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Compliance Planning for Character Writing Using Multi-Fingered Hands

Byoung-Ho Kim°,†, Sang-Rok Oh†, Byung-Ju Yi°, and Il Hong Suh°
° : School of Electrical Eng. and Computer Science, Hanyang Univ., Seoul, Korea
† : Intelligent System Control Research Center, KIST, Seoul, Korea
(E-mail : bj@email.hanyang.ac.kr)

Abstract

When people write a character with a pen, proper compliance planning is necessary. In this paper, we present compliance planning for character writing task using multi-fingered hands. First, the general stiffness relation of multi-fingered hand is described. Next, we discuss the grasp configuration of a pen and then, we analyze the conditions of the specified stiffness matrix in the operational space to successfully and more effectively achieve the given character writing task. Through the analysis, it is shown that the location of compliance center on the pen plays important role for successful character writing and also the operational compliance characteristics should be properly planned for effective writing task.
Keywords : *multi-fingered hand, character writing task, compliance planning.*

1. Introduction

Many approaches have been investigated in the field of grasp stiffness or compliance [1]-[4]. The stiffness of object grasped by virtual springs was analyzed in cases of planar and three-dimensional space in [1]. Yokoi, et al. [2] proposed a direct compliance control method and applied the method to a parallel arm. In [3], it is pointed out that a stiffness matrix containing some off-diagonal terms can be useful to prevent jamming in the peg-in-the-hole problem. However, the methodology to achieve the desired stiffness characteristic is still an open research field. Recently, Kim, et al. [4] proposed an independent finger/joint-based compliance control method for robot hands manipulating an object, and also the geometric condition for successful implementation of compliance control scheme have been addressed. They showed that an independent finger/joint-based compliance control via redundant actuation was more adequate to modulate the operational stiffness comparing with the case of the kinematically redundant structured fingers or manipulators. Shimoga, et al. [5] presented that the desirable location of compliance center should be the point on the grasped object which first touches or which already is in contact with the inserting work piece. Related to character writing tasks, Hashimoto et al.[6] mentioned the basic motion characteristics of writing tasks by robot hands. However, the proper location of compliance center and the determination of stiffness characteristics to effectively achieve the given writing task have not been considered yet. Moreover, there are few research works relating character writing tasks using multi-fingered hands.

In this paper, to set up a fundamental compliance planning for character writing tasks, we investigate both the location of compliance center and the stiffness characteristics for effective character writing tasks. And an independent finger-based compliance control method is applied to character writing tasks with a grasped pen by multi-fingered hands.

2. Stiffness Relation of Multi-Fingered Hand

The stiffness or compliance can be employed for characterizing the grasping and manipulation of robot hands in the case that it is specially dominated in approximated linear analysis where low velocities and small relative motions lead to small inertial forces. In this section, we analyze the stiffness relation between the operational space and the fingertip space.

Consider a rigid object being manipulated by a n_f-fingered robot hand as shown in Figure 1, where each finger has ${}^i n_j$-joints, and the relation between the generalized force vector in the operational space and the fingertip force vector is given by

$$T_o = [\boldsymbol{G}_o^f]^T T_f, \tag{1}$$

where $T_o \in \mathcal{R}^{n\times 1}$ denotes the generalized force vector in the operational space including the inertial load and external load, the fingertip force vector $T_f \in \mathcal{R}^{m\times 1}$ in the fingertip space is expressed as

$$T_f = \begin{bmatrix} ({}^1T_f)^T & ({}^2T_f)^T & \cdots & ({}^{n_f}T_f)^T \end{bmatrix}^T,$$

and the Jacobian matrix between the operational space and the fingertip space $[\boldsymbol{G}_o^f] \in \mathcal{R}^{m\times n}$ is given by

$$[\boldsymbol{G}_o^f] = \begin{bmatrix} [{}^1\boldsymbol{G}_o^f]^T & [{}^2\boldsymbol{G}_o^f]^T & \cdots & [{}^{n_f}\boldsymbol{G}_o^f]^T \end{bmatrix}^T,$$

$$[{}^i\boldsymbol{G}_o^f] = \begin{bmatrix} {}^f_o\boldsymbol{R}_i & {}^f_o p_i \times {}^f_o\boldsymbol{R}_i \\ 0 & {}^f_o\boldsymbol{R}_i \end{bmatrix}.$$

Here, ${}^f_o\boldsymbol{R}_i$ and ${}^f_o p_i$ denotes the rotation matrix and the position vector from the operational space to the fingertip space, respectively. Also, $m(m = \sum_{i=1}^{n_f} {}^i n_{fp}$, where ${}^i n_{fp}$ denotes the dimension of the ith fingertip) denotes the total dimension of wrenches applied to the grasped object by n_f fingers.

