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CPG-Based Manipulation: Adaptive Switchings of Grasping Fingers by Joint Angle Feedback*

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***Abstract*— In this paper, the CPG-based control method for the rotating manipulation that can adaptively change the issuing cycle of motion-triggers is proposed. The CPG model consists of the mutual inhibition network and the rotating manipulation is performed by the motion-triggers that are issued from the CPG model. The smooth change of the desired velocity can be given by the output of neurons that keep smooth increase and decrease. Experimental results using 4-fingered hand system suggest that the issuing cycle of the motion-triggers can be adaptively changed by the feedback of joint angle according to an object size.**

***Index Terms*— Manipulation, Multi-fingered hand, CPG**

I. INTRODUCTION

Human can dextrously manipulate various objects using his/her fingers cooperatively. A number of researches on human's manipulation skills are investigated in the physiology and the occupational therapy[1], [2], [3]. Many engineering approaches based on the theoretical analysis have also been proposed by the studies of grasping and dextrous manipulation using multi-fingered robotic hands in the past years, such as the stability of grasping[4], force optimization[5], and dextrous manipulation using primitive motions[6].

Neurophysiological studies have revealed that rhythmic motor patterns such as locomotion in animals and insects are coordinated by neural circuits referred to as central pattern generators (CPG)[7]. Several studies have been made on the rhythmic pattern generators for locomotion using neural oscillators[8], [9]. However, few approaches based on the analysis of human's rhythmic motions have been proposed for multi-fingered manipulations because the dexterity and the complexity of the manipulation using fingers have been emphasized more strongly than locomotion. Recently, Taguchi et al. have measured the trajectories of human's finger motions during the rotating manipulation of a cylindrical object by a motion capturing system. They have reported that fingers are rhythmically controlled when subjects attain proficiency[10]. This result indicates that CPG-based control is efficient for such rhythmic manipulations.

The rhythmic rotating manipulation has been performed in simulation using motion-triggers that are generated from a CPG model[11]. The period, phase and amplitude of the rhythmic output generated from the CPG model are determined by several parameters of neural oscillators. Moreover, the property of oscillatory output can be changed adaptively by appropriate feedback to the neurons. By using these characteristics of CPG, the manipulation patterns can be adaptively generated according to the change in environments. In this paper, in order to change the switching cycle of grasping fingers adaptively according to the change of an object size, joint angle feedback is used. The experimental results using a multi-fingered hand system suggest that the proposed CPG-based control is efficient for such a rhythmic manipulation.

II. ROTATING MANIPULATION USING A ROBOTIC HAND

A. Rhythmic Manipulation using Fingers

Occupational therapists have proposed various classification methods of human's manipulations using fingers. Exner has classified in-hand manipulations into the following three categories in order to evaluate human's manipulation skills[12]: **Translation:** movements of an object from a palm to finger surface and the vise versa. **Shift:** manipulations by alternating movements of fingers. **Rotation:** manipulations using fingertips to move an object around its axis. In the shift and the rotation, switching motions of grasping fingers are included, for example, regrasping of a pen and rotation of an object.

Rhythmic motions appear in these switching motions of grasping fingers. In rotating motions, because the object rotates only about $\pi/2$ to π [rad] at once, switching motions and rhythmic motions consequently appear. CPG-based control is efficient for shifting and rotating manipulations in that the switching motions are included. In this paper, the CPG-based control for rotating manipulations using a robotic hand is proposed.

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Fig. 1. External view of the multi-fingered hand

