Proposal of A Humanlike Two-joint Link Mechanism Provided with the Bi-articular and the Mono-articular Actuators
Part 1 : Force Control : Hexagonal Output Force Distribution

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A series of the present studies proposes a humanlike two-joint link mechanism provided with one antagonistic pair of the bi-articular actuators and two antagonistic pairs of the mono-articular actuators to be able to develop really humanlike force control (part 1), trajectory control (part 2) and posture control (part 3) properties. In this study, differences in force control properties between the humanlike two-joint link mechanism operated with the muscle coordinate system and a conventional robot arm link mechanism operated with the joint coordinate system consisting of only the mono-articular antagonistic actuators on each joint without the bi-articular actuators were clarified in terms of theoretical and experimental robotics. The results obtained here demonstrated that; 1) the output force distribution exerted at the endpoint of the humanlike two-joint link mechanism showed a hexagonal shape, whereas that of the conventional link mechanism showed a quadrangular shape; 2) the output force direction was perfectly controlled utilizing three pairs six actuators with only single command signal informing force direction via the simple electrical circuit just as like as a human spinal level neural network.

1. INTRODUCTION

Recently, many robots named a humanoid, a human mimetic robot, a my robot or a human friendly robot who seem to imitate the human activities or to contact the human directly has being developed. In the almost all cases, it is hard to say that a so-called humanoid robot could perfectly imitate human control properties from the viewpoint of a two-joint link mechanism. There is great difference between muscle/actuator arrangements of human extremities and of conventional robot arm link mechanisms. In the conventional robots, even in the so-called humanoid robot, their link mechanisms are provided with one motor/one pair of antagonistic actuators on each joint, whereas in the human both upper and lower extremities, their link mechanisms are provided with one antagonistic pair of the bi-articular muscles acting on the both end joints simultaneously in addition to two antagonistic pairs of the mono-articular muscles [1]. Thus the conventional robot arm link mechanism is operated with the joint coordinate system, whereas the human extremity is operated with the muscle coordinate system.

Relationship between output force developed in the task coordinate system and joint torque in the joint coordinate system is widely known in robotics field. In general, generated torque by actuator (contained reduction gear) is equal to the joint torque. However, in the human extremity, generated torque by the muscles is not equal to the joint torque because of existence of the bi-articular muscles acting on the both end joints simultaneously. It is necessary and very important to well discuss relationships between the muscle coordinate system and the task coordinate system in a humanlike two-joint link mechanism.

In this study, first; in a fundamental motion of two-joint link mechanism with two degrees of freedom, relationships between the joint coordinate system and the task coordinate system, and between the muscle coordinate system and the task coordinate system were comparatively examined in terms of robotics, and second; a humanlike two-joint link mechanism was built utilizing three antagonistic pairs of pneumatic controlled artificial rubber actuators (Mackibben artificial muscles), and its output force control properties were examined theoretically and experimentally. Results obtained in this part showed that; First, the two-joint link mechanism operated with the joint coordinate system exerted a quadrangular output force distribution at the endpoint of the mechanism, whereas the mechanism operated with the muscle coordinate system exerted a hexagonal output force distribution at the endpoint of the mechanism. Second, the two-joint link mechanism equipped with three pairs six actuators could perfectly control force direction in all round direction, and arbitral force direction could be controlled with single command signal via a simple electric circuit just as like as a human spinal level neural network.

2. JOINT COORDINATE SYSTEM AND MUSCLE COORDINATE SYSTEM

2.1 Joint Coordinate System  In general, a robot arm has equal number of actuators (motors) to number of its joints as shown in Fig. 1.

A typical two-joint link mechanism such as the robot arm
with two degrees of freedom is shown in Fig. 2(a). Each joint is driven by only one actuator, m1 or m2. Joint torques, $T_{m1}$ and $T_{m2}$, can be expressed by the two dimensional joint coordinate system as shown in Fig. 2(b). Output force $F(F_x, F_y)$ developed in the two dimensional task coordinate system by the joint torques of $T_{m1}$ and $T_{m2}$ is shown in Fig. 2(c). Therefore, the output force distribution comes a quadrangular shape (Fig. 2(c)). Further, even if number of actuator increases, number of degrees of freedom of its motion and number of actuators are the same as the number of coordinate axes of the joint coordinate system.

