

A Joint Motion Planning Based on a Bio-Mimetic Approach for Human-like Finger Motion

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Abstract: Grasping and manipulation by hands can be considered as one of inevitable functions to achieve the performances desired in humanoid operations. When a humanoid robot manipulates an object by his hands, each finger should be well-controlled to accomplish a precise manipulation of the object grasped. So, the trajectory of each joint required for a precise finger motion is fundamentally necessary to be planned stably. In this sense, this paper proposes an effective joint motion planning method for humanoid fingers. The proposed method newly employs a bio-mimetic concept for joint motion planning. A suitable model that describes an interphalangeal coordination in a human finger is suggested and incorporated into the proposed joint motion planning method. The feature of the proposed method is illustrated by simulation results. As a result, the proposed method is useful for a facilitative finger motion. It can be applied to improve the control performance of humanoid fingers or prosthetic fingers.

Keywords: Humanoid fingers, human-like finger motion, joint motion planning, interphalangeal coordination of human finger.

1. INTRODUCTION

Recently, many research groups have directed their attention to develop intelligent humanoid robots [1] with walking capability. In order to achieve the performances desired in humanoid operations, grasping and manipulation by hands can be considered as one of inevitable functions. A lot of researches on multi-fingered robot hands performed can be adopted to accommodate a variety of tasks of humanoid robots [2-5]. Some researchers tried to mimic the skills of human hands for dexterous robotic and prosthetic hands [6,7]. Since the manipulation tasks by multi-fingered hands should be realized by ultimately the actions in the joint coordinates, a methodology that plans effectively a joint motion of humanoid fingers is still considered as one of essential research topics for dexterous hand operations. Actually, it is closely related to comfortable hand control.

In practice, the joint configuration of a finger is very important in multi-fingered operations. Especially, if a finger has certain redundancy, there

exists certain preferable configuration depending on the purpose of a given task, and it is not easy to take an effective joint configuration due to the redundancy. In this field, Yoshikawa suggested a manipulability criterion as one measure to determine an effective posture of robot manipulators with multiple joints [8]. Chiu also presented a compatibility index as a basis to determine a posture of redundant manipulators [9]. These studies were mainly applied to resolve the singularity posture of a manipulator as well as to avoid obstacles. Some researchers have been concerned about characterizing the interphalangeal relationship in a human finger [10,11]. Recently, Secco *et al.* [12] presented a minimum jerk-based motion planning approach for a prosthetic finger. Their work is thought to have two main contributions. The first contribution is the suggestion of a jerk-based motion planning at the Cartesian space of a finger. The second one is to find a constant joint relation minimizing a jerk function defined at the joint space and utilize it to analytically solve the inverse kinematics of a human middle finger with three joints. By their approach, it is found that the third joint of the middle finger should actuate identically as the second joint. Unfortunately, the motion ranges of those two joints in the middle finger are not usually identical [11,13]. Moreover, since the method doesn't consider the phalangeal length parameters, they may suffer from making a consistent grasp configuration in multi-fingered cases with different dimension. Hasegawa *et al.* [14] proposed a grasp planning algorithm for a hand-arm system. When a humanoid

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robot tries to perform a dextrous manipulation by his hands, in fact, it is very desirable to make a human-like finger motion.

For implementing a human-like finger motion, this paper proposes a simple and useful joint motion planning method based on an interphalangeal coordination existing in human fingers. Particularly, this method provides an effective initial finger configuration for a manipulating task, and also guides the finger to plan a real joint configuration required for a desired fingertip motion.

2. KINEMATICS AND DYNAMICS OF HUMANOID FINGERS

Consider a human hand of Fig. 1 which shows a typical flex posture. In order to lead a joint motion planning technique for humanoid fingers, this paper especially focuses on the planar motion of the index finger with three joints in Fig. 1. A humanoid finger defined in this paper means a finger attached in a hand of humanoid robots. Physically, it also implies that each joint of a humanoid finger actuates within a certain feasible range as human fingers.

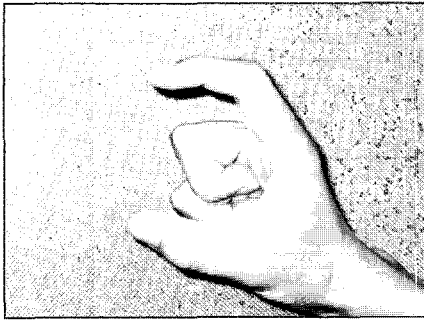


Fig. 1. A human hand with a posture.

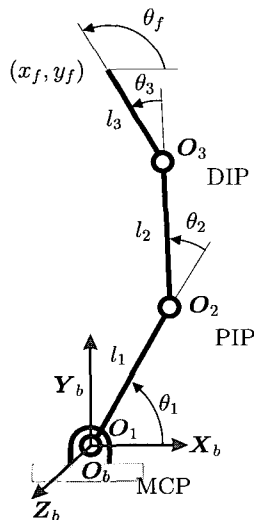


Fig. 2. A planar schematic structure of the index finger.

