Gain-Tuning of Sensory Feedback for a Multi-Fingered Hand Based on Muscle Physiology

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Abstract: This paper discusses dynamic characteristics of motion of a pair of multi-degrees of freedom robot fingers executing grasp of a rigid object and controlling its orientation with the aid of rolling contacts. In particular, the discussions are focused on a problem of gain-tuning of sensory feedback signals proposed from the viewpoint of sensory-motor coordination, which consist of a feedforward term, a feedback term for controlling rotational moment of the object, and another term for controlling its rotational angle. It is found through computer simulations of the overall fingers-object dynamics subject to rolling contact constraints that some dynamic characteristics of torque-angular velocity relation may play an important role likely as reported by experimental results in muscle physiology and therefore selection of damping gains in angular velocity feedback depending on the guess of object mass is crucial. Finally, a guidance of gain-tuning in each feedback term is suggested and its validity is discussed by various computer simulations.

Keywords: Stable grasp, Robot fingers, Sensory feedback, Rolling contact, Gain tuning, Force-velocity characteristics

1. INTRODUCTION

The research on concurrent grasp and orientation control of an object by a pair of multi-degrees of freedom robot fingers with hemispherical ends has been carried out in our research group since a few years ago [1] $\sim$ [3]. Firstly, a set of motion equations of the fingers and the object was derived on the basis of Hamilton's principle. Secondly, it was shown that there exists a family of sensory feedback signals that can be constructed by referring to only physical parameters of fingers and measurement data of finger joint angles, their velocities, and the rotational angle of the object. From the passivity analysis, control input was designed for a pair of multi-degrees of freedom robot fingers with hemispherical finger-ends to realize concurrent grasping and orientation control of the object. Thirdly, concurrent grasp and orientation control has been observed through computer simulations and experiments. The noteworthy novelty of this result lies in the use of rolling contacts between finger ends and object surfaces for enhancing dexiterity of motion control. This enabled the use of only a pair of robot fingers to fulfil stable grasp and orientation control in two dimensional motion, regardless of the traditional observation that at least four fingers are needed in the case of grasp of force-torque closure for even 2D polygonal objects and three or four frictional fingers are required to immobilize 2D polygones. However, at this stage, there still remains a problem of best tuning feedback gains for a variety of objects. In fact, it has been observed that transient responses of the closed-loop fingers-object dynamics when a fixed control input is fed becomes more oscillatory with increasing of the object mass. This observation leads us to notice of the experimental results in muscle physiology and the dynamic characteristics between the load on a muscle and the maximum velocity of its shortening in motion of human arms. Hence, a torque-angular velocity model of robot fingers including damping factors are derived and a systematic method of tuning each feedback gain for robot fingers is suggested. Then, the effectiveness of this gain-tuning method is verified by computer simulation of motions of the overall fingers-object system under various load conditions. Further, it is shown that the torque-angular velocity characteristics of a pair of robot fingers using the tuned feedback gains can work well as dynamic force-velocity characteristics of human muscle governs dexterous human motion.

2. DYNAMICS OF 3 D.O.F. ROBOT FINGERS

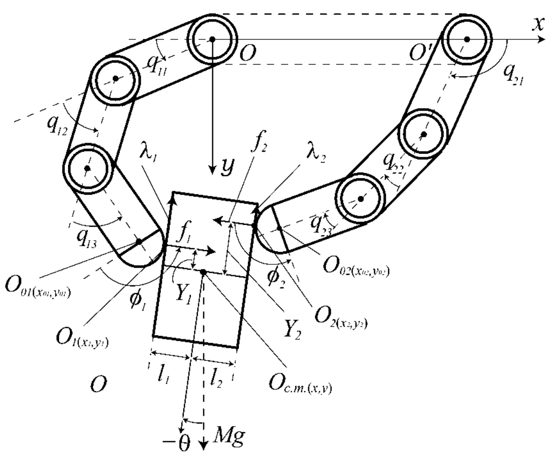

Fig. 1: A finger robot with 3 D.O.F. and an object under the gravity effect

Before discussing the gain-tuning problem of sensory feedback for multi-degrees of freedom robot fingers with hemispherical rigid ends, it is necessary to derive its dynamics. Each finger is made up of 3 D.O.F. and regarded as the thumb and index finger of a human hand, as shown in Fig.1. The object is a rigid rectangular parallelepiped and motion of the overall fingers-object system is confined to the vertical plane under the gravity effect. Firstly, constraint conditions between coordinates O_i and $O_{c.m}$ are shown by the following expressions:

$$\begin{cases} l_1 + r_1 = (x - x_{01})\cos\theta - (y - y_{01})\sin\theta \\ l_2 + r_2 = -(x - x_{02})\cos\theta + (y - y_{02})\sin\theta \end{cases} \quad (1)$$

