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A Soft Robot Arm with Flexible Sensors for Master-Slave Operation †

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Abstract: In our study, a soft robot arm consisting of McKibben artificial muscles and silicone rubber structure has been developed. This robot arm can perform bending and twisting motions by applying pneumatic pressure to the artificial muscles. The robot arm is made of flexible materials only, therefore, it has high flexibility and shape adaptability. In this report, as the fundamental investigation for the master-slave feedback control of the soft robot arm for intentional operation, we focus on the bending motion of the soft robot arm. Three flexible strain sensors are placed on the soft robot arm for measuring the bending motion. By establishing the master-slave feedback system using the sensors, the bending motion of the soft robot arm follows the operator's wrist motion detected by the wearable interface device.

Keywords: soft robot arm; artificial muscle; flexible strain sensor; master-slave control

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1. Introduction

In recent years, various soft actuators have attracted much attention due to their features of high compliance, light weight, and power-to-weight ratio. In addition, research on soft robot arms using these actuators has been actively conducted [1–3]. Due to their high flexibility and back-drivability, these soft robot arms can absorb the impact of collisions with people or objects and minimize the impact on the target. Therefore, the soft robot arm has higher safety than conventional robot arms, which are composed of rigid mechanical elements.

The McKibben artificial muscle used in this study is one of the most widely known soft actuators [4]. It contracts like a real muscle when pneumatic pressure is applied. In our research group, the soft robot arm with multiple McKibben artificial muscles has been developed. The robot arm can perform bending and twisting motions [5]. Because of its flexibility and safety, it is expected to apply to the mechanical systems in medical, welfare, and agricultural fields.

In these fields, unlike general industrial robot arms, which repeat predetermined motions at high speed based on high-precision positioning control, the operator's intention needs to be reflected in the motions of the robot arm flexibly depending on the situation and task. For intentional operation, research has been conducted on master-slave control using a manipulation interface that is similar to that of the robot arm, and on remote control using human motions through wearable devices [6–9]. In this study, we have developed an arm-mounted wearable interface with thin flexible strain sensors attached to a highly elastic arm cover. The interface detects the flexion of the operator's wrist and the twist of the operator's forearm, which are used as inputs for the bending and twisting motions of the soft robotic arm, respectively. This enables intuitive operation of the soft robot arm [10]. In order to reflect the operator's intention more efficiently to the motion of the soft robotic arm, it is effective to introduce feedback control to the master-slave operation.

In this paper, we focus on the bending motion as a basic research to realize the feedback control. Three flexible strain sensors were mounted on the soft robot arm for feedback control of the soft robot's bending motion. These sensors correspond one-to-one to the three sensors of the wearable interface that respond to the bending of the wrist. Feedback control of the bending motion of the soft robot arm was realized by comparing the corresponding sensor values.

2. Materials and Methods

2.1. Components and Structure of a Soft Robot Arm

2.1.1. McKibben Artificial Muscle

The general McKibben artificial muscle consists of a rubber tube covered with a sleeve made of woven nylon fibers. The rubber tube is sealed at one end, and an air supply tube is connected to the other end. The driving principle of the McKibben artificial muscle is shown in Figure 1. By applying air pressure from an air supply tube, the inner rubber tube expands in the radial direction, and the contractile displacement in the axial direction is generated by changing the braid angle of the sleeve. The contraction motion is used as the output of the actuator.

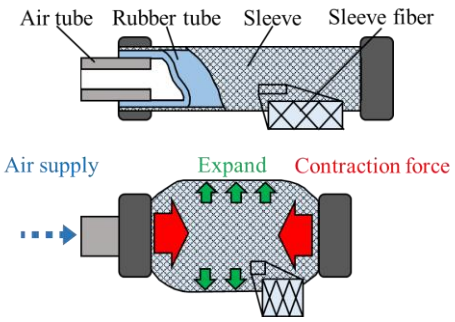


Figure 1. Structure and driving principle of the McKibben artificial muscle.

2.1.2. Flexible Strain Sensor

Figure 2 shows an overview of the flexible strain sensor（Stretchable dynamic strain sensor, Yamaha Corporation）used in this study. The sensor consists of an electric conductive CNT (carbon nanotube) sheet sandwiched between elastic polymer layers and electrodes attached to both ends. It is flexible and when strain occurs in the direction of the CNT array, the electrical resistance increases, and this change in electrical resistance is used as the output of the sensor to measure the strain. The thickness, the gauge length, and a width of the sensor are 0.2 [mm], 90 [mm], and 2.0 [mm] respectively.