For the purpose of describing the kinematic and dynamic relations, the index finger has been modeled as a representative humanoid finger with three revolute joints as shown in Fig. 2. Each link of the finger $l_i (i=1,2,3)$ corresponds to the proximal, middle, and distal phalanges in the index finger of a human hand, respectively, and each joint at the coordinate frame $O_i (i=1,2,3)$ can be considered as the MCP(Meta Carpo Phalangeal), PIP(Proximal Inter Phalangeal), and DIP(Distal Inter Phalangeal) joints, respectively [15]. Then, from the coordinate system, the kinematic relations of the finger are described by

$$x_f = l_1 c_1 + l_2 c_{12} + l_3 c_{123}, \tag{1}$$

$$y_f = l_1 s_1 + l_2 s_{12} + l_3 s_{123}, \tag{2}$$

$$\theta_f = \theta_1 + \theta_2 + \theta_3, \tag{3}$$

where x_f and y_f denote the x - and y -directional positions of the fingertip, respectively, and θ_f denotes the posture(or orientation) of the fingertip. The abbreviated parameters are defined as follows; $s_i = \sin(\theta_i)$, $s_{ij} = \sin(\theta_i + \theta_j)$, $s_{ijk} = \sin(\theta_i + \theta_j + \theta_k)$, $c_i = \cos(\theta_i)$, $c_{ij} = \cos(\theta_i + \theta_j)$, and $c_{ijk} = \cos(\theta_i + \theta_j + \theta_k)$.

By differentiating (1) and (2) with respect to time, the velocity relation between the joint space and the fingertip space is given by

$$\dot{u}_f = [G_\phi^f] \dot{\phi}, \tag{4}$$

where

$$\dot{u}_f = [\dot{x}_f \ \dot{y}_f]^T, \tag{5}$$

$$\dot{\phi} = [\dot{\theta}_1 \ \dot{\theta}_2 \ \dot{\theta}_3]^T, \tag{6}$$

and G_ϕ^f denotes the Jacobian matrix relating the joint space (ϕ) to the fingertip space (f). The Jacobian matrix can be expressed as

$$G_\phi^f = \begin{bmatrix} -l_1 s_1 - l_2 s_{12} - l_3 s_{123} & -l_2 s_{12} - l_3 s_{123} & -l_3 s_{123} \\ l_1 c_1 + l_2 c_{12} + l_3 c_{123} & l_2 c_{12} + l_3 c_{123} & l_3 c_{123} \end{bmatrix}. \tag{7}$$

Next, by using the modeling methodology based on the generalized principle of D'Alembert, the dynamic model of a finger has the following form:

$$I_{\phi\phi}^* \ddot{\phi} + \dot{\phi}^T P_{\phi\phi\phi}^* \dot{\phi} = \tau_\phi - \tau_{\phi c}, \tag{8}$$

where $I_{\phi\phi}^*$ and $P_{\phi\phi\phi}^*$ denote the effective inertia matrix and the inertia power array, respectively [16].

τ_ϕ denotes the torque vector at the joint space which is made by a control law employed. τ_{ϕ_c} implies the torque vector at the joint space which reflects the contact force at the fingertip space, e.g. internal and external forces, and it is obtained by

$$\tau_{\phi_c} = [G_\phi^f]^T f_c, \quad (9)$$

where $[G_\phi^f]^T$ is the transpose of the Jacobian matrix. In planar space, the contact force vector at the fingertip space f_c is given by

$$f_c = [f_{cx} \quad f_{cy}]^T. \quad (10)$$

Note that the index finger of a human in Fig. 2 can be considered as a kinematically redundant mechanism with three degree-of-freedom and there are infinite finger configurations for a fingertip position. Thus, it is required to have an effective method that determines an adequate joint configuration of the finger according to the trajectory desired in the fingertip space. This topic has been formulated as a problem of joint motion planning for humanoid fingers in the present paper. It is valuable for implementing a human-like finger motion when a humanoid robot tries to perform a dextrous manipulation by his hands.

3. JOINT MOTION PLANNING FOR HUMANOID FINGERS

3.1. A bio-mimetic model of interphalangeal coordination

In order to reveal an effective joint motion planning method for humanoid fingers, this paper initially pay attention to typical motions of human fingers in free or constrained space. For example, from a mouse movement for computer works, it is experienced that the human fingers manipulating the mouse usually doesn't handle it without changing their orientations. In other words, the posture of each fingertip is being changed simultaneously as the movement of its position. Also, the posture is available limitedly as shown in Fig. 3. Thus, it is remarked that the motions of human fingers should be imparted within the boundary range of the extension and flexion postures.