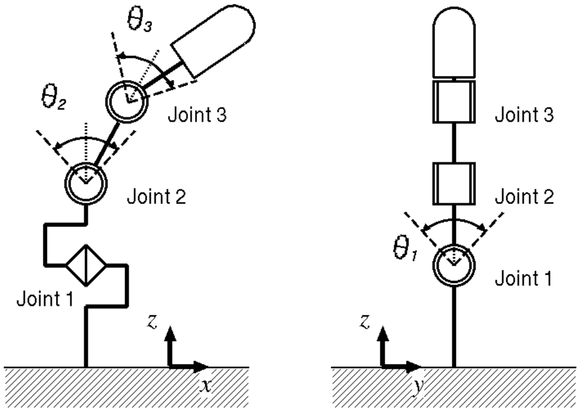


Fig. 2. DOF of the finger

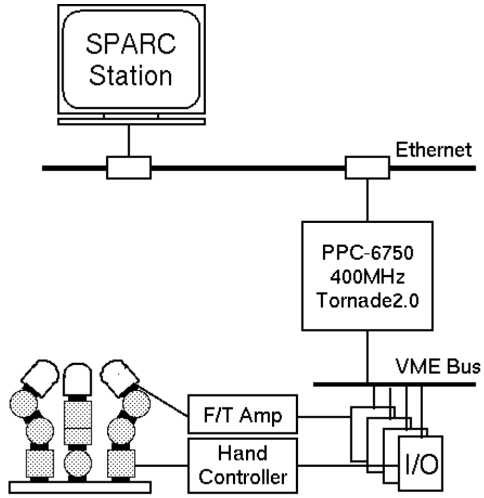
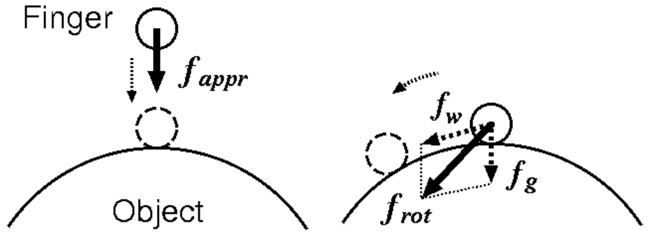
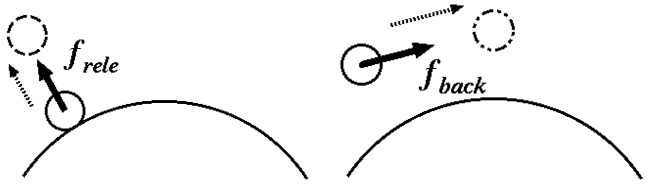


Fig. 3. Multi-fingered hand system



(1) Approach motion (2) Rotation motion



(3) Release motion (4) Back motion

Fig. 4. Finger motions during rotating manipulation

B. Hand System

The multi-fingered robotic hand that has four fingers and mounts a 6-axis force-torque sensor on each fingertip is used for the experiments[13]. Each finger has three degree-of-freedom. The external view of the multi-fingered hand is shown in Fig.1. The construction of the finger and the hardware system are shown in Fig.2 and Fig.3.

The hand system consists of a real-time layer and a non-real-time layer. The real-time layer is implemented in a CPU on the VME Bus and takes the real-time control of fingers. The non-real-time layer is implemented on a SPARC Station and displays various parameters of the system. The communication between both layers are made via Ethernet.

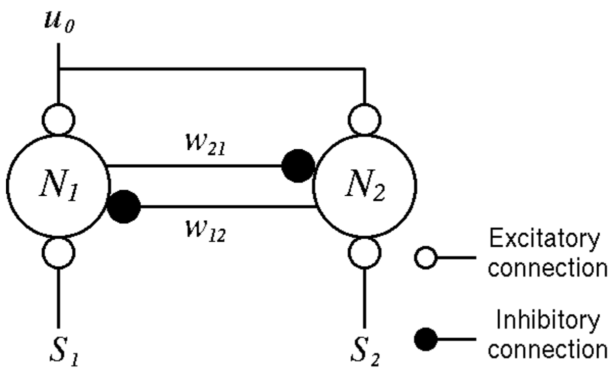
C. Rotating Manipulation based on Rhythmic Pattern from CPG Model

Fingers basically keep iterative motions on a constant trajectory during rhythmic motions. In rotating manipulations, motions of each finger have been classified into the following categories[11]:

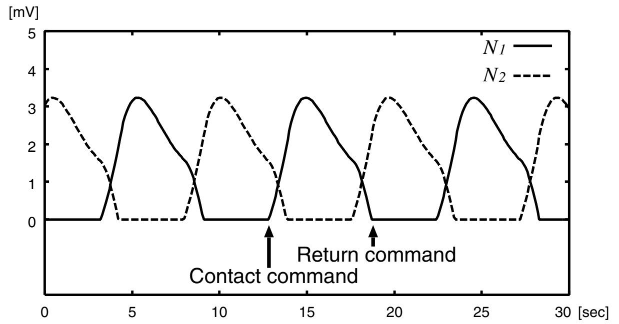
- Touching with the object (approach motion)
- Rotating the object with grasping (rotating motion)
- Releasing from the object (release motion)
- Moving back to the initial point (back motion)

