Experimental Verification on Novel Robot Arm Equipped with Bi-articular Driving Mechanism

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Abstract— **This paper describes a novel design of robot arm and its experimental verification. The proposed robot arm has a bi-articular driving mechanism . The bi-articular driving mechanism drives both shoulder and elbow joints simultaneously like a bi-articular muscles of animals. The mechanism is built by timing belt and pulleys. The proposed robot arm mimics human upper arm with 3 DC motors working as three muscular pairs. First design and development of robot arm are described. Then several experiments verifies that the bi-articular driving mechanism can work on both two joints. Furthermore its redundant actuation system can work well, if any one actuator is removed.**

I. Introduction

In the past, many industrial robots have worked in advanced factories. These robots are mostly isolated from human workers. They are demanded to move rapidly and accurately in known and stable environment. Recently there are new needs of robots in society. Robots are expected to work with human. Such new robots does not need excess high-speed and accurate movement but skillful and safety movement in unknown and unstable environment like animals.

To meet such new needs, we propose a novel design of robot arm inspired by animals. The unique point of proposed arm is bi-articular driving mechanism. It is based on bi-articular muscles of animal arm. Fig. 1 shows simplified conventional robot arm model and animal arm model. Conventional robot arm has actuators in each joint and each joint is driven independently. While animal arm has complex alignment of muscles. Bi-articular muscles are connected both two joints and drive both simultaneously. Our design realizes this characteristic mechanically.

Bi-articular muscles are ignored in many robotics research, but recently their important role is clarified. Van Ingen Schenau et. al. described a role of bi-articular muscles in vertical jump. Gastrocnemius muscle is a bi-articular muscles in the calf of the leg.It develops and transmits propulsive force [1]. Neville Hogan suggested that antagonistic bi-articular muscles can control mechanical impedance. He showed its effectiveness at contact tasks[2][3]. Mussa-Ivaldi verified stiffness ellipse at the end point of human arm in several postures experimentally[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-

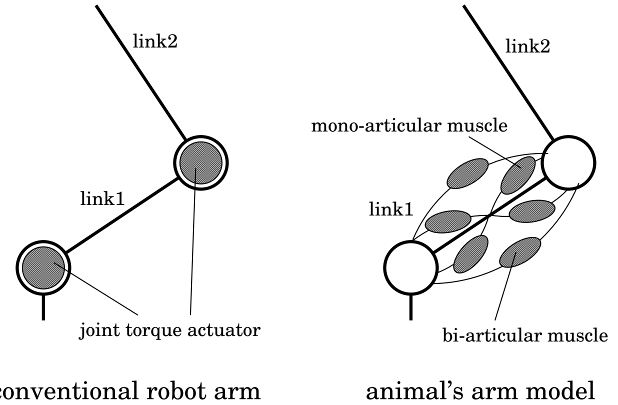

Fig. 1. Conventional robot arm model and animal‘s arm model

articular muscles. They proposed that direction of distal output force is controlled by switching pattern of antagonistic muscular pairs. This pattern is backed by recorded EMG patterns of human upper arm. [5]. Our previous research proposed path tracking algorithm utilizing muscular viscoelasticity. The algorithm can suppress model error in spite of feed-forward control[6][7].

There are several application to utilize bi-articular muscles. Kumamoto made experimental machine using pneumatic actuators to verify their theory[5]. Oshima proposed jumping leg robot. They connected knee and ankle joints with wire. The wire is corresponding to gastrocnemius muscles. It contributes to stabilization of posture [8]. Niiyama made jumping frog robot. Their robot imitates frog muscular alignment. However they omit some redundant muscles. Their robot can jump with simple control [9]. Oda and et al. developed unique actuator to mimic muscular viscoelasticity mechanically. They mount this actuators on their robot arm. Also they develops jumping robot leg which has springs as bi-articular muscles.[10] These robots use nonlinear actuators or passive components as muscles. However such approach reduces their control performance. We realize robot arm based on bi-articular muscle principle by using electromagnetic motors and simple mechanism.

