Motion Control for a Humanoid Robot with Characteristics of Bi-Articular Simultaneous Drive

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***Abstract* — Technology of motion control for a humanoid robot is advancing with consideration of biology and medical science field these days. For instance, characteristics of bi-articular simultaneous drive have been already discussed from the biological field. In this paper, bi-articular simultaneous drive which makes rotational torques to adjacent joints simultaneously is mathematically calculated and discussed at 2-link robot arm model. Moreover, combined dynamics motion control using as mentioned drive and machine learning control is taken into account.**

***Keywords* — Bi articular-simultaneous drive, d'Alembert's principle, Lagrange equation of motion, Machine learning, Principle of virtual work**

I. Introduction

Technology of dynamic motion 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, there are some differences between these conventional humanoid robots and biological objects from the point of mechanism and its control. Therefore, the motion control conception for a humanoid robot has been reconsidered little by little by some researchers who study about biology and medical science. When we focus on the muscle composition of human beings which connects a joint and a link, we have one characteristic muscle, which is called a bi-articular muscle.

The left part in Fig.1 shows the top view of an arm model. Human being has bi-articular muscles like e5 and f5 as illustrated in Fig. 1. One of the characteristic of a bi-articular muscle is that it connects between two joints and the bi-articular muscles generate the contractive force to those joints simultaneously. All quadruped and biped animals have the bi-articular muscles, and it is said that standard motions using the bi-articular muscles are realized without any complicated dynamic calculations[1].

On the contrary, the simultaneous actuation of two joints by a bi-articular muscle was not considered in conventional designs of artificial humanoids. They have for instance, rotational motors at their cubital and shoulder joints, which operate individually as the role mono-articular muscles. With such hardware configuration, an operator absolutely needs calculating complicated inverse kinematics and it needs a lot of calculation costs to the computer.

Right part of Fig. 1 shows a measurement result of signals of each muscle, in the case that it was measured by Electromiogram (EMG) when a human generates a torque to a tip on static state. According to the previous research as [1], relationship between the magnitude of each muscle force and the force characteristics of the tip point has already confirmed.

For instance, when the human subject tries to generate a force from the tip point to direction D1 in the figure, it is measured that muscles of f1, e2 and e3 respond. Then, the direction of the force is changed a little bit toward D2, bi-articular muscles e3 and f3 cooperate and balance the force on the tip point. Muscles f1 and e2 keep the initial muscle force respectively at the moment. These alternations of each muscle force are depending on linear function as illustrated in the EMG result of Fig. 1. Therefore, magnitude and direction of the force on the tip point is controlled easy force control of cooperated muscles and existence of bi-articular muscles and its simultaneous drive for adjacent joints are quite important[1].

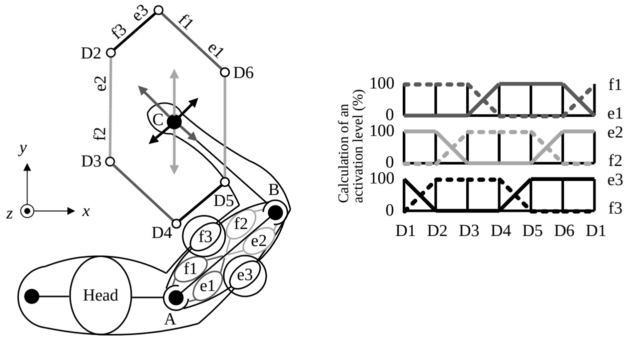

Fig. 1. Force direction from EMG measurement on static condition[1].

In this paper, possible advantages of the bi-articular simultaneous drive are mathematically summarized from engineering point of view. In addition, dynamic motion in case the tip of the arm moves straightly is also mathematically analyzed for the explaining substantial engineering advantages of considering a bi-articular muscle mechanism in the robot arm. Finally, concept of machine learning control in order to compensate the nonlinear part of the calculation model during the motion is discussed. Basically, each muscle force is treated as each actuator torque in this paper.

II. Characteristics Of Force On The Tip Point With Consideration Of Bi-Articular Simultaneous Drive

The authors have already mathematically calculated and discussed about the static characteristics of previous research[1], for example in [2]. Consequently, it is simply explained in order to show the consideration with bi-articular simultaneous drive to a humanoid robot.