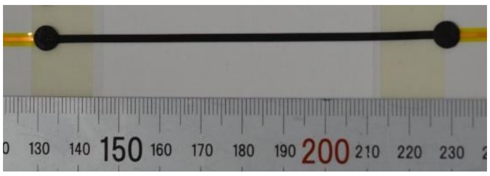


Figure 2. Overview of the flexible strain sensor.

2.1.3. Structure of a Soft Robot Arm

Figure 3 shows a model of the soft robot arm developed in our study. The robot arm consists of five McKibben artificial muscles. The robot arm is fabricated by placing the artificial muscles in a mold and then pouring liquid rubber into the mold to harden it.

Three artificial muscles, which are represented as red lines in Figure 3, are placed at equal intervals in parallel to at the axial direction and they generate bending motion of the soft robot arm. Two artificial muscles, which are shown in green lines in Figure 3, are wound spirally, one is in the clockwise direction and the other is in the counterclockwise direction. They enable the robot arm to twist. Table 1 shows the parameters of the robot arm.

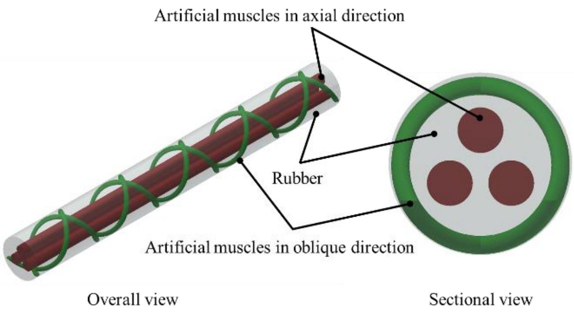


Figure 3. Structure of the soft robot arm.

Table 1. Parameters of the robot arm.

Robot arm	Overall length [mm]	190
	Outer diameter [mm]	22
Artificial muscles in the axial direction	Length [mm]	180
	Outer diameter [mm]	5.5
Artificial muscles in the clockwise and counter-clockwise directions	Length [mm]	350
	Outer diameter [mm]	2.5
	Number of rolls [times]	5
Rubber material	Hardness	30 (durometerOO)

2.1.4. Mounting Flexible Strain Sensors on a Soft Robot Arm

Figures 4 and 5 indicate the layout and the actual placement of the sensors. In this report, focusing on the feedback control of the bending motion of the soft robot arm, three flexible strain sensors (rs_1, rs_2, rs_3) are attached on the surface of the soft robot arm at 120 [°] intervals in the axial direction to match each artificial muscle one-to-one. The sensors (rs_1, rs_2, rs_3) and artificial muscles (ra_1, ra_2, ra_3) arranged oppositely each other make a pair, and the artificial muscle contracts, then the corresponding sensor is stretched and electrical resistance increases.

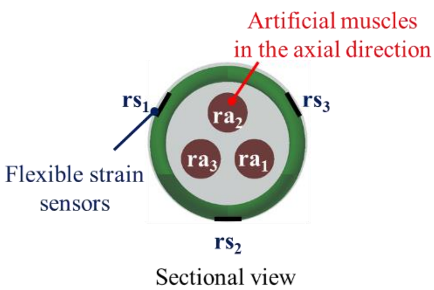


Figure 4. Layout of the sensors on the soft robot arm.

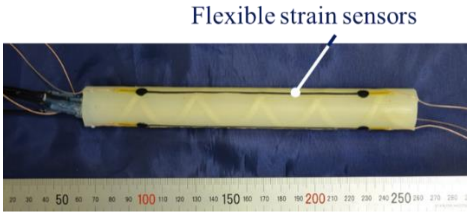


Figure 5. The flexible strain sensors on the soft robot arm.

2.2. Structure of a Wearable Interface

A wearable interface was developed in previous research as shown in Figure 6 [10]. It was fabricated by attaching flexible strain sensors to a stretchable arm cover. To detect the bending motion of the wrist, three sensors (ws_1, ws_2, ws_3) were placed at equal intervals in the axial direction at the wrist. In addition, two sensors (ws_4, ws_5) were placed crosswise on the forearm to detect the twisting motion of the forearm. In this report, three sensors in the axial direction are used because only the bending of the wrist is targeted as a basic study.