Fig.4 shows motions of each finger under these motion categories. $\boldsymbol{f}_{appr}$ is the force to contact on the object, $\boldsymbol{f}_{rot}$ is the force to grasp and rotate the object, $\boldsymbol{f}_{rele}$ is the force to release from the object, and $\boldsymbol{f}_{back}$ is the force to move back to the initial point. $\boldsymbol{f}_{rot}$ is the resultant force of the grasping force $\boldsymbol{f}_g$ and the rotating force $\boldsymbol{f}_w$.

The rotating motion is taken after the approach motion and the back motion is taken after the release motion. Therefore, rhythmic rotating manipulations can be performed by issuing motion-triggers appropriately; "contact command" that starts the approach motion and the rotating motion, and "return command" that starts the release motion and the back motion. These commands are issued by



(a) CPG model



(b) Output of neurons
$(\tau = 1, \tau' = 9, u_0 = 10, \beta = 6, w_{ij} = 1.8, S_i = 0)$

Fig. 5. Constructed CPG model and its output

the neuron oscillators that construct a CPG. In this paper, the neural oscillator model that is proposed by Matsuoka[8] is adopted. The neural oscillator can be mathematically represented by the following non-linear equations:

$$\tau \dot{u_i} = -u_i - \beta v_i + \sum_{j=1}^{n} w_{ij} y_j + u_0 + S_i \qquad (1)$$

$$\tau' \dot{v_i} = -v_i + y_i \qquad (2)$$

$$y_i = f(u_i) \qquad (\, f(u_i) = \max(0, u_i)\,) \qquad (3)$$

where u_i is an inner state of the i-th neuron, v_i is a variable representing the degree of adaptation or self-inhibition, y_i is output of the neuron, u_0 is external input with a constant rate, S_i is a feedback signal, w_{ij} is a connecting weight between i-th and j-th, β is an adaptation constant, τ and τ' are time constants of the inner state and the adaptation respectively.

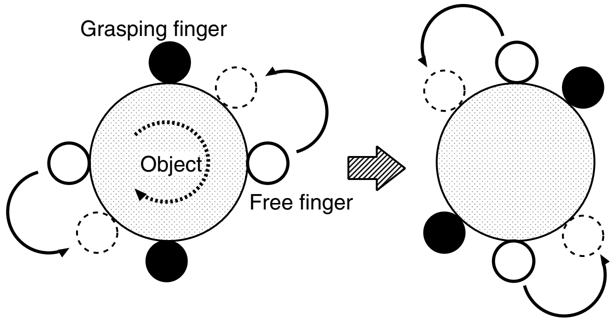


Fig. 6. Switching motions of grasping fingers during rotating manipulation

The mutual inhibition network that consists of two neurons N_1 and N_2 is shown in Fig.5(a) and the rhythmic output generated from each neuron is shown in Fig.5(b). The contact command is issued when output of the neuron becomes $y_i > 0$ from $y_i = 0$ and the return command is issued when the output becomes $y_i = 0$ from $y_i > 0$. Switching motions of grasping fingers in rotating manipulations using a four-fingered robotic hand can be taken as shown in Fig.6. In the manipulation, a set of facing two fingers moves synchronously. The neurons N_1 and N_2 are assigned to each set of facing fingers and each neuron issues motion-triggers to fingers. Accordingly, the rotating manipulation can be performed.

III. ADAPTIVE CHANGE OF SWITCHING CYCLE BY JOINT FEEDBACK

A. *Effect of Movable Range during Rotating Manipulation*

Switching cycle of grasping fingers during rotating manipulations is affected by movable range of joints. When the movable angle of the finger that is shown in Fig.2 is restricted, the movable area of the finger can be shown in the meshed area of Fig.7. This indicates that the rotatable angle of an object in one cycle changes depending on the size of the object.

