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Development of Intelligent McKibben Actuator

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***Abstract* – The aim of this study is to develop an Intelligent McKibben actuator with an integrated soft displacement sensor inside, so that displacement of this actuator can be controlled without having any extra devices attached. In addition, the high compliance which is a positive feature of the McKibben actuator is still conserved.**

This paper consists of four main parts. First of all, different types of soft displacement sensors made out of rubber were composed, and tested for their functional characteristics. Secondly, the Intelligent McKibben actuator was developed with the soft displacement sensor incorporated within. Then, experiments of the position servo control with a single Intelligent McKibben actuator were carried out. At last a robot arm mechanism was designed with two Intelligent McKibben actuators, and those experimental results showed a great potential for its future applications.

Index Terms – Soft sensor, soft mechanism, McKibben actuator, Intelligent actuator,

I. INTRODUCTION

In recently years, many rescue robots and power assist devices have been developed increasingly. As their nature they have to have direct contact with humans, therefore, safety issues must be carefully examined prior to its use with people.

The McKibben actuator is pneumatically driven and generates muscle-like contractile motions [1] [2]. This actuator is known for its advantages including flexibility and light weight, which makes this apparatus safer for its use. In fact, robots and power assist devices have been developed using this actuator [3] [4]. In a case of servo control with this actuator, its system requires sensors such as potentiometers, encoders and valves in general, and as a result the system tends to grow in size and weight. Moreover, the McKibben actuator's positive characteristic, the high compliance, is lost with this.

Regarding sensors such as pressure and displacement sensors with rubber, which are soft and light in weight, they have been studied and developed [5].

The goal of this study is to make the McKibben actuator more intelligent in a way that a micro valve, displacement sensor and pressure sensor can be incorporated into the McKibben actuator. Therefore, a control of the actuator can be achieved without having external sensors and valves. In this paper, we will present a model of the McKibben actuator with integrated soft displacement sensor made of rubber, and name it Intelligent McKibben actuator after its intelligence.

Following to a series of tests to examine the servo control with single Intelligent McKibben actuator, we will investigate a robot arm system configured with two Intelligent McKibben actuators for its potentials and future applications.

II. SOFT DISPLACEMENT SENSOR

A .Configuration

It is necessary to design the displacement sensor with a soft material, so that high compliance of the Intelligent McKibben actuator is maintained. Three types (A, B, C) of sensors were prototyped (Table 1). Each type has a base made of hexahedral rubber (2.5mm x 120mm x 1mm, or 5mm x 120mm x 1mm), and a conductive material which is either a thin film placed on the surface of base rubber or blended inside the rubber.

Table 1
Conduction method of 3 type sensors

Type	Conductive material	Conduction area
A	Carbon	Included in whole rubber
B	Carbon	2.5 or 5 x 30-120mm on one surface 10-100μm in thickness
C	Gold	2.5 or 5 x 50mm on one surface

Fig.1 shows a configuration of sensor type-B which has a conductive area thinly coated with a resin ink onto the surface of rubber. The ink included carbon particles and binder in toluene. Thus, when toluene evaporated, the surface of the rubber is left with a thin carbon film which is flexible enough to stretch without breaking when the rubber is deformed. The thickness of the film can be controlled and using a spin coater can vary from 10μm to 100μm.

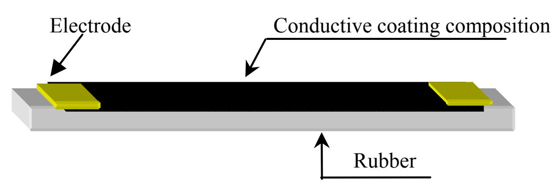


Fig.1 Configuration of soft displacement sensor type-B

Type-A and type-C also consist of conductive materials and the rubber base. While type-A, the carbon is contained within the rubber, the type-C has an Au thin film sputtered on the surface of the rubber. In all types, therefore, changes in the electrical resistance following extending and contracting motions of the rubber can be used as a displacement sensor.

