Development of Outer Diameter Sensor for Position Control of McKibben Artificial Actuator Using Hall-effect Sensor

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***Abstract*—In a super-aged Japanese society, it is very important to take advantage of engineering support for elderly assist. In recent years, many assistive and rehabilitation devices using the pneumatic (McKibben) artificial actuators have been developed in such a public situation. In this study, development of a rehabilitation device driven by pneumatic actuator is aimed. Thus, the purpose of this paper is to develop the McKibben artificial actuator with the built-in outer diameter sensor for position control. However, it is difficult to measure the displacement (length) of McKibben artificial actuator which does not lost the flexibility. The developed sensor measures the constraint position (outer diameter) of the actuator by using the Hall-effect (magnetic) sensor. In addition, this paper proposes the sensor characteristics between the displacement and the sensor value. The position control scheme is designed by solving the mixed sensitivity problem (robust stability and nominal performance) for the PAM (Pneumatic Artificial Muscle) system. As a result, the effectiveness of the 2 DOF (position) control system using the outer diameter sensor is confirmed by experimental results.**

***Index Terms*— outer diameter sensor, McKibben artificial actuator, Hall-effect sensor, Position control**

I. Introduction

According to “The 2017 White Paper on an Aging Society” published by the cabinet office [1], the total population of Japan is 126.93 million. The aged population comprised of persons 65 years over is 34.59 million which is the largest number ever. The ratio of the aging population (65 years over) was 27.3% in 2016, but will increase to 39.9% in 2060, showing that Japan has become a super-aged society in 2007. The ageing of the population raises the risks of a decline in the working population (shortage of caregivers) and an increase in pressure on government finances due to pension payments and medical expenses. In a super-aged society, it is very important to take advantage of engineering support for elderly assist.

As one of engineering support, the power-assisted rehabilitation devices which assist the moving force using some actuators and spread their areas of life have been enhanced. And, many researches about care support or rehabilitation device have been reported [2]-[5]. Some reports have used the McKibben artificial actuator (muscle) as an actuator of rehabilitation device. The McKibben artificial actuator is a kind of pneumatic actuators. In addition, the actuator has advantages of better flexibility and larger generated force compared to another actuator. However, it is difficult to measure the displacement (length) of McKibben artificial actuator that does not deteriorate the flexibility.

The purpose of this paper is to develop the McKibben artificial actuator with the built-in outer diameter sensor for position control which does not deteriorate the flexibility of actuator. Some researchers [6][7] have proposed the inner diameter sensor using few photo-reflectors. Since the photo-reflector is influenced by irregular reflection light or light transmitted from the outside, there is a problem that noise occurs to the sensor value. The inner diameter sensor can't directly measure the position of the geometric constraint (sleeve) and needs to approximate by the high (six) order function[7]. Therefore, the developed sensor measures the constraint position (outer diameter) of the sleeve by using the Hall-effect (magnetic) sensor in this study. In addition, the thin magnetic sheet is placed between the rubber tube and the sleeve of the McKibben artificial actuator. Finally, the position control scheme is designed by solving the mixed sensitivity problem (robust stability and nominal performance) for the PAM (Pneumatic Artificial Muscle) system. As a result, the effectiveness of the 2 DOF (position) control system using the outer diameter sensor is confirmed by experimental results.

II. Outer Diameter Sensor

A. Estimation Principle of Displacement

In general, the position control system using a McKibben artificial muscle has used a rigid displacement sensor such as a linear potentiometer and encoder. However, the system might lose its flexibility and miniaturization by means of using the rigid sensor.

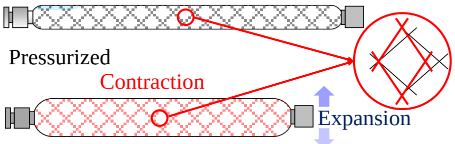

Figure 1. Operational principle of McKibben artificial actuator.