Then, let's consider the feasible postures of Fig. 3 in detail. We can find empirically that the motion of the index finger does not exceed the maximum extension boundary. To be specific, the minimum angles of the PIP and DIP joints, given by $\theta_{2,min}$ and $\theta_{3,min}$, can be assigned as 0 degree at the maximum extension posture, respectively. The minimum angle

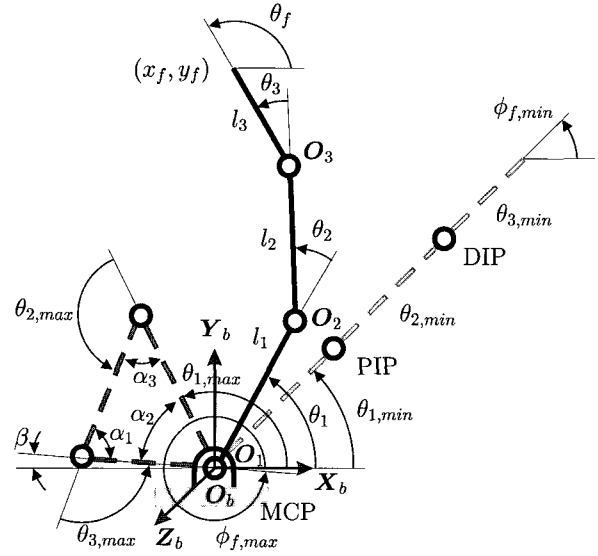


Fig. 3. Feasible postures of the index finger.

of the MCP joint $\theta_{1,min}$ can be measured by properly defining the base coordinate frame of the finger O_b . In this paper, it has been set as 0 degree such that the maximum extension posture of the finger is placed on the axis of X_b .

On the other hand, we need an idea to characterize the maximum motion range of the finger. So, this paper made use of a virtual triangle model that forms the maximum flexion posture as shown in Fig. 3. By using the law of cosines for an arbitrary triangle, the angle α_1 corresponding to the first phalange can be determined by

$$\alpha_1 = \cos^{-1} \left(\frac{(l_2)^2 + (l_3)^2 - (l_1)^2}{2l_2l_3} \right), \quad (11)$$

and also the angle α_3 corresponding to the third phalange can be determined by the law of sines as follows:

$$\alpha_3 = \sin^{-1} \left(\frac{l_3}{l_1} \sin(\alpha_1) \right). \quad (12)$$

In addition, the angle α_2 is given by

$$\alpha_2 = 180^\circ - (\alpha_1 + \alpha_3). \quad (13)$$

Thus, the maximum angles of the PIP and DIP joints of the finger can be expressed by, respectively,

$$\theta_{2,max} = 180^\circ - \alpha_3 \quad (14)$$

and

$$\theta_{3,max} = 180^\circ - \alpha_1. \quad (15)$$

Also, the maximum angle of the MCP joint is determined by

$$\theta_{1,max} = 360^\circ - (\theta_{2,max} + \theta_{3,max}) - \beta, \quad (16)$$

where β denotes the angle from the line of distal phalanx to the horizontal axis of X_b at the flexion posture, and it can be assigned properly according to the purpose of users in real applications. In this paper, β has been set as 0 degree such that the distal phalanx lies on the palm (or the horizontal axis of X_b) at the maximum flexion posture. It is noticeable that the virtual triangle model can give us somewhat interesting relationships for characterizing the maximum motion range of a finger.

Next, an interphalangeal coordination model that prescribes a relative motion of neighboring joints is introduced. In the previous research, Hahn *et al.* [11] and Kamper *et al.* [13] reported that the DIP joint of the index finger in human hands rotates in a certain ratio when its PIP joint rotates, and of course, the ratio is different individually. It is actually experienced that these joints move together in flexion and extension motions. Based on the observation, this paper utilizes an interphalangeal coordinative relationship between DIP and PIP joints as follows:

$$\theta_3 = \lambda \theta_2, \quad (17)$$

where λ is suggested in this paper as λ_o which is determined by

$$\lambda_o = \frac{\theta_{3,max}}{\theta_{2,max}}. \quad (18)$$

This relationship can be applied to the middle, ring, and little fingers of a human hand.

Note that if $l_3 < l_2 < l_1$, $\theta_{3,max}$ is less than $\theta_{2,max}$ so that $\lambda_o < 1.0$. This condition can be observed in normal human fingers. The present paper, unlike the Secco's approach [12], suggests a bio-mimetic interphalangeal coordination ratio that considers the phalangeal geometric motion of a human finger through (11)~(18). Also the idea to determine the bio-mimetic factor given by λ can be applied to general fingers having different dimension. Thus, the proposed approach is more compatible with general humanoid fingers.

3.2. Conventional Manipulability-based Joint Motion Planning (MJP)

This section introduces an algorithm based on the conventional manipulability criterion that determines an effective configuration of fingers with redundancy.

The manipulability concept has been widely used to obtain certain optimal solutions in robotic applications

[8]. Since the manipulability implies the quality of being controllable by skilled movements of a mechanism, it can be applied for us to avoid the singular posture as well as to find a proper configuration of redundant manipulators or fingers. As the literature, the manipulability w for a finger can be represented by

$$w = \sqrt{\det[G_\phi^f [G_\phi^f]^T]}, \quad (19)$$

where $\det[G_\phi^f [G_\phi^f]^T]$ implies the determinant of $G_\phi^f [G_\phi^f]^T$. G_ϕ^f and $[G_\phi^f]^T$ were defined in (4) and (9), respectively.

