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Development of smart inner diameter sensor for position control of Mckibben artificial muscle

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Abstract

Due to the ageing and the decreasing birth rate in Japanese society, an important problem of providing nursing care for the elderly has occurred. Therefore, it is strongly desired to develop a wearable actuator to use in nursing care or rehabilitation. The purpose of this study is to develop a high-power flexible actuator with a displacement sensor which can be used in supporting a bathing. In our previous study, we proposed and tested a rubber artificial muscle with the inner diameter sensor. The inner diameter sensor consists of two electric circuit boards with two photo reflectors. Two boards are bonded together to contract the inner diameter sensor. The sensor also has a doughnut-shaped bulkhead to keep a seal. The sensor is inserted into the tube of the artificial muscle. The senor is set at the end of tube. This sensor can be expected to estimate the axial direction displacement of the rubber artificial muscle, because the relation between the inner diameter and the axial directional displacement of the muscle has a strong correlation. However, if the external bending force is applied to the end of the muscle, the inner diameter sensor cannot hold at the center position of the tube. Therefore, the sensor cannot measure the inner diameter exactly. In this study, the improvement of the inner diameter sensor was executed. The improved sensor has 4 photo reflectors on the two electric circuit boards to compensate the measuring error. The position control was also carried out by using the actuator with the built-in inner diameter sensor. As a result, the axial direction displacement of the muscle could be estimated well by the tested inner diameter sensor, and a relatively good position control performance was obtained.

Keywords: Rubber artificial muscle; Built-In sensor; Position control; Inner diameter sensor;

1. 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. Therefore, it is strongly desired to develop a wearable actuator to use in nursing care or rehabilitation. As a result, a lot of research about nursing care support or rehabilitation device has been reported [1] [2]. Some of them have used a rubber artificial muscle as a wearable actuator [3] [4], because the actuator can generate larger force compared to its weight. The rubber artificial muscle is a kind of pneumatic actuators [5]. The purpose of this study is to develop a high-power flexible actuator with a sensor for positioning which can be used in supporting a bathing. As other studies about measuring the displacement of rubber artificial muscle using soft sensors, semi-conductive rubber sensors were used from the outer side of the muscle [6] [7]. In our previous study, the flexible displacement sensor using nylon

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string coated with carbon was used as a flexible potentiometer to measure displacement of the muscle from the outside of the muscle [8]. However, these outer sensors were affected by water. It prevents the muscle to use it in the water. Therefore, we proposed and tested a rubber artificial muscle with a built-in inner diameter sensor which consisted of two photo reflectors [9]. However, when the external bending force is applied to the muscle, the inner diameter sensor cannot be hold at the center of the tube. It means that the sensor cannot measure the inner diameter exactly. Therefore, in this paper, we propose and test the improved inner diameter sensor to compensate the measuring error of the inner diameter of the muscle. In addition, the compactness of the air supply port and the sensor signal lines was executed. The position control was also carried out using the actuator with the built-in inner diameter sensor and the quasi-servo valve [10].

2. Previous inner diameter sensor

2.1. Estimation of longitudinal displacement by measuring the inner diameter

Typical position control system using a rubber artificial muscle has used an external rigid displacement sensor such as a potentiometer. However, by using the rigid sensor, the system might lose its flexibility. The environment where the system can be used is limited. Therefore, we aim to develop a rubber artificial muscle with a built-in inner diameter sensor. The measuring method for axial-directional (longitudinal) displacement of the rubber artificial muscle is as follows. Figure 1 shows the operational principle of a rubber artificial muscle. As shown in Fig.1, the rubber artificial muscle has the following characteristics. The crossed angle of the covered fiber of the muscle changes as increasing the diameter of the muscle according to the input pressure. This angular change converts into the longitudinal displacement. Therefore, it is possible to estimate the longitudinal displacement of the rubber artificial muscle by measuring the inner diameter of the muscle. Figure 2 shows the analytical model of the rubber artificial muscle reported by Chou [5]. In the model, the thickness of tube and fiber of the rubber artificial muscle is ignored. From the geometric configuration, the following equation can be obtained.

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

Where L is the length of rubber artificial muscle, b is the length of the diagonal of the inner fiber, n is the number of rolling and D is the diameter of rubber artificial muscle. From Eq. (1), we can know that the length of the rubber artificial muscle becomes shorter almost linearly as increasing the diameter of rubber artificial muscle.