It is easy to understand that type-B and type-C have electrical resistance as they have conductive film on the surface of the rubber. The reason why type-A has an electrical resistance is known as the tunnel effect theory or conductive pass theory. Therefore, it is possible that deformation of the rubber in any of these sensors could lead to changes in electrical resistance. As shown in Table 1, several sensors of type-B and type-C were made by changing the size and thickness of the conductive area.

B. Characteristics of 3 type sensors

Fig. 2 shows an experimental system for testing those three types of sensors described earlier. One end of a tested sensor is fixed on the stator stage, and the other is fixed on the movable stage.

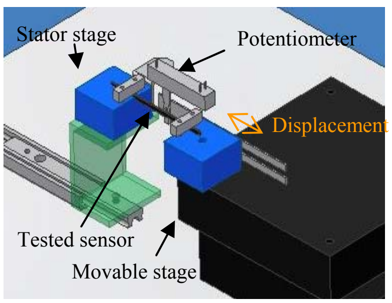


Fig.2 Experimental system for soft displacement sensor

As a result of motion of the movable stage, changes in electrical resistance of each sensor were measured, and displacement measurements of the movable stage were obtained with a potentiometer.

Fig. 3, 4, 5 display the relationship between resistance and displacement over time for type A, B, C sensors respectively. The electrical resistance was monitored while the movable stage was slid by 5mm. These tests were done using 2.5mm x 120mm x 1mm size rubber as a base.

As shown in Fig.3 with sensor type-A, the electrical resistance increased as displacement occurred in extending direction. In contrast, in case of displacement for contracting motion, the electrical resistance decreased gently.

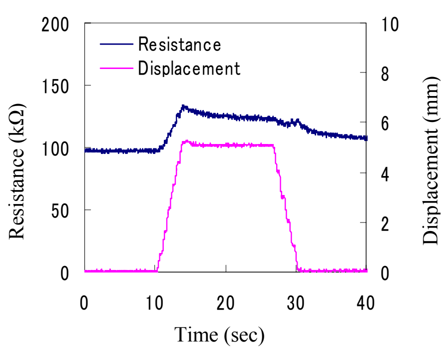


Fig.3 Relationship between displacement and electrical resistance of type-A

The displacement was maintained at 5mm, but the electrical resistance could not be kept at a constant value. This was due to the viscosity of the rubber including carbon particles.

Fig.4 shows a clear relationship between electrical resistance following a direction of the displacement for both extending and contracting motion. With this sensor, a carbon film had an area of 2.5mm x 30mm and thickness of100μm which made it possible to keep both electrical resistance and displacement at constant values. A series of tests were carried out varying in rubber width (2.5mm or 5mm), film area (2.5mm or 5mm x 30mm-120mm), and film thickness (10μm-100μm). All of them showed similar trends to Fig.4 except for the absolute value of the resistance.

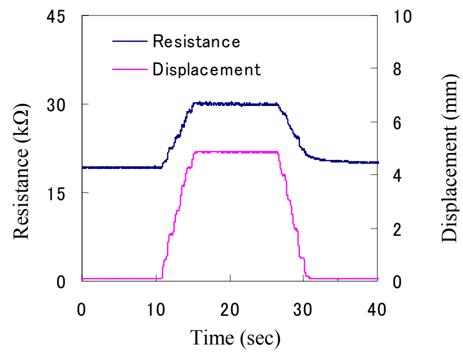


Fig.4 Relationship between displacement and electrical resistance of type- B

The type–C sensor displayed similar characteristics in electrical resistance seen in Fig.3 for its point of instability (Fig.5). The reason for the electrical resistant did not follow the displacement is thought due to cracks happened in the non-elastic Au film, and such a thin film could have been easily influenced by the viscosity of the rubber.