In order to find an optimal finger configuration for a given fingertip position, it is useful to investigate the manipulability of all possible finger postures that satisfy the feasible range of the finger, and simultaneously, give priority to each finger configuration according to the magnitude of manipulability. In this procedure, it is necessary to check the feasible minimum and maximum postures of the finger which ultimately determine the minimum and maximum joint configurations in practice. Practically, the minimum posture of the finger $\theta_{f,min}$ in Fig. 3, can be given by

$$\theta_{f,min} = \sum_{i=1}^3 \theta_{i,min}, \quad (20)$$

and also the maximum posture of the finger can be obtained by

$$\theta_{f,max} = \sum_{i=1}^3 \theta_{i,max}. \quad (21)$$

Thus, a finger configuration can be investigated in the following range:

$$\theta_{f,min} \leq \theta_f \leq \theta_{f,max}. \quad (22)$$

Consequently, a procedure to find an effective finger configuration in a manipulation process can be summarized as follows;

MJP algorithm:

1. Specify a feasible fingertip position, x_f and y_f .
2. Determine the Jacobian G_ϕ^f and $[G_\phi^f]^T$.
3. Find all joint candidates satisfying the range of θ_f in (22) with a proper deviation, $d\theta_f$.
4. Compute the manipulability w by (19) for all joint combinations.
5. Choose the set of joint angles satisfying both the feasible range of each joint, $\theta_{i,min} \leq \theta_i \leq \theta_{i,max}$ ($i = 1,2,3$), and the maximum value of w .

6. Assign these angles as the corresponding joint angles.
7. Repeat all steps for the given trajectory at the fingertip space.

It is remarked that the finger configuration evaluated by the *MJP* algorithm is optimal in terms of manipulability criterion. So, it is possible to obtain a skillful finger configuration by using this approach. However, it should consider some computing time for the procedure to find an optimal finger configuration at each sampling time.

3.3. Proposed Interphalangeal Coordination-based Joint Motion Planning (*ICJP*)

This section proposes a methodology to find a suitable joint configuration of a humanoid finger that supports the desired trajectory of the fingertip during a manipulation process. It is based on the interphalangeal coordination model described in Section 3.1.

Once an initial finger configuration in a manipulation process has been determined, it is necessary to confirm the original λ given by (18) whether it is compatible with the initial configuration. To do that, an additional factor λ_s has been chosen by

$$\lambda_s = \frac{\theta_{3s}}{\theta_{2s}}, \quad (23)$$

where θ_{3s} and θ_{2s} represent the initialized angles of the DIP and PIP joints of a finger as shown in Fig. 3, respectively. Hopefully, the *MJP* algorithm can be used to determine those initial joint angles. If the magnitude of λ_s is no larger than λ_o , λ assigned by (17) is necessary to be changed as λ_s in (23). This makes the finger work within the feasible workspace of real applications. Thus, the reasonable interphalangeal coordination ratio λ is resultantly assigned by

$$\lambda = \begin{cases} \lambda_s & : \lambda_s \leq \lambda_o \\ \lambda_o & : \lambda_s > \lambda_o. \end{cases} \quad (24)$$

Next, by rearranging (17) and combining (24), the following relation can be obtained by

$$0 = -\lambda\theta_2 + \theta_3. \quad (25)$$

Also, augmenting (4) and (25) yields

$$\dot{u} = G_\phi^u \dot{\phi}, \quad (26)$$

where $\dot{\phi}$ is given by (6),

$$\dot{u} = \begin{bmatrix} \dot{u}_f \\ 0 \end{bmatrix} \text{ and } G_\phi^u = \begin{bmatrix} G_\phi^f \\ G_\lambda \end{bmatrix}$$

with $G_\lambda = [0 \ -\lambda \ 1]$.

Thus, the velocity vector at the joint space can be obtained by

$$\dot{\phi} = G_u^\phi \dot{u}, \quad (27)$$

where G_u^ϕ represents the inverse of G_ϕ^u . As a result the joint angles of the finger can be generally updated by

$$\phi(t + dt) = \phi(t) + \dot{\phi}(t)dt, \quad (28)$$

where dt is the sampling time of the finger control system.

Finally, the above algorithm to plan a finger configuration in a manipulation process can be summarized as follows;

***ICJP* algorithm:**

1. Specify an initial fingertip position, x_f and y_f .
2. Determine an initial joint configuration by using the *MJP* algorithm.
3. Determine λ by (24)
4. Determine the Jacobian G_ϕ^u in (27).
5. Find the next joint angles through (26)~(28) for given \dot{u}_f .
6. Repeat steps 4 and 5 for the given trajectory at the fingertip space.