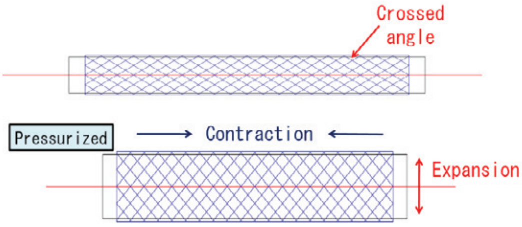

Fig. 1. Operating principle of rubber artificial muscle

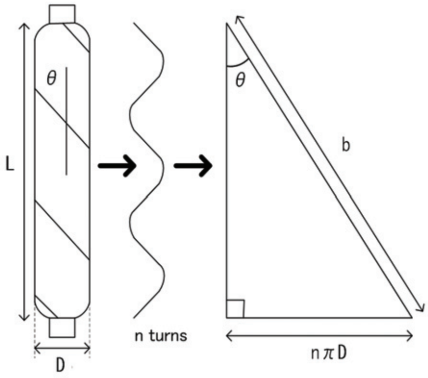

Fig. 2. Model of Mckibben artificial muscle [5]

2.2. Construction and operating principle of the previous inner diameter sensor

Figure 3 shows the construction of the inner diameter sensor developed in our previous study. The sensor consists of two photo reflectors (GENIXTEK Co. Ltd., TPR-105F), an electronic circuit board and an acrylic board to adjust their height.

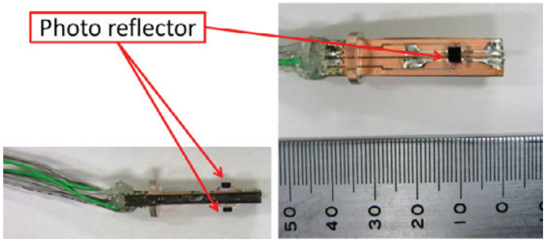

Fig. 3. Previous inner diameter sensor

The output terminal from two photo reflectors is set at the base of the sensor and is connected with the bulkhead with the outer diameter of 12mm and the thickness of 2mm. Figure 4(a) shows the view of tested actuator. Figure 4(b) shows the inner construction of the rubber artificial muscle with the inner diameter sensor. In this study, the rubber artificial muscle (FESTO Co. Ltd., MXAM-10-AA) with a natural length of 250mm and an inner diameter of 10mm was used. The measuring point of inner diameter was decided so that the diameter becomes same diameter at the middle point of the tube when a rubber artificial muscle is pressurized. The initial clearance between the inner wall of the muscle and the photo reflector is set to be 1mm because of measuring range of the photo reflector. By using the bulkhead of the sensor, the sensor can keep at a constant position and keep a seal at the same time.

The operating principle for measuring the inner diameter of the rubber artificial muscle is as follow. The length between the photo reflector and the inner wall of the tube becomes longer until the maximum of 5.5mm when the rubber artificial muscle is pressurized. As increasing this distance, the output voltage from the photo reflector becomes lower. We can estimate the inner diameter of the rubber artificial muscle from the output voltage changes. The mass of the inner diameter sensor is only 10g, the total mass including the sensor and the rubber artificial muscle is very lightweight, that is 70g.

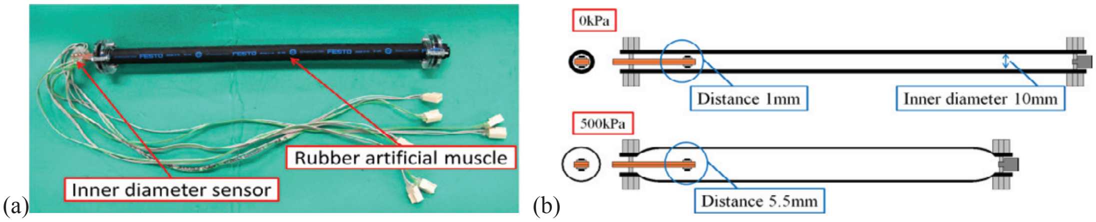

Fig. 4. Rubber artificial muscle with inner diameter sensor (a) View of tested actuator; (b) Cross-section view

