Development of Intelligent Rubber Artificial Muscle with Integrated Pneumatic Driving System and Built-in Inner Diameter Sensor

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***Abstract*— A high-power flexible actuator with a built-in displacement sensor that can support bathing is attractive as a wearable actuator. In the previous study, a rubber artificial muscle with the inner diameter sensor was proposed and tested. The sensor could measure the axial length of the rubber artificial muscle based on the geometric model of the muscle, indirectly. The position control of the muscle using the tested sensor based on the model and the identified parameter was successfully carried out. However, a measuring error caused by a setting error of the sensor was also observed. In this paper, to decrease the measuring error based on the sensor's setting position error in the muscle, an improved inner diameter sensor with radially arranged three photo reflectors was proposed and tested. To get larger generated force, the muscle with larger diameter compared with the previous one was also used. In addition, to realize the wearable actuator that can be easily operated, an intelligent rubber article muscle with an integrated pneumatic driving system and the built-in inner diameter sensor was proposed and tested. The position control of the tested muscle was also carried out. As a result, it could be confirmed that the tested muscle controlled by giving reference electric signal was be realized.**

***Index Terms*— built-in inner diameter sensor, integrated pneumatic driving system, radially arranged photo reflectors, rubber artificial muscle, embedded controller.**

I. Introduction

Due to the ageing and the decreasing birth rate in Japanese society, an important problem of providing nursing care for the elderly has occurred [1-2]. Based on such a situation, it is strongly desired to develop a wearable actuator to use in nursing care or rehabilitation [3]. The target of this study is to develop a high-power and intelligent flexible actuator with a built-in displacement sensor and a driving system which can be used in supporting a bathing [4]. A rubber artificial muscle is well known as a wearable actuator because of its flexibility and larger generated force of more than 300 N [5]. In the previous study, a rubber artificial muscle with built-in inner diameter sensor was proposed and tested. The inner diameter sensor which had 4 photo reflectors on the two electric circuit boards to compensate the inclined angle of the sensor toward axial direction of the muscle was also proposed and tested. This sensor could be expected to estimate the axial displacement of the rubber artificial muscle with an outer diameter of 10 mm, because the relation between the inner diameter and the axial directional displacement of the muscle has a strong correlation [6]. The model based axial displacement measurement using the sensor was also carried out [7]. As a similar research work, the displacement sensor that could estimate the axial displacement of the muscle by measuring the circumference displacement from the outside of muscle was reported [8]. Compared with the sensor referred by [8], the sensor in this study has advantage of waterproof, because the inner diameter sensor is installed into the muscle. The sensor could compensate the measuring error from sensor setting error toward vertical direction to the surface that photo-reflectors were located. However, it could not compensate error from horizontal directional setting error.

Therefore, in this paper, a built-in inner diameter sensor that can measure inner diameter from various radial direction from the center of the muscle is proposed and tested. In order to get larger generated force of the rubber artificial muscle, the development of built-in inner diameter sensor installed into the middle-sized muscle with an outer diameter of 20 mm is also carried out. In order to measure the axial displacement of the muscle with larger diameter, the model of the muscle for measurement and the identified parameters are described in the paper. The result of position control of the muscle using the tested sensor is also described.

Typically, to realize a wearable driving system, many wearable actuators are required. At the same time, a pneumatic drive actuator requires a control valve. So each actuator should be also controlled by an on-board controller, the control system that includes pneumatic driving equipment such as valve and sensor becomes very complex. The complex electric signal lines and pneumatic supply pipes must be also set in the system like blood vessels and nerves stick of a body. Therefore, an easy operated wearable actuator that can be operated and controller by only one reference signal is needed. In the previous study, a small-sized and low-cost quasi-servo valve was proposed and tested [9-11]. In this study,

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an intelligent rubber artificial muscle with an integrated pneumatic driving system using the quasi-servo valve and a built-in inner diameter sensor is also proposed and tested. The construction and control system of the actuator is also described.

