Control of pneumatic five-fingered robot hand using antagonistic muscle ratio and antagonistic muscle activity

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Abstract—Recently, research into robots that coexist with people in 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 has natural compliance and is lightweight. Our research focuses on a joint angle control method for a five-fingered robot hand using low-pressure driven pneumatic actuators. This robot imitates the structure of the human hand, 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”, and implemented the proposed method in a five-fingered robot hand.

I. INTRODUCTION

Recently, research into robots that coexist with people in areas such as the service and medical industries is active. Such robots need to be safe because they directly contact human [1]. To satisfy this demand, a pneumatic actuator has gained attention because it has natural compliance [2]. As one of usage examples, our research focuses on a five-fingered robot hand using low-pressure driven pneumatic actuators. This robot imitates the structure of the human hand, which has antagonistic muscle pairs for each joint. The objective of our research is to develop a control method of such a five-fingered robot hand.

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]. Also, it is observed that human antagonistic muscles contract simultaneously although usage of one muscle is enough while bending a joint [4]. Based on these clues, we hypothesize 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. Our research explores the relation between the joint angle and the difference in pressures between extensor and flexor. 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.

In this paper, we introduce the five-fingered robot hand which imitates human hand and propose the control method using new parameters. In order to investigate validity of the proposed method, we implement the method in an one-degree-of-freedom finger model. Then, we implement it in a five-fingered robot hand and conduct joint angle control.

II. FIVE-FINGERED ROBOT HAND

A. Manipulator part

A five-fingered robot hand has five fingers, which appearance is similar to humans. In such a robot, we use SQUSE robot hand type-G (developed by SQUSE Co., Ltd.). The structure, which has antagonistic muscle pairs for each joint driven by pneumatic actuators (see II-B), imitates that of a human hand. The actuators are located on: DIP, PIP and MP joints for an index finger, a middle finger and a ring finger; PIP and MP joints for a little finger; IP, MP, CMC joints for a thumb. Two pairs of actuators on CMC joint of the thumb enable movements of flection, extension, inner rotation and outer rotation. Fig. 1 shows a manipulator part of the five-fingered robot hand. Table I shows the specification 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 [6]. 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 the brief specification of the McKibben pneumatic actuators. For more technical details, see [7].

C. One-degree-of-freedom finger model

To verify the proposed control method, we developed one-degree-of-freedom finger model. It is considered to be an ideal finger joint model, which its one-degree-of-freedom joint moves symmetrically and embedded actuators are the same. Fig. 3 shows the appearance of the one-degree-of-freedom finger model. Table III lists the specification of the one-degree-of-freedom finger model.

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

A. Ideal joint model

Suppose that a robot joint model has an one-degree-of-freedom joint which has antagonistic muscle pairs made of McKibben pneumatic actuators. 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.

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

We define “antagonistic muscle ratio (Ar)” as ratio of air pressures between extensor and the sum of extensor and flexor. We also define “antagonistic muscle activity (Ac)” as the sum of the air pressures of extensor and flexor [8]. Ar and Ac represent joint angle and joint stiffness, respectively. These parameters are given by:

\[ Ar \equiv \frac{P_e}{P_e + P_f} \]  
\[ Ac \equiv P_e + P_f > P \]  

where \( P_e \) and \( P_f \) 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, \( P_e \) and \( P_f \) can be expressed by:

\[ P_e = ArAc \]  
\[ P_f = (1 - Ar)Ac \]
C. Correspondence between antagonistic muscle ratio and joint angle

We discuss 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 (θmax) is 180(deg) and the minimum joint angle (θmin) is 0(deg).

