A Novel Design and Realization of Robot Arm Based on the Principle of Bi-articular Muscles

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Abstract— **Recently there are many trials to introduce animal characteristics into robots. Conventional robot arm has only actuators similar to mono-articular muscles. Though animal's arm has not only mono-articular muscles but also bi-articular muscles. Existence of bi-articular muscles can give robots remarkable ability to realize various motions without feedback control, which may provide skillfulness and safety like animals.**

In this paper, we consider some properties of robot arm based on the principle of bi-articular muscles. We suggest a driving mechanism using equilibrium position originated muscular elasticity. This mechanism realize trajectory tracking as feedforward control in simulations. Finally we described our attempt to make a robot arm based on the principle of bi-articular muscles.

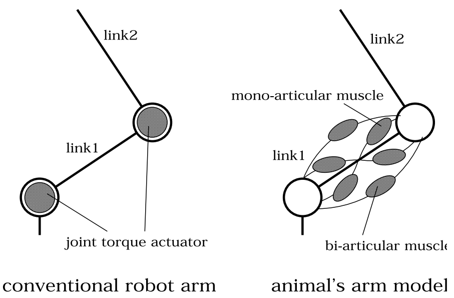


Fig. 1. Conventional robot arm model and animal‘s arm model

I. Introduction

Today, many robots which have animal-like appearance are researched and developed, and they can move like animals. However they don't have animal-like actuators and control mechanisms.

Conventional robots have actuators which drive only one joint, and usually rotational motor are installed in each joint. On the other hand, animas have actuators which drive one or more joints. For example both mono-articular muscles and bi-articular muscles exist in arm of animals. (Fig. 1) Furthermore robots move with rapid feedback control, and their control methods need complex calculation. However animals mainly use feedforward control, especially working, running and other unique movements.

Robots can move very fast and precisely in known and stable environments. But they easily get unstable by small disturbances. While animals can act in response to various environments and disturbances. Robots must obtain robustness like animals to act close to people. For this purpose, we try to introduce animal characteristics into robots.

As animal characteristics, we focused on bi-articular muscles. They exist in animal arms and limbs universally and play an important roll in skillful control abilities of animals.

Van Ingen Schenau et. al. described a role of bi-articular muscles in vertical jump. Gastrocnemius muscle which is a bi-articular muscles in the calf of the leg develops and transmits propulsive force.[1]

Neville Hogan suggested that antagonistic bi-articular muscles can control mechanical impedance. And he showed its effectiveness at contact tasks. [2][3]

Mussa-Ivaldi ascertained changes of a stiffness ellipse at the end point of human arms by changing arm postures through experiments. [4]

Kumamoto and Oshima et. al. suggested modeling of human arms and legs using two antagonistic pairs of mono-articular muscles and one antagonistic pair of bi-articular muscles. And they revealed that this model can explains recorded EMG patterns when human arms and legs output forces. [5][6]

Recently some application using the principle of bi-articular muscles are developed. For example Kadota et. al. developed a robot arm which has mechanical elasticity almost equal to muscular elasticity.[7] And some robots which replaced bi-articular muscles by wires or springs can jump skillfully.[8][9][10] Furthermore this principle were utilized in sports science, automotive steering system, physiotherapy and so on. [11][12][13]

However those researches used almost only static properties of bi-articular muscles. We deals with both static and dynamic properties. In order to realize various motions without feedback control like animals, we suggest a novel control mhod using equilibrium position originated muscular elasticity. And we attempt to make a robot arm

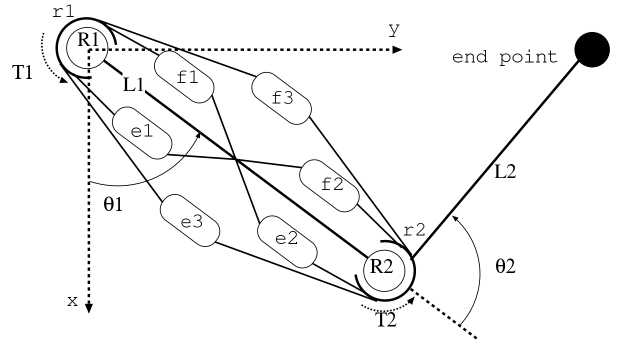


Fig. 2. Two joint link model with both mono-articular muscles and bi-articualr muscles