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The environment where the PAM system can be used is limited. Therefore, we aim to develop a McKibben artificial actuator with a built-in outer diameter sensor. The measuring method for axial-directional (longitudinal) displacement of the McKibben artificial actuator is as follows. Fig. 1 shows the operational principle of a McKibben artificial actuator. The McKibben artificial muscle has the following characteristics as shown in Fig. 1. The crossed angle θ of the covered fiber of the actuator changes as increasing the diameter of the actuator according to the input pressure. This constraint fiber acts like a pantograph mechanism. This angular change converts into the longitudinal displacement of the actuator. Therefore, the displacement L of the McKibben artificial actuator can be estimated by measuring the outer diameter of the muscle. Fig. 2 shows the analytical model of the McKibben artificial actuator reported by Ref. [8]. In the static model, the thickness of rubber tube and fiber of the artificial muscle is ignored. From the geometric configuration, the simple equation (1) can be obtained

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

where L is the length of McKibben artificial muscle, b is the diagonal length of the fiber, n is the number of turns and D is the diameter of McKibben artificial actuator. Equation (1) expresses that the length of the McKibben artificial actuator becomes shorter as increasing the diameter of artificial muscle.

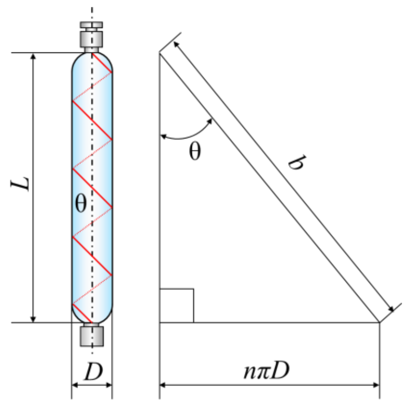


Figure 2. Analytical Model of McKibben artificial muscle

B. Static Characteristics of Hall-effect Sensor

The Hall-effect was discovered by Dr. Edwin Hall in 1879. When a perpendicular magnetic field is present as shown in Fig. 3, a Lorentz force affects to the current.

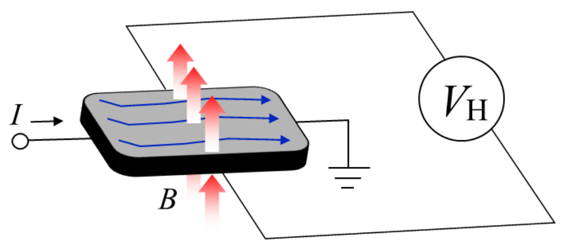


Figure 3. Principle of Hall-effect

Since this force disturbs the current distribution, a potential difference (voltage) of the output occurs. This voltage is called the Hall voltage V_H. The interaction of the current and the magnetic field is shown as equation (2). The Hall voltage V_H is proportional to the vector cross product of the current vector $\boldsymbol{I}$ and the magnetic field vector $\boldsymbol{B}$.

$$V_H \propto \boldsymbol{I} \times \boldsymbol{B} \tag{2}$$

If the magnetic field (magnetic sheet) is perpendicular to the Hall-effect sensor as shown in Fig. 4, this sensor can be applied to the displacement sensor. This study was adopted a thin (1.0 mm) and soft magnetic sheet (MAGNA Co., Ltd. Neodymium magnet sheet, magnetic flux density: 430±50 mT) rather than a hard magnet for a McKibben system. Fig. 4 shows the Hall-effect sensor (Allegro Microsystems LLC., A1324, size: 1.5×4×3mm) used in this study. The dynamic characteristic (Bandwidth) of this sensor is 17 kHz by the sensor specification. The dynamic response is sufficient for the pneumatic (McKibben actuator) system. However, the static characteristics with respect to the magnetic sheet are unknown. In particular, the distance characteristics that related the difference of polarity are unknown. Fig. 5 shows the relations between the distance and the output voltage $V_S(V_H)$ of Hall-effect sensor as shown in Fig. 3.

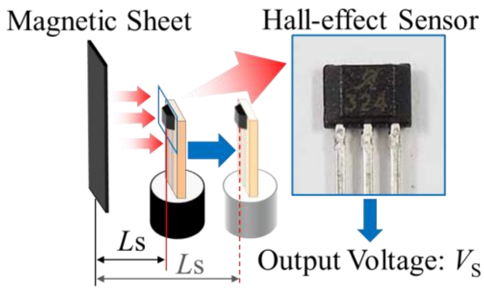


Figure 4. Hall-effect sensor and static experimental device.