This paper shows design and development of proposed robot arm. Then experiments verify bi-articular driving mechanism in dynamic motion and effectiveness of redundant system.

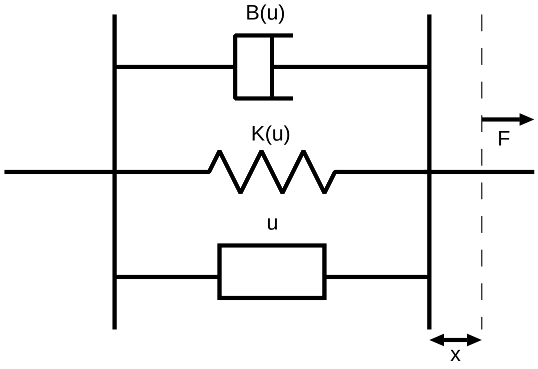

Fig. 2. Model of a muscle

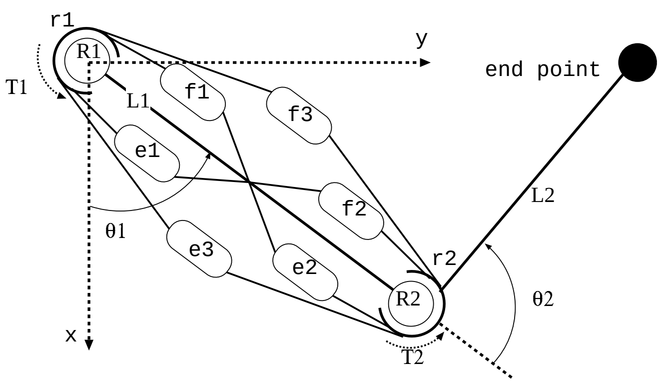

Fig. 3. Two joint link model with both mono-articular muscles and bi-articular muscles

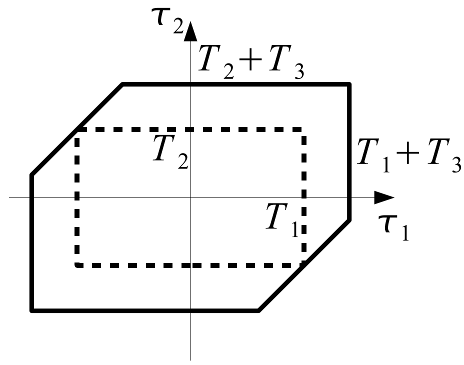

Fig. 4. Range of joint torque with or without bi-articular muscle

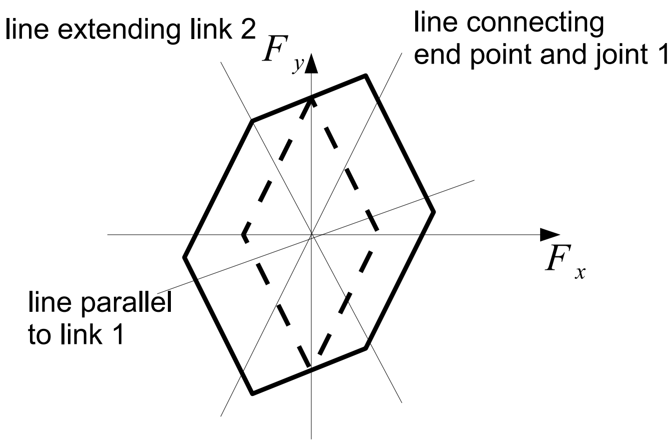

Fig. 5. Range of output force with or without bi-articular muscle

II. Modeling of Animal Arm

Muscle has unique viscoelasticity. Animal muscular model is shown in Fig. 2. Muscular output force F is a function of contractile force u.

$$F = u - K(u)x - B(u)\dot{x} = u - kux - bu\dot{x} \tag{1}$$

Here x is contracting length of the muscle and $\dot{x}$ is shortening velocity. k is elastic coefficient and b is viscosity coefficient. Muscles only generates forces when they shrink. Therefore muscles construct antagonistic pair to generate dual-directional force.