It is also important to note that Y_1 and Y_2 can be expressed as

$$\begin{cases} Y_1 = (x_{01} - x)\sin\theta + (y_{01} - y)\cos\theta \\ Y_2 = (x_{02} - x)\sin\theta + (y_{02} - y)\cos\theta \end{cases} \quad (2)$$

where r_i denotes the radius of the hemisphere of finger i $(i = 1, 2)$. On the other hand, rolling contacts induce geometric constraints

$$\begin{cases} Y_1 = c_{01} - r_1(\pi + \theta - q_{11} - q_{12} - q_{13}) \\ Y_2 = c_{02} - r_2(\pi - \theta - q_{21} - q_{22} - q_{23}) \end{cases} \quad (3)$$

where c_{0i} expresses the value of Y_i when $\phi_i = 3\pi/2 - (-1)^i\theta - q_{i1} - q_{i2} - q_{i3} = \pi/2$. The values of Y_1 and Y_2 evaluated in eq.(3) must be equal to eq.(2) respectively. Then, it is necessary to introduce Lagrange multipliers λ_1 and λ_2 corresponding to these constraints and define

$$R = \lambda_1 R_1 + \lambda_2 R_2 = 0 \quad (4)$$

$$\begin{cases} R_i = Y_i - c_i + r_i(\pi + (-1)^{i-1}\theta \\ \qquad - q_{i1} - q_{i2} - q_{i3}) = 0, \quad i = 1, 2 \end{cases} \quad (5)$$

It is also convenient to write all geometric relations between O_{0i}, O_i, and $O_{c.m.}$ in the following ways:

$$\begin{cases} x = x_1 + l_1\cos\theta - Y_1\sin\theta = x_2 - l_2\cos\theta - Y_2\sin\theta \\ y = y_1 - l_1\sin\theta - Y_1\cos\theta = y_2 + l_2\sin\theta - Y_2\cos\theta \end{cases} \quad (6)$$

$$\{\ x_1 = x_{01} + r_1\cos\theta, \quad y_1 = y_{01} - r_1\sin\theta \quad (7)$$

$$\{\ x_2 = x_{02} - r_2\cos\theta, \quad y_2 = y_{02} + r_2\sin\theta \quad (8)$$

It is easy to calculate the following partial differentials of R:

$$\begin{cases} \dfrac{\partial R}{\partial x} = -(\lambda_1 + \lambda_2)\sin\theta, \quad \dfrac{\partial R}{\partial y} = -(\lambda_1 + \lambda_2)\cos\theta \\ \dfrac{\partial R}{\partial \theta} = -l_1\lambda_1 + l_2\lambda_2 \end{cases} \quad (9)$$

$$\begin{cases} \left(\dfrac{\partial R}{\partial q_1}\right)^{\mathsf{T}} = \lambda_1 \left\{ J_{01}^{\mathsf{T}} \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix} - r_1 e_1 \right\} \\ \qquad = \lambda_1 \left(\dfrac{\partial R_1}{\partial q_1}\right)^{\mathsf{T}}, \\ \left(\dfrac{\partial R}{\partial q_2}\right)^{\mathsf{T}} = \lambda_2 \left\{ J_{02}^{\mathsf{T}} \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix} - r_2 e_2 \right\} \\ \qquad = \lambda_2 \left(\dfrac{\partial R_2}{\partial q_2}\right)^{\mathsf{T}} \end{cases} \quad (10)$$

where $q_i = (q_{i1}, q_{i2}, q_{i3})^{\mathsf{T}}$, $e_i = (1, 1, 1)^{\mathsf{T}}$ and J_{0i} denotes the Jacobian matrix defined as $J_{0i} = \partial(x_{0i}, y_{0i}) / \partial(q_{i1}, q_{i2}, q_{i3})$ for $i = 1, 2$. On the other hand, equalities of eq.(1) express contact constraints, which induce scalar quantities as Lagrange multipliers f_1 and f_2 in such a way that