From Fig. 5, the static characteristics of sensor regarding the difference of polarity denotes a completely opposite properties, and the dead zone of the N-pole is larger than it of S-pole (See dashed line).

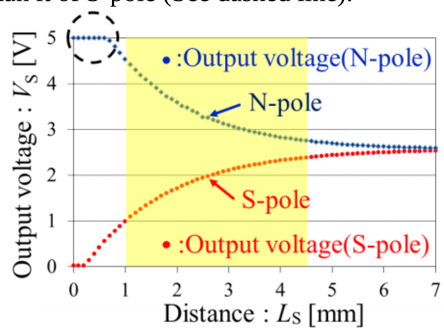


Figure 5. Experimental results of static characteristics.

Although the relation between the distance L_S and the output voltage V_S is non-linear characteristics, it was confirmed that Hall-effect sensor can be applied as a displacement sensor by using the magnetic sheet of S-pole.

As a result as shown in Fig. 6, the following approximation equation between the distance *Ls* mm and the sensor value V_H V can be expressed as an exponential function

$$V_S = V_O\{1.0 - e^{-\alpha(L_S - L_O)}\} \quad \because L_S > L_O \tag{3}$$

where V_O (=2.57 V) is the terminal voltage of the senor in the case of S-pole, α (=0.617) is the rising constant and L_O (=0.20 mm) is the dead zone value. Fig. 6 shows the output voltage of sensor in magnetic sheet of S-pole and the approximation equation. From Fig. 6, it can be seen that the approximation equation corresponds reasonably well with the measurement data of the Hall-effect sensor.

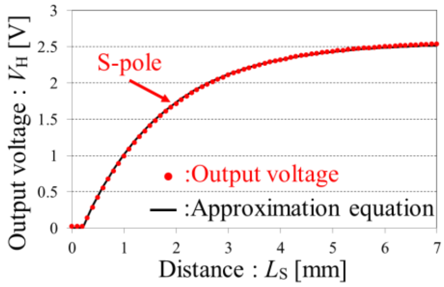


Figure 6. Approximation equation and measurement data

C. Construction of Outer Diameter Sensor

Fig. 7 shows the construction of the outer diameter sensor developed in our study. The sensor consists of two Hall-effect sensors on the electronic substrate and a plug of an artificial muscle.

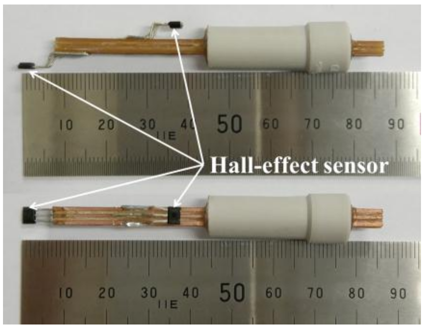
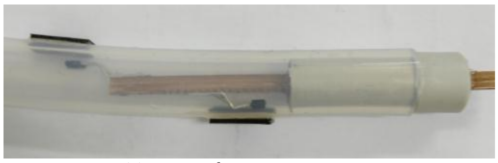


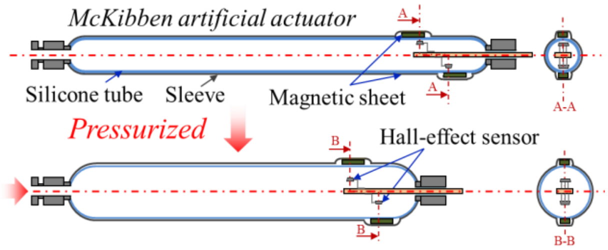
Figure 7. Outer diameter sensor

Two Hall-effect sensors attached to both surfaces at the terminal point of the electronic substrate. The outer diameter sensor is inserted into the McKibben artificial actuator (tube) of outer diameter 15 mm (thickness: about 1.5 mm). Fig. 8(a) shows the view of prototype actuator. Fig. 8(b) shows the outer construction of the McKibben artificial actuator with built-in the outer diameter sensor. The thin magnetic sheet is placed between the silicone (rubber) tube and the sleeve of the McKibben artificial actuator.