Because switching motions of fingers themselves do not make a contribution to rotation of an object, too many switchings of grasping fingers are not preferable from the point of energy efficiency. Therefore, the grasping fingers should move up to the limit of the movable range. The limit of the movable range can be calculated by the length of each link, the movable range of joints, and the diameter of the object. However, it is difficult to measure strictly the diameter of the object without the object model.

Neuron oscillators have characteristics in that the output of neurons is synchronized to oscillatory input to the feedback S_i in Eq.(1) when the frequency of the oscillatory input is sufficiently close to that of neuron oscillators. The issuing cycle of the motion-triggers can be adaptively changed by joint angle feedback to neurons.

B. *Joint Angle Feedback*

When the jth joint angle of the ith finger is denoted by θ_{ij}, the movable range of the joint can be given by $C_{ij\,\min} \leq \theta_{ij} \leq C_{ij\,\max}$ where $C_{ij\,\min}$ and $C_{ij\,\max}$ are the minimum and the maximum movable angle of the joint respectively. Now, the joint margin m_{ij} is defined as the following:

$$m_{ij} \triangleq \min\left(\left|C_{ij\,\min} - \theta_{ij}\right|, \left|C_{ij\,\max} - \theta_{ij}\right|\right) \qquad (4)$$

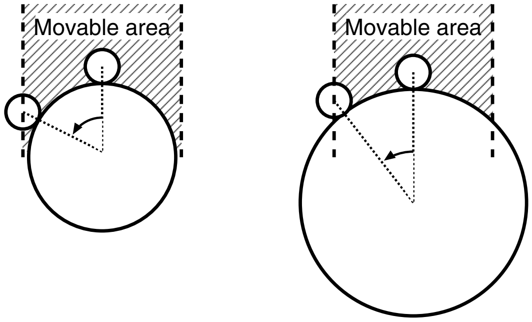


Fig. 7. Effect of movable area during rotating manipulation

the joint margin gets close to 0 as the jth joint angle is close to the limit. Furthermore, total joint margin of the ith finger is defined as following:

$$n_i \overset{\triangle}{=} \min\left(m_{i1}, \cdots, m_{ij}, \cdots, m_{iN_j}\right) \tag{5}$$

where N_j is the number of joints. The total joint margin n_i is the joint margin of the ith finger that is the closest to 0 among all the joints.

The feedback S_i in Eq.(1) is given by the following equations using the total joint margins:

$$\begin{aligned} S_1 &= k_s \min\left(a_1 n_1, \cdots, a_i n_i \cdots, a_{N_f} n_{N_f}\right) && (6) \\ S_2 &= k_s \min\left(b_1 n_1, \cdots, b_i n_i \cdots, b_{N_f} n_{N_f}\right) && (7) \end{aligned}$$

where a_i is the variable that is 1 when ith finger is the grasping finger and 0 when the finger is the free finger, b_j is the variable that is 1 when ith finger is the free finger and 0 when the finger is the grasping finger, and k_s is the feedback gain.

C. Control of Fingers

Fingers during manipulations can be classified into grasping fingers and free fingers from the viewpoint of function. The grasping fingers keep grasping an object stably. The free fingers are fingers that move actively to manipulate an object and do not contact with the object surface in switching motions. If a soft finger contact is assumed between the fingertip and the object surface, the force of the grasping finger have to satisfy the following equations:

$$\begin{aligned} \sum_{i=1}^{N_f} a_i \boldsymbol{f}_i &= -\sum_{j=1}^{N_f} b_j \boldsymbol{f}_j - \boldsymbol{f}_e && (8) \\ \sum_{i=1}^{N_f} a_i \boldsymbol{r}_i \times \boldsymbol{f}_i &= -\sum_{i=1}^{N_f} a_i s_i \boldsymbol{n}_i - \sum_{j=1}^{N_f} b_j \boldsymbol{r}_j \times \boldsymbol{f}_j \\ &\quad -\sum_{j=1}^{N_f} b_j s_j \boldsymbol{n}_j - \boldsymbol{r}_e \times \boldsymbol{f}_e - \boldsymbol{m}_e && (9) \\ \boldsymbol{n}_i \cdot \boldsymbol{f}_i &\geq \frac{1}{\sqrt{1+\mu^2}} \, || \, \boldsymbol{f}_i \, || && (10) \end{aligned}$$