II. Previous Rubber Artifical Muscle with Bulit-in Inner Diameter Sensor

A. Construction and Measuring Principle

Fig. 1 shows the construction of the inner diameter sensor developed in our previous study [7]. The sensor consists of four photo reflectors (GENIXTEK Co., TPR-105F), an electronic circuit board and an acrylic board to adjust their height. The sensor also has three through holes between two electric circuit boards so as to realize compact electric lines and circuit. The size of the sensor is 9 × 60 × 8 mm. The output terminal from four photo reflectors is set at the base of the sensor and is connected with the bulkhead with the outer diameter of 12 mm and the thickness of 2 mm. Fig. 2 shows the inner construction of the rubber artificial muscle (FESTO AG & Co. KG., MXAM-10-AA: an outer diameter of 10 mm, a natural length of 250 mm) with the inner diameter sensor. The sensor has a bulkhead to hold it at a constant position and keep a seal at the same time.

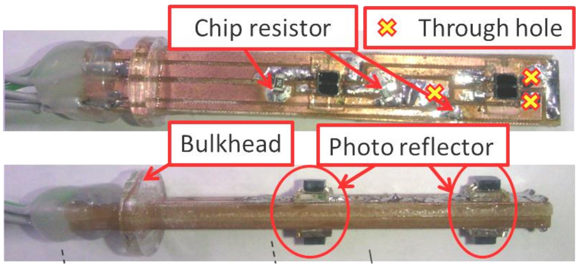

Figure 1. Inner diameter sensor using photo reflector.

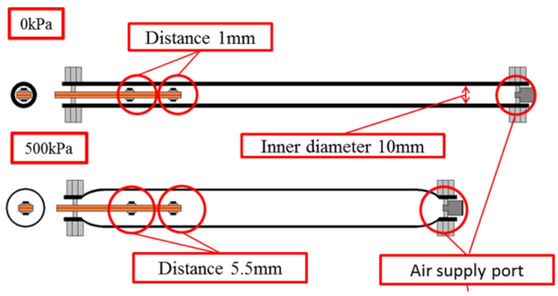

Figure 2. The muscle with inner diameter sensor.

The measuring principle of the inner diameter is as follows. When the muscle is pressurized as shown in Fig. 2, the distance between the photo reflector and the inner wall of the muscle becomes longer until the maximum distance of 5.5mm. The output voltage from the photo reflector becomes lower as increasing the distance. The embedded controller (Renesas Electronics Co., H8/3664) can detect the voltage change through the inner A/D converter. By using the empirical formula based on the analytical model of the artificial muscle mentioned later, the displacement of the muscle can be estimated. The mass of the inner diameter sensor is only 10 g. The total mass including the sensor and the muscle is very small, that is 70g. The material cost of the inner diameter sensor is very low, that is about 2 US dollars.

B. Model for Measurement and Identified Parameters

Fig. 3 shows the geometric model of the rubber artificial muscle proposed by Chou [6]. The model shows that the string with the length of b is turned n-times on the elastic tube with inclined angle of θ. From the geometric relation, the following equation can be obtained. To recover the moving area of damaged joints and the function of nerves and muscles.

$$L = \sqrt{b^2 - (n\pi D)^2} \tag{1}$$

where, D and L mean the effective inner diameter and length of the muscle, respectively. From Eq. (1), by measuring the effective inner diameter of the muscle exactly, the length of the muscle is calculated theoretically. In addition, it can also identify the design parameters of n and b that are useful to estimate the physical property of the muscle.

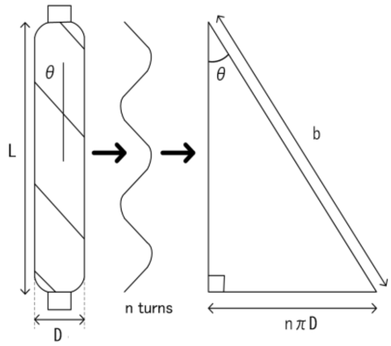

Figure 3. Model of rubber artificial muscle [6].