2.2 Muscle Coordinate System

Human extremities have very complicate muscle arrangements. However, the second joint has only one degree of freedom, because of its anatomical structure, to determine location of the third joint in three dimensional space. Therefore, as long as concerning an arm or leg motion with two degrees of freedom, the complex muscle arrangement could be simplified into three pairs of antagonistic muscles as shown in Fig. 3(a) (upper extremity) and Fig. 3(b) (lower extremity). In Fig. 3, two antagonistic pairs of mono-articular muscles individually drive two joints. In addition to the mono-articular muscles,

Fig. 1 General Robot arm link mechanism

First joint

Output force $F(F_x, F_y)$

End point

Tn

Second joint

Tn

(a) Two-joint link mechanism equipped with two actuators

(b) Joint coordinate system

(c) Task coordinate system

Fig. 2 Coordinate system of general robot mechanism

(a) Effective muscular arrangement of human upper arm

(b) Effective muscular arrangement of human thigh

Fig. 3 Simplified functionally effective muscular arrangements of human extremity

Fig. 4 Coordinate system of humanlike mechanism
one antagonistic pair of bi-articular muscles exists and drives the
both joints simultaneously. Such a muscle arrangement
consisting of three pairs six muscles including the bi-articular
muscles is commonly seen in limbs of not only mammal but
also birds, reptile and even amphibian. Even in the most
sophisticated humanoid robot, the bi-articular muscles are
never applied on its arm link mechanism.

A typical two-joint link mechanism functionally
equivalent to the human extremity with two degrees of
freedom is shown in Fig. 4(a). In Fig. 4(a), f1 and e1 are the
mono-articular actuators acting on the first joint, f2 and e2 are
the mono-articular actuators acting on the second joint, and
f3 and e3 are the bi-articular actuators acting on the both
end joints simultaneously. Joint torques in proportion to
contraction strengths of actuators are $T_n$, $T_{e1}$, $T_2$, $T_{e2}$, $T_3$ and
$T_{e3}$, and they can be expressed by the three dimensional
muscle coordinate system as shown in Fig. 4(b). Now, joint
torques, $T_1$ and $T_n$, calculated from these six torques
are shown by the two dimensional joint coordinate system in
Fig. 4(c). Output force $F(F_n, F_3)$ developed in the two
dimensional task coordinate system by the joint torques, $T_1$ and
$T_n$ is shown in Fig. 4(d). Thus, the output force
distribution comes a hexagonal shape.

3. HUMANLIKE TWO-JOINT LINK MECHANISM

3.1 Experimental robot arm  An experimental robot
arm consisting of two-joint link mechanism provided with
six pneumatic artificial rubber actuators was constructed in
a horizontal plane as shown in Fig. 5. The actuators used
had same size and same characteristics (maximum contractile
force : 210N), and were installed on the two-joint link
mechanism (length : 300mm each) via sprockets (radius of
pitch circle: 12.5mm) and chains. A load cell to measure an
output force developed in the task coordinate system was
installed at the end point of the robot arm.

3.2 Generated torque of actuator and output force
distribution  Individual output forces expressed by their
magnitudes, $F_n$, $F_{e1}$, $F_2$, $F_{e2}$, $F_3$ and $F_{e3}$, and their direction,
$\theta_n$, $\theta_{e1}$, $\theta_2$, $\theta_{e2}$, $\theta_3$ and $\theta_{e3}$, developed in the task coordinate
system by the generated torques of actuators, $T_n$, $T_{e1}$, $T_2$, $T_{e2}$, $T_3$
and $T_{e3}$, are calculated by following equations, and
shown in Fig. 6(a).