$$Q = f_1 Q_1 + f_2 Q_2 = 0 \quad (11)$$

$$\begin{cases} Q_i = -(l_i + r_i) + (x - x_{0i})\cos\theta \\ \qquad + (-1)^i (y - y_{0i})\sin\theta = 0, \quad i = 1, 2 \end{cases} \quad (12)$$

$$\begin{cases} \left(\dfrac{\partial Q_1}{\partial q_1}\right)^{\mathsf{T}} = -J_{01}^{\mathsf{T}} \begin{pmatrix} \cos\theta \\ -\sin\theta \end{pmatrix} \\ \left(\dfrac{\partial Q_2}{\partial q_2}\right)^{\mathsf{T}} = J_{02}^{\mathsf{T}} \begin{pmatrix} \cos\theta \\ -\sin\theta \end{pmatrix} \end{cases} \quad (13)$$

Now, it is possible to introduce the Lagrangian for the overall fingers-object system, which is defined as

$$L = K - P + Q + R \quad (14)$$

where

$$K = \sum_{i=1,2} \frac{1}{2}\dot{q}^{\mathsf{T}} H_i(q_i)\dot{q}_i + \frac{1}{2}\dot{z}^{\mathsf{T}} H_0 \dot{z} \quad (15)$$

$$P = P_1(q_1) + P_2(q_2) - Mgy \quad (16)$$

where $P_i(q_i)$ denotes the potential energy for finger i, $H_i(q_i)$ denotes the inertia matrix for finger i, and $H_0 = \mathrm{diag}(M, M, I)$ in which M and I stand for the mass and the inertia moment of the object. Applying Hamilton's principle for the variational form

$$\int_{t1}^{t2} \left\{ \delta(K - P + Q + R) + u_1^{\mathsf{T}}\delta q_1 + u_2^{\mathsf{T}}\delta q_2 \right\} d\tau = 0 \quad (17)$$

the Lagrange equation of motion of the overall fingers-object system is obtained as follows:

$$\left\{ H_i(q_i)\frac{d}{dt} + \frac{1}{2}\dot{H}_i(q_i) \right\} \dot{q}_i + S_i(q_i, \dot{q}_i)\dot{q}_i$$
$$-f_i \left(\frac{\partial Q_i}{\partial q_i}\right)^{\mathsf{T}} - \lambda_i \left(\frac{\partial R_i}{\partial q_i}\right)^{\mathsf{T}} + g_i(q_i) = u_i, \ i = 1, 2 \quad (18)$$

$$M\ddot{x} - (f_1 - f_2)\cos\theta + (\lambda_1 + \lambda_2)\sin\theta = 0 \quad (19)$$

$$M\ddot{y} + (f_1 - f_2)\sin\theta + (\lambda_1 + \lambda_2)\cos\theta - Mg = 0 \quad (20)$$

$$I\ddot{\theta} - f_1 Y_1 + f_2 Y_2 + l_1\lambda_1 - l_2\lambda_2 = 0 \quad (21)$$

where $g_i(q_i) = (\partial P_i(q_i)/\partial q_i)^{\mathsf{T}}$ and eq.(18) expresses dynamics of robot fingers, eqs.(19) $\sim$ (21) the object. Then, the sum of inner products between $\dot{q}_i$ and eq.(18) for $i = 1, 2$, $\dot{x}$ and eq.(19), $\dot{y}$ and eq.(20), and $\dot{\theta}$ and eq.(21) respectively is expressed as

$$\dot{q}_1^{\mathsf{T}} u_1 + \dot{q}_2^{\mathsf{T}} u_2 = \frac{d}{dt}(K + P) \quad (22)$$