Animal upper arm has complex muscular alignment but this alignment can be simplified by limiting planar motion. Simplified animal upper arm model is shown in Fig. 3. In Fig. 3 e1 and f1 is a pair of antagonistic mono-articular muscles attached to the 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:

$$\begin{aligned} T_1 &= (F_{f1} - F_{e1})r_1 + (F_{f3} - F_{e3})r_1 \\ T_2 &= (F_{f2} - F_{e2})r_2 + (F_{f3} - F_{e3})r_2 \end{aligned} \tag{2}$$

Output force at end point is represented by Eq. 3. Where J_{aco} denotes the Jacobian matrix.

$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = ({J_{aco}}^T)^{-1} \begin{pmatrix} T_1 \\ T_2 \end{pmatrix} \tag{3}$$

However T_1, T_2 are not independent from each other. Characteristic of joint torque and output force is shown Fig. 4 and 5. Shape of both characteristics is tetragon in conventional arm (bold dotted line), which has only independent actuator. While it is hexagon in animal arm (bold solid line).

III. Design and Development of Robot Arm

A. Design of Robot Arm Based on Bi-articular Muscle

Proposed robot design is based on animal arm model shown in Fig. 3. Each antagonistic muscular pair is replaced with one electromagnetic motor. Since the motor can generate torque both direction. Whole design of robot arm is shown in Fig. 6. Link1 is fixed with joint axis 1 and link2 is fixed with joint axis 2.

Mono articular driving mechanism corresponding to mono-articular muscular pairs is quite same with conventional robot arm structure. Motor 1 drives joint 1 and motor 2 drives joint 2 respectively.

Bi-articular driving mechanism corresponding to bi-articular muscular pair is realized by a timing belt and

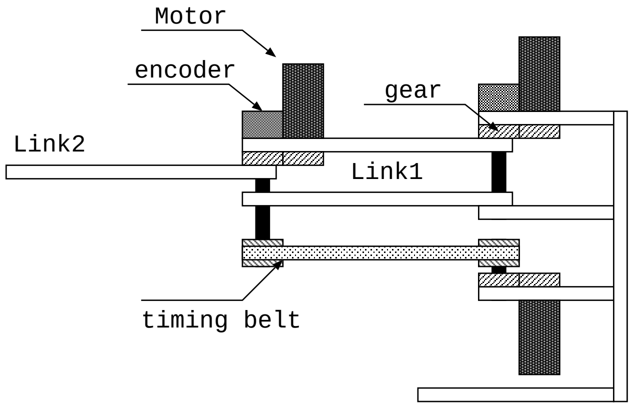

Fig. 6. Outline view of robot arm design

Fig. 7. A photo of robot arm

pulleys. One pulley is fixed on joint axis 2. The other pulley is separated from joint axis 1 but this pulley and joint axis 1 are colinear. Motor 3 is placed on the body. The bi-articular mechanism connects body and link2 and is quite free from link 1.

Animal arm structure has three important characteristics: (1)bi-articular driving, (2)antagonistic driving and (3)non-linear viscoelasticity. TABLE I shows comparison of animal arm and proposed design.

B. Development of Robot Arm

Fig. 7 shows implementation of proposed design. Major parameters of mechanical part is shown in TABLE II. Fig. 8 shows detail of actual bi-articular driving mechanism. Fig. 9 is a component to transfer the torque of the motor 3 to the joint 2. This component is floated from the joint 1 by bearings. Cross-sectional drawing is shown in Fig. 9. In Fig. 10, the pulley is fixed to joint 2.