In this study, the McKibben artificial actuator with a natural length of 201mm and an outer diameter of 15mm was used. The measurement point of outer diameter was decided so that the diameter becomes same diameter at the outer point of the tube when a McKibben artificial actuator is pressurized. The initial clearance between the outer wall of the silicone tube and the sensor is set to be 1mm because of measurement range of the Hall-effect sensor. By fixing the sensor to the plug, the sensor can keep at a constant position and keep a seal at the same time.



(a) View of prototype actuator



(b) Cross-sectional view

Figure 8. McKibben artificial actuator with outer diameter sensor.

The operating principle for measuring the outer diameter of the McKibben artificial actuator is as follows:

- The length between the Hall-effect sensor and outer wall of the silicone tube becomes longer until the maximum of 4.5 mm when the McKibben artificial actuator is pressurized.
- As increasing this distance, the output voltage from the Hall-effect sensor becomes lower.
- The outer diameter sensor of the McKibben artificial actuator can be estimated by the output voltage changes.

The mass of the outer diameter sensor is only 10 g, the total mass including the sensor and the McKibben artificial actuator is very lightweight (total mass is about 80 g).

D. Exprimental Results of Outer Diameter Sensor

Fig. 9 shows the experimental setup and the relation between output value from the sensor and the axial displacement of the McKibben artificial actuator with outer diameter sensor, respectively.

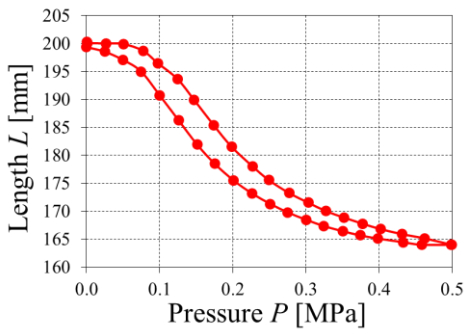


Figure 9. Characteristics between outer pressure and the displacement.

In the experiment, the true value of displacement measured by the linear potentiometer (MIDORI Precisions Co. Ltd., LP-100FJ) as shown in Fig. 9. The supplied pressure to the McKibben artificial actuator (muscle) was given from 0 to 500 kPa and from 500 to 0 kPa every 25 kPa. Then, both the sensor output and the displacement of the muscle were measured. From Figure 9, the characteristics between outer pressure and the displacement of the muscle have a large hysteresis and nonlinear relationship.

In Fig. 10, the output values (red circles) show the voltage values of Hall-effect sensor through an A/D converter. From Fig. 10, it can be seen that the relationship between the displacement and the output from the outer diameter sensor has no hysteresis and reproducible even if there is nonlinear relationship. This nonlinear relationship depends on the characteristics of the McKibben artificial actuator and the outer diameter sensor.

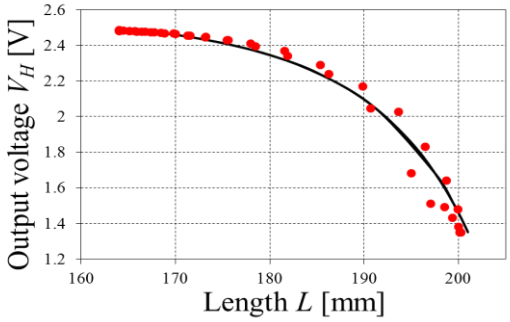


Figure 10. Characteristics between output voltage of the outer diameter sensor and the displacement.