$$
\begin{align*}
F_n &= T_n \div (l\sin\theta_n), & F_{e1} &= T_{e1} \div (l\sin\theta_{e1}), \\
\theta_n &= \theta_1 + \theta_2, & \theta_{e1} &= \theta_1 + \theta_2 + \pi, \\
F_2 &= T_2 \div (l\sin\theta_2), & F_{e2} &= T_{e2} \div (l\sin\theta_{e2}), \\
\theta_2 &= \theta_1 + \theta_3 - \theta_2, & \theta_{e2} &= \theta_1 + \theta_2 - \theta_3 + \pi, \\
F_3 &= T_3 \div (l\sin\theta_3), & F_{e3} &= T_{e3} \div (l\sin\theta_{e3}), \\
\theta_3 &= \theta_1 + \pi, & \theta_{e3} &= \theta_1 + \pi, \\
\theta_3 &= l\sin\theta_3 \div (l^2 + l^2 + 2l\cos\theta_3)^{\frac{1}{2}}
\end{align*}
$$

--- (1)

Where, l and b are lengths of the link, and $\theta_1$ and $\theta_2$ are the
joint angles. Direction $\theta_n$ and $\theta_{e1}$ (direction b-e) are along
the second link, direction $\theta_2$ and $\theta_{e2}$ (direction a-d) are
passing through the first joint and the second joint, and
direction $\theta_3$ and $\theta_{e3}$ (direction c-f) are parallel to the first
link.

The output force distribution obtained by such a
procedure comes to be a hexagonal shape. In this shape, A - F
show corners of the hexagon. Like this case, if six actuators
have the same characteristics, the directions a - f are passing
over the corners A ~ F, respectively. This hexagonal shape
has following characteristics.

1) Opposite side lines, C-D and F-A, are parallel to the second
link. And, lengths of C-D and F-A are same and equal to
sum of the output force magnitudes, $F_n$ and $F_{e1}$.
2) Opposite side lines, B-C and E-F, are parallel to the line
through the first joint and the endpoint. And, lengths of B-C
and E-F are same and equal to sum of the output force
magnitudes, $F_2$ and $F_{e2}$.
3) Opposite side lines, A-B and D-E, are parallel to the first
link. And, lengths of A-B and D-E are same and equal to
sum of the output force magnitudes, $F_3$ and $F_{e3}$.

Fig. 5 Experimental robot arm
For example, in the corner A, actuator f1, e2 and e3 generate the maximum torque. And, in the corner B, actuator f1, e2 and f3 generate the maximum torque. In the direction between A and B, the output force direction is controlled by the actuator f3 and e3. It is possible to rewrite Fig. 6(b) as shown in Fig. 7 for the force direction. In Fig. 7, the horizontal axis shows the force direction. Because the directions a-f are different depending on the joint angles of various postural conditions, intervals of adjacent directions are normalized in order to become equal interval. The vertical line shows the generating torque of each actuator.

3.3 Experimental procedure A control system of the robot arm is shown in Fig. 8. Using outputs from the host computer to the servo valve controllers, the servo valve controllers adjust the servo valves by feedback signals from pressure sensors, and contractile forces of the actuators used are controlled. Then, the joint angles and the output force are measured by the joint angle sensors and the load cell, and they are recorded in the host computer.

Location of the load cell is adjusted in order to get the optional joint angles. As the actuators generate the torques, the output force exerted at the endpoint is measured. The relationship between the torques generated in the muscle coordinate system and the output force exerted in the task coordinate system is confirmed.

3.4 Experimental results The first experiment is carried out in order to clarify the relationship between the muscle coordinate system and the task coordinate system (Fig. 6(a)). Table 1 shows the theoretical values and the simulation values (experimental values) of torques and output forces during the actuators were driven independently under three kinds of postural conditions, joint angles. Since the experimental values are very close to the theoretical values as shown in the Table 1, we may conclude that the robot arm is useful for humanlike link mechanism experiments.

In the second experiment, it is confirmed that the hexagonal output force distribution showed in Fig. 6(b) was obtained by the changing pattern of torques showed in Fig. 7. In Fig. 9, changes in the output force distribution shape with changes in postural conditions, joint angles, were demonstrated.

It was confirmed that, when the three pairs six actuators of the two-joint link mechanism robot arm was generated with the changing pattern of torques showed in Fig. 7, the robot arm perfectly performed the output force direction control.