This shows the energy conservation law of the overall system. In this condition, it is convenient to substitute

$$\begin{cases} \lambda_i = \Delta\lambda_i + \dfrac{Mg}{2}\cos\theta - (-1)^i \dfrac{Mg}{l_1 + l_2}(Y_1 + Y_2)\sin\theta \\ f_i = \Delta f_i + f_d - (-1)^i \dfrac{Mg}{2}\sin\theta \end{cases} \quad (23)$$

into eq.(19)-(21). This results in the form

$$\begin{cases} M\ddot{x} - (\Delta f_1 - \Delta f_2)\cos\theta \\ \qquad + (\Delta\lambda_1 + \Delta\lambda_2)\sin\theta = 0 \\ M\ddot{y} + (\Delta f_1 - \Delta f_2)\sin\theta \\ \qquad + (\Delta\lambda_1 + \Delta\lambda_2)\cos\theta = 0 \\ I\ddot{\theta} - \Delta f_1 Y_1 + \Delta f_2 Y_2 \\ \qquad + l_1\Delta\lambda_1 - l_2\Delta\lambda_2 = f_d(Y_1 - Y_2) \end{cases} \tag{24}$$

From the past papers [2][3], a feedback signal for concurrent stable grasping and orientation control under the effect of gravity is proposed in the following way:

$$\begin{aligned} u_i = g_i(q_i) - c_i\dot{q}_i + \left(\frac{\partial Q_i}{\partial q_i}\right)^{\mathrm{T}}\left\{-f_d + (-1)^i\frac{Mg}{2}\sin\theta\right\} \\ + \left(\frac{\partial R_i}{\partial q_i}\right)^{\mathrm{T}}\left\{-\frac{Mg}{2}\cos\theta + (-1)^i\frac{Mg}{l_1+l_2}(Y_1+Y_2)\sin\theta\right\} \\ + (-1)^i\frac{r_i f_d}{r_1+r_2}(1+k_p)(Y_1-Y_2)e_i \\ + (-1)^i\left(\frac{\partial R_i}{\partial q_i}\right)^{\mathrm{T}}(\beta\Delta\theta + \alpha\dot{\theta}), \qquad i = 1,2 \end{aligned} \tag{25}$$

where $g_i(q_i)$ for $i = 1,2$ denote the gravity terms in motion equations of a pair of fingers.

3. GAIN-TUNING METHOD OF THE FINGER ROBOT ON THE BASIS OF HUMAN MODEL

Although the dynamics of eqs.(18) and (24) and the control input of eq.(25) are fully analyzed in the past papers [2] $\sim$ [4], there still remains a question 'How to choose each feedback gain and damping coefficient'. The reasons are 1) many feedback gains and damping coefficients (Table.1) in order to realize grasp and orientation control of the object at the same time and 2) interactions between each feedback gain and coefficient. The role of each feedback gain, damping coefficient and variable in the designed control input can be discussed by investigating the computer simulation results. The computer simulation is carried out by using the CSM method[6] under the conditions given in Table.2.

Table 1: Feedback gains and damping coefficients

k_p	P-Gain for stable grasping
c	Damping coefficient for stable grasping
α	P-Gain for orientation control
β	Damping coefficient for orientation control

Firstly, in order to see the effects of change of the sensory feedback gain k_p for balancing the rotational moments of the object, we investigate the transient behaviors of $Y_1 - Y_2$ and $\Delta\theta$ while other feedback gains c, β, and α are fixed. As seen in Figs.2 and 3, the transient response of $Y_1 - Y_2$ is improved by increasing of the value of k_p which does not incur any change in $\Delta\theta$. However, larger values for k_p than $k_p = 5.0$ could no more improve the performance of $Y_1 - Y_2$.

Table 2: Physical Paramaters for simulation

l_{ij} ($i = 1,2$ $j = 1,2,3$)	link length	0.04 [m]
$m_{11} = m_{21}$	link mass	0.0450 [kg]
$m_{12} = m_{22}$	link mass	0.0300 [kg]
$m_{13} = m_{23}$	link mass	0.0150 [kg]
$I_{11} = I_{21}$	inertia moment	6.0×10^{-6}[kgm^2]
$I_{12} = I_{22}$	inertia moment	4.0×10^{-6}[kgm^2]
$I_{13} = I_{23}$	inertia moment	2.0×10^{-6}[kgm^2]
$l(l_1 = l_2 = l/2)$	object width	0.03 [m]
L	origin distance	0.064 [m]
$r_1 = r_2$	radius	0.010 [m]