As a result as shown in Fig. 10, the following approximate equations between the displacement L mm and the sensor value V_H voltage can be obtained.

$$Y = L^2 = b^2 - (n\pi)^2 D^2 = \beta - \gamma X \tag{4.1}$$

$$\because \beta = b^2, \gamma = (n\pi)^2$$

$$D = L_S = -\frac{1}{\alpha}\ln\left(\frac{V_O - V_S}{V_O}\right) + L_O \tag{4.2}$$

In the approximation, we used a natural logarithmic function in order to get suitable approximation value of the displacement from the sensor output. In the position control of the McKibben artificial actuator, this approximate equation was used in the position control of the artificial muscle.

In the equations (4), let $Y=L^2$ and $X=D^2$ then the nonlinear function (4.1) is a linear function with respect to the parameters β and γ. The natural logarithmic function (4.2) is the inverse function of the equation (3). When the McKibben artificial actuator with the outer diameter sensor is pressurized, the output voltage data V_S of the outer diameter sensor and the length data L were measured. The outer diameter D of the McKibben artificial actuator was calculated by substituting the output voltage data V_S for the equation (4.1). The unknown parameters β and γ were estimated by using the obtained measurement data.

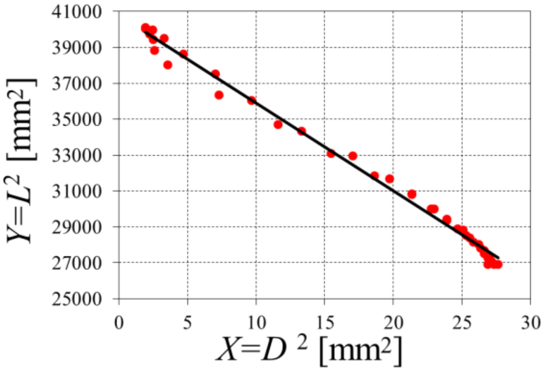


Figure 11. Linear relationship of equation (4.1)

The result is shown in Fig. 11. These obtained values of β and γ were 40470 mm^2 and 410, respectively. Thus, the diagonal length of the fiber (sleeve) b is 201 mm and the number of turns n is 6.4. The standard deviation (accuracy) of length L was about 1.0 mm. Although this accuracy is not extremely precise even if air compressibility is taken into consideration, it may be applied to the some applications such as rehabilitation.

III. System Identification of Dynamic Model

In order to identify the dynamic model of McKibben artificial actuator with the built-in outer diameter sensor, the dynamic experiment of supply (500kPa) and exhaust (0 kPa) motions was performed by using the experimental device as shown in Fig. 12. The experimental device consists of the control valve system including the controller (Micro-computer: Renesas Co. Ltd., H8/3664F), the artificial muscle and the linear potentiometer. However, the potentiometer was used to measure the true length of the artificial muscle.

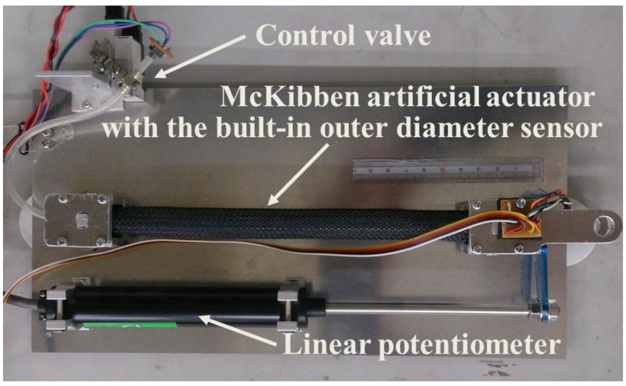


Figure 12. Experimental device for system identification

The transfer function of PAM (Pneumatic Artificial Muscle) system is given by a second-order form[9]. Fig. 13 shows the result (Gain diagram) of system identification (Autoregressive with exogenous: ARX Model) [10], where the blue line and the red line denote transfer functions of the real PAM system and the nominal model: G_n(s), respectively.