![Fig. 8 Robot control system](image-url)
Table 1 Torques in the muscle coordinate system and output forces in the task coordinate system

<table>
<thead>
<tr>
<th>Joint angle</th>
<th>Theoretical value</th>
<th>Simulation value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Torque N·m</td>
<td>Output force N</td>
</tr>
<tr>
<td>(a) (\theta_1 = \pi/6), (\theta_2 = 2\pi/3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_n = 2.6)</td>
<td>(F_n = 9.9)</td>
<td>(F_n = 10.0)</td>
</tr>
<tr>
<td>(T_{x1} = 2.6)</td>
<td>(F_{x1} = 9.9)</td>
<td>(F_{x1} = 9.9)</td>
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<tr>
<td>(T_{x2} = 2.6)</td>
<td>(F_{x2} = 9.9)</td>
<td>(F_{x2} = 9.9)</td>
</tr>
<tr>
<td>(T_{x3} = 2.6)</td>
<td>(F_{x3} = 9.9)</td>
<td>(F_{x3} = 9.9)</td>
</tr>
<tr>
<td>(b) (\theta_1 = \pi/4), (\theta_2 = \pi/2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_n = 2.6)</td>
<td>(F_n = 8.6)</td>
<td>(F_n = 8.5)</td>
</tr>
<tr>
<td>(T_{x1} = 2.6)</td>
<td>(F_{x1} = 8.6)</td>
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</tr>
<tr>
<td>(T_{x2} = 2.6)</td>
<td>(F_{x2} = 12.1)</td>
<td>(F_{x2} = 12.1)</td>
</tr>
<tr>
<td>(T_{x3} = 2.6)</td>
<td>(F_{x3} = 8.6)</td>
<td>(F_{x3} = 8.6)</td>
</tr>
<tr>
<td>(c) (\theta_1 = \pi/3), (\theta_2 = \pi/3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_n = 2.6)</td>
<td>(F_n = 9.9)</td>
<td>(F_n = 9.9)</td>
</tr>
<tr>
<td>(T_{x1} = 2.6)</td>
<td>(F_{x1} = 9.9)</td>
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<tr>
<td>(T_{x3} = 2.6)</td>
<td>(F_{x3} = 9.9)</td>
<td>(F_{x3} = 9.9)</td>
</tr>
</tbody>
</table>

Fig. 9 Output force distribution

Fig. 10 Output force control electric circuit
4. CONCLUSIONS

4.1 Output force control  The differences in force control properties between the joint coordinate system and the muscle coordinate system were clarified. In the two-joint link mechanism operated with the muscle coordinate system, where the system was equipped with one antagonistic pair of the bi-articular actuators in addition to two antagonistic pairs of the mono-articular actuators, the link mechanism developed a hexagonal output force distribution at the endpoint, whereas the two-joint link mechanism operated with the joint coordinate system, a quadrangular output force distribution. In the two-joint link mechanism operated with the muscle coordinate system, when torques of the six actuators were generated with the coordinating changing pattern of the torques, the two-joint link mechanism could demonstrate perfect output force direction control in all round direction.

4.2 Control procedure  Motor link mechanisms of conventional robots are operated by describing the relationship between the joint coordinate system and the task coordinate system in the manipulator Jacobian. Therefore, the control system with very high speed and large memory capacity is required. In the muscle coordinate system, the control pattern shown in Fig. 7 can be realized, for example, by a simple electric circuit as shown in Fig. 10. In Fig. 10, torques of the six actuators can be simply generated by only a single input signal informing output force direction. The force control circuit is very similar to the spinal level neural network proposed to reproduce the coordinating activity pattern of the three pairs six antagonistic muscles [2,3]. Such a very simple output force control system is not applicable to the conventional robots, even to the most sophisticated robot arms, because of lack of the bi-articular actuators.

4.3 Further results  The humanlike two-joint link mechanism proposed here, where the mechanism was provided with the bi-articular and the mono-articular actuators, has great advantages on control properties, whereas the two-joint link mechanism of conventional robots could never demonstrate. We could demonstrate the force control properties here in Part 1, and we will demonstrate the trajectory control by the force control in the next Part 2 and the posture control by the force control in Part 3.

REFERENCES