Development of a 6-DOF Manipulator Actuated with a 
Straight-Fiber-Type Artificial Muscle

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Abstract—Robots have become an integral part of human life, 
and the relationship between humans and robots has grown closer. Thus, it is desired that robots have characteristics similar to 
humans. In this context, we paid attention to an artificial 
muscle actuator. We used straight-fiber-type artificial muscles, 
derived from the McKibben type, which have excellent 
characteristics with respect to the contraction rate and force. 
We developed a 6-DOF manipulator actuated by a straight fiber 
artificial muscle. Furthermore, we tried to control the 
manipulator position by considering its characteristics.

Index Terms Straight-fiber-type artificial muscle, 6-DOF 
manipulator, Inverse kinematics, Position control.

I. INTRODUCTION

Robots are common in various fields, such as medical treatment, nursing, and as mechanical pets. There is a high probability that robots will come into even greater interaction with humans in future. Therefore, there is an increased need for safety with regards to robot–human interaction, as well as for suitable operating performance when collaborating with humans.

We studied straight-fiber-type artificial muscles [1] as robot actuators. This type of artificial muscle has a greater contraction ratio and power than the conventional McKibben-type muscles [2–6]. These muscles are extremely lightweight and flexible, giving greater drivable range and torque to a manipulator made of straight-fiber-type artificial muscle. Furthermore, the muscles also have high compliance. The manipulator can assure safe operation during robot–human interaction and thus, seems suitable for collaborating in human activities.

However, the muscles have nonlinear characteristics and the position control tends to be unstable. As this manipulator does not use gears, position control can be affected adversely by load torque, thus making it difficult to control the artificial muscle.

In this study, we developed a 6-DOF manipulator, consisting of a shoulder, an elbow, and wrist joints, based on human arm. In addition, we also introduced a mechanical equilibrium model [7–8] for the artificial muscle manipulator. This method provides more stable control than the conventional PI control, and can control joint stiffness that affects the inertial and load torque.

This paper consists of five sections. In the second section, we explain the straight fiber artificial muscle. In the third section, we outline the development of the 6-DOF manipulator and controller. The fourth section shows experimental results for the positional control of the manipulator. We offer our conclusions in the fifth section.

II. STRAIGHT-FIBER-TYPE ARTIFICIAL MUSCLE

A. Outline of the Artificial Muscle

Fig. 1 shows a schematic diagram of the straight-fiber-type artificial muscle. The tube, shown in this figure, is made from natural latex rubber with glass fibers fixed at either end by a terminal inserted in the long-axis direction.

Since glass fiber of the muscle suppresses the axial expansion, the muscle expands radially with air pressure and exerts a contractile force axially. In addition, the ring installed in the muscle prevents an explosion due to excessive expansion, and its influence can be modified by adjusting the ratio between the length and radius of the muscle under different conditions.

B. Pressure Characteristics of the Artificial Muscle

Fig. 2 shows the pressure characteristics of the straight-fiber-type artificial muscle. The muscle length is represented $l_0$ and its contraction as $x$. As shown in the figure, muscle contraction can be controlled with the pressure characteristics, and the muscle can be used as an actuator. However, the muscle pressure characteristics are highly nonlinear and have strong hysteresis due to the material used. These characteristics affect the manipulator position control.

C. Compliance of the Artificial Muscle

Since the straight-fiber-type artificial muscle has compliance, safety can be assured during manipulator–human contact. However, compliance introduces instability in position control. Therefore, we can control the effect of inertial and load torque by control compliance.

Fig. 3 shows the load characteristics, i.e., the relationship
between the displacement and load. In this figure the pressure is related to the load characteristics, and compliance can be regarded as linear for small displacements (0–40 mm). Therefore, we consider that compliance can be controlled with pressure. Fig. 4 shows the artificial muscle stiffness for each pressure value, where the relationship between pressure and stiffness is almost proportional. Therefore, the stiffness is expressed by the equation

\[ k = k_a P, \]

where, the artificial muscle stiffness is \( k \), the pressure exerted on the artificial muscle \( P \), and the stiffness characteristic constant \( k_a = 37.6 \times 10^{-9} \).

III. 6-DOF MANIPULATOR

A. 6-DOF Manipulator

Fig. 5 shows the manipulator developed in this study. It consists of six joints that create a human-like structure and behavior. The manipulator uses the artificial muscle as an actuator and the muscles are arranged to cover the arm link with an endoskeletal framework. This structure assures safety during the manipulator–human interaction.

Fig. 6 shows a schematic diagram of all of the manipulator joints. Each joint is controlled by two antagonistic muscles, each of which is connected to a proportional solenoid valve. Two artificial muscles are tied with a wire and arranged with a pulley fixed to the joint rotation axis, such that they work in opposition. An initial pressure \( P_0 \) is applied to both muscles; In addition \( +\Delta P \) is applied to one artificial muscle at the same time as \( -\Delta P \) is applied to the other muscle. The difference between the muscles is the contractile force, which is converted into a rotational movement by the pulley, thus driving the joint. The initial pressure \( P_0 \) changes the antagonistic force. Fig. 4 shows that the initial pressure changes the joint stiffness, thus joint angles and stiffness can be controlled individually.

