b), we found that the tracking control performance using the proposed control system was improved. We can confirm that the proposed controller is useful to apply the rehabilitation device.

Fig.7 Whole view of wrist rehabilitation device

Fig.8 Schematic diagram of proposed control system
6. Conclusions

In order to measure the length of bending cylinders in the wearable wrist rehabilitation device, the measuring method using the wire type linear potentiometer and simple analytical model was proposed and tested. The experiment of measuring lengths of bending cylinders was carried out. As a result, the measured length agrees well with the real length of the cylinder in the range from 90 to 210 mm. We can confirm that the proposed method is useful to apply as a displacement measurement method of the flexible pneumatic cylinder in the rehabilitation device.

In order to improve the attitude control performance of the wrist rehabilitation device, the built-in controller with the two-degrees-of-freedom control system including the disturbance observer with time-delay compensation and the Smith’s compensator was proposed and tested. The disturbance and the time-delay were able to be compensated by the disturbance observer and the Smith’s compensator. The attitude tracking control of the tested device was also carried out. As a result, we can confirm that the proposed controller is valid to apply the rehabilitation device because of less tracking error.

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