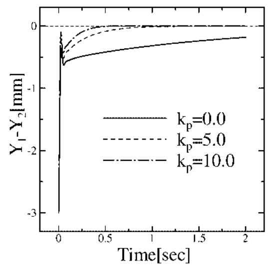

Fig. 2: $Y_1 - Y_2$

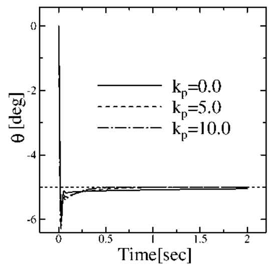

Fig. 3: θ

Secondly, the effects of changes of the damping feedback gain c for motion of fingers are shown in Figs.4 and 5. In this case, other feedback gains k_p, β, and α are fixed. Change of the damping gain c affects considerably the transient behaviour of both $Y_1 - Y_2$ and $\Delta\theta$ as shown in Figs.4 and 5. In this case the object mass is 20 gram. Figs.4 and 5 suggest that the value for c should be set around $c = 0.003$ because choice of larger c than $c = 0.003$ damps both the responses of $Y_1 - Y_2$ and $\Delta\theta$ and that of smaller c than $c = 0.003$ makes the response of them oscillatory. However, as it will be discussed later, the best choice of damping factor c for motion of fingers should depend on the value of the object mass.

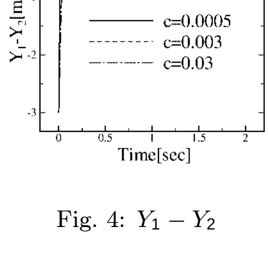

Fig. 4: $Y_1 - Y_2$

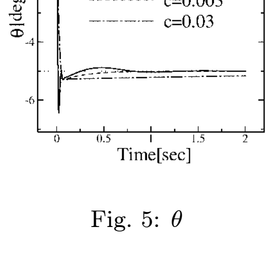

Fig. 5: θ

Thirdly, the effects of the feedback gain β related to regulation of orientation angle of the object on the transient performances of $Y_1 - Y_2$ and $\Delta\theta$ are shown in Figs.6

and 7. If β is chosen too small like $\beta \leq 1.0$, then the convergence of $\Delta\theta$ becomes slow but the response of $Y_1 - Y_2$ becomes less affected. On the contrary, if β is chosen so large like $\beta \geq 10.0$ then the speed of convergence of $\Delta\theta$ to zero becomes higher but both responses of $Y_1 - Y_2$ and $\Delta\theta$ become oscillatory. The best choice for β that compromise improvement of the speed of convergence against the steady response without much oscillation is around $\beta = 5.0$. However, both the transient responses of $Y_1 - Y_2$ and $\Delta\theta$ can be more adequately stabilized by choosing a better gain for α(the velocity feedback gain for the object rotational angle). In Figs.8 and 9 the effects of changes of gain α on the transient responses of $Y_1 - Y_2$ and $\Delta\theta$ are shown. Both convergences of $Y_1 - Y_2$ and $\Delta\theta$ to zero as $t \to \infty$ can be attained even if $\alpha = 0$. Increasing of $\alpha \geq 0$ can damp the oscillatory phenomena of $Y_1 - Y_2$ and $\Delta\theta$ in an early stage of their transient responses, but too much increasing of α induces delay of the response.

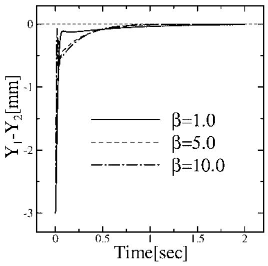

Fig. 6: $Y_1 - Y_2$

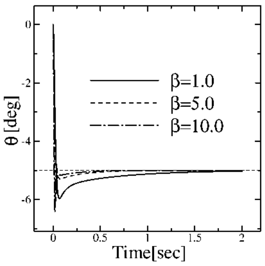

Fig. 7: θ

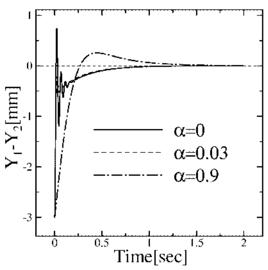

Fig. 8: $Y_1 - Y_2$

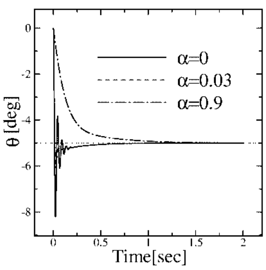

Fig. 9: θ

Fourthly, in Figs.10 and 11 we show how the responses of $Y_1 - Y_2$ and $\Delta\theta$ can be affected by changes of the object mass M while all feedback gains k_p, c, β, and α are fixed. Under such constant gains, the responses become oscillatory with increase of the object mass M. It is worth investigating the result more generally beyond the scope of robot control. In fact this result suggests us that feedback gains must be re-adjusted according to change of the object mass as human can change damping factors of muscles and tendons according to an estimation of the object mass to be grasped. We shall return to this subject later.