TABLE I

PARAMETERS USED IN THE EXPERIMENT

parameters	value	parameters	value
τ	1	$C_{1\,\min}$	$-\pi/9$ [rad]
τ'	9	$C_{1\,\max}$	$\pi/9$ [rad]
u_0	10	$C_{2\,\min}$	$\pi/2$ [rad]
β	6	$C_{2\,\max}$	$4\pi/9$ [rad]
w_{ij}	1.8	$C_{3\,\min}$	0 [rad]
		$C_{3\,\max}$	$\pi/2$ [rad]

where $\boldsymbol{f}_i$ is the force from the ith finger, $\boldsymbol{r}_i$ is the contact point, $\boldsymbol{n}_i$ is the normal vector of the contact, s_i is the amplitude of the moment, N_f is the number of fingers, and μ is the friction coefficient between the fingertip and the object surface. $\boldsymbol{f}_e$, $\boldsymbol{m}_e$, and $\boldsymbol{r}_e$ are the external force, the moment, and the point of application respectively. Eq.(8) and Eq.(9) indicate the equilibrium condition between the force from the finger and the external force. Eq.(10) indicates the friction condition in that the grasping fingers do not slip on the object surface.

The velocity of the fingertip $\boldsymbol{v}_i$ in order to move an object at translation velocity $\boldsymbol{v}_o$ and rotation velocity $\boldsymbol{w}_o$ is calculated by following equations:

$$\boldsymbol{v}_i = \boldsymbol{v}_o + \boldsymbol{w}_o \times \boldsymbol{r}_i \tag{11}$$

The joint angle is determined by the calculation of the inverse-kinematics to move the desired position based on the fingertip velocity.

In the following experiment, fingers rotate an object along z-axis. The desired rotation velocity of the object w_{oz} is given by output of neurons.

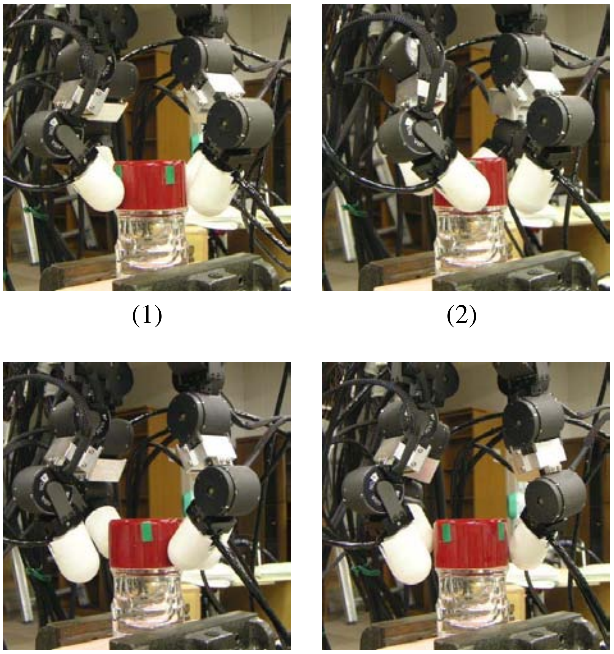
$$w_{oz} = k_w \, y_g \tag{12}$$

where y_g is the neural output of the grasping finger and k_w is the conversion coefficient. Although output cycle of neurons change depending on the object size by the joint feedback, the neural output keep smooth increase and decrease. The smooth change of the desired velocity can be given by the neural output.

IV. EXPERIMENTS

In order to confirm the efficiency of the proposed method, rotating manipulation is performed using the 4-fingered hand system that is described in the section II-B. The robotic hand is fixed downward and rotates a cylindrical object whose diameter is 50[mm] or 75[mm].