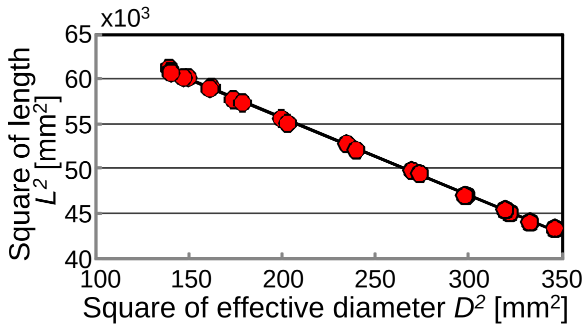

Figure 4. Relation between D^2 and L^2.

Fig. 4 shows the relation between the square values of the effective inner diameter D^2 and length L^2 of the muscle. The relation between the inner diameter and outer diameter of the muscle was measured by inserting the brass cylinder with various outer diameters. The effective inner diameter means the diameter of the reinforced string in the muscle. The value of the effective inner diameter could be obtained as a mean value between the inner and outer diameter of the muscle tube.

From Fig. 4, it can be seen that the relation between both squared values D^2 and L^2 has a linear relationship so as to agree well to the theoretical relationship given by Eq. (1). From this result, the length of the string *b* of 270.2 mm and the number of turns *n* of 2.97 for the muscle with natural length of 247.6 mm were identified.

C. Measurring Result of Muscle Length Using the Model

Fig. 5 shows the relation between the calculated effective inner diameter using the sensor and the actual inner diameter. The circles show the calculated results. The solid line shows the ideal case that the calculated diameter and the actual diameter are same. The calculated diameter can be obtained by using 4th order approximate equation [7] based on the relation between the A/D values from the senor output and the measured effective inner diameter. From Fig. 5, it can be seen that the inner diameter of the muscle can be calculated within standard deviation of error of 0.10 mm.

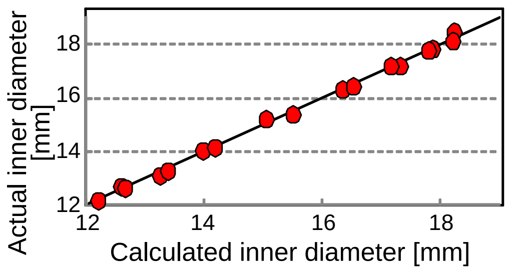

Figure 5. Calculated effective inner diameter.

Fig. 6 shows the relation between the measured and calculated length of the muscle using the calculated effective inner diameter, the model of the muscle given by Eq.(1) and identified parameters such as *n* and *b*. The calculation was done by the embedded controller. In Fig. 6, the circles show the calculated length, the solid line shows the ideal case that the calculated and measured lengths of the muscle are same. From Fig. 6, it can be confirmed that the length of the muscle can be obtained based on the analytical model. The standard deviation of error is about 0.6 mm.

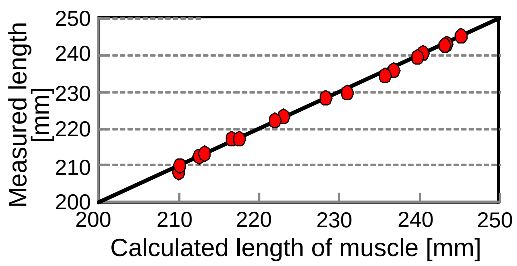

Figure 6. Calculated length of the muscle.

III. Improved Inner Diameter Sensor for Middle-Sized Rubber Artifical Muscle

A. Construction of Improved Inner Diameter Sensor

The measuring error using the previous sensor depends on the setting location error of the inner diameter sensor. Although the deviation in the direction perpendicular to the sensor surface can be corrected, it cannot correspond to the shift with respect to the horizontal direction. The measurement errors are also caused by irregular reflected light. Therefore, it is necessary to improve the sensor so as to measure the inner diameter of the muscle even if the sensor setting position move toward both horizontal and vertical directions. In addition, the theoretical generated force of the previous rubber artificial muscle with built-in sensor is about 630 N at Max. supplied pressure of 800 kPa. However, the generated force of the muscle decreases according to increasing its displacement. Therefore, the effective generated force seems to one third, that is about 200 N. This vale is the generated force when its displacement is 15 % of natural length [12]. The generated force of 200 N is enough to lift up human arm and hands. However, to lift a whole body of human in a bath, it is necessary to larger generated force of more than 500 N. Therefore, in this study, the development of a built-in inner diameter sensor for middle-sized rubber artificial muscle (FESTO AG & Co. KG., MXAM-20-AA: an outer diameter of 20 mm) that can generate the pulling force of 1500 N at supplied pressure of 600 kPa is carried out.