Fifthly, various responses are presented in Figs.12 $\sim$ 14 when initial values of sensory feedback signal $Y_1 - Y_2$ are changed. In this case, values of changes of initial $Y_1 - Y_2$ do not affect the convergences of $Y_1 - Y_2$ and $\Delta\theta$. On the other hand, the differences are shown in the responses of angular velocity of the object as predicted in eq.(24). It will be discussed later that the angular velocity of the object can be controlled by adjusting the internal desired force f_d.

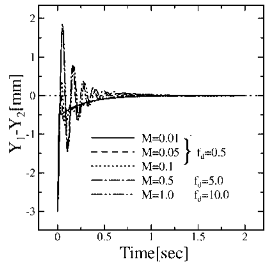

Fig. 10: $Y_1 - Y_2$

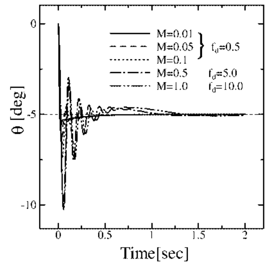

Fig. 11: θ

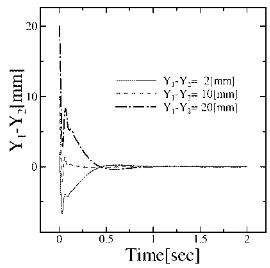

Fig. 12: $Y_1 - Y_2$

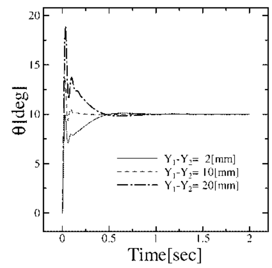

Fig. 13: θ

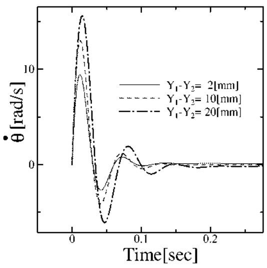

Fig. 14: Angular velocity of the object

Now, let us return to the problem of copeing with arise of oscillatory phenomena when the object masses is changed under constant feedback gains. In relation to this, a famous observation in muscle physiology drew our attention, which says that human regulate damping coefficients of muscle dynamics according to the relevant load. Fenn and Marsh [4] found dynamic characteristics of shortening muscle and Hill [5] showed that the force-velocity relationship could be approximated very closely by the equation

$$(v + b)(P + a) = \text{constant}$$

where P is load, v is shortening velocity, and a and b are positive constants. Then, the torque-angular velocity characteristics for robot fingers can be constructed from investigating the mathematical characteristics of Hill's model as follows:

$$\dot{q}_{\mathsf{max}} \cdot f_{\mathsf{d}}(r_1 + r_2) = \text{constant} = \gamma_1 \quad (26)$$

$$\dot{q}_{\mathsf{max}} \cdot 6c\dot{q}_{\mathsf{max}} = \text{constant} = \gamma_2 \quad (27)$$

where constants a and b are ignored, $\dot{q}_{\mathsf{max}}$ denotes the maximum angular velocity of finger joints, $f_{\mathsf{d}}(r_1+r_2)$ is the total load of two finger-end spheres, $6c\dot{q}_{\mathsf{max}}$ denotes the total of damping torques of six finger joints with assuming $c_1 = c_2 = c$ when $\dot{q}_{\mathsf{ij}}$ attains the approximate maximum speed $\dot{q}_{\mathsf{max}}$. If we intend to fix $\dot{q}_{\mathsf{max}}$ independently of change of the load mass M or f_{d}, then it follows from eqs.(26) and (27) that the damping factor should satisfy

$$\frac{6c}{f_{\mathsf{d}}(r_1+r_2)} = \frac{\gamma_2}{\gamma_1 \dot{q}_{\mathsf{max}}} = \text{constant} \quad (28)$$

Since γ_2/γ_1 must be of the order of r/l_0 where $r = 0.01$ [m] and $l_0 = 0.04$ [m] as shown in Table.2, it follows that

$$\frac{c}{2f_{\mathsf{d}}(r_1+r_2)} = \left(\frac{\gamma_2}{12\gamma_1}\right)\dot{q}_{\mathsf{max}}^{-1} = \frac{1}{3\dot{q}_{\mathsf{max}}} \text{ [s/radian]} \quad (29)$$

This eq.(29) shows a relation between internal desired force f_{d} and object mass M. Therefore, if one of them is decided we can compute another parameter.