First, relationship between the magnitude and the direction of the force on the tip point and characteristics of each muscle force on the static condition is calculated using following 2-link arm model as illustrated in Fig. 2.

Here, the coordinate on the tip point is described as follow when the original point is set to the shoulder point.

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \end{bmatrix} \tag{1}$$

Where, l_1, l_2 mean length of each link (m), and θ_1, θ_2 mean angle of each joint (rad).

Jacobian matrix $\boldsymbol{J}(\theta)$ on the tip point is calculated by the differential of angle as follow;

$$\boldsymbol{J}(\theta) = \begin{bmatrix} -l_1 \sin\theta_1 - l_1 \sin(\theta_1 + \theta_2) & -l_2 \sin(\theta_1 + \theta_2) \\ l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) & l_2 \cos(\theta_1 + \theta_2) \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \tag{2}$$

There is a relationship between joint torques $\boldsymbol{\tau}$ and force of the tip point $\boldsymbol{F}$ from a principle of virtual work. Bi-articular muscles work both joints at the same time.

$$\begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} = \begin{bmatrix} T_1 + T_3 \\ T_2 + T_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} = \boldsymbol{J}(\boldsymbol{\theta})^{\mathrm{T}} \begin{bmatrix} F_x \\ F_y \end{bmatrix} \tag{3}$$

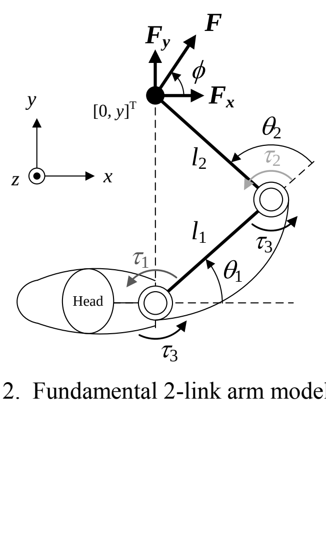

Fig. 2. Fundamental 2-link arm model[2].

When we consider the 2-link model, inverse matrix of Jacobian matrix can be derived by hand.

In (3), joint torques $\boldsymbol{\tau}$ are described using three actuator torques. T_1 and T_2 mean the rotational torques by mono-articular muscles, and T_3 means the rotational torque by bi-articular muscles. When radii of rotation of each joint are assumed as same, (3) represents the simplified coordinates-transformation to the joint torques from these actuator torques[3]. The simultaneous drive of both joints by the bi-articular muscles is described by the factor at the 2th row and the 3th column in the transformation matrix.

In the case that the length of each link is same *i.e.*, $l_1 = l_2 = l$, the force of the tip point $\boldsymbol{F}$ is derived as follows; Also, trigonometrical function is expressed as following values in this paper; where $\cos\theta_1 = \mathrm{C}_1$, $\sin(\theta_1+\theta_2) = \mathrm{S}_{12}$.

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{1}{l^2 \mathrm{S}_2} \begin{bmatrix} l\mathrm{C}_{12} & l\mathrm{C}_1 + l\mathrm{C}_{12} \\ l\mathrm{S}_{12} & -(l\mathrm{S}_1 + l\mathrm{S}_{12}) \end{bmatrix} \begin{bmatrix} T_1 + T_3 \\ T_2 + T_3 \end{bmatrix} \tag{4}$$

Furthermore, on specific condition for the bi-articular simultaneous drive is considered in this paper. If we consider that position of the tip point is at the y-axis in Fig. 2, relationship between each joint angle becomes as follow when length of each link is same;

$$2\theta_1 + \theta_2 = \pi, \ \ \mathrm{C}_1 + \mathrm{C}_{12} = 0 \ \text{ and } \ \mathrm{S}_1 = \mathrm{S}_{12} \tag{5}$$

Hence, force on the tip point $\boldsymbol{F}$ can be described as (6) by using actuator torques.

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{1}{l\mathrm{S}_2} \begin{bmatrix} l\mathrm{C}_{12}(T_1 + T_3) \\ l\mathrm{S}_{12}(T_1 - 2T_2 - T_3) \end{bmatrix} \tag{6}$$

This result matches the previous research using EMG measurement and it can be considered that this situation is one of the simple control methods for the external force on the tip point. In addition, x-direction force is depending on the total torque balances of shoulder point T_1 and bi-articular muscle T_3. Furthermore, it has been found that situation of length of each link is same, and maximal value of each actuator torque is same are quite important to control the model simply.