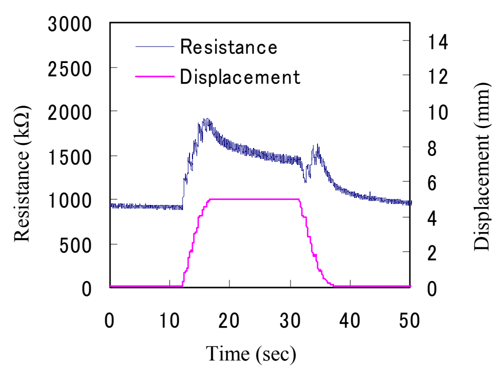


Fig.5 Relationship between displacement and electrical resistance of type-C

These experiments suggest that type-B sensor seems to be most superior over the other two as a soft displacement sensor. Therefore, type-B was chosen for the following experiments, and in the rest of this paper the soft displacement sensor represents the type-B sensor otherwise indicated.

C. 4-terminal measurement method

In the electrode area of the soft displacement sensor, the electrical lines are bonded by a conductive bond, the area is boundary of the elastic material and the rigid material, therefore the contact resistance appears strongly. To measure the resistance of the soft sensor accurately, it is effective to measure with 4-terminal measurement method.

Fig. 6 shows the 4-terminal measurement method and its equivalent circuit. The 4-teminal measurement method the current line and voltage line of which were set separately was able to reduce the influence on the contact resistance. The electrical current flue from the electrode 1 to 2, and the voltage was measured between the electrode 3 and 4. By using Ohm's low, resistance values were calculated.

In this figure, r_1, r_2, r_3, r_4 represent the contact resistance of the electrode 1, 2, 3, 4 respectively, and R is the actual resistance of the soft displacement sensor. The internal resistance of the voltmeter was so large (10MΩ) that the contact resistance of r_3 and r_4 could be ignored. Therefore, the resistance of the soft displacement sensor fairly close to the actual resistance was obtained. The constant current was 0.24mA which was generated by a constant current diode (To92 J500).

Fig. 7 shows the differences of resistance between 2-terminal measurement method and 4-terminal measurement method which were measured using the same sensor with an area of the carbon film (5mm x 100mm). ■ indicates the result of 2-terminal measurement method which is a conventional measurement method of electrical resistance (i.e. the voltmeter is set on the current line). ▲ shows the results of 4-terminal measurement method indicating that the measured resistance was about 50 to100kΩ lower than 2-terminal measurement method. Theses differences were created by the contact resistance.

As described earlier, in the area of electrode which is the boundary of the elastic and rigid material, the electrical resistance can be unstable because of the joggle of the electrical lines and the deformation of the rubber. This confirmed that using 4-terminal method is more effective to measure the electrical resistance of the soft sensor.

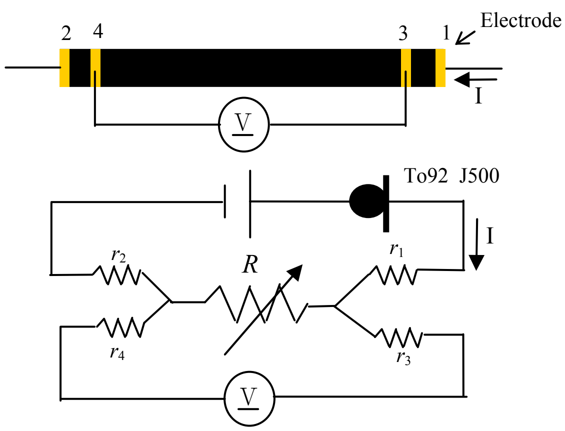


Fig.6 Principle of 4-terminal measurement method

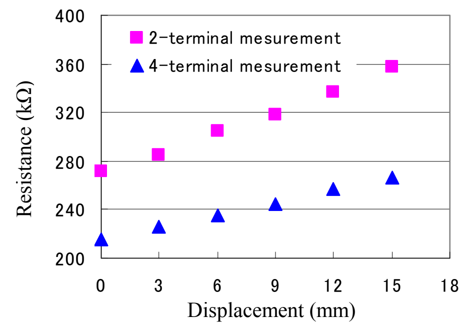


Fig.7 Differences of resistance between 2-terminal measurement method and 4-terminal measurement method

