Coordinated control for a robot arm with bi-articular muscle mechanism

Hiroyuki Fukusho [a] and Takafumi Koseki [b]

[a] Department of Electrical Engineering, School of Engineering,
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan
[b] Department of Communication and Information, School of Information Science and Technology,
The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan

hiro@koseki.t.u-tokyo.ac.jp

***Abstract* — Technology of motion control for a humanoid robot is advancing with consideration of biology and medical science field these days. For instance, to use a bi-articular muscle mechanism has been already discussed for easy motion control like walking or moving on free space. Trajectory control of an arm model using torque input system of electrical motors as role of an elbow and bi-articular muscle is studied on this paper. This theory has been examined by actual arm model in Munich, and one possibility for trajectory control based on feed forward torque control has been considered as well. Moreover, flexible control for electrical motor as role of a muscle has examined on the experimental machine.**

***Keywords* — Bi articular-muscle, cooperated control, damping factor, humanoid robot, spring factor**

I. Introduction

Although technology of a humanoid robot like e.g., ASIMO from HONDA Co. Ltd. has been advanced by a mechanical model which can be realized a complicated kinematics calculation by software and by a high performance processor for the calculation compare to a few years ago.

However, the mechanism of these conventional humanoid robots and mechanisms of human beings are quite different. Therefore, the motion control conception for a humanoid robot has been reconsidered little by little by some researcher who studies about biology and medical science. When we focus on the point around a joint and a link from the point of muscle composition and function, a concept of a bi-articular muscle mechanism can be considered.

Fig. 1. shows an arm system of a human including bi-articular muscles. This is drawn by top view. In the figure, f3 and e3 are bi-articular muscles. All quadruped and biped animals have the bi-articular muscles. It has being said that most of basic controls like walking or moving on free space might be achieved by easy control using bi-articular muscle theory.

Because, the characteristics of it are that it is connected between two joints and it moves the link at the same time. The trajectory of a robot is decided as one simple output because of the restriction of the motion by interconnected muscle mechanism [1].

On the contrary, many of conventional humanoid robots have no parts as artificial bi-articular muscles. They have for instance only rotational motors at their cubital and shoulder joints, which operate the roles of mono-articular muscles. With such hardware configuration, one absolutely needs calculating complicated inverse kinematics and it needs a lot of calculation cost to the computer.

Furthermore, total torque for trajectory is composed of the sum of torques which are generated by each muscle. It makes one easy solution for the trajectory control based on feed forward torque control depending on one simple torque input pattern as shown in Fig. 2. Fig. 2 is a measured result of signals of each muscle in case a human generates a torque to a tip on static state.

Hence, the consideration of a bi-articular muscle mechanism for the motion control of a humanoid robot will be advanced from some research field and actual experiments and demonstrations has been already done [1].

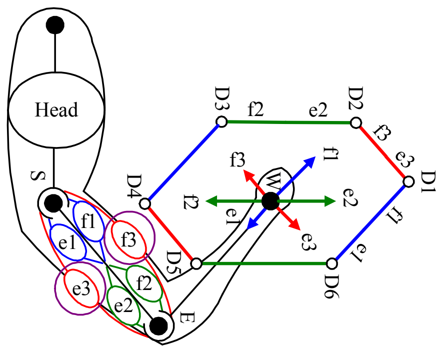

Fig. 1. Unique characteristics of output force distribution [1].

In this paper, trajectory of the tip of arm model which has two rotary motors on elbow and bi-articular point has been taken into consideration. Also the effect to the actual machine using this composition has considered. The simple and speedy trajectory control without any complex calculation as inverse kinematics might be achieved from these consideration.

In addition, the flexible control for the rotary motors like a muscle function has also been included for the input function. Finally, characteristics of the motion has been measured and discussed on those situation. An upper arm based on a human has taken into consideration on this paper in case of nothing special comment.