Fig. 7 and 8 show the overview of an inner construction and whole view of an improved inner diameter sensor for middle-sized muscle, respectively.

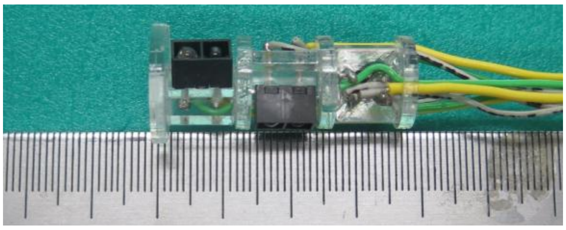

Figure 7. Overview of inner elements of the improved inner diameter sensor.

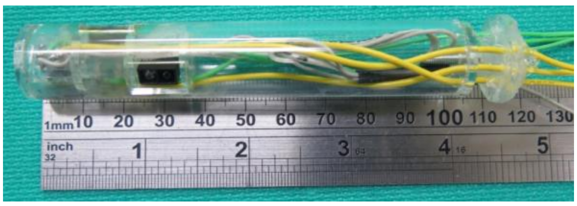

Figure 8. Whole view of the improved inner diameter sensor

Fig. 9 shows the schematic diagram of the improved sensor. Compared with the previous sensor, the measuring range of the inner diameter becomes wider, because the middle-sized muscle is used. Therefore, photo reflectors with a wider measuring range from 1 to 10 mm (Letex Technology Co., LBR-127HLD) were used in the inner diameter sensor. Then, the size of the reflector is 4.4 × 8.2 × 5.6 mm. The cost is almost same as the previous one, that is about 2 US dollars. The improved inner diameter sensor is composed of three photo reflectors that each reflector is set on acrylic plates and covered by round-shaped acrylic plate from both sides, and the acrylic pipe with inner diameter of 14 mm and the outer diameter of 17 mm. By using these acrylic plates, three photo reflectors are arranged at the point of 120 degrees from the center of the sensor. Each photo reflector is also arranged every 10 mm in longitudinal direction. The inner element as shown in Fig. 7 is inserted into the acrylic pipe with three holes for photo reflectors. By using the covered acrylic pipe, it seems that the irregular reflection from the inner wall can be prevented. As shown in Fig. 8, the end of the acrylic pipe with a length of 100 mm is connected to bulkhead so as to set in the muscle while keeping a sealing as same as the previous one. The size of the improved inner diameter sensor without extra length of acrylic pipe is a cylindrical shape with a length of 38 mm and the outer diameter of 18 mm.

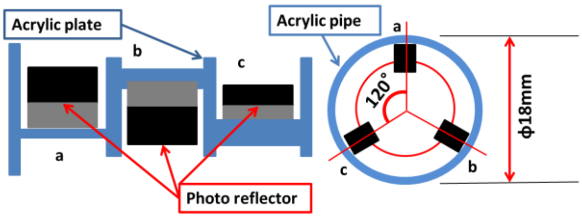

Figure 9. Schematic diagram of the improved inner diameter sensor.

B. Measuring principle and identified parameters

Fig. 10 shows the overview of the middle-sized artificial rubber muscle with the improved built-in inner diameter sensor. The measurement principle of the improved sensor is as follows. Each photo reflector measures the distance between the surface on the photo reflector and the inner wall of artificial rubber muscle through A/D convertor in the embedded controller. From these A/D value, the embedded controller calculates the distance by using the empirical equation for each photo reflector. The inner diameter is calculated as an averaged value from measured three distances. The estimated error of the measured inner diameter using this method is about 0.126 mm (0.7 %) in the case of the sensor's locational drift of 3 mm from the center of the muscle. In real, it does not seem to occur more than 3 mm deflection.

