Angle control of pneumatically-driven musculoskeletal model using antagonistic muscle ratio and antagonistic muscle activity

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Abstract—Recently, research into robots that coexist with people in many areas such as the service and medical industries is active. Such robots need to be both safe and flexible. To satisfy this demand, a pneumatic actuator is appropriate because it is lightweight and has natural compliance. Our research focuses on a joint angle control method for a five-fingered robot hand using low-pressure driven pneumatic actuators. This robot mimics appearance of a human hand and musculoskeletal structure, which has antagonistic muscle pairs for each joint. We proposed a biologically-inspired control method using the following parameters: “antagonistic muscle ratio” and “antagonistic muscle activity”. We also investigated the validity of the proposed method by implementing it in a one-degree-of-freedom joint model, developed a feedback control system and conducted the joint angle control.

I. INTRODUCTION

Recently, research into robots that coexist with people in a variety of areas such as the service and medical industries is active. Such robots need to be safe because they directly contact with human [1]. To satisfy this demand, pneumatic actuators have gained much attention because they have natural compliance [2]. As one of examples, our research focuses on a five-fingered robot hand using low-pressure driven pneumatic actuators. This robot mimics not only appearance of a human hand but also the structure of a musculoskeletal model, which has antagonistic muscle pairs for each joint. The objective of our research is to develop a control method of such a pneumatically-driven robotic joint.

To get clues of the essence of the control method, we focus on a hypothesis that humans use muscle synergy to control redundant structure [3]. It is also observed that human antagonistic muscles contract simultaneously although the usage of one muscle is enough while bending a joint [4]. Based on these clues, we hypothesize that humans use synergies of antagonistic muscle pairs when they move one joint. Concerning this hypothesis, we propose a biologically-inspired control method using the following parameters: “antagonistic muscle ratio” and “antagonistic muscle activity”. Antagonistic muscle ratio is defined as the ratio of air pressures between extensor and the sum of extensor and flexor, and it is supposed to be relevant with a joint angle. Antagonistic muscle activity is defined as the sum of air pressures of extensor and flexor, and it is supposed to be relevant with a joint stiffness.

Previous studies suggested joint angle control methods for a robotic joint driven by antagonistic pairs of pneumatic actuators. Tsujiuchi et al. [5] developed PID control system with highly accurate performance. However, it activates only one actuator while bending a joint, resulting in the invariable joint stiffness. The classical angle control approach uses difference in pressure between agonist and antagonist as a control command and many researchers use the method [6][7]. For example, Tondu et al. [2] derived a relation between the joint angle and the difference in the pressure. However, the relation between the angle and the difference in the pressure depends on the properties of actuators since parameters of actuators are necessary to derive the relation. To describe the relation between the joint angle and control command more easily, our research explores the relation between the joint angle and the ratio of air pressures of antagonistic pairs, and implements the joint angle control in a five-fingered robot hand driven by pneumatic actuators [10].

In this paper, we propose the control method using the new parameters after introducing a five-fingered robot hand which mimics human hand. Then, we implement it in a one-degree-of-freedom joint model in order to investigate the validity of the proposed method. Furthermore, we expand the method into the PID feedback control system and conduct the joint angle control using the model.

II. FIVE-FINGERED ROBOT HAND

A. Manipulator part

The appearance of the five-fingered robot hand is similar to humans. In such a robot, we use SQUESE robot hand type-G (developed by SQUESE Co., Ltd.). The structure, which has antagonistic muscle pairs for each joint driven by pneumatic actuators (see II-B), mimics that of a human hand. The actuators are located on: DIP, PIP and MP joints for the index finger, the middle finger and the ring finger; PIP and MP joints for the little finger; IP, MP, CMC joints for the thumb. Two pairs of actuators on CMC joint of the thumb enable movements of flexion, extension, inner rotation and outer rotation. Table I shows the specification of the five-fingered robot hand. Fig. 1 illustrates a manipulator part of the five-fingered robot hand.

B. Low-pressure driven McKibben pneumatic actuator

A McKibben pneumatic actuator is an artificial muscle which generates axial tension from air pressure. It consists of a rubber inner tube and a braided shell. The actuator
developed by SQUSE Co., Ltd. is compact, light-weighted and low-pressure driven compared to conventional ones because its rubber inner tube is thinner and softer [8]. This type of actuator can work by using a relatively small-sized compressor, and its compact volume enables the actuators to be arranged directly in the five-fingered robot hand. Therefore, it enables to reduce the size of the driving system. Fig. 2 shows McKibben pneumatic actuators embedded in the five-fingered robot hand. Table II presents a brief specification of the McKibben pneumatic actuators. For more technical details, see [9].