Components of control system is shown in TABLE III. Fig. 11 represents connection of each component. Each current of motor is controlled by motor drivers. Control PC outputs current commands to these drivers.

TABLE IV is properties of the robot arm. Total height

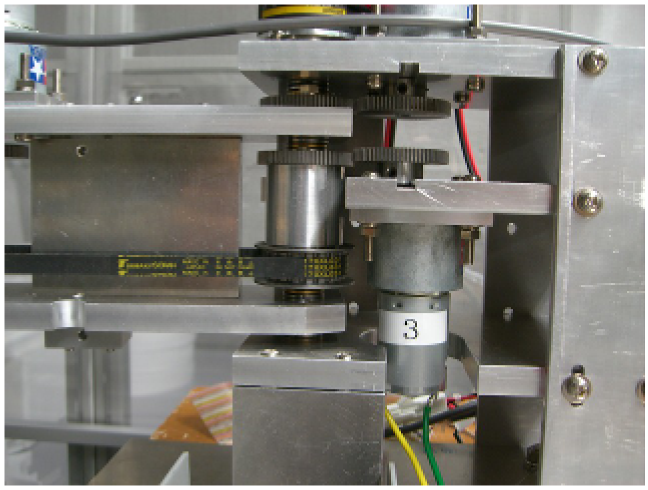

Fig. 8. Detail of actual bi-articular driving mechanism (R1 side)

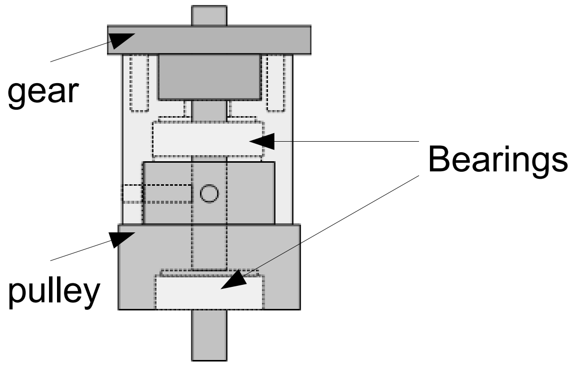

Fig. 9. Cross-section drawing of R1 side

Fig. 10. Detail of actual bi-articular driving mechanism (R2 side)

TABLE I
Comparison of animal arm and proposed design

Characteristic	**Animal arm**	**Proposed design**
Bi-articular driving	Bi-articular muscles	Bi-articular driving mechanism
Antagonistic driving	Antagonistic muscular pair; Mono-articular muscle and bi-articular muscle	Muscular pair is replaced by one motor. Mechanical antagonistic driving only exists between mono-articular driving mechanism and bi-articular driving mechanism
Non-linear viscoelasticity	Muscular viscoelasticity	Software control

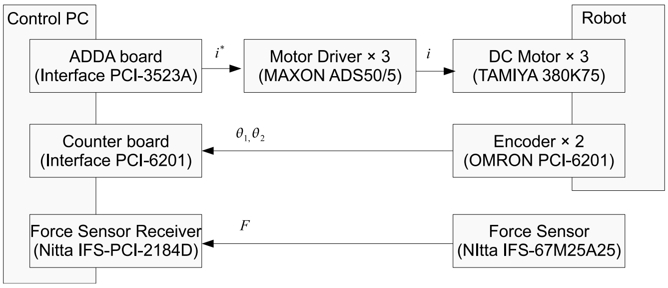

Fig. 11. Connection of components in control system

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(380K75)
Encoders	OMRON(E6H-CWZ6C)
Force Sensor	NITTA(IFS-67M25A25-l40-ANA)
Current Sensor	MAXON ADS 50/5

does not contain cables and a base plate but motors and encoders. Total length is measured with the arm full extended. Influences of small parts are omitted in calculation of mass and inertia.