Since the *ICJP* approach proposed in this paper considers an interphalangeal factor in a human finger, it is bio-mimetic. So, a human-like finger motion can be implemented by this algorithm. It also utilizes one of advantages in the *MJP* algorithm that allows a finger to be placed in the best configuration at the initial stage for a given task. Of course, this is actually not related to the real executing time. In particular, singularity issue can be occurred usually in the case of utilizing an extended Jacobian. However, it is not necessary to worry about that in the present paper because the determinant of G_ϕ^u goes to be zero when only $\theta_2 = 0$ since $\lambda > 0$. This is actually the boundary condition of the workspace which is determined by the motion of the humanoid finger.

4. SIMULATION RESULTS FOR FINGER MOTION ANALYSIS

This section validates the feature of the proposed interphalangeal coordination-based joint motion planning method (*ICJP*).

4.1. Task of a humanoid finger

For simulation studies, let me consider a three-joints humanoid finger as shown in Fig. 2. The

human-scale parameters of the finger is specified in Table 1 and those are assigned as the dimension of the author's index finger multiplied by 1.5. The dynamic link parameters has been modeled by considering their material as Aluminum. The interphalangeal ratio is determined by (18), (23), and (24).

The task of the finger is to follow the x - and y -directional trajectories predefined in planar space as follows:

$$\begin{aligned} x_f &= x_0 + r_x \cos\left(\frac{4\pi}{t_f}t\right) \cos\left(\frac{2\pi}{t_f}t\right), \\ y_f &= y_0 + r_y \cos\left(\frac{4\pi}{t_f}t\right) \sin\left(\frac{2\pi}{t_f}t\right), \end{aligned} \quad (29)$$

where x_0 and y_0 denote the x - and y - directional initial positions of the fingertip. The parameters of r_x and r_y are set as 0.0035 m. t_f is the terminal time for the task. Since the given trajectory consists of a quadrantal curve, it is valuable for analyzing the motion of a finger.

4.2. Initial finger configuration

The procedure of determining the initial joint configuration of the finger has been illustrated in this section. Practically, this procedure is helpful for a finger to be placed in the best configuration at the initial stage for a given task.

Fig. 4 indicates a lot of joint configurations, investigated by the *MJP* algorithm, for an initial position of the fingertip which is given by $x_0 = -0.0225\text{m}$ and $y_0 = 0.0900\text{m}$. The trajectories of the three joints and the manipulability criterion(w) according to each joint set are plotted in Fig. 5. It is

Table 1. Physical parameters of a three-joints humanoid finger.

Items		Humanoid finger	Unit
Length	l_1	0.0750	meter
	l_2	0.0450	
	l_3	0.0375	
Mass	m_1	0.1821	kg
	m_2	0.1093	
	m_3	0.0911	
Inertia	I_{1zz}^c	9.90×10^{-5}	kgm^2
	I_{2zz}^c	2.66×10^{-5}	
	I_{3zz}^c	1.75×10^{-5}	
Interphalangeal ratio	λ	0.3126	

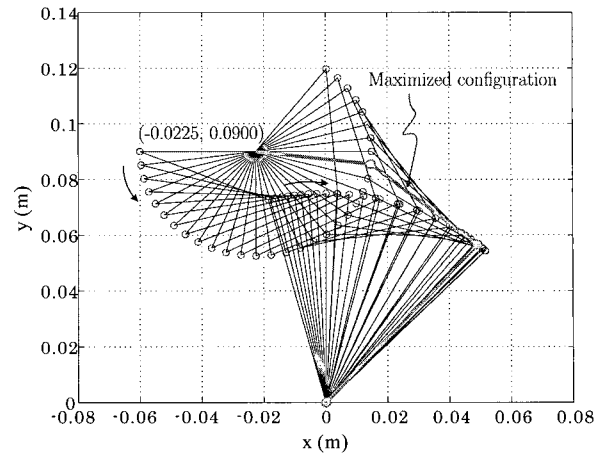


Fig. 4. Evaluation of finger configurations.

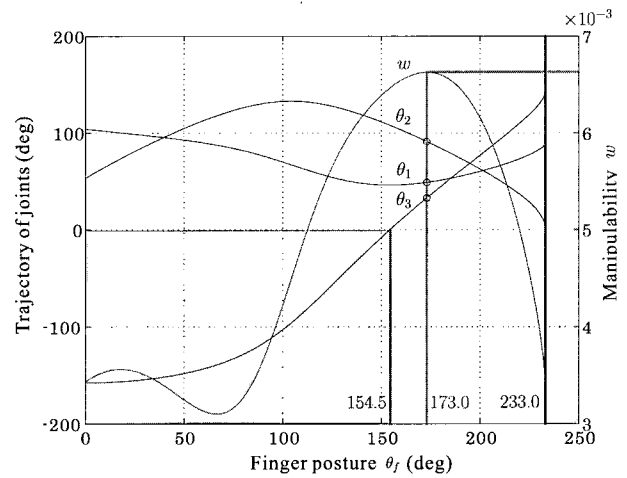


Fig. 5. Trajectory of three joints and the manipulability criterion.

firstly found from Fig. 5 that the third joint angle is less than 0° in the range of the finger posture, given by $\theta_f < 154.5^\circ$. There is no solution satisfying the given initial position of the fingertip in the range of $\theta_f > 233.0^\circ$ and hence, the range can be said as a dead zone. Also, since θ_3 should be larger than $\theta_{3,min}$ for the feasible finger configuration, any feasible joint configuration cannot be obtainable in these ranges. That is, the feasible range of θ_f is decided by $154.5^\circ \leq \theta_f \leq 233.0^\circ$. Therefore, the available initial finger configuration should be found in this region.