In this experiment, the CPG shown in Fig.5(a) is exploited for the manipulation. The output of the N_1 neuron is assigned to the first and the third fingers, and the output of the N_2 neuron is assigned to the second and the fourth fingers. The approach, rotation, release, and back motion are performed by the motion-triggers (the contact/release commands) issued by each neuron. The amplitude of the neural output is assigned to the desired angular velocity



(1) (2)

(3) (4)

Fig. 8. Experimental scene

of the object. The parameters of the CPG model and the movable range of the joint are shown in Table I.

The output of the N_1 neuron y_1, the feedback value S_1, and the desired rotation velocity w_{oz} for 30[sec] during the manipulation of each object are shown in Fig.9(a) and (b) respectively. The joint angle of the first finger that is given by the calculation of the inverse-kinematics to move the desired position and the movable limit of the first joint ($\pi/9$[rad]) are also shown in Fig.9(c) and (d). When the output of the neuron y_1 exceeds 0 (**A** and **C** in the figures), the contact command is issued to a set of facing two fingers (the first and the third fingers) and the fingers begin to rotate the object after the contact. When the output of the neuron y_1 becomes 0 (**C** in the figures), the return command is issued to the fingers and the fingers begin to move back to the initial position after the release. The desired rotation velocity during the rotation (from **A** to **B** in the figures) is given by Eq.(12) The conversion coefficient is set $k_w = 0.0004$.

The joint angle increases or decreases in the rotation motion and the finger moves back to the specified initial position in the back motion. Since the motion-triggers are issued iteratively, the joint angle oscillates during the manipulation. In the experiment, the angle of the first joint at the initial position in the back motion is 0[rad] (**a** in the figures) and the angle increases in the rotation motion (**b** in the figures). Since the first joint has the smallest movable range, the angle of the first joint has the dominant effect on the feedback value S_i. When the object whose diameter is 50[mm] is manipulated, the feedback value increases by the rotation motion (**D** in the figure) because the joint margin after the start of the rotating motion is larger than that at the start position. However, the feedback value decreases as the joint moves close to the movable limit (**E** in the figure). When the object whose diameter is 75[mm] is manipulated, since the feedback value similarly increases by the rotation motion (**F** in the figure), the value decreases quickly (**G** in the figure) and the angle of the first joint reaches the movable limit (**c** in the figure) because the joint angle largely changes according to the object size.

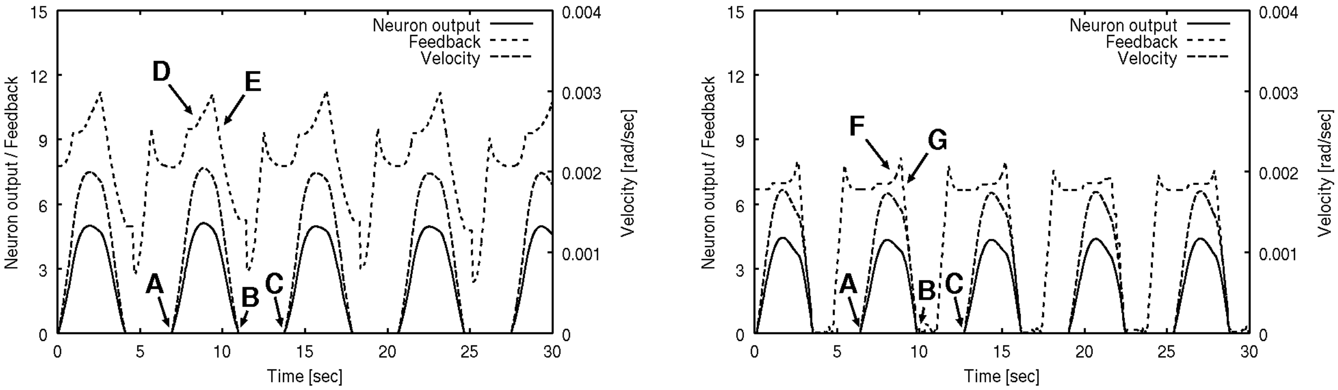
It can also be observed that the output cycle of the neuron changes depending on the size. When the object's diameter is 50[mm], it is about 7.9[sec] in a cycle (a period between **A** and **C** in the figures), and when the diameter is 75[mm], it is about 6.3[sec] in a cycle.