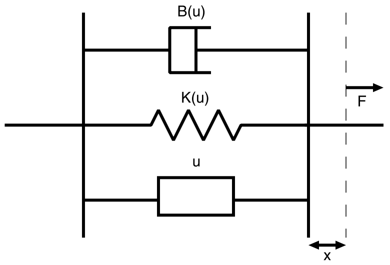


Fig. 3. Model of a muscle

equipped with bi-articular muscles for actual experiments.

II. Modeling of arm with bi-articular muscles

Two joint link model with muscles is shown in Fig. 2. In Fig. 2 e1 and f1 are a pair of antagonistic mono-articular muscles attached to joint R1. e2 and f2 are attached to R2. e3 and f3 are a pair of antagonistic bi-articular muscles attached both R1 and R2.

We define output forces of each muscle as F_{f1}, F_{e1}, F_{f2}, F_{e2}, F_{f3}, and F_{e3}. r_1 and r_2 are radii of R1 and R2. Joint moments T_1 and T_2 are as follows:

$$\begin{aligned} T_1 &= (F_{f1} - F_{e1})r_1 + (F_{f3} - F_{e3})r_1 \\ T_2 &= (F_{f2} - F_{e2})r_2 + (F_{f3} - F_{e3})r_2 \end{aligned} \tag{1}$$

Each muscle has unique viscoelasticity. Animal Muscular model is shown in Fig. 3. According to Ito and Tsuji, muscular output force F is a function of contractile force u.[14]

$$F = u - K(u)x - B(u)\dot{x} = u - kux - bu\dot{x} \tag{2}$$

Here x is contracting length of the muscle and $\dot{x}$ is shortening velocity. k is elastic coefficient and b is viscosity coefficient. Contractile force u is only settled actively and others are passive elements. In other word u is assumed as activation level of muscle.

The link model equipped both mono-articular muscles and bi-articular muscles like Fig. 2 can control output force and stiffness independently at its end point. When summations and differences of contractile forces are defined in each pair of antagonistic muscles, summations control stiffness and differences control force direction at end point. u_{f1}, u_{e1}, u_{f2}, u_{e2}, u_{f3} and u_{e3} are defined as contractile force in each muscle. Summations S_1, S_2, S_2 and differences D_1, D_2, D_3 are as follows:

$$\begin{aligned} S_1 &= u_{f1} + u_{e1} \quad , \quad D_1 = u_{f1} - u_{e1} \\ S_2 &= u_{f2} + u_{e2} \quad , \quad D_2 = u_{f2} - u_{e2} \\ S_3 &= u_{f3} + u_{e3} \quad , \quad D_3 = u_{f3} - u_{e3} \end{aligned} \tag{3}$$

under the following conditions:

$$|S_1| > |D_1|\ ,\ |S_2| > |D_2|\ ,\ |S_3| > |D_3|$$

Eq. (4) is derived from Eq. (1), Eq. (2) and Eq. (3). Joint torques T_1, T_2 are expressed using summations and differences of contractile forces.

$$\begin{aligned} T_1 &= r_1 D_1 - k r_1^2 \theta_1 S_1 - b r_1^2 \dot{\theta}_1 S_1 \\ &\quad + r_1 D_3 - k(r_1\theta_1 + r_2\theta_2) r_1 S_3 - b(r_1\dot{\theta}_1 + r_2\dot{\theta}_2) r_1 S_3 \\ T_2 &= r_2 D_2 - k r_2^2 \theta_2 S_2 - b r_2^2 \dot{\theta}_2 S_2 \\ &\quad + r_2 D_3 - k(r_1\theta_1 + r_2\theta_2) r_2 S_3 - b(r_1\dot{\theta}_1 + r_2\dot{\theta}_2) r_2 S_3 \end{aligned} \tag{4}$$