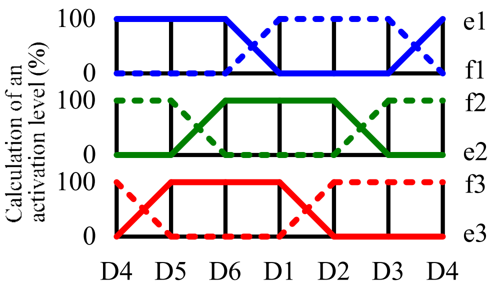

Fig. 2. Theoretically calculated activation level of each muscle can be applied on torque pattern of each actuator respectively [1].

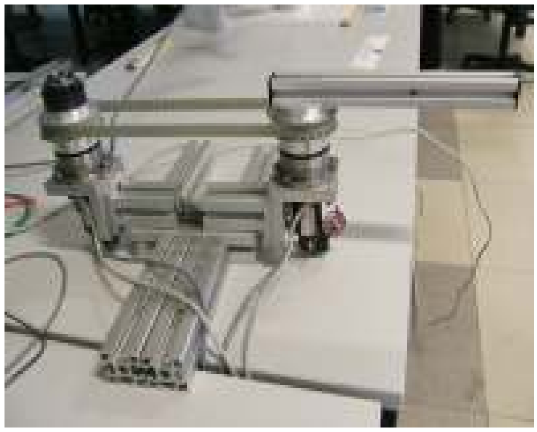

Fig. 3. Experimental machine which has two rotary motors as role of an elbow and a bi-articular muscle.

II. Basic Control Theory Of The Motion Control And Explanation Of The Experimental Machine [1].

A. Overview of the experimental machine and torque pattern control for the actuators

One of the main functions of bi-articular muscle is assisting flexion and extension actions of an upper arm. As it has been already written before, bi-articular muscle operates both two joints on the moment. However, the trajectory of the tip from an elbow point has been especially focused on this paper. Because, the main function of it is related the elbow point.

Fig. 3 shows the experimental machine to confirm the motion using the proposed theory. And table I is the setting of the experimental machine. This machine has made of the assistance from Institute of Automatic Control Engineering (LSR), Technical University of Munich. A timing belt is used for the cooperated torque output. Each torque of a motor has generated through a harmonic drive and it has factors to express flexibility of a muscle. This control method is explained at the follow section.

Fundamentally, a torque pattern using two motors for e2, f2 and e3, f3 muscles has been examined on the base of Fig. 2. Then effect on the point of the tip of elbow has considered.

TABLE I
SETTING OF THE EXPERIMENTAL MACHINE

Parts	Elements
Motor	Maxon motor, Re40, 150W
Encoder	HEDL 5540
Harmonic Drive	Harmonic Drive HFUC -17-100-2UH, Gear Ratio 100:1
Amplifier for the control box	Copley Amplifier 4112 Z
Flexible Coupling	Hausmann + Haensgen GmbH & Co.KG, SK1/15/W/20/15/12-25

B. Fundamental algorithm of thrust control type mechanical impedance control system

When we think about a flow of which a human beings sends a signal for a motion from a brain to a muscle, not a position reference but a torque reference is used basically. An input signal of the proposed control system is used by a thrust signal in the same way.

A block diagram of the proposed control system is shown in Fig. 4. Fundamentally, an actuator generates a thrust F^*_m depending on an input signal of thrust F^*_{m0}. This suggestion was designed and experimented by a linear synchronous motor. The author has designed a compact, light weight and large thrust linear synchronous motor for bi-articular muscles [2]. However, this theory can be applied to the other type of an electrical motor definitely because it does not change to use the position and speed information of a motor.

Moreover, flexible control of an electrical motor like a human muscle characteristic can be thought from the concept of Fig. 5. Though this is quite common expression to make flexibility for mechanical machine, factors of spring and damper are adapted to generate elasticity and viscosity.

This control system can be named as thrust control type mechanical impedance control system compare to conventional impedance control system.