Figure 10. Overview of the artificial rubber muscle with built-in inner diameter sensor.

In order to estimate the length of an artificial rubber muscle using the muscle model, the number of turns n and the fiber length b is needed to identify. Also, in order to apply the measuring model of the muscle, the relation between the inner diameter and outer diameter of the muscle is required for calibration of the sensor. In the previous study, by inserting the brass cylinder with various outer diameters to the muscle, this relation was investigated. However, it is difficult to apply this direct measurement to the middle-sized muscle. Then, in previous study, it had been confirmed that the wall thickness of the artificial muscle does not change with respect to the expansion of the artificial muscle [7]. Using this principle, the fiber diameter of the muscle is estimated. Fig. 11 shows an appearance of the middle-sized rubber artificial muscle. Assuming that the tube volume before and after pressurization are constant, the following equation is given by

$$\frac{\pi}{4}(D_{10}^2 - d_0^2)L_0 = \frac{\pi}{4}(D_1^2 - d^2)L \tag{2}$$

where D_1, d and L mean the outer diameter and the inner diameter of the muscle and length of the muscle, respectively. Subscript 0 means the initial condition with no supplied pressure. Then, the inner diameter of the muscle d is given by

$$d = \sqrt{D_1^2 - \{(D_{10}^2 - d_0^2)\frac{L}{L_0}\}}. \tag{3}$$

When the muscle is pressurized, the fiber diameter of the muscle D is given by

$$D = \frac{D_1 + d}{2}. \tag{4}$$

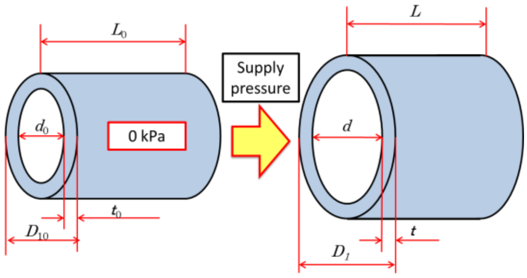

Figure 11. Appearance of the middle-sized rubber artificial muscle

Fig. 12 shows the relation between the calculated fiber diameter D and outer diameter of the middle-sized muscle D_1. From Fig. 12, the relation between outer diameter of the muscle D_1 [mm] and the fiber diameter D [mm] is expressed as follows.

$$D = 1.083 \cdot D_1 - 4. \tag{5}$$

Fig. 13 shows the relation between square of fiber diameter D^2 and length of artificial rubber muscle L^2 obtained by measuring the outer diameter and length of the muscle for various suppled pressures. From Eq.(1), the number of turns n of 2.03 and the fiber length b of 327 mm are identified. By using these identified parameters, the model and sensor output, the length of artificial rubber muscle can be calculated by Eq.(1) to (5).

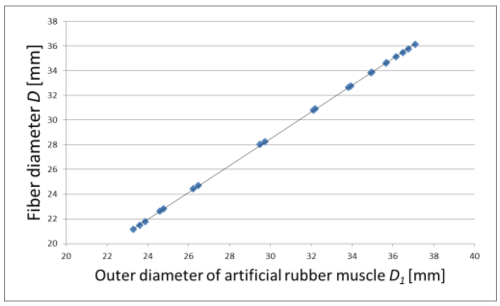

Figure 12. Relation between the fiber diameter D and the outer diameter D_1. of the middle-sized muscle

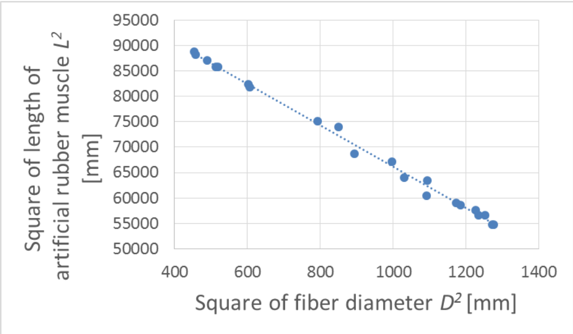

Figure 13. Relation between the square of fiber diameter D^2 and the length L^2 of the middle-sized muscle.