Finally, by distinguishing each joint angle satisfying both the feasible range of θ_f and the maximum manipulability, the joint angles for the initial position of the fingertip have been initialized as follows: $\theta_1 = 48.96^\circ$, $\theta_2 = 91.15^\circ$, and $\theta_3 = 32.89^\circ$.

The initial finger posture are resultantly decided by 173.0° . Through the analysis, the maximized configuration indicated in Fig. 4 has been settled as the best initial configuration for the finger. From the initialized configuration, λ_s in (23) is obtained by 0.3609. Thus, the ratio λ in Table 1 has been assigned as λ_o by (18) and (24).

4.3. Joint motion planning and control effects

In order to evaluate the bio-mimetic approach *ICJP* proposed in the present paper, this section reveals several simulation results compared with the optimization-based approach *MJP*. In particular, this section presents the joint trajectory planning for a finger, real joint motion, and control effort for a finger. In fact, the manipulability concept used in *MJP* has been widely used to resolve an optimal posture of a redundant manipulator or a finger. Especially, Yoshikawa [8] prospected that it can be used to find the best finger posture. Even though the *MJP* method is basically adequate for a certain off-line tuning problem, it can be used to obtain an effective finger configuration during a manipulation process of fingers. So, it is worthwhile to analyze the performances by the two approaches.

In this paper, a typical PD(Proportional and Derivative) controller is used for the given task. The joint torque command τ_ϕ in (8) is made by

$$\tau_\phi = K_p \theta_e + K_d \dot{\theta}_e, \quad (30)$$

where the PD gains of the controller have been assigned as

$$K_p = \begin{bmatrix} 1.25 & 0 & 0 \\ 0 & 1.5 & 0 \\ 0 & 0 & 3.5 \end{bmatrix}, K_d = \begin{bmatrix} 0.22 & 0 & 0 \\ 0 & 0.22 & 0 \\ 0 & 0 & 0.22 \end{bmatrix},$$

and $\theta_e = \theta_d - \theta_a$ and $\dot{\theta}_e = d\theta_e/dt$. The control signal is updated every 2 ms and the terminal time t_f has been set as 1.6 s. The deviation $d\theta_f$ for the optimal procedure in *MJP* algorithm is set as 0.5 degree.

The results of trajectory following and error are illustrated in Figs. 6 and 7, respectively. It is shown that the trajectory of the fingertip when the *ICJP* method is employed in the manipulation process is very smooth and well-balanced, while the response by the *MJP* method is rather rough and unsteady. This trend is also confirmed from the error patterns shown in Fig. 7.

Analyzing those phenomena of the two approaches is very important for their robotic applications. To do that, this paper tried to explore the original joint trajectory planning, actual joint motion, and actual

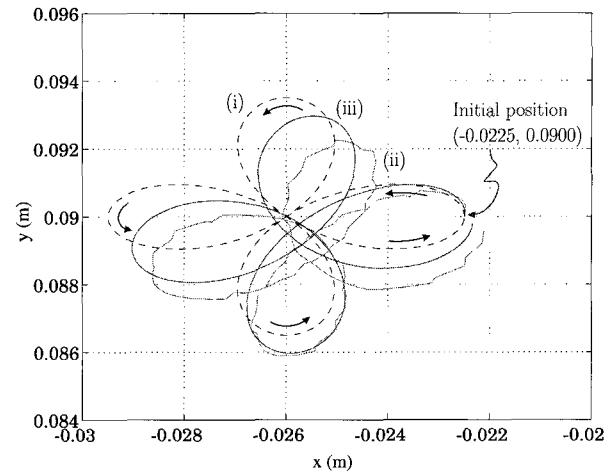


Fig. 6. Fingertip trajectories: (i) desired trajectory, (ii) actual trajectory when the *MJP* method is employed, and (iii) actual trajectory when the proposed *ICJP* method is employed.