2.3. Experimental results

Figures 5 (a) and (b) show the experimental setup and the relation between output value from the sensor and the axial displacement of the rubber artificial muscle with inner diameter sensor, respectively. In the experiment, the longitudinal displacement of the muscle as a true value measured by the potentiometer (Sakae Tsushin Kogyo Co. Ltd., 18FLPA50) as shown in Fig.5 (a). The supplied pressure to the rubber artificial muscle was given from 0 to 500 kPa and from 500 to 0 kPa every 50kPa. Then, both the sensor output (A/D value) and the displacement of the muscle were measured. The measuring process mentioned above was repeated five times. In Fig.5 (b), the output value shows the sum of the difference from the initial value of each photo-reflector through an A/D converter. The initial value of the sensor is defined as zero when no pressure was applied to the rubber artificial muscle. From Fig.5 (b), it can be seen that the relation between the axial displacement and the output from the inner diameter sensor has no hysteresis and reproducible even if there is nonlinear relationship. This nonlinear relationship depends on the characteristics of the rubber artificial muscle and the photo-reflector. As a result as shown in Fig.5 (b), the following approximate equation between the displacement y [mm] and the sensor value x [A/D value] can be obtained.

$$y = 2.003 \times 10^{-13} x^6 - 1.477 \times 10^{-10} x^5 + 3.878 \times 10^{-8} x^4 - 3.235 \times 10^{-6} x^3 - 1.091 \times 10^{-4} x^2 + 6.086 \times 10^{-2} x \quad (2)$$

In the approximation, we used the six degree of function in order to get suitable approximate value of the axial displacement from the sensor output. In the position control of the rubber artificial muscle, this approximate equation was used in the position control of the artificial muscle.

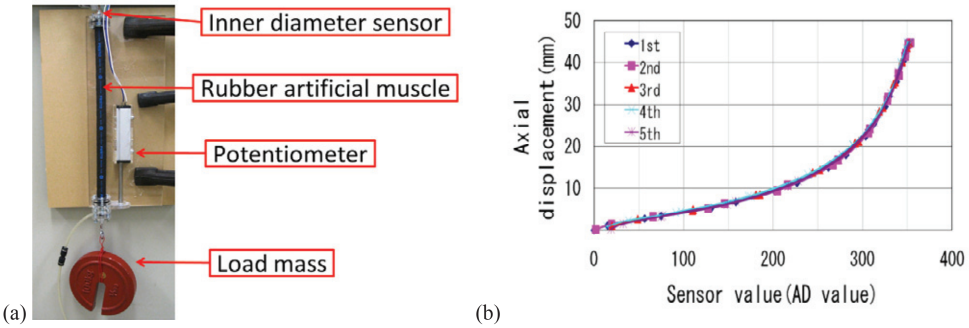

Fig. 5. Experimental setup and characteristics of inner diameter sensor (a) Experimental setup and (b) static characteristics

In order to estimate the validity of the proposed measuring method using the tested sensor, Figs.6 (a) and (b) show two types of characteristics about the axial displacement of rubber artificial muscle. Figure 6 (a) shows the relation between the supplied pressure and the axial displacement of the rubber artificial muscle. Figure 6 (b) shows the relation between the sensor output and the axial displacement of the muscle. From Fig.6 (a), we can see that the hysteresis is large. Especially, there is a larger difference in a decompressed process. This phenomenon depends on the characteristics of the typical rubber artificial muscle. From Fig.6 (b), we can find that there is no hysteresis. It means that it is possible to realize position control system of the rubber artificial muscle for axial direction using the tested sensor with a compact sensor arrangement.

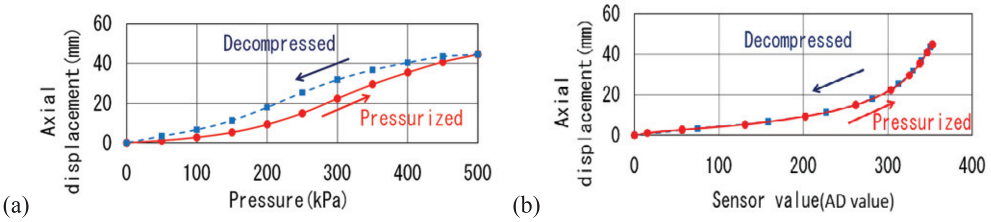

Fig. 6. Comparison of hysteresis characteristics (a) Hysteresis for input pressure; (b) Hysteresis for sensor output

In order to confirm the validity of measuring value using the tested sensor, Figure 7 shows the relation between the actual displacement of the rubber artificial muscle measured with the potentiometer and the estimated displacement calculated by using the output from the inner diameter sensor and Eq.(2). In Fig.7, symbols and the blue line show the experimental results and the ideal case that both the measured and actual displacement are same, respectively, As a result, we can confirm that the estimated displacement agrees well with the actual displacement. At the point of larger displacement in Fig.7, it can be seen that there is a little error. We think that this error is caused by the nonlinear characteristics of the photo-reflector. We found that the standard deviation of the error is 0.4 mm and the maximum estimated error is less than 2.0 mm.