III. Driving mechanism using equilibrium position

A. Derivation of equilibrium position

When the contractile force of each muscle is settled, an equilibrium position is specified. Even robot arm takes any postures, it goes back to the equilibrium position. To change each contractile force we can drive the robot arm along the path of equilibrium position. At equilibrium joint angles θ_1, θ_2 are obtained from Eq. (4) in conditions of $T_1 = T_2 = 0$ and $r = r_1 = r_2$.

$$\begin{aligned} \theta_1 &= \frac{1}{kr} \frac{(D_1 + D_3)S_2 + (D_1 - D_2)S_3}{S_1 S_2 + S_2 S_3 + S_3 S_1} \\ \theta_2 &= \frac{1}{kr} \frac{(D_2 + D_3)S_1 - (D_1 - D_2)S_3}{S_1 S_2 + S_2 S_3 + S_3 S_1} \end{aligned} \tag{5}$$

When joint angles of equilibrium position are given, contractile forces of each muscle are derived. However S_1, S_2, S_3 are settled for stiffness control and D_3 is settled arbitrarily. Differences of contractile forces are as follows:

$$\begin{aligned} D_1 &= -kr\left(\frac{S_1 S_3}{S_2}\theta_1 + \frac{(S_1 + S_3)S_2}{S_1}\theta_2\right) \\ D_2 &= -kr\left(\frac{(S_2 + S_3)S_1}{S_2}\theta_1 + \frac{S_2 S_3}{S_1}\theta_2\right) \\ D_3 &= -kr\left(\frac{\theta_1}{S_2} + \frac{\theta_2}{S_1}\right) \end{aligned} \tag{6}$$

u_{f1}, u_{e1}, u_{f2}, u_{e2}, u_{f3} and u_{e3} are derived from Eqs. (3) and (6).

$$\begin{aligned} u_{f1} &= \frac{S_1 + D_1}{2} \quad , \quad u_{e1} = \frac{S_1 - D_1}{2} \\ u_{f2} &= \frac{S_2 + D_2}{2} \quad , \quad u_{e2} = \frac{S_2 - D_2}{2} \\ u_{f3} &= \frac{S_3 + D_3}{2} \quad , \quad u_{e3} = \frac{S_3 - D_3}{2} \end{aligned} \tag{7}$$

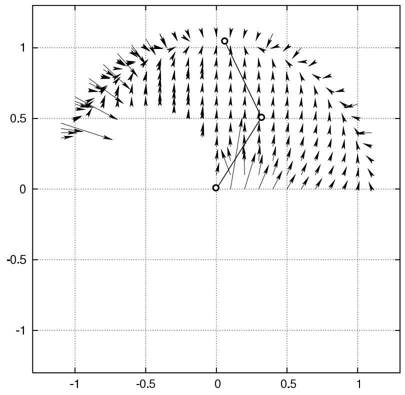


Fig. 4. Output force at end point when arm deflects from equilibrium position

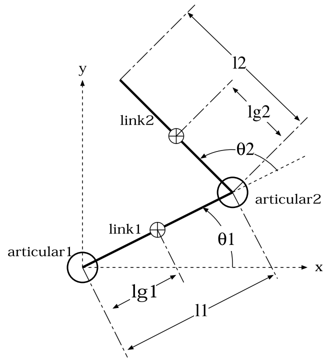


Fig. 5. Model for simulation

Behavior of robot arm which deflects from equilibrium position is visualized in Fig. 4. Contractile forces of each muscle are calculated from the equilibrium position using Eqs. (5), (6) and (7). After that, output force at the end point of robot arm is derived from Eqs. (4) in each posture.