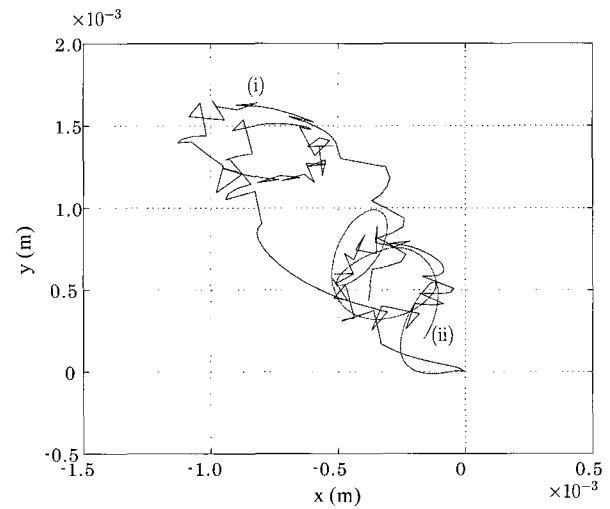
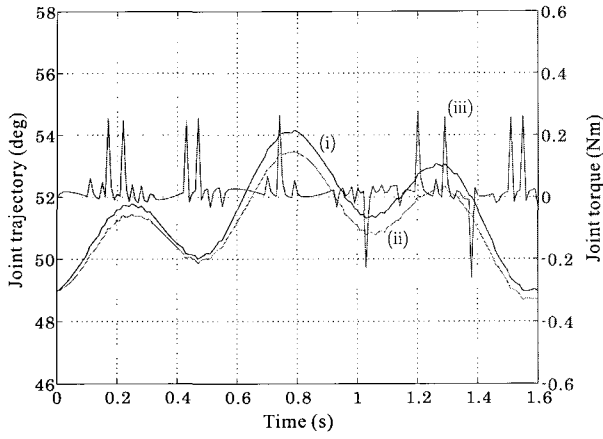
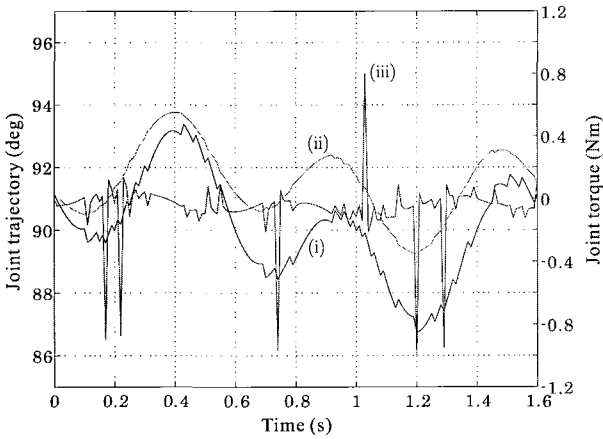


Fig. 7. Fingertip tracking errors to the x - and y -directions: (i) *MJP* and (ii) *ICJP*.

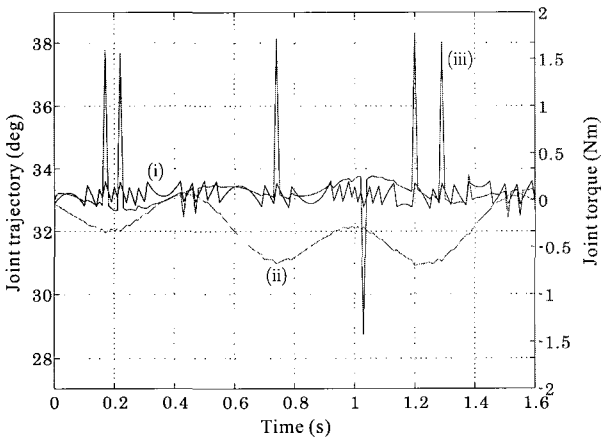
joint torque profiles of all finger joints during the given manipulation process. These results, performed by the *MJP* and *ICJP* methods, are shown in Figs. 8 and 9, respectively. It is found that the trajectory pattern for each joint in the case of using *MJP* has been planned irregularly, while that of *ICJP* is very smooth as a natural pattern relatively. More specifically, it is identified that the trajectories for the second and third joints have been planned with some vibrations when the *MJP* method is employed. In fact, it is estimated that this phenomenon is closely related to the optimal procedure that determines the joint configuration maximizing the manipulability criterion at each time. That is, each joint configuration in *MJP* should be determined for the finger to be placed on the best posture with regard to the manipulability criterion. So, it is pointed out that each joint trajectory



(a) Joint 1.



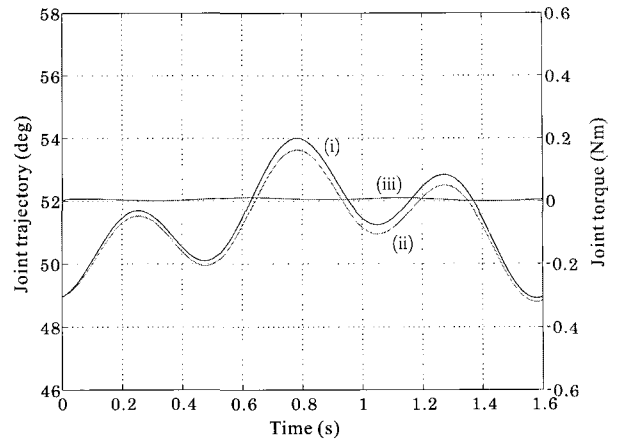
(b) Joint 2.