B. Kinematics Calculation

It is necessary to compute the extent of displacement of each joint angle in order to make the end effector of the manipulator take a specific position and configuration. Conversely, it is necessary to calculate the position of the end effector from the current joint angle, plan the orbit, and use this information for control.

In this study, we carried out direct and inverse kinematics calculations to determine the relationship between each joint angle and the end effector position and configuration.
1) Direct Kinematics Calculation

The origin of the standard coordinates is set in the axis of rotation of the second joint. As shown in Fig. 7, the coordinate system expressing the end-effector position and posture is provided and posture are calculated from Table 1.

Table 1 Link parameters.

<table>
<thead>
<tr>
<th>i</th>
<th>$\alpha_i$ [deg]</th>
<th>$\alpha_i$ [deg]</th>
<th>$d_i$ [mm]</th>
<th>$\theta_i$ (max) [deg]</th>
<th>$\theta_i$ (min) [deg]</th>
<th>$l_i$ [mm]</th>
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<tbody>
<tr>
<td>1</td>
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<td>-90</td>
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<td>160</td>
<td>0</td>
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<tr>
<td>3</td>
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<td>90</td>
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<td>400</td>
</tr>
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<td>130</td>
<td>0</td>
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<td>0</td>
<td>90</td>
<td>$l_5 + l_6$</td>
<td>90</td>
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<td>-90</td>
<td>0</td>
<td>160</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

2) Inverse Kinematics Calculation

We calculated each joint angle $\phi_i$ from the position and posture of the end effector, by inverse kinematics calculations. Here, $J_i$ is the joint coordinate vector of $\Sigma_i$, $e_{iy}$ the directional vector of the axis of rotation of $J_i$, and $e_{ix}$ the directional vector of the axis of $J_i$.

Firstly, the end effector coordinates positional vector $P$ and posture are provided and $J_6$ is obtained. Further, $J_4$ is obtained from the point at the intersection of the ball of $l_2 + l_3$ in the radius that centers on $J_2$ with the circle of $l_4 + l_5$ in the radius that centers on $J_6$, as shown Fig. 8 and Eq. (3).

$$|J_6|^2 = (l_2 + l_3)^2$$

$$|J_4|^2 = (l_4 + l_5)^2$$

$$\|J_6 - J_4\| \cdot e_{iy} = 0$$

$\phi_i$ and $\phi_2$ are calculated from the position of $J_d$ (shown in Fig. 9), $\phi_2$ from the angle between $e_{2x}$ and $e_{6y}$, $\phi_1$ from the angle between $e_{2x}$ and $e_{4y}$, $\phi_3$ from the angle between $e_{4x}$ and $e_{6y}$, and $\phi_4$ from the angle between $e_{4x}$ and $e_{6y}$.

By this procedure, the group in each joint angle has eight types of solutions.

C. Control System

1) Equilibrium Model Linearization

Here we talk about the manipulator control system. This artificial muscle manipulator has a highly nonlinear characteristic, and the gain of the input and output angles is unequal. Due to this unequal gain, position control tends to be unstable. Therefore, we use the mechanical equilibrium model for linearization[8]. The equations of the mechanical equilibrium model are expressed as

\[ P_1(\theta_1, \tau) = \frac{K_1}{K_{22}} \left( G_{22}(\phi_0) G_{12}(\phi_0) - G_{22}(\phi_0) G_{12}(\phi_0) \right) \]

(4)

\[ + \frac{K_1}{K_{32}} \left( G_{32}(\phi_0) G_{21}(\phi_0) + \frac{\tau}{r} G_{21}(\phi_0) G_{21}(\phi_0) \right) \]

(5)

where \( \phi_0(x_0) \) is:

\[ \phi_0(x_0) = \frac{2a_1 l_{01}^{1.5} x_0^{0.5}}{(l_{01} - x_0)^2 + \alpha^2 x_0^2} \]

(6)

\[ G_{11}(\phi_0) = \frac{4K_{11}}{d_{01}} \left[ l_{01} \right] \left[ \sin \phi_0 - \phi_0 \cos \phi_0 \right] \]

(7)

\[ G_{21}(\phi_0) = \frac{M \tan \phi_0}{d_{01} n_b} \]

(8)

\[ G_{31}(\phi_0) = 2 \left[ \frac{d_{01}}{d_{01}} \left[ \phi_0 - \phi_0 \right] \cos \phi_0 \right] \]

(9)

\[ + 4 \frac{l_{01}}{d_{01}} \sin \phi_0 - \frac{M a_{01}}{n_b} \tan \phi_0 \]