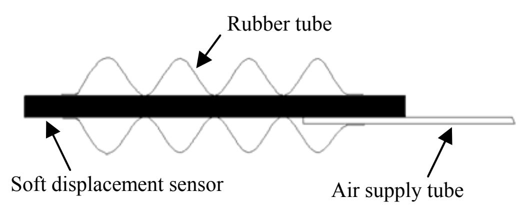
III. INTELLIGENT MCKIBBEN ACTUATOR

The soft displacement sensor was incorporated in the McKibben actuator. The conventional McKibben actuator is fabricated with a rubber tube which is covered with a braided fibrous sleeve.

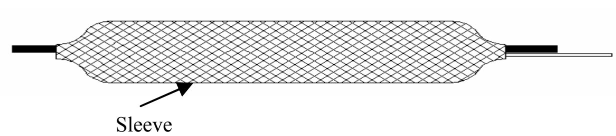
When air pressure is supplied to the rubber tube, the actuator generates the contracting displacement in a longitudinal direction.

A. Configuration and driving principle

Fig. 8-a shows an internal configuration of the Intelligent McKibben actuator. When this was constructed, the length of the rubber tube had to be adjusted to its contraction state (the length of L_a-d) by creasing it, and a length of soft displacement sensor, L_b, was incorporated in it. The sleeve covers over the two is L_c-d. Fig.8-b shows the outlook of the Intelligent McKibben actuator where L_a, L_b, L_c are natural lengths of the rubber tube, the soft displacement sensor, and the sleeve, respectively. d is a maximum displacement which is about 20% of the rubber tube length (i.e. $d \approx L_a$ x 0.2).



a. Internal configuration of Intelligent McKibben actuator



b. Outlook of intelligent McKibben actuator

Fig.8 Configuration of Intelligent McKibben actuator

When the Intelligent McKibben actuator was used singly, a load had to be placed to keep the natural lengths of the rubber tube (L_a) and the sleeve (L_c) as an initial state of the actuator. Moreover, by setting a length of the soft displacement sensor to L_b + d at the initial state, the sensor was able to avoid buckling as it reached the driving state, i.e.

the sensor could not be shorter than its natural length (L_b) when it is maximally contracted (Fig 9).

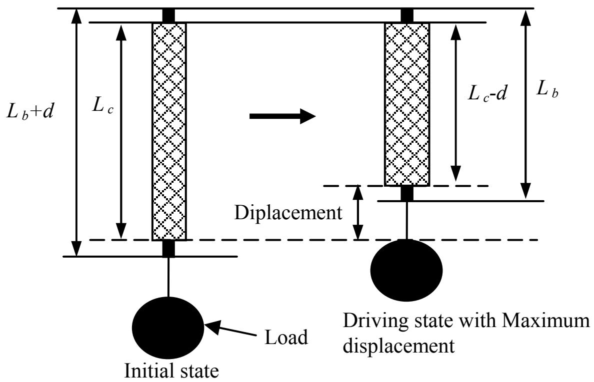


Fig.9 Initial state and driving state of Intelligent McKibben actuator

This Intelligent McKibben actuator has advantages as follows;

1. It is easy to drive with the position servo control because the actuator can perform self displacement using the soft displacement sensor incorporated within.
2. Degree of compliance of the soft displacement sensor is much higher compared to the one in the conventional McKibben actuator, so high compliance of the overall system is maintained.
3. The soft displacement sensor is incorporated in the actuator; therefore it is capable of reducing the size of the system.
4. Compared with the conventional McKibben actuator, the output power of the actuator does not decrease.