The gain-tuning method of finger robots may be summarized as follows:

1. Finding a rough guess $\hat{M}$ of the object mass M.
2. Calculating the desired internal force f_{d} by substituting the estimated mass $\hat{M}$ into the following equation:

$$\frac{\hat{M}g}{f_{\mathsf{d}}} = 1.0 \quad (30)$$

3. Calculating the damping gain c for stable grasping from the following relation:

$$\frac{c}{2f_{\mathsf{d}}(r_1+r_2)} = 0.1 \sim 0.3 \text{ [s/radian]} \quad (31)$$

which can be obtained from eq.(29) if we set $\dot{q}_{\mathsf{max}} = \pi/3 \sim \pi$ [radian/s].

4. Calculating the feedback gain β for regulation of the orientation angle of the object by equating the energies Y and $\mathbf{\Theta}$ discussed in previous our paper [3] at initial time $t = 0$.

$$\mathsf{Y}(0) = \frac{(1+k_{\mathsf{p}})f_{\mathsf{d}}}{2(r_1+r_2)}(Y_1(0) - Y_2(0))^2 \quad (32)$$

$$\mathbf{\Theta}(0) = \frac{\beta l}{2}(\theta(0) - \theta_{\mathsf{d}})^2 \quad (33)$$

where k_{p} is fixed to 5.0 and f_{d} is the known value determined by step 2. From this calculation, an approximate relation $f_{\mathsf{d}}/\beta = 0.1$ is obtained.

5. Calculating the damping gain α for regulation of the orientation angle of the object by equating D_1 with D_2 approximately, where D_1 and D_2 are given as

$$\mathsf{D}_1 = \int_0^{t_0} \sum_{i=1,2} (c_{\mathsf{i}}||\dot{q}_{\mathsf{i}}||^2) d\tau \quad (34)$$

$$\mathsf{D}_2 = \int_0^{t_0} \sum_{i=1,2} (l\alpha|\dot{\theta}|^2) d\tau \quad (35)$$

where t_0 can be chosen around $t_0 = 0.5$(sec). This leads to an approximate relation $c/\alpha = 0.1$.

Computer simulation results by the proposed gain-tuning method are presented in Figs.12 and 13. Both convergences of $Y_1 - Y_2$ and $\Delta\theta$ to desired values respectively are established around at $t = 1.0$.

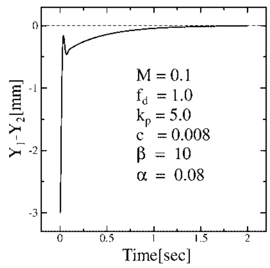

Fig. 15: $Y_1 - Y_2$

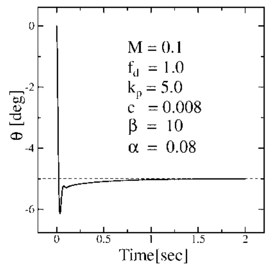

Fig. 16: θ

4. FINGER ROBOTS FROM THE VIEW POINT OF PHYSIOLOGY

Let us now look at robot fingers from different angles. Tracing the history of robotics research, we found that various robots have been designed and made on the basis of human models. This fact shows us that human may be the most advanced existence, which was evolved over a few million years. Therefore, robotics research may be developed more rapidly through unveiling the secret of physical characteristics of human skeltomotor system as well as the central nervous system involved in generation of dexterous limb motions. In this relation,