(10)

\[ x_{21}' = \frac{r \psi_1 - r \theta_0}{3} \]

(11)

If the joint angle, \( \theta_0 \) has the target value, \( \theta_0 \) then pressures \( P_1 \) and \( P_2 \), given by (4) and (5), are the pressure values needed to realize the target value, \( \theta_0 \). Therefore, \( \theta_1 \) and \( \theta_2 \) have a linear relationship. Here torque is fed back to those equations. In this study, these compensations are called as equilibrium model linearization (EML). By inputting a desired value \( K_{dd} \), joint stiffness \( K_0 \) can be controlled, which further controls the effect of inertia and load torque. If stiffness characteristic constant \( K_{d1}, K_{d2} \) are equal, relationship between joint stiffness \( K_0 \) and initial pressure \( P_0 \) is proportional. So we can select desirable joint stiffness or average pressure method.

Fig. 10 shows a block diagram of the EML. Fig. 11 shows the experimental results of joint control using the EML as a parameter of joint stiffness. Although some errors may be observed in this figure, it has sufficient line linearization. Fig. 12 shows the experimental results of joint stiffness. Joint stiffness is measured with a constant desirable angle and variable joint stiffness and load torque. Although the figure shows some errors, we can select the approximate joint stiffness.

2) Feedback Control System

This artificial muscle manipulator can be controlled by EML, but errors result from inaccuracies in the mechanical equilibrium model and due to the hysteresis characteristics. The dynamic characteristics of EML, as parameters of the desired position, are almost constant. Therefore, we introduce PI control, to the EML position feedback, so that it compensates for the positional errors. Thus, we control the manipulator by both EML and PI control.

The block diagram of the position control is shown in Fig. 13, where \( x, y, \) and \( z \) are the position, \( \phi, \theta, \) and \( \psi \) the configurations of the end effector, \( \theta_0 \) the desired angle of each joint, and \( \theta \) the measured angle. We applied inverse kinematics to convert \( (x, y, z) \) and \( (\phi, \theta, \psi) \) into \( \theta_0 \). The proportional gain and integral gain of the PI controller are constant values set by the cut-and-try method. The load torques from each joint is fed back to the EML for torque compensation.
IV. EXPERIMENT

In order to evaluate the stability of the manipulator, we executed two experiments on position control. Experiment 1 compared the controller stability between the proposed method and conventional PI control. Experiment 2 evaluated the disturbance rejection by compliance control. Both experiments used the same desired positions, as shown in Table 2.

We used two video cameras to measure the end effector position, placed at right angles to each other, with one recording in the x-y plane and the other in z-x plane. After recording, the end effector position was measured by analyzing the two movies using the Movias Pro (NAC Image Technology) operating analysis software.

<table>
<thead>
<tr>
<th>Table 2 Target position and configuration</th>
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<tbody>
<tr>
<td>(a) Initial value</td>
</tr>
<tr>
<td>$x$</td>
</tr>
<tr>
<td>$y$</td>
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<tr>
<td>$z$</td>
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<tr>
<td>$\theta$</td>
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<tr>
<td>$\phi$</td>
</tr>
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<td>$\psi$</td>
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</table>

A. Experiment 1 (Comparison of the proposed method with PI control)

Figs. 14 and 15 show the experimental results of position and control signal comparison between the proportional and conventional PI control and the open loop control (feed forward control).

As shown in Fig. 14, feed forward control has some error, caused by model accuracy and hysteresis, associated with it. On the other hand, PI feedback controls converge in the desired position. This demonstrates that manipulator position control is possible with the introduction of PI feedback control. Fig. 15 shows that the response of the proposed method is faster than the conventional PI control. On the contrary conventional PI control uses a larger control signal than the proposal method. This means that the proposed method reduces load on the control system, by taking into account the nonlinear characteristics of the manipulator, which is more stable than the conventional PI control.

B. Experiment 2 (Disturbance rejection by compliance control)

Fig. 16 shows the experimental results of comparison of position control with various initial pressures $P_0$. In this experiment, we fixed a weight (0.5 kg) on the manipulator end effector. The controller was then proposed as a method of PI + feed forward control.

A high initial pressure provides more stability than low initial pressure. This means that the robustness of the manipulator to disturbance torque can be changed by changing the initial pressure, which is independent from the position control system. Also, an appropriate compliance adapting manipulator for the environment can be selected.
V. CONCLUSION

In this study, we developed a 6-DOF artificial muscle manipulator and considered a stable position control method. Our results were as follows:

1. We developed a 6-DOF artificial muscle manipulator based on human arm and carried out kinematics calculations for end effector position control.
2. PI control was used to compensate for the displacement angles.
3. The mechanical equilibrium model with an artificial muscle manipulator produced a good linear relationship and reduced the controller load.
4. Applying the proposed joint stiffness control to the manipulator changed the manipulator disturbance rejection.

REFERENCES