B. Control system

The experiments of the position control using single Intelligent McKibben actuator were carried out. Fig. 10 shows the control system which consists of a PC, air compressor, regulator, analog valve, and the Intelligent McKibben actuator. Notice that the potentiometer was used for the evaluation but not as a feedback control. The control algorithm is the PI control, and K_f shows the feed back gain.

Fig. 11 demonstrates the experiment of position control with single Intelligent McKibben actuator. In an initial state, the length (L_c) and diameter of the actuator were 100 mm and 5 mm, and the length (L_b+d) and width of the soft displacement sensor were 140 mm and 2mm respectively. The air pressure supplied to the analog pneumatic valve was 400kPa, and a load was 5N.

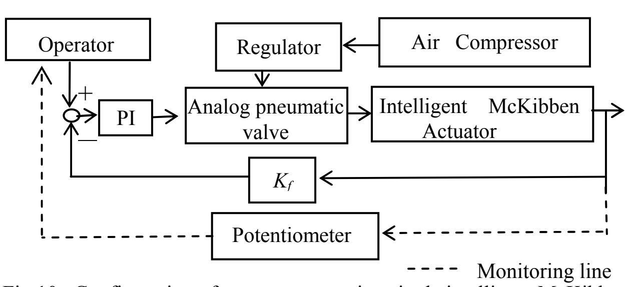


Fig.10 Configuration of servo system using single intelligent McKibben actuator

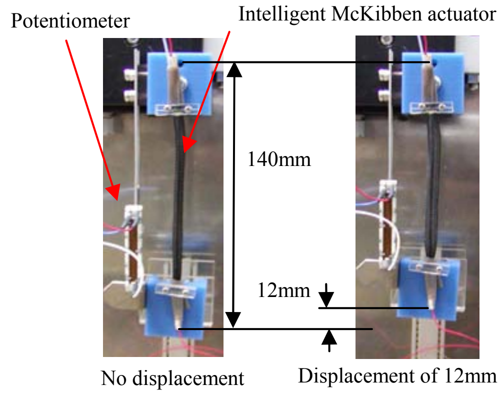


Fig.11 Experimental system of Intelligent McKibben actuator

C. Static characteristics of soft displacement sensor

Fig.12 shows the static characteristics of the soft displacement sensor incorporated in the Intelligent McKibben actuator. As it can be seen in the following section IV, characteristics of this sensor normally depend on the velocity of the deformation, but, in this section the static characteristics in each point were obtained with much time (Fig.12).

A series of electrical resistance of the sensor were measured from the initial state to the maximum driving state (the displacement was 18mm). Plotting points ■ were obtained while the contracting motion of the actuator was achieved with increasing air pressure and ▲ were measured following the extending motion of the actuator with decreasing air pressure. The results were satisfying as hysteresis was minimal and the linearity was relatively high.

In this measurement, the position control was carried out by using the potentiometer.

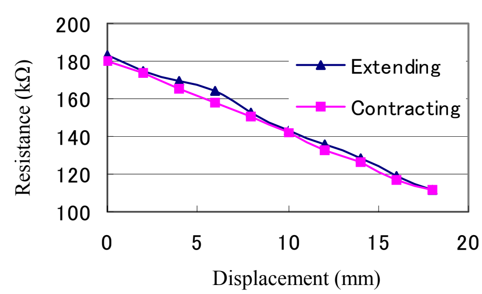


Fig.12 Static characteristics of soft displacement sensor incorporated in McKibben actuator

D. Experiment

Using the system shown in Fig.11, the experiment of the position servo control was carried out where electrical resistance of the soft displacement sensor incorporated in the Intelligent McKibben actuator was used as the feedback value.

As results shown in Fig.13, the target value was a pulse function whose amplitude was 14 mm, and cycle was 15 seconds. The actual value represents the output of the potentiometer. There was an error between the target value and actual value which was about 1 mm; a main reason for this was that experiment was based on the static characteristics of the sensor only.