When the trajectory of the grasped object is pre-specified, the task of load distribution will be the determination of the

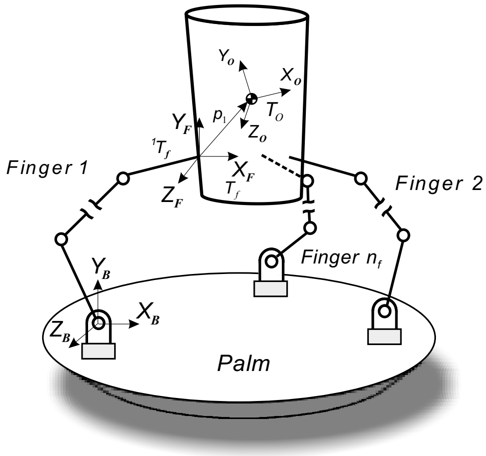


Figure 1: A multi-fingered robot hand.

fingertip forces and moments in order to achieve a desired motion of the object and to maintain the grasp. The general solution of (1) is given by

$$T_f = ([\boldsymbol{G}_o^f]^T)^+ T_o + (\boldsymbol{I} - ([\boldsymbol{G}_o^f]^T)^+ [\boldsymbol{G}_o^f]^T)\xi_f, \tag{2}$$

where the superscript T implies the transpose of a matrix, $([\boldsymbol{G}_o^f]^T)^+$ is a pseudo-inverse of $[\boldsymbol{G}_o^f]^T$, and ξ_f is an arbitrary $m \times 1$ vector. $\boldsymbol{I}$ denotes an $m \times m$ identity matrix.

According to (2), we need 3 fingers to control 6×1 operational force and 3×1 internal force vectors under the assumption that contact type is point contact with friction. However, the number of required fingers will be different in the case of compliance control.

Using (2), we can perform explicit force control of robot hands by using force sensor signal, but the fine finger motion control is practically hard because force measurement at the fingertip is not easy and the real force signal is very noisy. Therefore, stiffness or compliance control method can be usefully applied to robot hand instead of using explicit force control method and also, compliance control approach is believed to be more human-like.

Taking the partial derivative of (1) with respect to u_o, the $n \times n$ stiffness matrix in the operational space including the effect of the change of contact configuration can be obtained as follows:

$$[\boldsymbol{K}_o^{'}] = [\boldsymbol{G}_o^f]^T [\boldsymbol{K}_f][\boldsymbol{G}_o^f] - ([T_f]^T \circ [\boldsymbol{H}_{oo}^f]), \tag{3}$$

and we define

$$\begin{aligned} [\boldsymbol{K}_o] &= [\boldsymbol{K}_o^{'}] + ([T_f]^T \circ [\boldsymbol{H}_{oo}^f]) \\ &= [\boldsymbol{G}_o^f]^T [\boldsymbol{K}_f][\boldsymbol{G}_o^f], \end{aligned} \tag{4}$$

where $[\boldsymbol{K}_f]$ representing the $m \times m$ stiffness matrix in the fingertip space is expressed as

$$[\boldsymbol{K}_f] = \begin{bmatrix} {}^1\boldsymbol{K}_f & {}^{12}\boldsymbol{K}_f & \cdots & {}^{1n_f}\boldsymbol{K}_f \\ {}^{21}\boldsymbol{K}_f & {}^2\boldsymbol{K}_f & \cdots & {}^{2n_f}\boldsymbol{K}_f \\ \vdots & \vdots & \ddots & \vdots \\ {}^{n_f1}\boldsymbol{K}_f & {}^{n_f2}\boldsymbol{K}_f & \cdots & {}^{n_f}\boldsymbol{K}_f \end{bmatrix},$$

in which ${}^i\boldsymbol{K}_f (i = 1, \cdots, n_f)$ is given by

$$[{}^i\boldsymbol{K}_f] = \begin{bmatrix} {}^i\boldsymbol{K}_{fxx} & {}^i\boldsymbol{K}_{fxy} & {}^i\boldsymbol{K}_{fxz} \\ {}^i\boldsymbol{K}_{fyx} & {}^i\boldsymbol{K}_{fyy} & {}^i\boldsymbol{K}_{fyz} \\ {}^i\boldsymbol{K}_{fzx} & {}^i\boldsymbol{K}_{fzy} & {}^i\boldsymbol{K}_{fzz} \end{bmatrix},$$

and ${}^{ij}\boldsymbol{K}_f$ denotes the inter-finger coupling stiffness matrix between the ith finger and the jth finger. The operator of ($\circ$) and $[\boldsymbol{H}_{oo}^f]$ represent the Generalized Scalar Dot Product[7] and the second-order kinematic influence coefficient matrix which represents the change of $[\boldsymbol{G}_o^f]$ with respect to contact configuration[8], respectively.