However, the sensor has a little problem that the sensor may not be able to measure the inner diameter exactly when the disturbance force is acted at the end of the muscle. Therefore, the compensation of the error in the case of acting the disturbance force to the muscle should be executed. In addition, the making the inlet compact is executed so as to unite the inlet of the air supply and the electrical signal lines for the sensor.

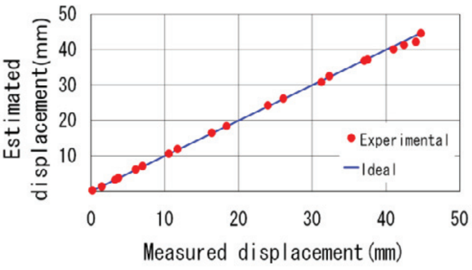

Fig. 7. Relation between measured value and estimated one

3. Improved inner diameter sensor

3.1. Single type inner diameter sensor

Figure 8 shows the construction of an improved inner diameter sensor. The sensor consists of two photo reflectors (GENIXTEK Co. Ltd., TPR-105F), an electronic circuit board, an acrylic board to adjust their height, four chip resistors, two plastic sheets and air supply port. Compared with the previous sensor, this sensor has the electric circuits using the chip resistor in order to decrease the electrical lines from the sensor. In the case of the improved sensor, electric lines connected to the sensor are decreased from 8 to 4 lines. As a result of this improvement, it is possible to unite the electric lines and air supply port into the bulkhead. In addition, in order to set the sensor in the middle point of the artificial muscle, two butterfly shaped thin plastic films are used so as to hold the sensor in the center of the tube, as shown in Fig.8. Each plastic sheet has two incisions with the width of 8mm around the photo reflector so as not to prevent the measurement of the inner diameter.

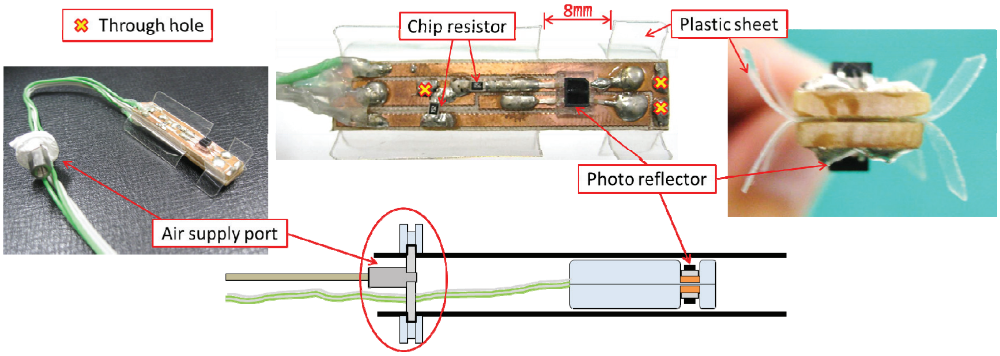

Fig.8. Improved inner diameter sensor (single type)

Figure 9 shows the relation between output value from the sensor through the A/D converter and the axial displacement of the rubber artificial muscle. In the experiment, the supplied pressure to the rubber artificial muscle was given from 0 to 500 kPa every 50kPa. After that, the supplied pressure was also changed from 500 to 0 kPa every 50kPa. This measuring process was repeated five times. From Fig.9, it can be found that the repeatability of the sensor output is not good. We think that it is caused by inclining the sensor board according to changing the inner diameter. Therefore, the compensation for this inclination is required.