B. Simulation result

Simulation model is shown in Fig. 5. Each link is a thin rod which has no thickness and width. Here l_1 and l_2 are lengths of L1 and L2, m_1 and m_2 are the masses, I_1 and I_2 are the inertia moments of links related to R_1 and R_2 , l_{g1} and l_{g2} are distances from each center of R_1 and R_2 to each gravity center of L_1 and L_2.

In Lagrangian mechanics the equation of motion are written in Eq. (8) T_1 and T_2 are joint torques. And θ_1 and θ_2 are joint angles. Gravitational effect are ignorable because robot arm moves only in horizontal plane.

$$\begin{pmatrix} T_1 \\ T_2 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} \ddot{\theta_1} \\ \ddot{\theta_2} \end{pmatrix} + \begin{pmatrix} h_{11} \\ h_{21} \end{pmatrix} \tag{8}$$

where:

$$m_{11} = I_1 + I_2 + 2m_2 l_1 l_{g2} \cos\theta_2 + m_2 l_1^2$$
$$m_{12} = m_{21} = I_2 + m_2 l_1 l_{g2} \cos\theta_2, m_{22} = I_2$$
$$h_{11} = -m_2 l_1 l_{g2} \sin\theta_2 (2\dot{\theta_1}\dot{\theta_2} + \dot{\theta_2}^2)$$

TABLE I

Parameters of simulation model

l_1	0.6[m]	l_2	0.6[m]
lg_1	0.3[m]	lg_2	0.3[m]
m_1	2.5[kg]	m_2	1.0[kg]
I_1	0.3[kg·m^2]	I_2	0.12[kg·m^2]
r_1	0.1[m]	r_1	0.1[m]

$$h_{21} = m_2 l_1 l_{g2} \sin\theta_2 \dot{\theta_1}^2$$

In this simulation we show that robot arm can move with only feedforward position control using muscular viscoelasticity. When expecting path of the end point $X_{end}(t) = [x_{end}, y_{end}]^T$ are given, we derived joint angle $\theta_1(t)$ and $\theta_2(t)$ by Eq. (9).

$$\begin{aligned} \theta_1 &= \arctan(y,x) - \arctan(\sqrt{x^2+y^2-z^2}, z) \\ \theta_1 &= \arctan(y,x) - \arctan(\sqrt{x^2+y^2-w^2}, w) \end{aligned} \tag{9}$$

where:

$$z = \frac{x^2+y^2+l_1^2-l_2^2}{2l_1}$$
$$w = \frac{x^2+y^2+l_2^2-l_1^2}{2l_2}$$

This expecting path is considered as trajectory of equilibrium position. We can calculate each contractile forces by Eqs. (6) and (7). When the equilibrium position are changed, contractile forces are also changed to track the expecting path.

Simulation result is shown in Fig. 6. And parameters of arm model are shown in TABLE I. Summation of contractile force are settled as $S_1 = S_2 = S_3 = 1$[N]. Some postures $(\theta_1, \theta_2) = (0,0), (-1,1), (-1,2), (0,1)$ are given and expecting path is generated by connecting each postures simply. In simulation it can track the expecting path only with feedforward control.