C. One-degree-of-freedom joint model

To verify the proposed control method, we developed a one-degree-of-freedom joint model. It is considered to be an ideal joint model of the joint whose one-degree-of-freedom joint moves symmetrically and embedded actuators are the same. Fig. 3 shows the appearance of the one-degree-of-freedom joint model. Tables III and IV list the specification of the model and the properties of the McKibben pneumatic actuator embedded in the model, respectively.

III. CONTROL METHOD USING “ANTAGONISTIC MUSCLE RATIO” AND “ANTAGONISTIC MUSCLE ACTIVITY”

A. Ideal joint model

A muscle is called “flexor” if it inflects a joint, and called “extensor” if it extends a joint. It is assumed that the properties of these two kinds of muscles are the same. An antagonistic muscle pair consists of a flexor and an extensor. Suppose that a robot joint model has a one-degree-of-freedom joint which has antagonistic muscle pairs made of McKibben pneumatic actuators. The actuators are connected with a driving pulley.

B. Definition of “antagonistic muscle ratio” and “antagonistic muscle activity”

We define “antagonistic muscle ratio (Ar)” as the ratio of air pressures between extensor and the sum of extensor and flexor. We also define “antagonistic muscle activity (Ac)” as

<table>
<thead>
<tr>
<th>Property</th>
<th>Extensor</th>
<th>Flexor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum length</td>
<td>44.6(mm)</td>
<td>45.0(mm)</td>
</tr>
<tr>
<td>Contraction ratio</td>
<td>31.6(%)</td>
<td>32.4(%)</td>
</tr>
<tr>
<td>External diameter(during contraction)</td>
<td>12.1(mm)</td>
<td>12.3(mm)</td>
</tr>
<tr>
<td>Maximum contraction force</td>
<td>28.5(N)</td>
<td>29.4(N)</td>
</tr>
</tbody>
</table>
the sum of the air pressures of extensor and flexor [10]. \( Ar \) and \( Ac \) represent joint angle and joint stiffness, respectively. These parameters are given by:

\[
Ar = \frac{Pe}{Pe + Pf} \quad (1)
\]

\[
Ac = \frac{Pe + Pf > P}{(2)}
\]

where \( Pe \) and \( Pf \) indicate air pressures of extensor and flexor, respectively, and \( P \) denotes minimum air pressure that enables the joint model to move its joint to the maximum and minimum angles.

Solving (1) and (2) as simultaneous equations, \( Pe \) and \( Pf \) can be expressed by:

\[
Pe = ArAc \quad (3)
\]

\[
Pf = (1 - Ar)Ac \quad (4)
\]

C. Correspondence between antagonistic muscle ratio and joint angle

We examine correspondence between antagonistic muscle ratio (\( Ar \)) and a joint angle. To design this correspondence, we introduce a certain joint model which the maximum joint angle (\( \theta_{\text{max}} \)) is 180(deg) and the minimum joint angle (\( \theta_{\text{min}} \)) is 0(deg).

In Fig. 4, the first graph shows the state of the joint model in \( Ar = 0 \). In this state, we get \( Pe = 0 \), \( Pf = Ac \) from (1), then the joint angle is \(-90\text{(deg)}\) since the joint model is considered to be fully flexed. The middle graph shows the state of the joint model in \( Ar = 0.5 \). In this state we obtain \( Pe = 0.5Ac \), \( Pf = 0.5Ac \) from (1), then the joint angle is 0(deg) since tension between extensor and flexor is considered to be the same.

The last graph shows the state of the joint model in \( Ar = 1 \). In this state we obtain \( Pe = Ac \), \( Pf = 0 \) from (1), then the joint angle is 90(deg) since the joint model is considered to be fully extended. From these examples above, we get the correspondence between \( Ar \) and a joint angle (\( \theta \)) in three states: \( \theta = -90 = \theta_{\text{min}} \) when \( Ar = 0 \), \( \theta = 0 = \frac{\theta_{\text{max}} + \theta_{\text{min}}}{2} \) when \( Ar = 0.5 \), \( \theta = 90 = \theta_{\text{max}} \) when \( Ar = 1 \). If we assume that between \( Ar \) and \( \theta \) there is a linear relation passing through these three states, we get

\[
Ar = \frac{\theta - \theta_{\text{min}}}{\theta_{\text{max}} - \theta_{\text{min}}} \quad (5)
\]

where \( \theta_{\text{min}} \) and \( \theta_{\text{max}} \) are the minimum and maximum joint angles, respectively.