III. Bi-Articular Simultaneous Drive For Dynamic Motion Control

Characteristic of dynamic motion of a 2-link arm model is discussed in this section. In particular, straight motion based on (5) is taken into account. Calculation of motion is mainly based on [2] as well as Section II.

A. Motion equations for the 2-link robot arm system

Lagrange equation of motion has often used since conventional robotics control and this equation is also used in this paper.

TABLE I shows the parameters of 2-link model. It is assumed as same as Section II that length of each joint is same value and radii of rotations of each link are same value.

TABLE I

PARAMETERS OF A 2-LINK ROBOT ARM

θ_i	Angular position of joint *i*
m_i	Mass of link *i*
l_i	Lengh of link *i*
l_{gi}	Length between joint *i* and centre of gravity of link *i*
I_i	Moment of inertia through the centre of gravity of link *i*
τ_ι	Rotational joint torques (τ_1, τ_2)
g	Acceleration of gravity = 9.8 (m/sec^2)

Also, it is assumed that length between joint *i* and centre gravity of link *i* : $l_{g1} = l_{g2} = l/2$, and length of load : l_L and centre of gravity of load on the tip point : $l_{gL} = l_L/2$ respectively.

A cylindrical shape for each link and the load are also assumed. Centre of gravity of link2 with load is calculated as follow;

$$l_{gL2} = l_{g2} + \frac{m_L}{m + m_L}(l_{g2} + l_{gL}) \tag{7}$$

Therefore, moment of inertia of link2 with load can be derived as follows;

$$I_{2L} = I_2 + m_2\left(\frac{m_L}{m+m_L}(l_{g2}+l_{gL})\right)^2 + I_L + m_L\left(\frac{m_2}{m+m_L}(l_{g2}+l_{gL})\right)^2 \tag{8}$$

Equation of motion can be described as (9); where $\boldsymbol{M}(\boldsymbol{\theta})$: an inertia matrix, $\boldsymbol{h}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})$: sum of a centrifugal and Coriolis forces and $\boldsymbol{g}(\boldsymbol{\theta})$: gravity factor. Gravity factor will be needed when the tip of the arm moves *z*-axis direction as illustrated in Fig. 2, however it does not discuss in this paper.

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \boldsymbol{h}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) + \boldsymbol{g}(\boldsymbol{\theta}) \tag{9}$$

The inertia matrix is 2-by-2 square matrix, and its elements are described respectively. Also, sum of centrifugal and Coriolis, and gravity pars are written as follow;

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

$$M_{11} = I_1 + m_1 l_g^2 + I_{2L} + (m_2 + m_L)(l^2 + l_{g2L}^2 + 2ll_{g2L}\mathrm{C}_2)$$

$$M_{12} = M_{21} = I_{2L} + (m_2 + m_L)(l_{g2L}^2 + ll_{g2L}\mathrm{C}_2)$$

$$M_{22} = I_{2L} + (m_2 + m_L)l_{g2L}^2 \tag{10}$$

$$\boldsymbol{h}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}}) = \begin{bmatrix} -(m_2 + m_L)ll_{g2L}S_2\dot{\theta}_2(2\dot{\theta}_1 + \dot{\theta}_2) \\ (m_2 + m_L)ll_{g2L}S_2\dot{\theta}_1^2 \end{bmatrix} \tag{11}$$

$$\boldsymbol{g}(\boldsymbol{\theta}) = g\begin{bmatrix} m_1 l_g \mathrm{C}_1 + (m_2 + m_L)(l\mathrm{C}_1 + l_{g2L}\mathrm{C}_{12}) \\ (m_2 + m_L)l_{g2L}\mathrm{C}_{12} \end{bmatrix} \tag{12}$$

From (9) - (12), angular acceleration of shoulder and elbow joint can be calculated. It is conventionally called as direct dynamic equations.

B. Characteristic of acceleration on the tip point

Characteristics of acceleration on the tip point can be calculated from second order time differential of the coordinate of the tip point.

$$\ddot{\boldsymbol{x}} = \boldsymbol{J}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \dot{\boldsymbol{J}}(\boldsymbol{\theta})\dot{\boldsymbol{\theta}} \tag{13}$$

Finally, the two-dimensional tip acceleration is calculated as (14) by using (9) - (13); where Δ means determinant of the inertia matrix. Also, τ_{hg1} and τ_{hg2} consist of the sum of actuator torques and centrifugal and Coriolis forces and gravity factor respectively.