The transfer function of the block diagram is described as follow ;

$$s^2JX(s) = u\text{-}kuX(s) - CusX(s) - F_LX(s) \qquad (1)$$

J : Moment of inertia of a motor (kg*m^2)
k : Elastic coefficient (N/m),
C : Viscosity coefficient (Nsec/m)
u : Contractile force (N)
x : Contracting length (m)
F_L : Disturbance force (N)
s : Transfer function

Also, the characteristic equation of second order system which has spring and damping factor is shown as follows ;

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \qquad (2)$$

ω_n : Natural angular frequency (rad/sec)

ζ : Attenuation factor

One of the benefit using suggestions of Fig. 4 and Fig. 5 is that it can be accomplished by using only electrical motors and software. That indicates we can make the machine totally without any actual spring and damper and it makes some benefit as follow.

1. Mass of the machine can make light and composition of machine can make also simple.
2. It is possible to adjust those parameter quickly and freely by software.
3. It is easier to take into consideration about the sum of torques from two motors.

Consequently, the control system for the machine has been composed from the concepts of Fig. 2, Fig. 4 and Fig. 5 [3].

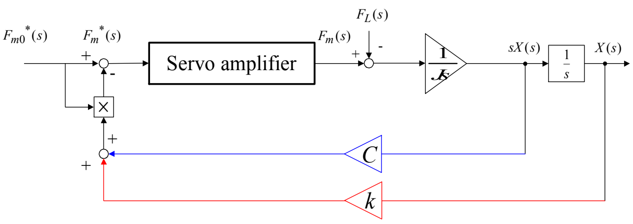

Fig. 4. Thrust control type mechanical impedance control system.

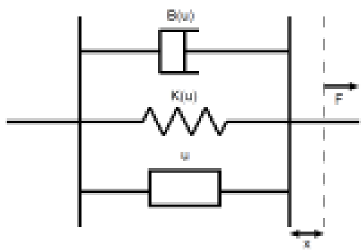

Fig. 5. Flexible control concept by spring-mass-damper system.

III. Trajectory Control With Cooperated Two Motors

In this section, the trajectory of the experimental machine using the proposed approach is mainly discussed. Fig. 6 is the total block diagram for cooperated control. Input torque control box in the figure means the proposed system of Fig. 4 and Fig. 5, and these input signals are sent to the motors respectively through a DA/AD sensory card.

Information of motor phases through reduced gears is loaded from encoders which are connected to harmonic drive directly and information of each motor speed are calculated by a differential from the position information. Hence, factor of flexibility is generated from those information and the constants of spring and damping factor in Fig. 5 all the time. It is also possible to use a variable number for those spring and damping factor.

Also, Fig. 7 shows the input pattern for each motor. These patterns are based on the Fig. 2. However, the condition without the motor for shoulder point which operates as e1 and f2 has been considered. Maximum torques for those motors through the harmonic drives were set to 30 N, because it is sufficient to make a rotary motion for the tip.

To avoid interference at the mechanical connected point cause of torques from these two motors, mechanical torque limiter has been equipped.

TABLE II

CHARACTERISTICS OF THE EXPERIMENTAL MACHINE

Elements	Parameter
Length and Mass between the tip and the elbow	300 (mm) 2.000 (kg)
Length and Mass between the tip and the shoulder	300 (mm) 2.000 (kg)
Moment of inertia of each motor I	1.638e-4 (kg*m^2)
Motor constant K_t	6.030e-2 (Nm/A)
Natural angular frequency of the elbow actuator ω_{ce}	0.275 (sqrt(k/m))
Attenuation factor of the elbow actuator ζ_e	0.25
Natural angular frequency of the elbow actuator ω_{ce}	0.2 (sqrt(k/m))
Attenuation factor of the elbow actuator ζ_e	0.25

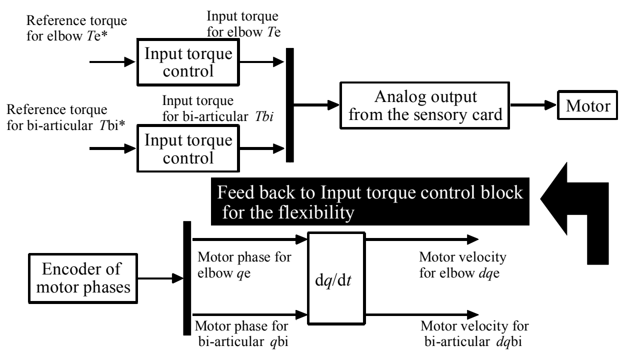

Fig. 6. Experimental machine which has two rotary motors as role of an elbow and a bi-articular muscle.