By using (5), we can derive air pressure from the desired joint angle \( \theta_d \). Since \( Ar \), represents for a joint angle, and \( Ac \), represents for joint stiffness, are assumed to be independent, it is considered that the joint model changes states with equal joint angles but different joint stiffnesses.

D. Feedback control method

In this section, we expand the proposed method into the PID feedback control. To begin with, the control signal \( u \) is calculated by:

\[
u = Kp(e + KI \int e dt) + KD \frac{de}{dt} \quad (6)
\]

In (6), \( e \) is defined as the deviation between the desired joint angle and the measured joint angle.

Then \( Ar \) is calculated by:

\[
Ar = \frac{u - \theta_{\text{min}}}{\theta_{\text{max}} - \theta_{\text{min}}} \quad (7)
\]

From (7) and a given \( Ac \), the air pressures of the extensor and the flexor are determined by (3) and (4). The block diagram of the control method is shown in Fig. 5.

IV. VERIFICATION EXPERIMENT

A. Experiment Objective

The objective of this verification experiment is to verify the basic idea of the proposed method by implementing it in the one-degree-of-freedom joint model (see Section II-C). This model, designed to be symmetrical, has a one-degree-of-freedom joint and two McKibben pneumatic actuators.

B. Experimental Procedure

- To remove effectiveness of the gravity, the joint model was fixed on a flat table so that flexion-extension plane was in parallel with the surface of the table.
- A joint angle was set to be: 0(deg) when the joint was straighten up; \(-90\text{(deg)}\) when the joint was minimum, and 90(deg) when the joint angle was maximum.
- We recorded the joint angle in step response, and considered the joint angle after 10 seconds as steady-state value. The joint angle was measured by electromagnetic sensors (microBIRD 3D Guidance motion tracking system: developed by Ascension Technology Corp.).
- We changed the desired angle from \(-90\text{(deg)}\) to 90(deg) by every 10(deg), which conducted air pressure given by (5), (3), and (4). In this range of the desired angle, we changed \( Ac \) following three patterns: 0.1(MPa),

![Fig. 4. Example of correspondence between antagonistic muscle ratio and joint angle](image_url)

![Fig. 5. Feedback control system](image_url)
0.15(MPa), and 0.2(MPa). The experiment was replicated over six trials in each pairs of $A_r$ (deducted from the desired joint angle) and $A_c$.

C. Results

Fig. 6 provides a plot of $(\theta - \theta_{\text{min}})/(\theta_{\text{max}} - \theta_{\text{min}})$, in which $\theta$ is the steady-state value of the joint angle, against $A_r$ calculated from the desired angle. Continuous line in Fig. 6 represents for a linear approximation, while dashed line represents for a theoretical formula expressed by (5). Fig. 7 provides a plot of steady-state values of joint angles against $A_r$ calculated from the desired angle. We changed $A_c$ for three patterns as follows: $A_c = 0.15$(MPa), $A_c = 0.15$(MPa), and $A_c = 0.2$(MPa).

D. Discussion

To show the validity of the proposed method, we discuss the following points:

1. Relation between $A_r$ and the joint angle
2. Independency of $A_r$ and $A_c$

First, we discuss the relation between $A_r$ and the joint angle. Determination coefficient between experimental values and its linear approximation in Fig. 6 was approximately 0.98 (the average of six trials also practically achieved this value). This value means that the experimental result considerably fits the linear approximation. Therefore, it can be stated that $A_r$ and the joint angle has a considerable linearity. The linear approximation and the theoretical formula vary slightly because the properties of flexor and extensor are different. Although these two actuators are designed to be the same, the qualities of actuator properties vary in manufacturing process.

Second, we discuss the independency of $A_r$ and $A_c$. From Fig. 7 it can be said that the plot in $A_c = 0.15$(MPa) is in accord with the plot in $A_c = 0.2$(MPa). Therefore, we concluded that $A_r$, which corresponds to a joint angle, is considerably independent of $A_c$, which corresponds to joint stiffness. The plot in $A_c = 0.1$(MPa) is inconsistent with the other two plots. This discrepancy indicates that $A_c = 0.1$(MPa) is below the value of $P$ shown in (2). As for other trials, we could confirm quite similar tendencies mentioned above.