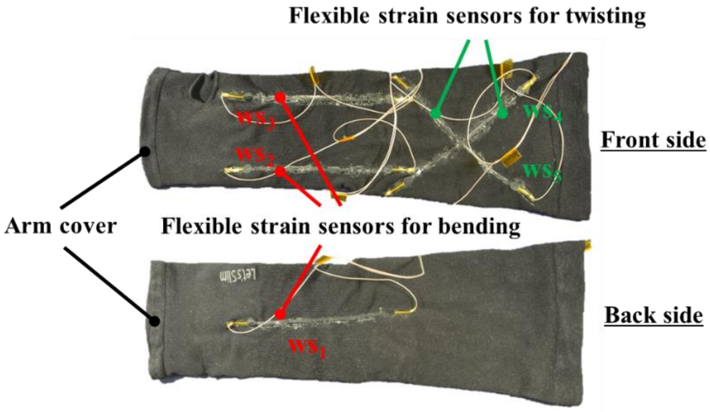


Figure 6. Wearable interface. [10].

3. Experiments and Results

Feedback Control of Bending Motion

The respective correspondence between the sensors of the wearable interface and the soft robot arm is shown in Figure 7. The block diagram of the Feedback control system is also shown in Figure 8. The sensor outputs of three sensors on the wearable interface change with the bending of the operator's wrist. The deviation E is the difference between the change of the electrical resistance R_{wsi} (i = 1,2,3) and the change of the resistance R_{rsi} (i = 1,2,3) of the three sensorson the soft robot arm. The feedback gain of K_{i} (i = 1,2,3) is set so that R_{wsi} at the maximum wrist bending match $K_{\mathrm{i}}R_{\mathrm{rsi}}$ at the maximum bending of the robot arm. P_{i} (i = 1,2,3) is the actuating pneumatic pressure value to the artificial muscles. The size and motion range of a wrist differ individually, in addition, the wearing position and tightness between the wearable interface and the arm varies slightly when an operator wears the interface each time, even if the same operator. Therefore, K_{i} need to be adjusted for each wearing before the feedback control. The proportional gain and the integral gain of the PI controller were determined experimentally.

The operator with the wearable interface bent the wrist in bending direction of 0[°] and extended it back to the initial state. The control results without load and with load of 10 [g] mass on the tip of the robot arm are shown in Figure 9 and Figure 10, respectively. In these graphs, R_{ws1} and R_{rs1} are focused, because the bending direction is in 0[°] and R_{ws1} and R_{rs1} change mainly. Figures 9a and 10a show R_{wsi}, $K_{\mathrm{i}}R_{\mathrm{rsi}}$, and P_{i}. Figures 9 and 10b represent the comparison of the ratio of bending angle to the maximum bending angle of the wrist and the robot arm. The maximum angles of the wrist and the robot arm are different, so the ratio to the maximum bending angle is compared. The bending angles of the wrist and robot arm were calculated by the motion capture system.

As shown in Figures 9 and 10, K_1R_{rs1} follows R_{ws1} in both cases of without load and with load, therefore it is found that feedback control system with PI controller works well. Moreover, the bending angle of the arm can follow the bending angle of the wrist mostly. The operator can operate the bending motion of the soft robot arm intentionally by bending his wrist as the master. Generally, soft strain sensors made of polymer materials have a drift characteristic where the sensor value fluctuates slightly even when the amount of strain is kept constant. Actually, the characteristic is observed slightly in our devices. However, by using the difference of the soft sensor's outputs between the interface and the soft robot arm, the drift fluctuations of both sensors are almost canceled out, and master-slave feedback control can be possible.

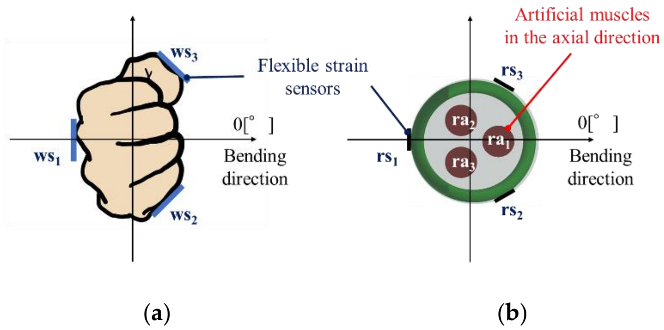


Figure 7. The respective correspondence between the sensors of the wearable interface and the soft robot arm (Cross sectional views). (**a**) Operator's wrist; (**b**) Soft robot arm.