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} J_{11}M_{22} - J_{12}M_{21} & -J_{11}M_{12} + J_{12}M_{11} \\ J_{21}M_{22} - J_{22}M_{21} & -J_{21}M_{12} + J_{22}M_{11} \end{bmatrix}\begin{bmatrix} \tau_{hg1} \\ \tau_{hg2} \end{bmatrix} - \begin{bmatrix} (l\mathrm{C}_1 + l\mathrm{C}_{12})\dot{\theta}_1^2 + l\mathrm{C}_{12}(2\dot{\theta}_1 + \dot{\theta}_2)\dot{\theta}_2 \\ (l\mathrm{S}_1 + l\mathrm{S}_{12})\dot{\theta}_1 + l\mathrm{S}_{12}(2\dot{\theta}_1 + \dot{\theta}_2)\dot{\theta}_2 \end{bmatrix} \tag{14}$$

C. Calculation of straight motion of the arm

Characteristic of the acceleration of the tip point while the tip moves straightly on the *y*-axis will be investigated in the following paragraphs. First, velocity of *x*-direction on the tip point should be kept zero at the straight motion. It is calculated from time differential of coordinate and each angular velocity under the motion.

$$\dot{x} = -l\dot{\theta}_1 S_1 - l(\dot{\theta}_1 + \dot{\theta}_2)S_{12} = 0 \quad \therefore 2\dot{\theta}_1 + \dot{\theta}_2 = 0 \tag{15}$$

Moreover, situation of *x*-direction acceleration keeps zero is calculated from (14). Therefore, there is a following equation;

$$\frac{\tau_{hg2}}{\tau_{hg1}} = \frac{J_{11}M_{22} - J_{12}M_{21}}{J_{11}M_{12} - J_{12}M_{11}} \tag{16}$$

When we focus on the *y*-direction acceleration on the tip point, sum of actuator torques T_1+T_3 and T_2+T_3 are calculated from as explained equations;

$$T_1 + T_3 = \frac{1}{2}\begin{Bmatrix} -I_1 - m_1 l_g^2 + I_2 + m_2(l_g^2 - l^2) \\ + I_L + m_L(4l_g^2 + 4l_g l_{gL} + l_{gL}^2 - l^2) \end{Bmatrix}\ddot{\theta}_2$$
$$g\{m_1 l_g \mathrm{C}_1 + (m_2 + m_L)(l\mathrm{C}_1 + l_{g2L}\mathrm{C}_{12})\} \tag{17}$$

$$T_2 + T_3 = \frac{1}{2}\begin{Bmatrix} I_2 + m_2(l_g^2 - ll_g\mathrm{C}_2) + I_L \\ + m_L(4l_g^2 + 4l_g l_{gL} + l_{gL}^2 - 2ll_g\mathrm{C}_2 - ll_{gL}\mathrm{C}_2) \end{Bmatrix}\ddot{\theta}_2$$
$$+ (m_2 + m_L)ll_{g2L}\mathrm{S}_2\dot{\theta}_1^2$$
$$+ g(m_2 + m_L)(l\mathrm{C}_1 + l_{g2L}\mathrm{C}_{12}) \tag{18}$$

Consequently, sum of actuator torques T_1+T_3 becomes simple function during the straight motion in the case that angular acceleration of elbow is input information. Because, we do not need to consider the gravity factor at the motion. On the other hand, consideration of nonlinear part due to joint angle is needed for the designing of sum of actuator torques T_2+T_3.

It can be found from (18) that designing of sum of actuator torque T_1+T_3 is close to the consideration of static condition. In fact, designing of T_1+T_3 is directly concerned to the setting of angular acceleration at the dynamic motion and setting of x-direction force at the static condition respectively.