Result of the trajectory motion against the input function Fig.7 is shown in Fig. 8. In Fig. 8, a blue line shows the angle phase of the tip of the arm and a red line is the speed of the arm. We can also see the motion of the tip with flexibility and the difference cause of using each different parameter for the elbow motor and the bi-articular.

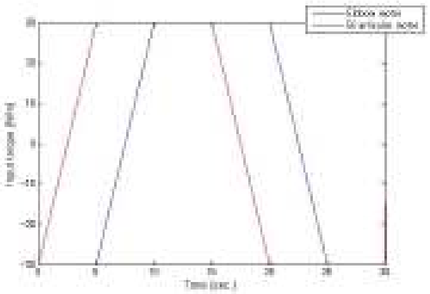

Fig. 7. Input signal for each motor.

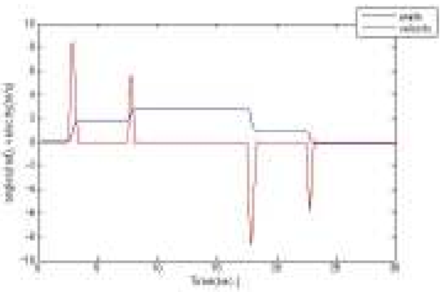

Fig. 8. Trajectory and velocity of the tip of the arm.

However, noise cause of the friction and impact had been result from the point of the joint, when the sum of the torques of those two motors changed for instance from clockwise to anticlockwise rotation. The system has no compensation for this mechanical interference except for a mechanical torque limiter. Consequently, this system needs an improvement for that.

IV. Discussion And Consideration Of an Improvement

Although the experimental machine system has designed especially for the rotational motion of elbow point, it was actually difficult to see the effect of bi-articular muscle mechanism only on this situation. Because the main point of bi-articular muscle is that it is connected by two joints in between and make a rotational motion to both point at the same time. Even if we focus on the effect of the elbow, it can be regarded unfortunately that this system has two motors instead of one big motor for one link.

Therefore, the improved design model in Fig. 9 is taken into consideration. The concept of this model is that there is a rotational system as role of a shoulder joint and the most important thing is that the shoulder joint can be moved by the torque of bi-articular mechanism.

However, it has no meaning that both shoulder and elbow rotate the same phase by the torque of bi-articular. Torque transfer mechanism has to think about to execute a simultaneously two joints drive control theory. An actuator which is located and connected shoulder and elbow joints in between and those two joints is pulled in the centre at the same time is supposed as one idea. If it will be possible to produce those kinds of actuator, this actuator becomes a complete one for the role of a bi-articular muscle.

How to produce those kinds of actuator by rotary system will be one future work.

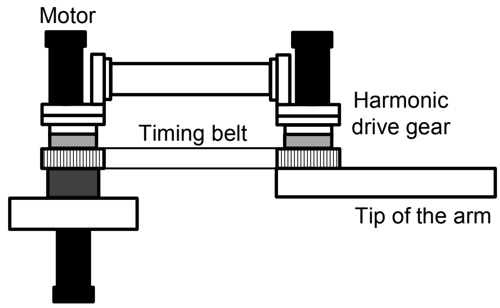

Fig. 9. Improvement model for two links rotating system.

V. Conclusion

In this paper, characteristics of bi-articular muscle mechanism which exits in the human beings for a robot has been introduced and discussed. It makes one easy solution for the trajectory control based on feed forward torque control depending on one simple torque input pattern.

The authors have designed an experimental machine of an arm model and cooperated torque control with elbow and bi-articular motors has been taken into consideration.

Whereas, problems of the experimental machine to inspect the effect of bi-articular muscle mechanism have been found in this study and one improvement design has simply proposed.

As a future work, the authors will think about the mechanical component for the improvement from a calculation of dynamics.

Furthermore, also adoption of the component to the conventional experimental machine will be considered.

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