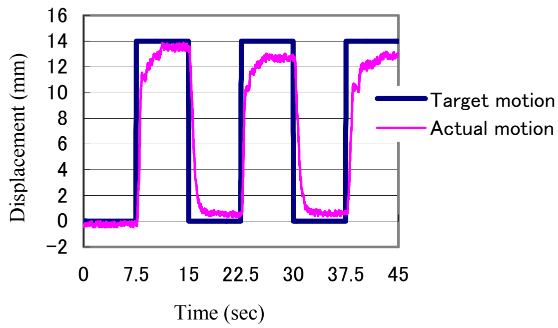


Fig.13 Experimental result of servo control using single Intelligent McKibben actuator

IV. ANTAGONISTIC MECHANISM

Currently, many of the conventional robot mechanisms using the McKibben actuators are developed using multiple McKibben actuators [6]. In this section, two Intelligent McKibben actuators were set antagonistically and the rotational angle control of a robot arm was realized and investigated.

Moreover, in this way accurate control of the antagonistic mechanism was achieved better than using only single Intelligent McKibben actuator.

A. Configuration

Fig.14 shows the robot arm system with two Intelligent McKibben actuators (Intelligent McKibben actuator 1 and 2) which were linked by a pulley belt. Extending and contracting motions of the actuators produced a rotational angle θ of the robot arm. The actual rotational angles were measured by the potentiometer which worked directly with the pulley. At the initial state of the system, the actuators needed to be set with 50% offset displacement of the maximum displacement. This is because one actuator extends while the other contracts in order to produce a rotational movement.

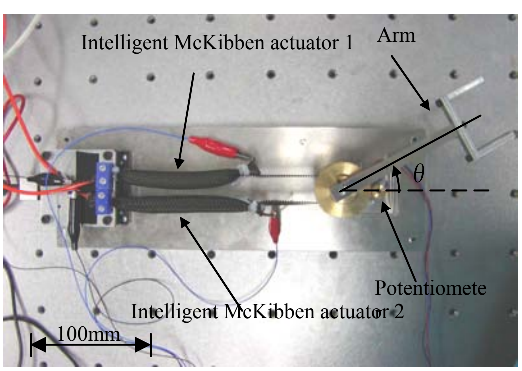


Fig.14 Configuration of robot arm system

B. Dynamic characteristics of soft displacement sensor

The experiment in the section III was based purely on the static characteristics, so the effects of deformation velocity of rubber were ignored. However, for more accurate control, it was important to investigate the dynamic characteristics here. The electrical resistance was measured during the arm rotational motion (sinusoidal motion of the amplitude of 30 degree and a cycle of 6.3 seconds) which was controlled by the potentiometer. Fig.15 shows the electrical resistance of the two soft displacement sensors with the horizontal axis and the vertical axis representing the arm angle and resistance respectively.

Shortly after driving, the resistance was disturbed (referred as an initial disturbance) due to viscosity of the rubber. After the initial disturbances, the resistance of two sensors exhibited fair linearity. However when they were approximated to the linear equation, the determination coefficients were R^2=0.9083, 0.9395 which did not approve a high linear relationship. However, using difference between the two sensors, two initial disturbances were cancelled out, as shown in Fig.16, and the high linearity of the sensor model was realized (determination coefficient achieved R^2=0.9705).

Several similar experiments were carried out with changing the cycle and the amplitude, and all of the results displayed much improved linearity.