C.Measuring Result Using the Improved Sensor

Fig. 14 shows the relation between the true length measured by using a potentiometer and the calculated length using the tested sensor. In Fig. 14, symbols and solid line show the experimental results and ideal case when both measured and true lengths are same, respectively. It can be seen that the measured length agrees well with the true length of the muscle. It can be confirmed that the middle-sized rubber artificial muscle using the tested built-in inner diameter sensor can be realized.

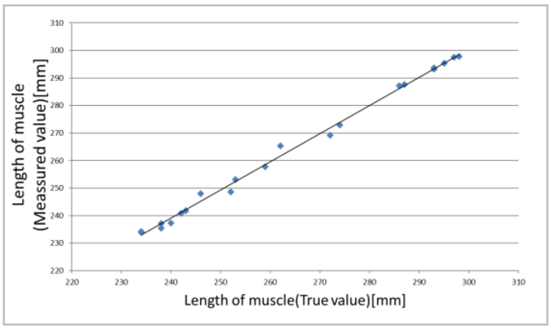

Figure 14. Relation between the true and measured length of the rubber artificial muscle with the improved inner diameter sensor.

IV. Intelligent Rubber Artificial Muscle with Integrated Pneumatic Driving System

As a wearable actuator, an actuator that can be controlled by giving only reference signal is ideal. In order to realize such an intelligent rubber artificial muscle that has a built-in sensor, valves and a controller is required. Figure 15 shows the overview of the intelligent rubber artificial muscle that can be operated by electric signal. The tested actuator consists of the artificial rubber muscle with built-in inner diameter sensor and an integrated position controller with a quasi-servo valve as shown in Figure 16. The integrated position controller consists of an embedded controller (Renesas Electronics Co., SH7125), a valve driver on the electric circuit and the quasi-servo valve. The quasi-servo valve consists of two on/off type control valves (Koganei Co. Ltd., G010). Two valves are connected in series. One is used as a switching valve that can change supply or exhaust. Another is PWM control valve as a variable orifice [9-10]. The built-in embedded controller can control the length of the muscle by using the feedback signal from the tested inner diameter sensor according to a reference voltage. Except for the reference signal, to drive the tested muscle, the muscle requires an electric and air power supply. It means that the actuator is only connected to a pneumatic supply pipe and an electric line with three core from the outside. The integrated controller is connected to the end of the muscle. The length of the tested muscle is 298 mm. The whole mass of the muscle is 120 g.

Figure 15. Overview of the intelligent rubber artificial muscle with built-in sensor, valves and controller.

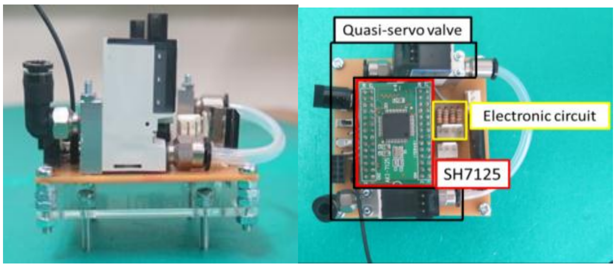

Figure 16. Overview of the integrated pneumatic driving system for position control of the muscle with quasi-servo valve.

Fig. 17 and 18 show an experimental setup and a schematic diagram of a position control system using the tested muscle, respectively. In the experiment, a potentiometer (MIDORI PRECISINS Co. Ltd., LP-100F-C) is used and connected with the tested muscle in order to measure the true displacement as a monitor. The position control is done as follows. First, the reference voltage from a function generator (TELEDYNE LECROY Co. Ltd., wave station2012) and the output voltage from the built-in inner diameter sensor are taken through an A/D converter in the embedded controller. In the embedded controller, both reference and current displacement are calculated using the model of the muscle and Eq.(1) to (5). The deviation from the desired position is also calculated. 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 [13]. And, the muscle is driven by the quasi-servo valve. As a control scheme, P control is used. The proportional gain of *Kp* 50 %/mm is decided by trial and error.