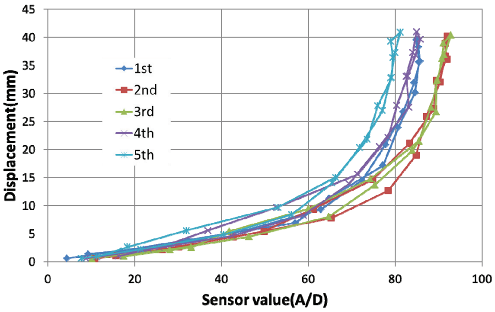

Fig.9. Relation between sensor output from single type sensor and axial displacement of the muscle

3.2. Double type inner diameter sensor

In order to compensate the measuring error for the inclination of the sensor, an inner diameter sensor that has 4 photo reflectors to measure the inclined angle of the sensor board is proposed. Figure 10 shows the model of the improved inner diameter sensor, we call it “Double type” for short. Each electric board in the double type sensor has two photo reflectors that are set on the parallel with a distance of W as shown in Fig.10. From the geometrical arrangement of the photo reflectors, the inclined angle of the board θ and the inner diameter of the muscle d can be obtained by following equations.

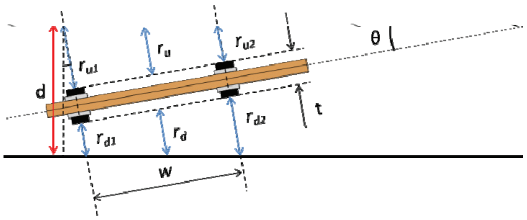

Fig.10. Model for compensation using double type inner diameter sensor

$$\tan\theta_1 = (r_{u1} - r_{u2})/W \tag{3}$$

$$\tan\theta_2 = (r_{d2} - r_{d1})/W \tag{4}$$

$$\theta = (\theta_1 + \theta_2)/2 \tag{5}$$

$$r_u = (r_{u1} + r_{u2})/2 \tag{6}$$

$$r_d = (r_{d1} + r_{d2})/2 \tag{7}$$

$$d = (r_u + r_d + t)\cos\theta \tag{8}$$

where *r* and *t* mean the distance between the tube of the muscle and each photo reflector and thickness of the inner diameter sensor, respectively. The subscripts of 1 and 2 show the location in the sensor as shown in Fig.10.

Figure 11 shows the construction of the double type inner diameter sensor. The sensor consists of four photo reflectors (GENIXTEK Co. Ltd., TPR-105F), two electronic circuit boards, acrylic plates to adjust their height, six chip resistors and two plastic sheets. In order decrease the electric lines from the sensor, there is three through holes between two electric circuit boards. As a result, electric lines from the sensor can be decreased 6 lines even if two additional photo reflectors are added. In addition, by redesigned the bulkhead, the air supply port and electric lines for the sensor are united in one end of the muscle. The size of the inner diameter sensor is same as previous one as shown in Fig. 3. That is 9 mm x 40 mm x 8 mm. The inner diameter sensor can be produced with low cost. The cost of the sensor is less than 3 US dollars. In addition, the cost including the measuring system with a micro-computer (Renesas Electronic Co. Ltd., H8/3664) is about 20 US dolloers.

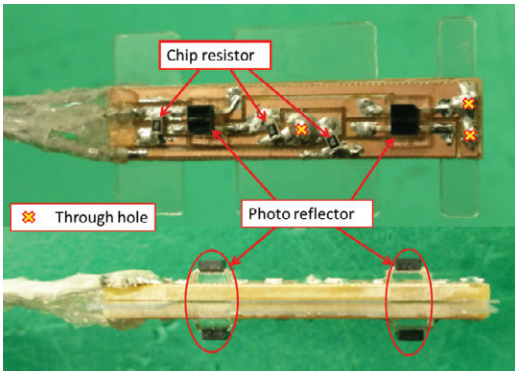

Fig. 11. Modified inner diameter sensor

Figure 12 shows the relation between the calculated inner diameter using the double type inner diameter sensor and the axial displacement of the rubber artificial muscle. In the experiment, the supplied pressure is given as a same method of previous experiment as shown in Fig.9. The inner diameter of the muscle is calculated by Equation (3) to (8) using low-cost micro-computer (Renesus electronics Co. Ltd., H8/3664). In the micro-computer, the program to calculate the distance between the tube and the photo reflector using the sensor output from each photo reflector is installed. The measuring process was repeated three times. From Fig.12, it can be seen that the repeatability of the sensor output using the double type sensor is superior to the result using the single type.