IV. Experimental Verification

This section describes verification of bi-articular driving mechanism in dynamic motion. An experimental procedure is the following. (1)One of three motors is removed from the arm. (2) The arm is driven by remaining two motors. (3) The same experiment is done changing a motor to be removed. In each case, position commands $\boldsymbol{\theta}^{\star} = \mathrm{diag}(\theta_1^{\star}, \theta_2^{\star})$ is given as square wave with amplitude is 0.3 rad. Fig.12 shows control diagram and control parameters are shown in TABLE V, where $\boldsymbol{K_p} = \mathrm{diag}(\mathrm{K_{p1}}, \mathrm{K_{p2}})$ and $\boldsymbol{K_d} = \mathrm{diag}(\mathrm{K_{d1}}, \mathrm{K_{d2}})$ denote proportional and differential gain of position controller. $\boldsymbol{J_n} = \mathrm{diag}(\mathrm{J_{n1}}, \mathrm{J_{n2}})$ denotes nominal inertia.

First experiment is done removing the motor 3 (case 1). In this condition, the arm has same structure with conventional robot arm. Fig. 13 shows this result.

TABLE III
Components of control system

Motor driver	MAXON ADS 50/5
OS	ART-Linux
CPU	Intel Pentium4 1.5MHz
AD-DA board	Interface PCI-3523A
Counter board	Interface PCI-6201E
Receiver of force sensor	Nitta IFS-PCI-2184D

TABLE IV
Properties of robot arm

Total height	270mm
Total length	500mm
Total mass of link 1	0.72kg
Total Length of link 1 between joint 1 and 2	165mm
Total mass of link 2	0.27kg
Total length of link 2 between joint 2 and center of force sensor	185mm
Moment of inertia of joint 1	0.034kg·m^2
Moment of inertia of joint 2	0.0058kg·m^2
Torque coefficient	0.20Nm/A

Next experiment is done removing motor 2 (case 2). In this case, the joint 1 is driven by motor 1 and 3. The joint 1 is driven by only motor 3. Fig. 14 shows the result. Bi-articular driving mechanism can clearly drive the joint 2. Furthermore response of this case is almost same with previous case. Relatively large overshoot of θ_2 is discernible. Last experiment is removing the motor 1(case 3). The joint 1 is driven only the motor 3. The joint 2 is driven by themotor 2 and 3. Fig. 15 shows the result. Bi-articular driving mechanism can drive the joint 1 but response is vibrating. Next section discusses about this problem. However these experiments verify that the proposed bi-articular driving mechanism can generate torque for both two joints.

V. Discussion

In case 3, the arm is not a underactuated manipulator. Fig. 16 is the result of experiment to prove that. The joint 2 is locked and the current command of motor 3 is a

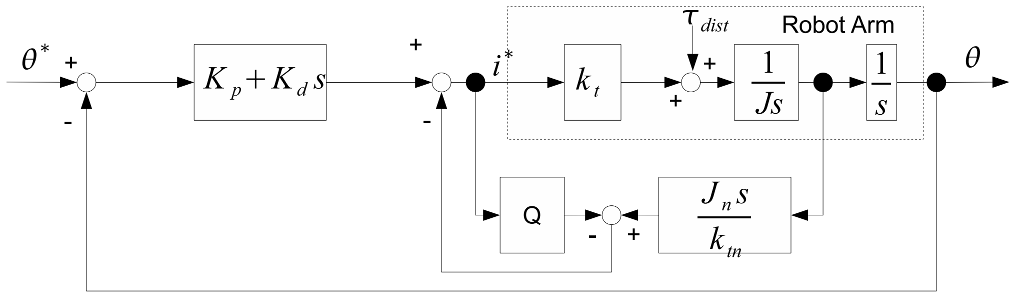

Fig. 12. Control diagram of this experiment

TABLE V
CONTROL PARAMETERS OF ROBOT ARM

K_{p1}	15.3	K_{d1}	2.45
K_{p2}	2.29	K_{d2}	0.367
J_{n1}	0.02kg·m^2	J_{n2}	0.003kg·m^2
kt_n	0.20 Nm/A		