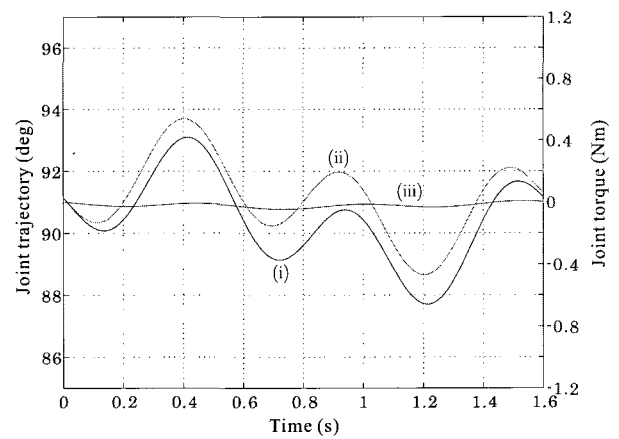
(c) Joint 3.

Fig. 8. Joint trajectories and torque signal when the *MJP* method is employed: (i) planned trajectory (θ_d), (ii) actual trajectory (θ_a), (iii) actual joint torque (τ_ϕ).

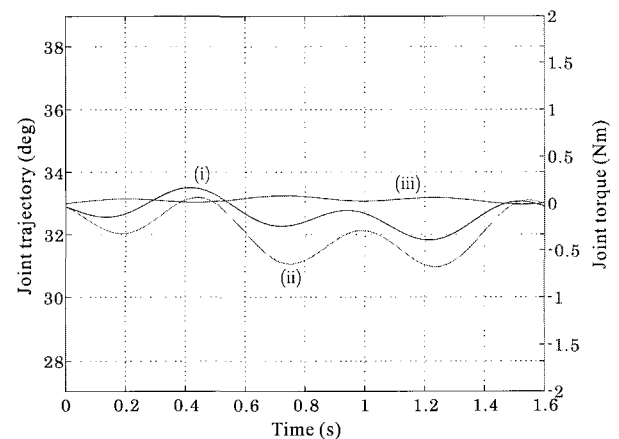
can be planned as an irregular pattern as shown in Fig. 8(i). In other words, the globally optimal finger configurations made by the manipulability measure may not be continuous. Of course, its variation depends on the sampling deviation of $d\theta_f$. In this



(a) Joint 1.



(b) Joint 2.



(c) Joint 3.

Fig. 9. Joint trajectories and torque signal when the proposed *ICJP* method is employed: (i) planned trajectory (θ_d), (ii) actual trajectory (θ_a), (iii) actual joint torque (τ_ϕ).

sense, it is remarked that although the finger intends to have a skillful posture by using an optimal procedure, much trouble can be loaded to real joint actuation because each joint should try to adapt to the hard motion planned. Practically, such irregularly

shaking joint motions make the controller produce greatly exciting torque signals as shown in Fig. 8(iii). As a result, it can be analyzed that the actual finger motion at the fingertip space has been made to be unstable as shown in Fig. 6(ii). In addition, if the controller's gains increase in order to reduce the tracking error, the torque change will be gradually increased in the case of using *MJP*. Since such highly fluctuating torques cause serious jerk motion at the fingertip space, it is undesirable in practice.

On the other hand, those responses by using *ICJP* are very stable relatively as shown in Fig. 9. This is basically because the desired joint trajectory of the finger for the task has been planned stably. This fact allows each joint to be controlled by a well-balanced torque signal. The well-balanced torque signal is advantageous in practical implementation aspect because it guides a finger to a moderate manipulation. Thus, it is remarked that stably planning a joint motion plays an important role for dexterous hand operations.

Through the analysis, it is pointed out that the *MJP* method is not adequate for the purpose of real-time joint motion planning due to the large computational load for the optimization procedure as well as the unsteady joint trajectory generation. However, it can be used for the initial stage to determine the best initial finger configuration without concerning the executing time. It is also recognized that the accuracy of a finger motion can be affected highly by the original joint motion planning. As a result, a more stabilized joint motion can be planned by employing *ICJP*. Thus, it is concluded that the approach *ICJP* is valuable for enhancing the control performance of humanoid fingers [3,5] as well as prosthetic fingers [13,17].

5. CONCLUDING REMARKS

This paper proposed a bio-mimetic joint motion planning method for humanoid fingers. The main contribution of this paper is to consider a suitable interphalangeal coordination model of a human finger for the joint motion planning of a humanoid finger. By employing the proposed method, it is possible to initialize an effective configuration of a finger as well as to plan a natural joint configuration of the finger in a manipulation process. Thus, it is expected that a human-like finger motion can be realized in humanoid finger operations. Through simulation studies, it is concluded that the accuracy of a finger motion basically depends on the joint trajectory planning for a given fingertip position, and thus the proposed joint motion planning method is applicable for implementing a more facilitative finger motion. Moreover, it can be applied to improve the control performance of humanoid fingers or prosthetic fingers.

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