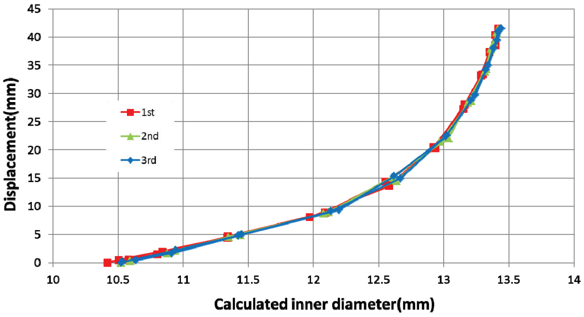

Fig. 12. Relation between the calculated inner diameter and the axial displacement of the muscle

Figure 13 shows the schematic diagram of a position control system using the rubber artificial muscle with the built-in inner diameter sensor. The control system consists of the rubber artificial muscle with the built-in inner diameter sensor, a potentiometer for the desired position, a microcomputer and a small-sized quasi-servo valve which consists of a switching valve and a PWM valve [6].

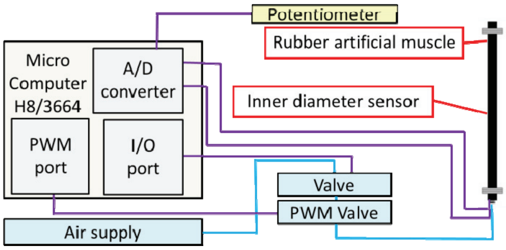

Fig. 13. Schematic diagram of control system

The position control is done as follows. First, the micro-computer gets the voltages from the potentiometer for the desired value and the inner diameter sensor through the A/D converter. The displacement of the muscle is calculated by the approximate equation mentioned above. The deviation from the desired position is also calculated. As a control method, we apply the On/Off control scheme and the proportional control scheme as shown in Eq. (3) to the system.

$$u = K_p \times e \tag{9}$$

Where e, K_p and u show the position error, the proportional gain and the input duty ratio for the PWM control valve in the quasi-servo valve, respectively. The sampling period for On/Off control is 2.6ms and the sampling period for P control is 2.8ms. The PWM period is 5ms.

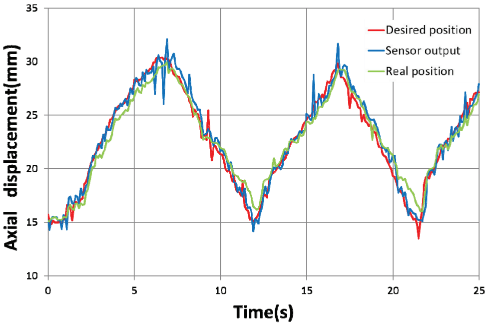

Fig. 14. Transient response of the displacement of the muscle in follow-up control

Figure 14 shows the transient response of the axial displacement of follow-up control that used the proportional control mentioned above. In Fig.14, the red, blue and green lines show the desired position, the calculated displacement using the sensor and the actual displacement measured by the potentiometer, respectively. From Fig.14, it can be seen that the tracking performance of the displacement is relatively good even if the simple control scheme was used. In addition, the error of the axial displacement of the muscle is small, that is less than ±2 mm.

4. Conclusions

We aim to improve the measuring and control system of the rubber artificial muscle that can measure the inner diameter sensor exactly even if the external force to the end of the muscle was applied. This study can be summarized as follows.

The single type inner diameter sensor with the thin plastic sheets was proposed and tested so as to arrange the sensor into the center part of the artificial rubber muscle. In addition, the electric circuit board using the chip resistors was composed, the number of electric lines from the sensor was decreased from eight to four. The electric lines and the air supply port were united in a same bulkhead to reduce the input lines.

To compensate the measuring error caused by inclination of the inner diameter sensor, the double type inner diameter sensor using four photo reflectors was proposed and tested. The method and model for compensation of measuring the inner diameter was also proposed. The cost of the sensor is very low, that is less than 3 US dollars. In addition, comparing the calculated displacement with the actual displacement, the validity of the measurement using the proposed model was confirmed.

The position control system using the rubber artificial muscle with the double type inner diameter sensor was proposed and tested. The follow up position control using the muscle was done. As a result, the estimated error was less than ±2mm, the validity of the tested inner diameter sensor was confirmed.

Acknowledgments

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