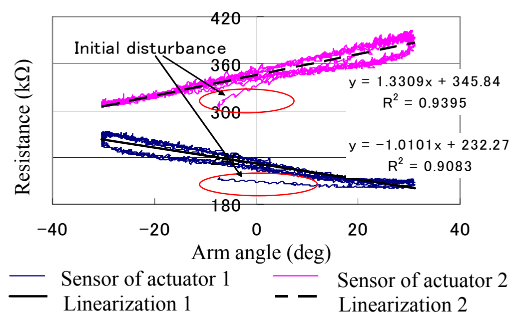


Fig.15 Dynamic characteristics of sensor 1 and sensor 2

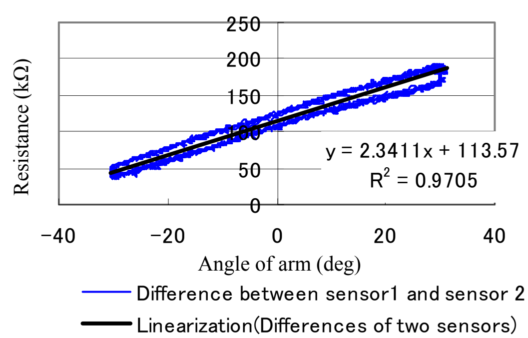


Fig.16 Difference between sensor 1 and sensor 2

C. Experiment

As shown in Fig.17, the difference between the actuator 1 and 2 was used for the feedback value. As results, the target motion was the sine function with amplitude of 25 degrees and cycle of 6.3 seconds, graphed in Fig.18.

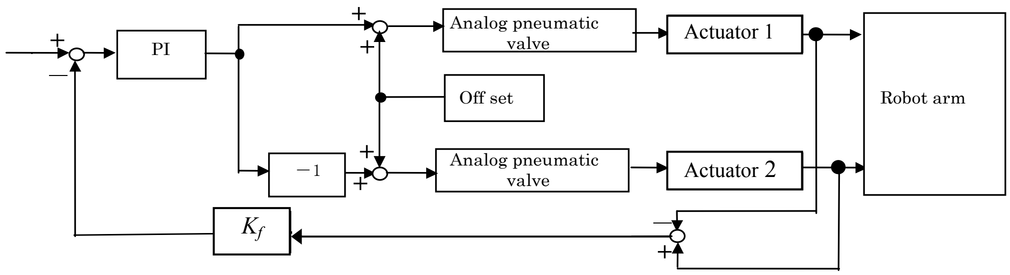


Fig.17 Servo control system of robot arm mechanism

As described earlier in Fig.16, when the sensor model was created, the small hysteresis existed. Therefore, a slight discrepancy between the target motion and actual motion was observed. However, comparing to Fig.13, it is clear that the results improved significantly. Moreover, a strength such as high compliance of the McKibben actuator is considered to be more important over accurate positioning like a micro order positioning. After all, the experiments were successfully carried out without the external sensors giving satisfying results.

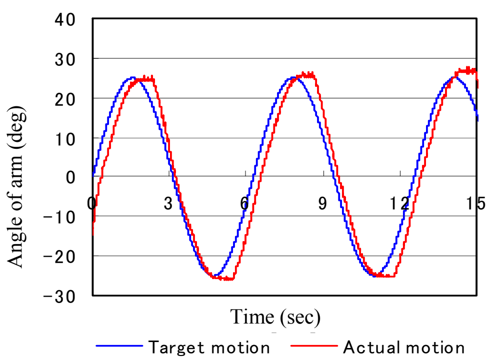


Fig.18 Experimental result of antagonistic mechanism

V. Conclusion

In our project, the Intelligent McKibben actuator with incorporated soft displacement sensor was successfully developed, and experimental results confirmed that it has a potential that can be more ideal for future applications in robotics.

The following results were obtained in this paper.

1. 3-types of soft displacement sensors were prototyped and checked for their characteristics. The results indicated that the type-B sensor with thin carbon film mounted on the surface of the rubber excelled other two.
2. The 4-terminal measurement method was superior to the 2-terminal measurement method for measuring the resistance of the soft sensor.
3. The Intelligent McKibben actuator with incorporated soft displacement sensor was successfully developed, and the servo system using this actuator was achieved.
4. The rotational robot arm system using two Intelligent McKibben actuators was manufactured. The robot arm was controlled accurately without external sensors.

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