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Position Control of Rubber Artificial Muscle Using Built-in Ultrasonic Sensor and Quasi-Servo Valve

So Shimooka, Shujiro Dohta, Tetsuya Akagi, and Yoshinori Moriwake
Department of Intelligent Mechanical Engineering, Okayama University of Science, Okayama, Japan
Email: {t14rm01ss, t14sd01my}@ous.jp, {dohta, akagi }@are.ous.ac.jp

***Abstract*—Today, the care and welfare pneumatic equipment to support a nursing care and a self-reliance of the elderly and the disabled are actively researched and developed by many researchers. These wearable devices require many servo valves for multi degrees of freedom and precise control performance of the wearable actuator. The total weight of the wearable devices increases according to the degree of freedom. In the previous study, a small-sized and light-weight pressure control type quasi-servo valve and rubber artificial muscle using built-in displacement sensor were developed. The quasi-servo valve consists of two on/off control valves and an embedded controller. In this study, an ultrasonic sensor is installed in the rubber artificial muscle as a displacement sensor. Then, the position control of the artificial muscle using the built-in displacement sensor is proposed and tested. As a result, it is confirmed that the position control of the muscle can be realized using the tested sensor.**

***Index Terms*—ultrasonic sensor, small sized control valve, rubber artificial muscle, embedded controller**

I. Introduction

Today, the care and welfare pneumatic equipment to support a nursing care and a self-reliance of the elderly and the disabled are actively researched and developed by many researchers [1]-[3]. These wearable devices require many servo valves for multi degrees of freedom and precise control performance of the wearable actuator [4]. The total weight of the wearable devices increases according to the degree of freedom. In our previous study, a small-sized and light-weight pressure control type quasi-servo valve was developed. The valve consists of two on/off control valves and an embedded controller. In this study, a position of a rubber artificial muscle is controlled by using a quasi-servo valve and an ultrasonic sensor which is used as a displacement sensor. The ultrasonic sensor is installed in the rubber artificial muscle. The position control of the artificial muscle using the built-in sensor is also proposed and tested.

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II. Artificial Rubber Muscle Using Built-in Sensor

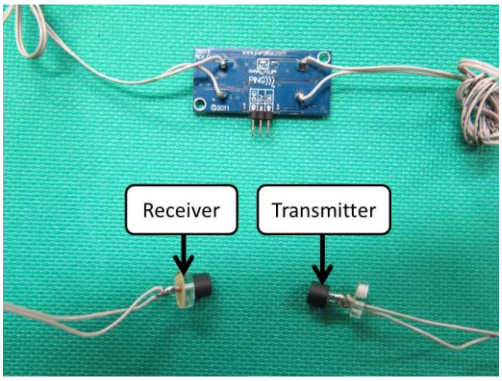

Figure 1. View of the modified ultrasonic sensor.

As a built-in position sensor of the rubber artificial muscle, an ultrasonic sensor was selected, because the ultrasonic sensor has many advantages that it can measure the displacement by non-contacting and is a low-cost sensor. Fig. 1, Fig. 2 and Fig. 3 show a view of the tested ultrasonic sensor, a schematic diagram of the system and a view of a rubber artificial muscle (Festo Co. Ltd., MXAM-20-AA) with a built-in sensor and an embedded controller, respectively. The original length of rubber artificial muscle is 220 mm and the inner diameter is 20 mm. The stroke of the muscle is about 50mm in the case when the supply pressure of 500 kPa is applied. The tested ultrasonic sensor is rebuilt by using the ultrasonic sensor on the market (Parallax Inc. Ltd., 28015). The transmitter and receiver on the sensor are changed smaller ones as shown in Fig. 1 on the right side (the transmitter: Nippon Ceramic Co. Ltd., T4008A1) and on the left side (the receiver: Nippon Ceramic Co. Ltd., R4008A1), respectively.