V. JOINT ANGLE CONTROL EXPERIMENT

A. Experiment Objective

The objective of this experiment is to implement the proposed method in the one-degree-of-freedom joint model and examine the performance in joint angle control. Evaluation criteria are accuracy in following up to the desired angle and the performance of the quick response.

B. Experimental Procedure

- To remove effectiveness of the gravity, the one-degree-of-freedom joint model was fixed on a flat table so that flexion-extension plane of the model was in parallel with the surface of the table.
- A joint angle was set to be: 0(deg) when the joint was straighten up; -90(deg) when the joint angle was minimum, and 90(deg) when the joint angle was maximum.
- We recorded the joint angle in step response and trajectory tracking of sine wave(amplitude: 60(deg)). The joint angle was measured by electromagnetic sensors (microBIRD 3D Guidance motion tracking system: developed by Ascension Technology Corp.). We changed $A_c$ following two patterns: 0.15(MPa) and 0.2(MPa).
- The PID gains were experimentally tuned to give the best tracking response at $A_c = 0.15$(MPa), desired angle: -60(deg).
- The experiment was replicated over five trials.

C. Results

Figs. 8 and 9 show the time series of the step response of the joint angle. Fig. 10 shows the response of the sine-wave trajectory tracking. Tables V and VI show the PID gains in the step response and the sine-wave trajectory tracking, respectively. In each figure, the dotted lines show the response of $A_c = 0.15$(MPa) and the long-dashed lines show the response of $A_c = 0.2$(MPa). For comparison, we also illustrate the result of the feedforward control in Figs.
The results presented in these three figures are the third trial, and for the other trials we could confirm quite similar tendencies.

D. Discussion

In this section, we discuss the following items: (1) positioning accuracy, (2) steady-state joint angle, and (3) quickness of response.

First, we discuss the positioning accuracy. From Figs. 8 and 9, it is obvious that steady-state errors exist in the feedforward control. This fact derives from the difference of the theoretical model and actual one in terms of the joint structure. In Section III-C we assumed that the actuators are connected with a driving pulley, thus the moment arms are supposed to be constant. However, the actual robot hand disagrees with the theoretical one in terms of the moment arms. According to Figs. 8 and 9, the joint needs to be more extended. This is because the moment arm of the flexor is longer than that of the extensor (shown in Fig. 11), resulting in the dominance of the flexor in terms of moment. We can see that the steady-state errors are reduced distinctly by implementing the feedback control.

Second, we discuss the steady-state joint angle. From Fig. 10, the plot in $A_c = 0.15 (\text{MPa})$ from around 7th (sec), which is considered as steady-state joint angle, is in accord with the plot in $A_c = 0.2 (\text{MPa})$. This result indicates that by changing $A_c$ with equal $A_r$, the joint model can change states with the equal joint angles but different stiffnesses. From Figs. 8 and 9, the steady-state errors exist even when we apply the feedback control. This is due to the joint friction. By lubricating the joint with oil, the joint is supposed to converge to the desired joint angle.

Third, we discuss the quickness of the response. It is said that humans move the index finger approximately up to 5.5 (Hz). The response of the joint model is apparently inferior to that of human. In order to achieve the quick response, we need to expand the inner diameter of the air tube and shorten the air tube as well.

VI. CONCLUSION AND FUTURE WORK

This paper described a joint angle control method of a one-degree-of-freedom joint model for a five-fingered robot hand driven by low-pressure pneumatic actuators. In this method we introduced two parameters: “antagonistic muscle ratio” expressed by the ratio of air pressures between extensor and the sum of extensor and flexor, and “antagonistic muscle activity” expressed by the sum of air pressures of extensor and flexor. Using a one-degree-of-freedom joint model, we verified that: (1) antagonistic muscle ratio and a joint angle have a linear relation, and (2) antagonistic muscle ratio and antagonistic muscle activity are independent. We also developed a PID feedback control, implemented it in the one-degree-of-freedom joint model and examined the performance in step response and trajectory tracking of sine wave.
In our future work, we will present (1) parameter correction in the correspondence between antagonistic muscle ratio and the joint angle for the five-fingered robot hand, and (2) implement the proposed feedback control in the five-fingered robot hand.

VII. ACKNOWLEDGEMENT

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REFERENCES