In Fig. 4, the first graph shows the state of the joint model in Ar = 0. In this state we obtain $P_e = 0$, $P_f = Ac$ from (1), then the joint angle is $-90$(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 $P_e = 0.5Ac$, $P_f = 0.5Ac$ 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 $P_e = Ac$, $P_f = 0$ 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 correspondence between Ar and a joint angle ($\theta$) in three states: $\theta = -90 = \theta_{min}$ when $Ar = 0$, $\theta = 0 = \frac{\theta_{max} + \theta_{min}}{2}$ when $Ar = 0.5$, $\theta = 90 = \theta_{max}$ when $Ar = 1$. If we assume that between $Ar$ and $\theta$ there is a linear relation that passes through these three states, we get

$$Ar = \frac{\theta - \theta_{min}}{\theta_{max} - \theta_{min}}$$  \hspace{1cm} (5)

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

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

D. Implementation to five-fingered robot hand

In this section, we explain how to implement the proposed method in the five-fingered robot hand. Link model of the index finger of the five-fingered robot hand is shown in Fig. 5. Each joint has one degree-of-freedom, resulting in three degree-of-freedom in total and has only one extensor. Now we solve the problem that conducts air pressure of $p_1$, $p_2$, $p_{3f}$, and $pe$ when desired angles of DIP, PIP, and MP joints, which is expressed by $\theta_1$, $\theta_2$, $\theta_3$, respectively, and $Ac_3$ = $p_{3f}$ + $pe$ are given. $Ac_3$ represents for antagonistic muscle ratio of MP joint.

First, we calculate values of $Ar_1$, $Ar_2$ and $Ar_3$, which represent for antagonistic muscle ratio of DIP, PIP and MP joints, respectively. From (5), we get

$$Ar_1 = \frac{\theta_1 - \theta_{min}}{\theta_{max} - \theta_{min}}$$  \hspace{1cm} (6)

$$Ar_2 = \frac{\theta_2 - \theta_{min}}{\theta_{max} - \theta_{min}}$$  \hspace{1cm} (7)

$$Ar_3 = \frac{\theta_3 - \theta_{min}}{\theta_{max} - \theta_{min}}$$  \hspace{1cm} (8)

From (3) and (4), we get

$$p_e = Ar_3Ac_3$$  \hspace{1cm} (9)

$$p_{3f} = (1 - Ar_3)Ac_3$$  \hspace{1cm} (10)

Since extensor in this model is embedded only one, $p_e$ is expressed by:

$$p_e = Ar_3Ac_3 = Ar_2Ac_2 = Ar_1Ac_1$$  \hspace{1cm} (11)

$Ac_1$ and $Ac_2$ represent for antagonistic muscle activity of DIP, PIP joints, respectively. From (11), these values are calculated by:

$$Ac_2 = \frac{Ar_3}{Ar_2}Ac_3$$  \hspace{1cm} (12)

$$Ac_1 = \frac{Ar_3}{Ar_1}Ac_3$$  \hspace{1cm} (13)

From (6), (7), (12) and (13), $p_1$ and $p_2$ are given by:

$$p_2 = (1 - Ar_2)Ac_2 = (1 - Ar_2)\frac{Ar_3}{Ar_2}Ac_3$$  \hspace{1cm} (14)

$$p_1 = (1 - Ar_1)Ac_1 = (1 - Ar_1)\frac{Ar_3}{Ar_1}Ac_3$$  \hspace{1cm} (15)

As mentioned above, we get $p_1$, $p_2$, $p_{3f}$ and $pe$ when $\theta_1$, $\theta_2$, $\theta_3$ and $Ac_3$ = $p_{3f}$ + $pe$ are given.

IV. Verification experiment

A. Experiment Objective

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

- To remove effectiveness of the gravity, the finger model was fixed on a flat table so that flexion-extension plane was in parallel with the surface of the table.
- A joint angle is set to be: 0(deg) when the joint is straighten up; -90(deg) when the joint angle is minimum, and 90(deg) when the joint angle is 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 an electromagnetic sensor (microBIRD 3D Guidance motion tracking system: developed by Ascension Technology Corp.).
- We changed the desired angle from -90(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), 0.15(MPa), and 0.2(MPa). The experiment was replicated over six trials in each pairs of Ar (deducted from the desired joint angle) and Ac.

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 \(Ar\) calculated from the desired angle. Continuous line shown 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 \(Ar\) calculated from the desired angle. We changed Ac for three pattern as follows: \(Ac = 0.1\text{(MPa)}, Ac = 0.15\text{(MPa)},\) and \(Ac = 0.2\text{(MPa)}\).