The measuring method using the ultrasonic sensor is as follows. The velocity of sound wave in the air V[m/s] is given by

$$V = 331.5 + 0.607t \tag{1}$$

where t means a temperature[℃]. The distance is estimated by the time until the ultrasonic wave reaches at the receiver from the transmitter. This time T is counted by

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an embedded controller (Renesas Co. Ltd., H8/3664). The distance between the transmitter and the receiver L can be calculated by using the velocity V and the time T as given by

$$L = V \cdot T \tag{2}$$

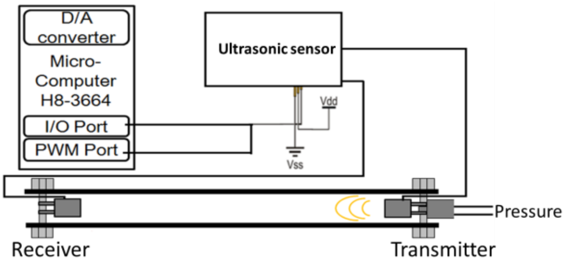

Figure 2. Schematic diagram of rubber artificial muscle with built-in sensor and embedded controller.

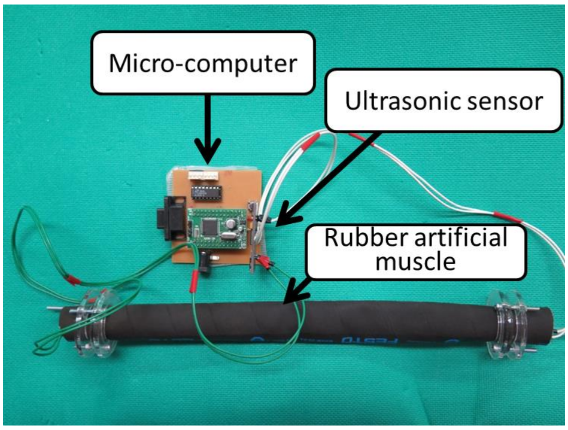

Figure 3. View of rubber artificial muscle with built-in sensor and embedded controller.

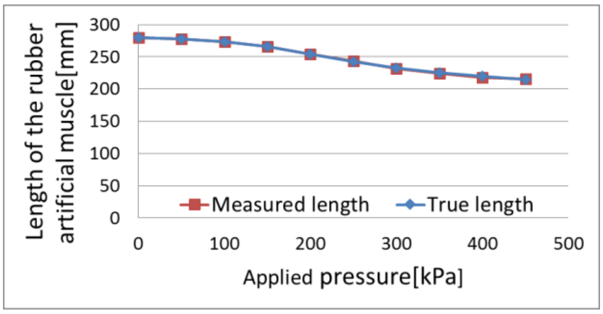

Figure 4. Relation between applied pressure and length of rubber artificial muscle.

Fig. 4 shows the relation between the applied pressure and the length of the rubber artificial muscle. The length was measured by the tested built-in ultrasonic sensor or a potentiometer. In the experiment, the artificial muscle was pressurized from 0 to 450 kPa every 50 kPa by using the regulator (KOGANEI Co. Ltd., PR100). The true length of the muscle was measured by a potentiometer connected with the muscle in series. In Fig. 4, the red line and the blue line show the measured length using the tested sensor and real length measured by the potentiometer, respectively. From Fig. 4, it can be confirmed that the sensor length and real length agreed well even if the applied pressure is changed. Fig. 5 shows the relation between the measured length and the true length of the muscle. From Fig. 5, it can be seen that the relation between the sensor output and the true length of the muscle is linear. This result means that the tested ultrasonic sensor is useful as a built-in displacement sensor of the rubber artificial muscle.

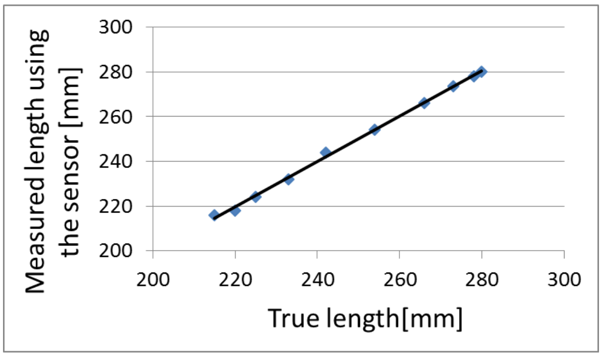

Figure 5. Relation between measured length using the sensor and true length of the tested muscle.