As discussed above, mixed design of dynamic motion control and force control for some external force with bi-articular simultaneous drive will be suggested, if the robot has force sensor on the tip point and encoders for each joint respectively. Because, each joint torque τ, *i.e.*, each sum of actuator torques T_1+T_3 and T_2+T_3 are actually mathematically derived as follow;

$$\begin{bmatrix} T_1+T_3 \\ T_2+T_3 \end{bmatrix} = \begin{bmatrix} \text{eq.}(17) \\ \text{eq.}(18) \end{bmatrix} + \begin{bmatrix} -2l\text{S}_{12} & -l\text{S}_{12} \\ 0 & l\text{C}_{12} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix} \quad (19)$$

(19) is based on d'Alembert's principle. Hence, actuator torques are designed by characteristics of static and dynamic motion as mentioned in this paper[2].

IV. Machine Learning Control Of The Compensation For The Nonlinearity

In this section, control with the nonlinearity of joint torque τ_2 at the straight motion is discussed. Nonlinear factors are depending on joint angles $\boldsymbol{\theta}$ in (18), therefore it is not difficult to compensate by using machine learning control, because joint angles are limited during the straight motion.

Basic mechanism of machine control is simply explained. First, it is assumed that trajectory on the tip point can be measured, and error of the k-th trial is calculated. In addition, it is assumed that a manipulator knows the base trajectory of the motion. Trial error of the trajectory $e(t)$ is described as follow; where $y_k(t)$: k-th trial trajectory, $y_d(t)$: base trajectory

$$e_k(t) = y_k(t) - y_d(t) \quad (20)$$

P-Type or D-Type rules are conventionally used when $y_k(t)$ and $y_d(t)$ are speed information respectively. Block diagram of P-Type rule is shown in Fig. 3 [4]-[5]. We are considering that P-Type rule will be applied for an experimental robot which has rotary encoders at each joint and get angles information respectively. The algorithm would be easily applied, because spatial motion pattern is constant during the straight motion.

Furthermore, compensation of a load on the tip point will be also taken into account using machine learning. However, actuator control is basically simple as long as we treat the motion as (18). Consequently, basic machine learning control as illustrated in Fig. 3 would be directly applied and this easy motion control would be one of the advantages to consider the bi-articular simultaneous drive.

One of the important things is to keep the tip position on the y-axis for the straight motion.

Designing of time dimensional trajectories for some motion on the assumptions of each linear dynamics model would be applied to the control[5].

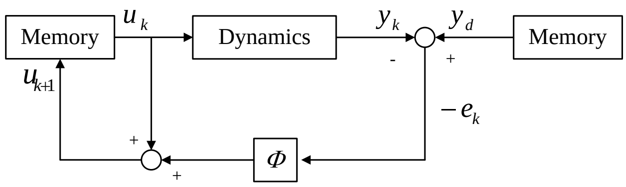

Fig. 3. Block diagram of P-Type learning control[4].

V. Conclusion

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

Especially, characteristics of straight motion for 2-link robot arm have been considered. When we assume that length of each link is same and the tip of the arm is always on y-axis as written in (5), sum of each actuator torque consists of dynamics characteristics and static characteristics based on d'Alembert's principle. As long as we follow this specific condition, actuator torques can be calculated simply from (19). In particular, it has been found that dynamic calculation can be realized simply as (18). Furthermore, machine learning control for the designing of trajectory with nonlinear factors has been also discussed.

As a future work, simple machine learning as illustrated in Fig. 3 will be designed to the straight motion model. Furthermore, actuator control design including the previous research [2] will be also concretely taken into account.

References

[1] Minayori Kumamoto et.al., : "Revolution in Humanoid Robotics," Tokyo, Denki University Press, 2006. (Japanese)

[2] Hiroyuki Fukusho, Takafumi Koseki and Takahiro Sugimoto : "Control of a Straight Line Motion for a Two-Link Robot Arm Using Coordinate Transform of Bi-articular Simultaneous Drive," AMC2010, 2010.3 (Submitted).

[3] Sehoon Oh and Yoich Hori : "Development of Novel Two-Degree-of-Freedom Control for Robot Manipulator with Biarticular Muscle Torque," 2009 American Control Conference (ACC2009), 2009.

[4] Suguru Arimoto : "Control and dynamics of a robot," System, control and information academic society," Asakura-Syoten, 2004. (Japanese)

[5] Norihisa Fukao, "Realization of Feedforward Inputs for Robotic Manipulators based on Time and Space Transformation, Ph. D dissertation of Ritsumeikan Asia Pacific University, 1999.