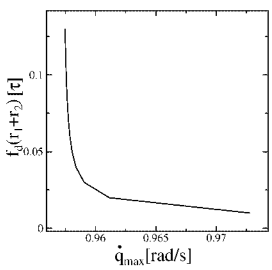

Fig. 17: Torque-angular velocity characteristics

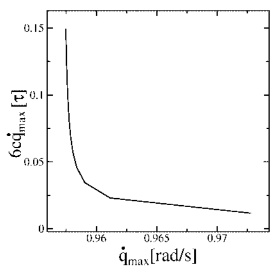

Fig. 18: Torque-angular velocity characteristics

in order to find a similarity of characteristics of motion of the finger robots grasping and object manipulation to Hill's force-velocity relationship, we show in Figs.17 and

18 the torque-angular velocity characteristics experimentally obtained by using the gain-tuning method based on the relations of eqs.(26) and (27). This is in good accord with the force-velocity characteristics in muscle physiology. The characteristics of human-like movement can be also analyzed in other ways by finding important physical relations among physical parameters and feedback gains.

Next, let us consider the ratio of each link length of robot fingers. In order to observe differences between motions in the case of the same link ratio and the human-like finger link ratio, computer simulations are executed under conditions given in Table.3. Here, each link length is selected from the ratio of human fingers and l_{1i} and l_{2i} mean link length of the index finger and the thumb respectively. The results of computer simulation are presented in Figs.19 and 20, when gains computed by the proposed gain tuning method are used. Both transient responses of $Y_1 - Y_2$ and $\Delta\theta$ converge to desired values similarly to the case of the same link length. Furthermore,

Table 3: Physical Paramaters

l_{11}	link length	0.045 [m]
l_{12}	link length	0.025 [m]
l_{13}	link length	0.010 [m]
l_{21}	link length	0.040 [m]
l_{22}	link length	0.035 [m]
l_{23}	link length	0.015 [m]
m_{11}	link mass	0.045 [kg]
m_{12}	link mass	0.030 [kg]
m_{13}	link mass	0.030 [kg]
m_{21}	link mass	0.040 [kg]
m_{22}	link mass	0.035 [kg]
m_{23}	link mass	0.025 [kg]
$l(l_1=l_2=l/2)$	object width	0.03 [m]
L	origin distance	0.064 [m]
$r_1 = r_2$	radius	0.010 [m]

Figs.21 and 22 show comparisons of kinetic energy and dissipated energy respectively when the same initial values of $Y_1 - Y_2$ and $\Delta\theta$ are used. There is a remarkable difference of maximum values of instantaneous kinetic energy of two cases 1) the same link ratio and 2) the human link ratio in Fig.21 but the dissipated kinetic energies are nearly the same as in Fig.22. Not only the maximum value of kinetic energy of the overall system with the human link ratio is by far bigger than that of the same link ratio, but also the convergence speed of dissipated energy of the former case is faster than that of the latter case. This suggests that the ratios between fingers link lengths may play an important role in fast and dexterous execution of grasping and object manipulation.

5. CONCLUSIONS

A systematic method of tuning feedback gains of sensory feedback control for a pair of multi-degrees of

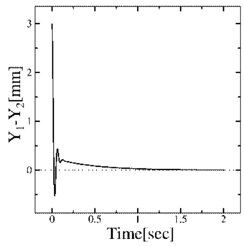

Fig. 19: $Y_1 - Y_2$

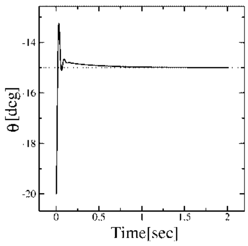

Fig. 20: θ

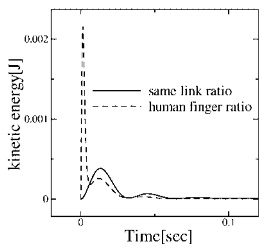

Fig. 21: Trainsient behaviour of kinetic energy

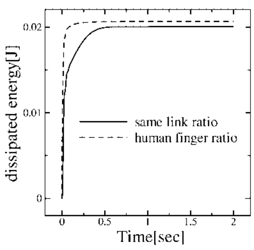

Fig. 22: Trainsient behaviour of dissipated energy

freedom robot fingers with rolling contacts grasping an object is proposed on the basis of a model of torque-angular velocity characteristics of robot fingers by referring to dynamic characteristics of human arms in muscle physiology. It is shown that the torque-angular velocity characteristics in motion of robot fingers tuned by the proposed systematic method is well coincident to the dynamic characteristics muscle shortenig found in muscle physiology.

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