III. Small-Sized Quasi-Servo Valve Using Embedded Controller

In order to develop the compact control valve that is possible to unite into the muscle, a small-sized quasi-servo valve using embedded controller was proposed and tested. Fig. 6 and Fig. 7 show the schematic diagram and the view of the tested quasi-servo valve, respectively. The tested valve consists of two small-sized on/off type control valves (SMC Co. Ltd., S070C-SDG-32) whose both output ports are connected to each other. One valve is used as a switching valve to supply or exhaust, and the other is used as a PWM control valve that can adjust output flow rate like a variable fluid resistance [5]-[7]. In this way, this valve can control the pressure and flow late. The size of the on/off valve is very small, that is 12 × 33 × 7mm. The mass of the valve is only 6g. The tested valve as shown in Fig. 7 is much smaller and lighter than a typical servo valve (Festo Co. Ltd., MPYE-5-8/1-HF-010B: 330g). The maximum output flow rate of the tested valve is 15 liter/min at the supply pressure of 500kPa. Fig. 8 and Fig. 9 show the schematic diagram and the view of the pressure control system of the tested valve, respectively. The control system consists of the tested quasi-servo valve, an inexpensive embedded controller (Renesas Co. Ltd., SH7125), a pressure sensor and a transistor. The pressure control is carried out as follows. First, the embedded controller gets the pressure sensor output voltage and the reference voltage through an inner 10 bit A/D converter. Then, the error between sensor output voltage and the reference voltage is calculated by a controller, and the control input is calculated based on a control scheme. Finally, the control input is applied to the quasi-servo valve as a PWM signal for PWM valve and an on/off signal for switching valve. In the experiment, P control scheme expressed by following equation is applied for the system.

$$u = k_p \cdot e \tag{3}$$

$$u > 0 \ \text{Switching valve: on (Supply)}$$
$$u \le 0 \ \text{Switching valve: off (Exhaust)} \qquad (4)$$
$$u_d = |u| + 20.0. \qquad (5)$$

where u, k_p, e and u_d mean the input, the proportional gain, the error from the reference pressure and the input duty ratio, respectively. The input duty ratio of the PWM valve is always added by 20.0% as shown in Eq. (5) to compensated for the dead zone of the PWM valve [8]. The PWM period of the PWM valve of 5 ms was decided by our preliminary experiment.

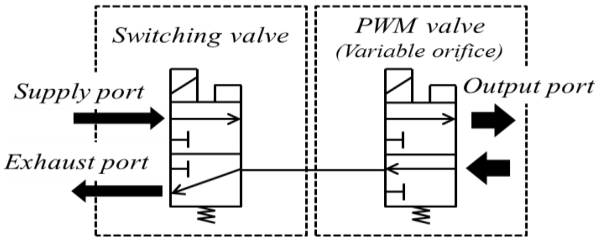

Figure 6. Schematic diagram of the tested quasi-servo valve.

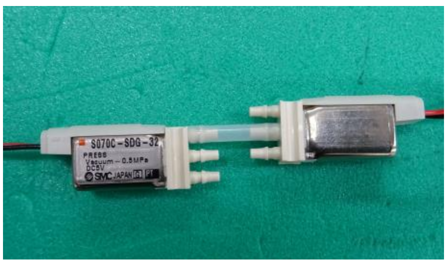

Figure 7. View of the tested quasi-servo valve.

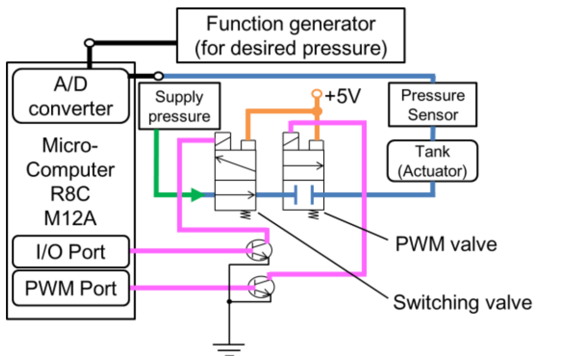

Figure 8. Schematic diagram of control system of the tested valve.