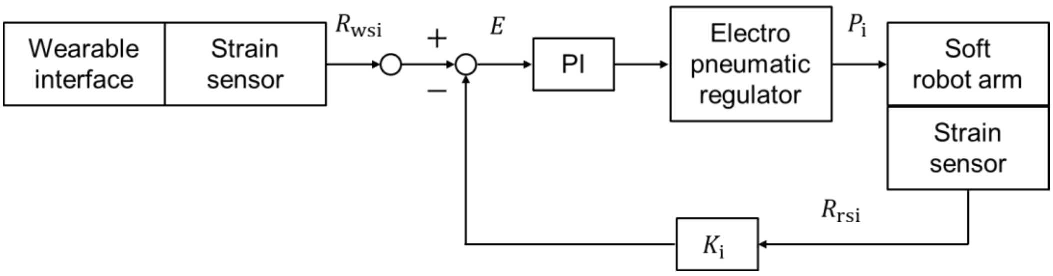


Figure 8. The block diagram of the feedback control system.

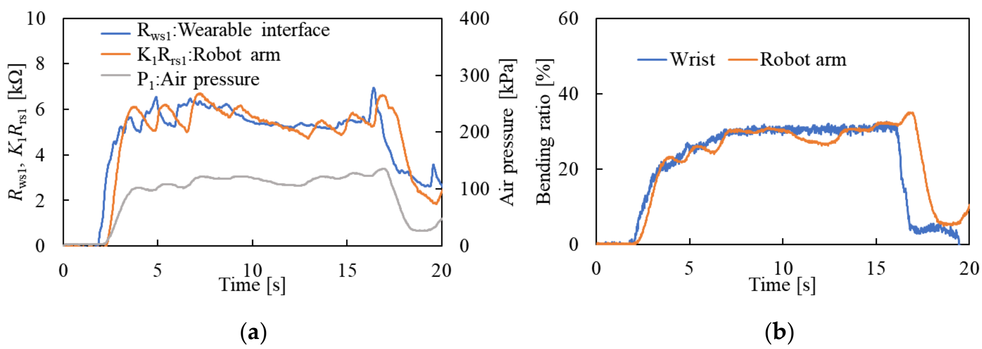
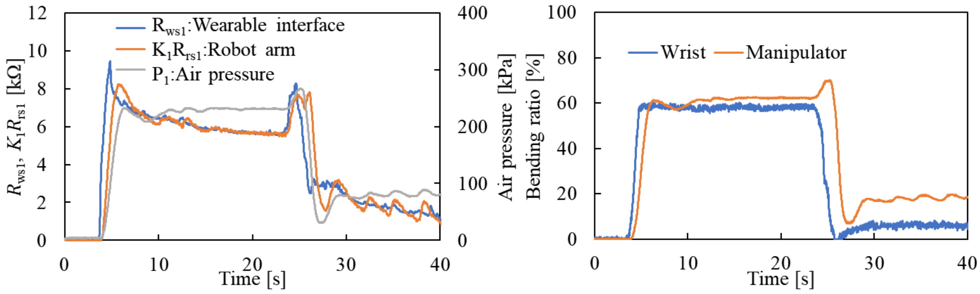


Figure 9. Control results without load. (**a**) Relation between R_{ws1}, K_1R_{rs1} and P_1; (**b**) Comparison of bending ratios between the wrist and the robot arm.



(**a**) (**b**)

Figure 10. Control results with load. (**a**) Relation between R_{ws1}, K_1R_{rs1} and P_1; (**b**) Comparison of bending ratios between the wrist and the robot arm.

4. Conclusions

In this study, flexible strain sensors were attached on the soft robot arm. The wearable interface was used to detect the wrist movement of the operator, and feedback control was performed to make the robot arm follow the movement of the wrist. As a result, it was confirmed that the robot arm was controlled well in bending motion in specific direction. This robot arm can perform bending and twisting motions. Therefore, now we are applying master-slave feedback control system to any directional bending and twisting motions to verify the operability.

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