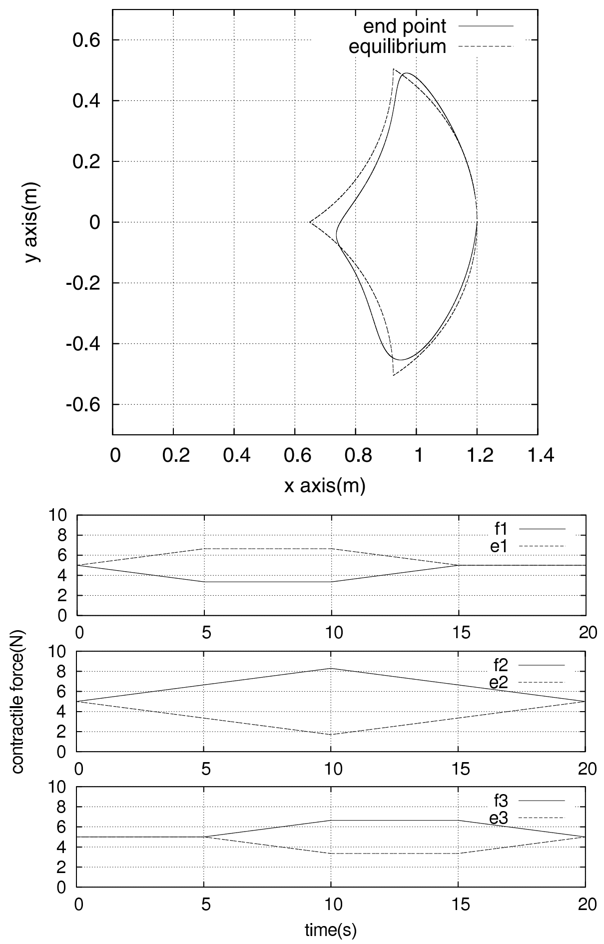
IV. Design of Robot arm using bi-articular driving mechanism

A. Bi-articular Driving Mechanism

Conventional robot arms are only equipped with mono-articular driving mechanism. We add bi-articular driving mechanisms which are implementation of animal characteristics to these robot arms. Ideally bi-articular driving mechanisms must satisfy following conditions.

- It can generate equivalent forces to both joints simultaneously.
- It must not be fixed to link. When each joint rotates, it can move itself not to block out their rotation.

One implementation which satisfy above conditions is shown in Fig. 7. It uses linear-actuators and movable pulleys. However it has some defects. Its structure is complex and electromagnetic linear actuator is not good at force to weight ratio. Accordingly we can not adopt it for our robot arm.



Changing contractile forces($\tau = 5$)

Fig. 6. Simulation result of driving robot arm using equilibrium

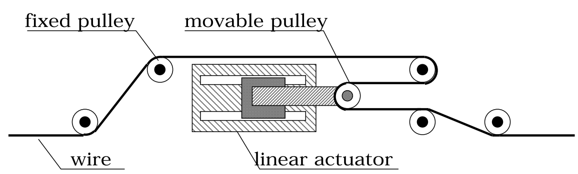


Fig. 7. Bi-articular driving mechanism using pulleys

Muscular viscoelasticity are actualized by a control diagram shown in Fig. 8. Each joint angles are detected by rotary encoders. This nonlinear feedback loop is derived from Eq. (2).

Fig. 9 is a complete implementation which has an antagonistic pair of bi-articular driving mechanisms and two antagonistic pairs of mono-articular driving mechanisms.

B. Design and Making of Robot Arm

Purposes of making robot arm are as follows.

1. Verification of static properties
2. Actual experiment of driving
3. Investigation of antagonistic structure

In this time we didn't choose complete bi-articular driving mechanism and tried to satisfy some requirement by

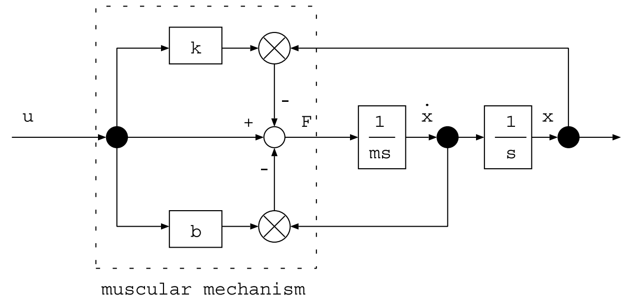


Fig. 8. Block diagram to realize muscular viscoelasticity

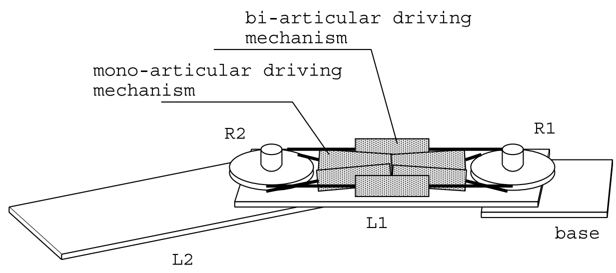


Fig. 9. A complete implementation of the animal arm model shown in Fig. 2

software. This robot arm is just a prototype for complete implementation. We designed a simple robot arm which uses three electric motors. It is shown in Fig. 10. Its main properties are shown in TABLE II.