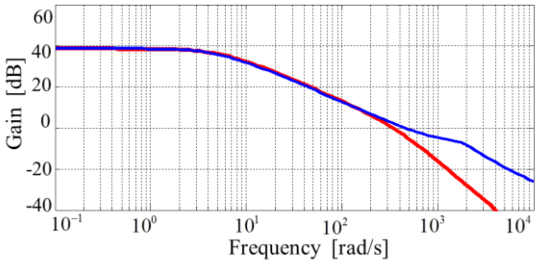


Figure 13. bode diagram of PAM system

Fig. 14 shows the experimental result and output of the nominal model. In Fig. 14, blue and red lines show the calculated length *L* using the developed sensor and the output of the nominal model, respectively. From Figure 14, it can be seen that the output results using the second-order model agree well with the experimental result. This model was a very simple model, but it could be confirmed that the actual valve system can be represented by means of a second-order form. The obtained nominal model G_n(s) can be expressed as following function:

$$G_n(s) = \frac{1.402 \times 10^{-4}}{(s+5.431)(s+358.3)} \quad \text{[m/Pa]}$$

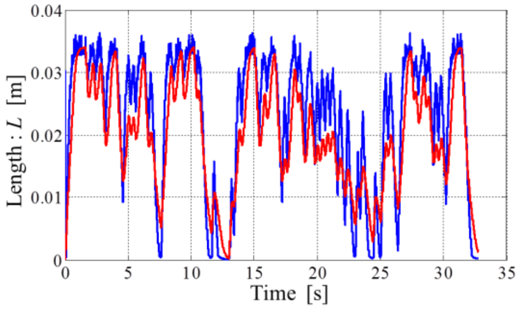


Figure 14. Results of identification experiment

IV. Position Control

A. 2 DOF Controller for PAM System

In general, a pneumatic artificial muscle (PAM system) such as McKibben artificial actuator has nonlinear characteristics which are the hysteresis and the nonlinearity between pressure and length (input vs. output). Therefore, 2 DOF controller is applied to the PAM system for the position control.

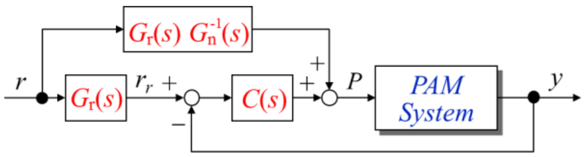


Figure 15. Two DOF control scheme for position control

A general form of the 2 DOF control system is shown in Fig. 15, where the controller consists of two compensators $G_r(s)$ and $C(s)$. $C(s)$ is the feedback compensator and $G_r(s)$ is the feedforward compensator.

The closed-loop transfer function $G_r(s)$ from *r* to *y* is given by

$$G_r(s) = \frac{y}{r} = \frac{\omega_n^2}{s^2 + \sqrt{2}\omega_n s + \omega_n^2}$$

where ω_n is a natural frequency that is determined by the system designer. Thus, the system designers can set the desired control performance. However, the natural frequency ω_n (=5.0 rad/s) can't be designed faster than the response (pole: 5.431 rad/s) of the nominal model.

B. Control System Design of Feedback Controller C(s)

The most famous and simple PI controller was adopted as the feedback controller. However, it was difficult that the PID controller (solution) with the derivative action is searched in order to satisfy the robust stability. The PI controller $C(s)$ is given by following transfer function.

$$C(s) = K_P\left(1 + \frac{1}{K_I s}\right)$$

where K_p is the proportional gain and K_I is the time constant of the integral action.

Since the PAM system has the nonlinear characteristics and the dead time in general, it is desirable that the feedback controller satisfies a robust stability. Therefore, the mixed sensitivity problem (robust stability and nominal performance) was solved by the following three steps for the feedback controller.

【Step 1】 The magnitude $|\triangle(\omega j)|$ of the multiplicative perturbation is obtained by the error between the nominal model and the real system (See Figure 13). In addition, The weight function $W_T(s)=(s/30+1)^2/10$ is determined to satisfy $|W_T(\omega j))|>|\triangle(\omega j)|$.

【Step 2】 The weight function $W_S(s)=(0.02s+\rho)/(s+0.001)$ was set to satisfy the nominal performance, where ρ is the control parameter.