The feedback value during the non-contact period (a period between **B** and **C**) is not so changed if the object size is different because the release motion and the back motion during the non-contact period are not changed. Accordingly, the time during the non-contact period is almost the same (about 2.9[sec] when the object is 50[mm] and about 2.8[sec] when the object is 75[mm]). The difference of the cycle is mainly affected by the difference of the time during the contact period (about 5.0[sec] when the object is 50[mm] and about 3.5[sec] when the object is 75[mm] in a period between **A** and **B**). The difference of the cycle affects the rotation angle of the object in one cycle. The rotation angle in one cycle is about $\pi/3$[rad] when the object is 50[mm] and $\pi/4$[rad]when the object is 75[mm].

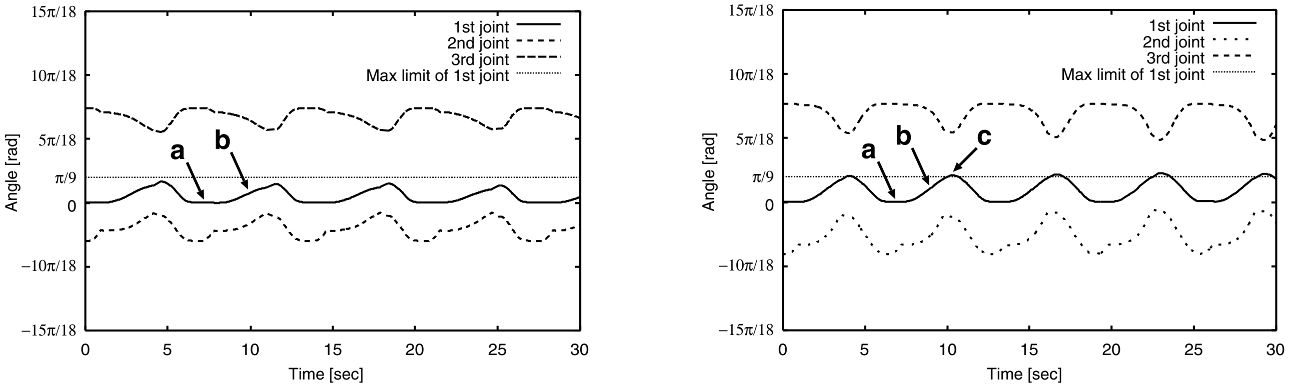
These experimental results suggest that the issuing cycle of the motion-triggers are adaptively changed by the feedback of the joint angle and the object is rotated for appropriate angle according to the object size. Furthermore, the smooth change of the desired velocity can be given by the neuron output that keeps smooth increase and decrease.

V. CONCLUSION

When a person rotates an object, switching motions of grasping fingers is rhythmically performed in the manipulation. CPG-based control is efficient for such rhythmic manipulations. In this paper, the CPG-based control method for rotating manipulations that can adaptively change the issuing cycle of motion-triggers is proposed. The rotating manipulation is performed by the motion-triggers from a CPG model. In the experiment, the rotating manipulation consists of approach, rotation, release, and back motions that are performed by the motion-triggers. The 4-fingered hand system is used for the manipulation and the CPG model is constructed by the simple mutual inhibition network that consists of two neurons. Experimental results suggest that the issuing cycle of the motion-triggers are changed by the feedback of joint angle according to the object size. Furthermore, a smooth change of the desired velocity can be given by neural output that keeps smooth increase and decrease.



(a) N_1 neuron output, feedback and velocity (R=50[mm]) (b) N_1 neuron output, feedback and velocity (R=75[mm])



(c) Joint angle of the first finger (R=50[mm]) (d) Joint angle of the first finger (R=75[mm])

Fig. 9. Experimental results during the rotating manipulation

The rotating manipulation has been performed only along z-axis in the experiment, but the proposed method can be applied on other in-hand rhythmic shift and rotation manipulation. In the studies of CPG-based walking control for multi-legged robots, various methods of the adaptive walking control on the rough terrain have been proposed [14]. In these researches, the neurons of the mutual inhibition network are correlated with the extension and the flexion of joints and a reflex system that is triggered by peripheral nerves is utilized for the adaptive walking. These method can be applied on the CPG-based manipulation and future works consider these applications.

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