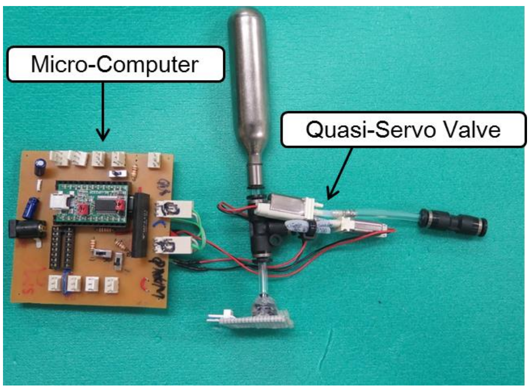

Figure 9. View of the whole control system of the tested valve.

IV. Position Control of Rubber Artificial Muscle

A. Structure of Position Control System

Fig. 10 and Fig. 11 show the schematic diagram and the view of the position control system of the tested rubber artificial muscle with built-in sensor, respectively. The control system consists of the tested quasi-servo valve, the tested rubber artificial muscle and two embedded controllers for positioning the artificial muscle and for the ultrasonic sensor. In addition, the potentiometer is connected with the tested muscle in order to measure the true displacement as a monitor. The position control is done as follows. First, the embedded controller for the ultrasonic sensor counts the time of the output signal from the tested sensor through I/O port. The embedded controller also calculates the length of the muscle from the counted value mentioned above. The embedded controller for the ultrasonic sensor sends the measured displacement of the muscle length to another embedded controller as a voltage signal through the extra D/A converter. The error between the measured displacement and the reference displacement is calculated by the controller for positioning and the control input for the quasi-servo valve is also calculated based on a control scheme. Finally, the control input is applied to the quasi-servo valve as PWM signal and on/off signal for two on/off valve in quasi-servo valve. The reason why two micro-computers are used in the system is as follows. It is easier to build the control system, and the sampling time for a control can be reduced.

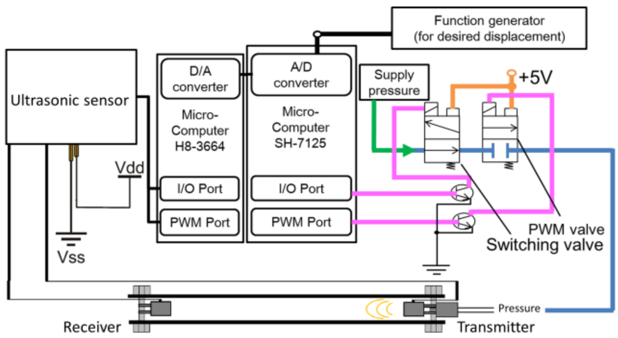

Figure 10. Schematic diagram of position control system

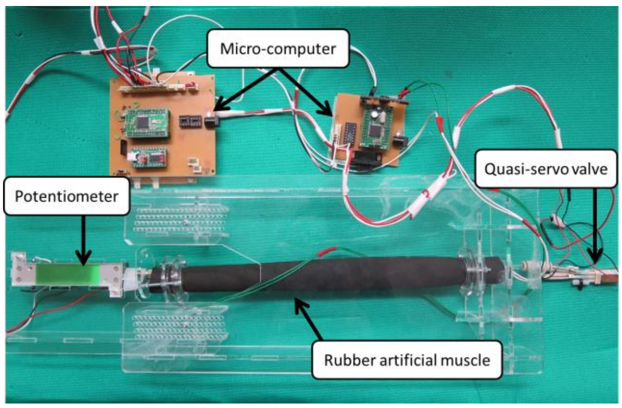

Figure 11. View of the position control system.