【Step 3】 These parameters K_p and K_I are designed to satisfy both robust stability and the nominal performance. The control parameter ρ should be as large as possible. However, if the parameter ρ is too large, there are no solutions that satisfy two conditions. Therefore, when the parameter ρ is 20 rad/s, parameters K_p and K_I of PI controller are 4.7×10^7 Pa/m and 0.125 s, respectively.

Fig. 16 shows the gain (S-T) diagram of the sensitivity function and the complimentary sensitivity function. S(s) is the sensitivity function and T(s) is the complimentary sensitivity function. Fig. 17 shows that satisfy both robust stability and nominal performance.

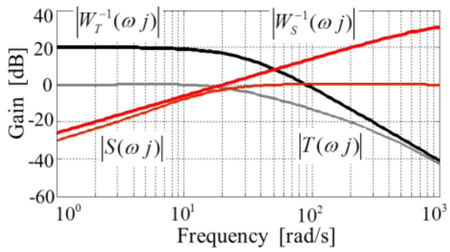


Figure 16. S-T diagram (Robust stability and nominal performance)

C. Control Experimental Results

Fig. 17 shows the position response (Length) of the tracking control (amp. 15mm and 0.5 Hz) that used the PI control in the case of non-load weight. The control experiment used same device as shown in Fig. 12. In Fig. 17, the blue and red lines show the desired tracking trajectory r_r (See Fig. 15) and the calculated length y using the outer diameter sensor, respectively.

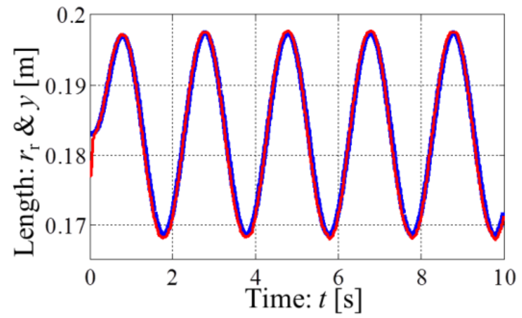


Figure 17. Experimental result (Non-load weight)

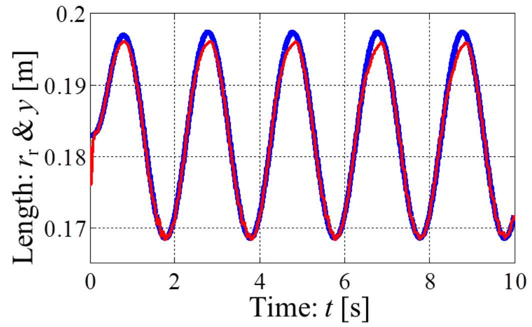


Figure 18. Experimental result (Load weight: 19.6 N).

From Fig. 18, it can be seen that the tracking performance of the displacement is good even if the simple control scheme (PI controller) was used. The standard deviation of the displacement error is small that is less than ±1 mm.

Fig. 18 shows the response of the tracking control in the case of load weight 19.6 N. From Fig. 18, it can be seen that the tracking performance of the displacement is relatively good even if there is the load weight.

V. Conclusions and Future Work

We aimed to propose the measurement method and position control system design of the McKibben artificial actuator that can measure the outer diameter sensor even if the external force was applied to the end of the actuator.

This study can be summarized as follows.

1. The outer diameter sensor using Hall-effect sensor was proposed and tested so as to place the sensor on the outer surface of the pneumatic artificial actuator.
2. The validity of the measurement using the proposed model was confirmed by comparing the calculated displacement with the actual displacement.
3. The measurement method using the McKibben artificial actuator with built in outer diameter sensor was proposed. As a result, the measurement error was less than ±1 mm and the validity of the outer diameter sensor was confirmed.
4. The tracking position control using the developed sensor was performed and the effectiveness of the control system design was confirmed.

In future work, we aim the system construction method that can estimate the load weight while controlling the position of the pneumatic artificial actuator. And, in the system identification and the tracking control experiments, there was no problem in the repeatability of the tested sensor. However, the repeatability and durability of the proposed sensor must be investigated to satisfy commercial specifications.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Takuya Yano and Shinsaku Fujimoto conducted the research, analyzed the data and wrote the paper. All authors had approved the final version.

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