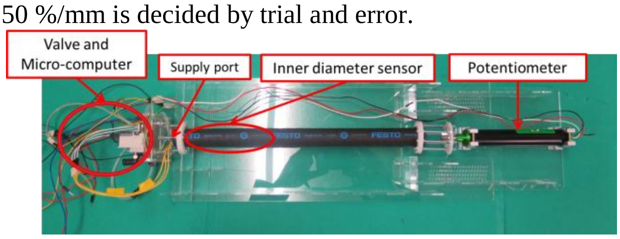

Figure 17. Overview of experimental setup of position control system using the tested intelligent rubber artificial muscle.

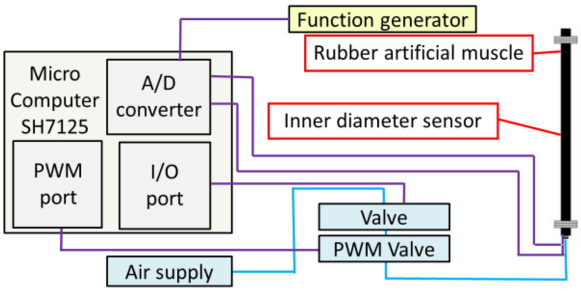

Figure 18. Schematic diagram of position control system.

Fig. 19 shows the position control result using the tested intelligent rubber artificial muscle using integrated pneumatic driving system and the improved inner diameter sensor. In Fig. 19, the blue, green and red lines show the desired position, the real displacement measured by the potentiometer and the calculated displacement from the sensor output, respectively. In the experiment, the desired sinusoidal position with the offset of 226 mm, the amplitude of 38 mm and the frequency of 0.1 Hz was applied to the control system as a desired position. The position control was carried out by only using the calculated displacement from the tested sensor as a feedback signal. From Fig. 19, it can be seen that the calculated displacement from the tested sensor output is changed stepwise even if the real displacement does not occur stepwise change. It does not depend on the sensor's resolution. The resolution of the tested sensor is enough, that is between 0.23 and 0.34 mm. In the result, the stepwise displacement change of 4 or 5 mm is occurred. The reason of this phenomenon is under an investigation. However, it can be seen that the displacement of the muscle can trace the desired position. Therefore, it can be confirmed that the intelligent rubber artificial muscle controlled by only giving reference voltage can be realized.

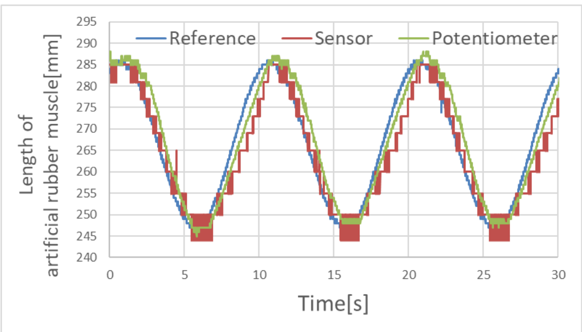

Figure 19. Position control result of the tested intelligent rubber artificial muscle.

V. CONCLISIONS

This study aiming to develop the intelligent rubber artificial muscle with the integrated pneumatic driving system and the built-in inner diameter sensor can be summarized as follows.

As an inner diameter sensor for middle-sized rubber artificial muscle to get larger generated force for lifting up whole human body, the novel inner diameter sensor with radial arrangement of three photo reflectors was proposed and tested. The model of the improved sensor for measuring axial displacement of the muscle was proposed. The parameters of model were identified. The measuring displacement of the muscle using the tested sensor and the model with identified parameter was carried out. As a result, it was confirmed that the tested inner diameter sensor could measure the displacement of the muscle.

As an easy operated wearable actuator that can be operated and controlled by only reference signal, the intelligent rubber artificial muscle with the integrated pneumatic driving system and the built-in sensor was proposed and tested. To drive the actuator, a pneumatic supply pipe and an electric line with three cores from the outside were required. The position control of the tested actuator was carried out. As a result, it was confirmed that the intelligent rubber artificial muscle controlled by only giving reference voltage could be realized.

As a future work, the improvement of the controlled position accuracy of the tested muscle will be carried out.

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