B. Experimental Results and Discussion

Fig. 12 shows the transient response of displacement of the rubber artificial muscle with built-in displacement sensor. In the experiment, the desired sinusoidal position with the offset of 25mm, the amplitude of 20mm and the frequency of 0.1Hz was applied to the control system as a reference. As a fedback displacement signal, the output signal from the potentiometer was used. The supply pressure is 400kPa. P control was applied as a control scheme. From Fig. 12, the blue, red and green lines show the reference displacement, the measured displacement by using ultrasonic sensor and the true displacement measured by potentiometer, respectively. From Fig. 12, it can be observed that the measured displacement using the ultrasonic sensor is changed stepwise. It is caused by the relative longer sampling period for measuring using the ultrasonic sensor and the embedded controller. It is found that the measured displacement of the tested sensor is changed rapidly at 8 seconds from the beginning of the control. We think that it is caused by the fact that the receiver detects the operating sound of the switching valve in the quasi-servo valve. The time delay between the reference and the present displacement is caused by the dynamics of the artificial muscle and the valve.

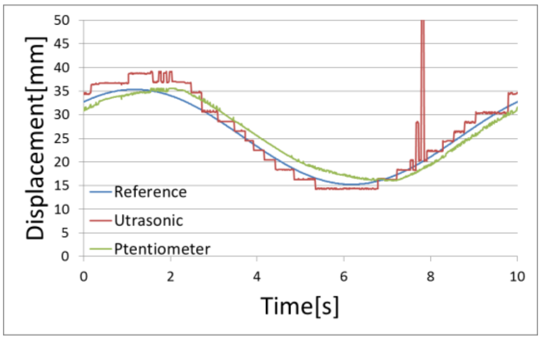

Figure 12. Position control result using the potentiometer as a feedback signal

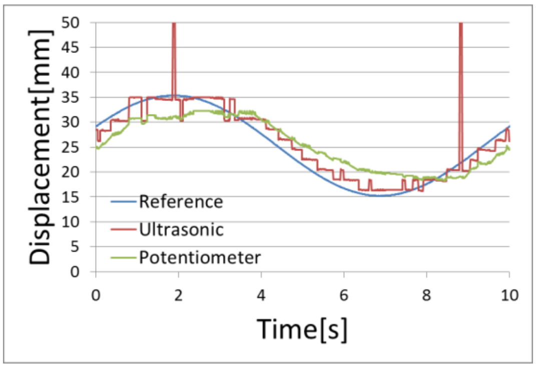

Figure 13. Position control result using the ultrasonic sensor as a feedback signal.

Fig. 13 shows the transient response of the displacement of the rubber muscle using the ultrasonic sensor as a fedback signal. Similar to Fig. 12, The output signal from the ultrasonic sensor changes suddenly at the point of 2 and 9 seconds. However, it seems that the displacement of the muscle can trace mostly to the desired position. Therefore, it is confirmed that the ultrasonic sensor might be useful to apply the built-in displacement sensor of the rubber artificial muscle. In our future work, it is necessary to improve the dynamics and resolution of the tested ultrasonic sensor to improve the position control performance of the rubber muscle.

V. CONCLUTIONS

The rubber artificial muscle using the built-in ultrasonic sensor was proposed and tested. The measuring system of the tested sensor using the embedded controller was also proposed and tested. In order to confirm the effectiveness of the tested sensor, the relation between the measured displacement using the tested sensor and true displacement measured by the potentiometer was investigated and compared. As a result, the validity of the tested sensor was confirmed.

The position control system that consists of the rubber artificial muscle with built-in displacement sensor, the small-sized quasi-servo valve and two embedded controllers was proposed and tested. As a result, it was confirmed that the ultrasonic sensor could be used as a built-in sensor of the rubber artificial muscle.

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So Shimooka received the B.S. degree in Engineering from Okayama University of Science, Japan in 2014. He is currently a master-course student in Graduate School of Engineering, Okayama University of Science. His research interests are focusing on wearable control systems using microcomputers and wearable control devices such as a quasi-servo valve with built- in sensor.

He is a member of The Japan Fluid Power System Society (JFPS) and The Japan Society of Mechanical Engineers (JSME).

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. 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.

Prof. Tetsuya Akagi 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).

Yoshinori Moriwake received the B.S. degree in Engineering from Okayama University of Science, Japan in 2012. And he received the M.S. degree in Engineering from Okayama University of Science in 2014. He is currently a Ph.D student in Graduate School of Engineering, Okayama University of Science. His research interests are focusing on wearable control systems using microcomputers and wearable control devices such as a small-sized servo valve.

He is a member of The Japan Fluid Power System Society (JFPS).