In this model three motors are corresponding to animal three antagonistic muscular pairs. In the case of conventional robot arm, two motors drive each joint independently. These are mono-articular driving mechanisms.

Bi-articular driving mechanism is made from a rotary actuator and timing belt. On the R2 side it uses same shaft with mono-articular driving mechanism. While on the R1 side it uses another shaft but it is mounted on concentric axis.

TABLE III is the comparison of four arm models. In this table we compared each models from four viewpoints. As is clear from this table we realized some features virtually at this manufacturing.

V. Conclusion and future works

In this paper we described the arm model which has bi-articular muscles. We showed existence of the equilibrium position derived from muscular elasticity.

Next we proposed the control mechanism using equilibrium position. And it realized trajectory tracking with only feedforward control in simulation.

Finally we showed our trying to make robot arm based on the principle of bi-articular muscles. Presently we completed its mechanical part. It is shown in Fig. 11. For the future works we will experiment actually to verify static and dynamic properties of the arm model equipped with bi-articular muscles.

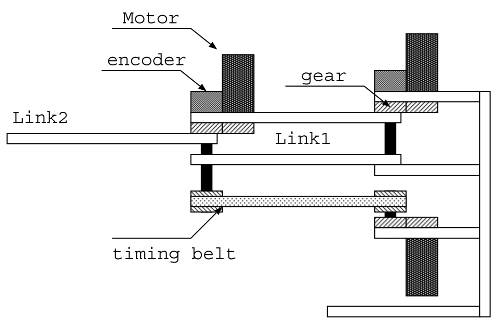


Fig. 10. Outline view of robot arm

TABLE II
MAJOR PARAMETERS OF ROBOT ARM

Link1(upper)	200×50×10[mm] 270[g]
Link1(bottom)	200×50×10[mm] 270[g]
Link2	200×50×10[mm] 270[g]
Motors	TAMIYA(540K75)
Encoders	OMRON(E6H-CWZ6C)

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TABLE III
A IS ANIMAL'S ARM. B1(FIG. 9) AND B2(FIG. 10) ARE ROBOT ARMS USING BI-ARTICULAR DRIVING MECHANISM. B2 IS WHAT WE ATTEMPT TO MAKE NOW. C IS CONVENTIONAL ROBOT ARM. ○ : EXISTING, △ : VIRTUALLY EXISTING, × : NO EXISTING.

-	A	B1	B2	C
(1)driving mono-articular	○	○	○	○
(2)driving bi-articular	○	○	△	×
(3)antagonistic pair	○	○	△	×
(4)muscular viscoelasticity	○	△	△	×

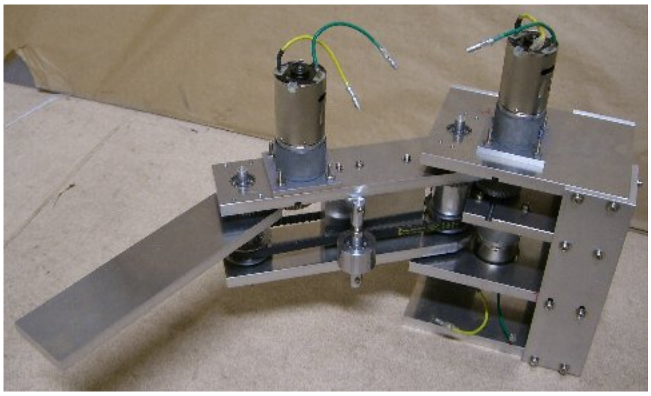

Fig. 11. A photo of robot arm which we are working on