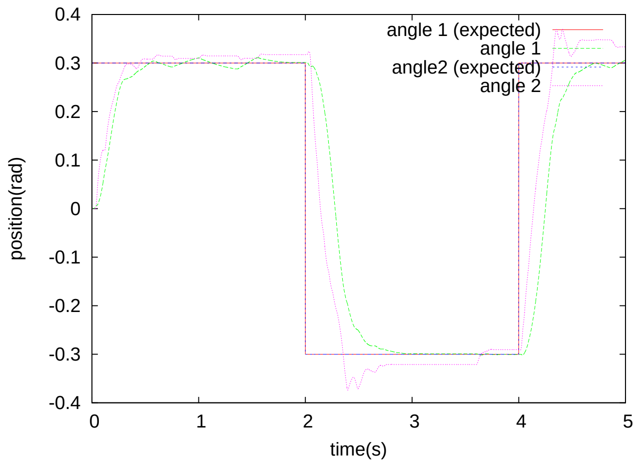

Fig. 13. Experiment without motor 3

sinusoidal wave. The joint 1 is driven without rotation of the joint 2.

This arm still has some problems: vibrating and low performance. They are caused by multiple factors. Mechanical structure of the arm has large friction and backlash. This bi-articular mechanism requires enough tension of the timing belt. Especially the arm needs coordinated movement when the joint 1 and the joint 2 move to particular direction to loosen the belt. Our current controller does not consider these problems. Some compensations are required for antagonistic driving and dominant disturbances. These improvements are our future works.

VI. Conclusion

This paper described design and development of robot arm equipped with bi-articular driving mechanism. Then several experiments verified that the proposed bi-articular driving mechanism can drive both joints; the proposed

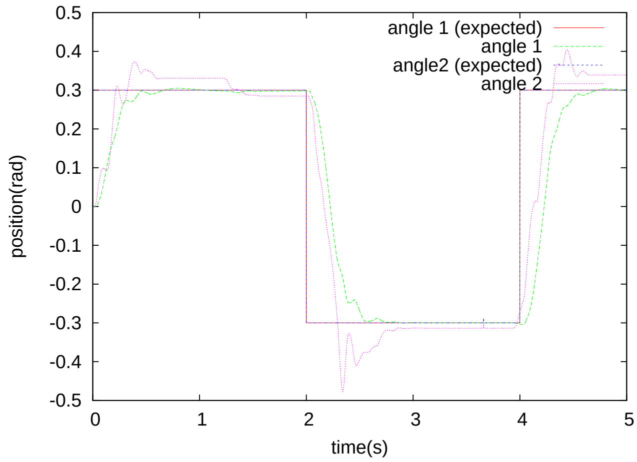

Fig. 14. Experiment without motor 2

robot arm can drive two joints with any two motors of three motors.

Animal arm structure has some advantages over conventional robot arm: e.g. improvement of distal output force and redundancy. The proposed bi-articular driving mechanism add these animal advantages to robot arms. By introducing animal characteristics, robot arm progresses to the next stage. It can work in new field not only in factories. Also such new robot can help to analyze human abilities.

References

[1] G. J. van Ingen Shenau, M. F. Bobbert and R. H. Rozendal, “The unique action of bi-articular muscles in complex movements”, Journal of Anatomy, 155, pp. 1-5, 1987

[2] Neville Hogan, “Adaptive Control of Mechanical Impedance by Coactivation of Antagonist Muscles”, IEEE Transactions on Automatic Control, vol.AC-29, No.8, pp. 681-690, 1984

[3] Neville Hogan, “On the stability of Manipulators Performing Contact Tasks”, IEEE Journal of Robotics and Automation, Vol. 4, No. 6, pp. 677-686, 1988