D. Discussion

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

1) Relation between \(Ar\) and the joint angle
2) Independency of \(Ar\) and \(Ac\)

First, we discuss the relation between \(Ar\) 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 \(Ar\) 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 embedded in the one-degree-freedom finger model is designed to be the same, the qualities of actuator properties vary in manufacturing process. Second, we discuss the independency of \(Ar\) and \(Ac\). From Fig. 7 it can be said that the plot in \(Ac = 0.15\text{(MPa)}\) is in accord with the plot in \(Ac = 0.2\text{(MPa)}\). Therefore, we concluded that \(Ar\), 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 $\bar{P}$ shown in (2). As for other trials, we could confirm quite similar tendencies which are mentioned above.

V. JOINT ANGLE CONTROL EXPERIMENT

A. Experiment Objective

The objective of this experiment is to implement the proposed method in the index finger of the five-fingered robot hand and examine the performance in joint angle control. Evaluation criteria are accuracy in following up to the desired angle and quick response.

B. Experimental Procedure

- To remove effectiveness of the gravity, the five-fingered robot hand was fixed on a flat table so that flexion-extension plane of the index finger was in parallel with the surface of the table.
- Joint angles of the robot was set to be 0(deg) when joint was extended and finger was parallel to its parent link, and when the joint state became flex, the joint angle was going to be minus. Initial condition of the joint was set to be fully extended for all joint of index finger.
- We recorded the joint angles in step response. The joint angles were measured by using a data glove (ShapeHand: developed by Measurand Inc.).
- Value of $A_c$ was set to be 0.2(MPa) constant, desired angles of DIP, PIP, MP joints were given by $-25$, $-30$ and $-40$(deg), respectively.
- We delayed output pressure of actuators driving MP joint for 0.5(sec) after trials without any delay of actuators. These actuators are represented as $p_3$, $p_e$ in Fig. 5.

C. Results

Figs. 8, 9 and 10 show the time series of step response of the joint angle (DIP joint, PIP joint, MP joint, respectively). In Figs. 8, 9 and 10, the green lines show the response without any delay of actuators and the blue lines show the response when actuators driving MP joint was delayed for 0.5(sec).

D. Discussion

In this section, we discuss the following items: (1) delaying activation of actuators, (2) positioning accuracy, and (3) quickness of response.

First, we discuss delaying activation of actuators. The blue lines in Figs. 8, 9 and 10 have more accuracy in following up to the desired angle than that of the green line. From the result it can be stated that the extensor ($p_e$ in Fig. 5) interrupts movement of flexion movement of DIP and PIP joints when the actuators activate simultaneously. This is because the length of the extensor is longer than that of the flexors of DIP and PIP joints, resulting in the dominance of the extensor in terms of its axial force.
Second, we discuss the positioning accuracy. From Figs. 8, 9 and 10 it is obvious that steady-state errors exist in all results. This fact derives from the difference of the models between theoretical and actual one. In Section III-C we assumed that the joint structure of the joint model is bilaterally symmetric and the properties of the actuators are the same. However, the actual robot hand disagrees with the theoretical one in terms of symmetric property. DIP and PIP joints need to be more flexed from Figs. 8, 9. This is because of the dominance of the extensor as mentioned above. On the other hand, MP joint needs to be more extended from Fig. 10. This is because the moment arm of flexor is longer than that of extensor (shown in Fig. 11), resulting in the dominance of the flexor in terms of its moment.

Third, we discuss the quickness of the response. Humans move index finger approximately up to 5.5(Hz). The response of the robot hand is inferior than that of human. In order to achieve 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 control method for a five-fingered robot hand driven by low-pressure pneumatic actuators. In this method we introduced two parameters: “antagonistic muscle ratio” expressed by ratio of air pressures between extensor and sum of extensor and flexor, and “antagonistic muscle activity” expressed by sum of air pressures of extensor and flexor. Using a one-degree-of-freedom finger model, we verified that; (1) antagonistic muscle ratio and a joint angle have a relation of linearity, and (2) antagonistic muscle ratio and antagonistic muscle activity are independent. We implemented the proposed method in a five-fingered robot hand and examined the existence of steady-state error.

In our future work, we will present (1) parameter correction in the correspondence between antagonistic muscle ratio and the joint angle, and (2) using angle sensors in real time and developing a feedback control method.

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