[4] F. A. Mussa Ivaldi, N. Hogan and E. Bizzi, “Neural, Mechanical, and Geometric Factors Subserving Arm Posture in Humans”, The Journal of Neuroscience, Vol. 5, No. 10, pp. 2732-2743, 1985

[5] Mizuyori Kumamoto, Toru Oshima, Tomohisa Yamamoto, “Control properties induced by existence of antagonistic pairs of bi-articular muscles -Mechanical engineering model analyses”, Human Movement Science 13, pp. 611-634, 1994

[6] Kengo Yoshida, Naoki Hata, Toshiyuki Uchida, Yoichi Hori, “A Novel Design and Realization of Robot Arm Based on the Prin-

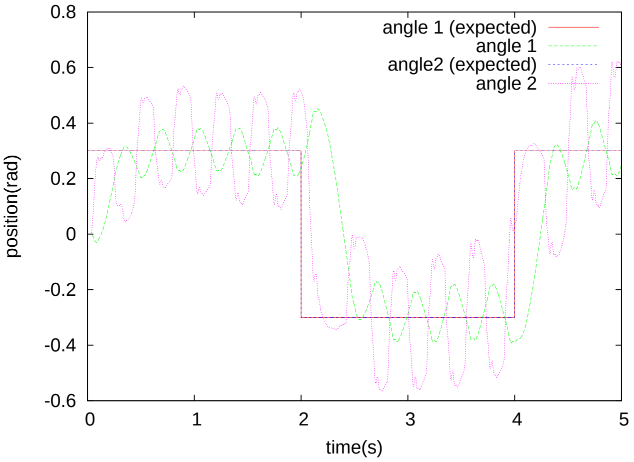

Fig. 15. Experiment without motor 1

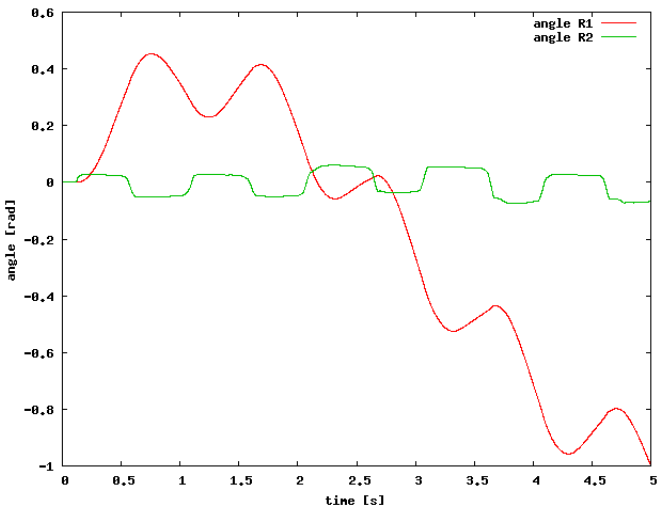

Fig. 16. Response to sinusoidal wave of i_3

ciple of Bi-articular Muscles", Proc. IEEE International Conference on Industrial Technology (ICIT), 2006. 12

[7] Kengo Yoshida, Naoki Hata, Toshiyuki Uchida and Yoichi Hori, "A Novel Design and Realization of Robot Arm Based on the Principle of Bi-articular Muscles", IEEE ICIT06, 2006. 12, India

[8] Toru Oshima, Noboru Momose, Kiyoshi Toriumi, "Jump mechanism using coordination in knee and ankle joint and application to leg orthosis" , The 2005 International Power Electronics Conference, 2005

[9] Ryuma Niiyama, Akihiko Nagakubo, Yasuo Kuniyoshi, "A bipedal jumping and landing robot with an artificial musculoskeletal system", IEEE International Conference on Robotics and Automation, 2007

[10] Mizuyori Kumamoto and et al., "Revolution in Humanoid Robotics", Tokyo Denki University Press, 2006 (in Japanese)