Generally, the six-degree of freedom operational compliance characteristics of (4) can be expressed by

$$\begin{bmatrix} \boldsymbol{K}_{o11} & \boldsymbol{K}_{o1j} & \cdots & \boldsymbol{K}_{o16} \\ \boldsymbol{K}_{oi1} & \boldsymbol{K}_{oij} & \cdots & \boldsymbol{K}_{oi6} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{K}_{o61} & \boldsymbol{K}_{o6j} & \cdots & \boldsymbol{K}_{o66} \end{bmatrix} = \begin{bmatrix} g_{11} & g_{1j} & \cdots & g_{16} \\ g_{k1} & g_{kj} & \cdots & g_{k6} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1} & g_{mj} & \cdots & g_{m6} \end{bmatrix}^T \begin{bmatrix} \boldsymbol{K}_{f11} & \boldsymbol{K}_{f1l} & \cdots & \boldsymbol{K}_{f1m} \\ \boldsymbol{K}_{fk1} & \boldsymbol{K}_{fkl} & \cdots & \boldsymbol{K}_{fkm} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{K}_{fm1} & \boldsymbol{K}_{fml} & \cdots & \boldsymbol{K}_{fmm} \end{bmatrix} \begin{bmatrix} g_{11} & g_{1j} & \cdots & g_{16} \\ g_{k1} & g_{kj} & \cdots & g_{k6} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1} & g_{mj} & \cdots & g_{m6} \end{bmatrix}, \tag{5}$$

where $i = 2, \cdots, 5$, $j = 2, \cdots, 5$, $k = 2, \cdots, m-1$, and $l = 2, \cdots, m-1$.

Using the independent finger-based compliance control scheme[4], (5) can be rearranged as a vector form

$$K_{oo} = [\boldsymbol{B}_f^o]\, K_{ff}, \tag{6}$$

and in the three-dimensional case, the independent stiffness relation given by (6) can be generally expressed by

$$K_{oo} = \begin{bmatrix} g_{11}^2 & g_{l1}^2 & \cdots & g_{m1}^2 \\ g_{11}g_{1i} & g_{l1}g_{li} & \cdots & g_{m1}g_{mi} \\ \vdots & \vdots & \ddots & \vdots \\ g_{11}g_{16} & g_{l1}g_{l6} & \cdots & g_{m1}g_{m6} \\ g_{12}^2 & g_{l2}^2 & \cdots & g_{m2}^2 \\ g_{12}g_{1k} & g_{l2}g_{lk} & \cdots & g_{m2}g_{mk} \\ \vdots & \vdots & \ddots & \vdots \\ g_{12}g_{16} & g_{l2}g_{l6} & \cdots & g_{m2}g_{m6} \\ \vdots & \vdots & \vdots & \vdots \\ g_{15}^2 & g_{l5}^2 & \cdots & g_{m5}^2 \\ g_{15}g_{16} & g_{l5}g_{l6} & \cdots & g_{m5}g_{m6} \\ g_{16}^2 & g_{l6}^2 & \cdots & g_{m6}^2 \end{bmatrix} K_{ff}, \tag{7}$$

where

$$K_{oo} = [\boldsymbol{K}_{o11}\ \boldsymbol{K}_{o1j}\ \cdots\ \boldsymbol{K}_{o16}\ \boldsymbol{K}_{o22}\ \cdots\ \boldsymbol{K}_{o26}\ \cdots\ \boldsymbol{K}_{o66}]^T,$$

$$K_{ff} = [\boldsymbol{K}_{f11}\ \boldsymbol{K}_{fll}\ \cdots\ \boldsymbol{K}_{fmm}]^T,$$

and here $i = 2, \cdots, 5$, $j = 2, \cdots, 5$, $k = 3, \cdots, 5$, and $l = 2, \cdots, m-1$.

From (6) and (7), the structure of $[\boldsymbol{B}_f^o]$ may change according to the grasping geometry. To be specific, the sign of some elements of $[\boldsymbol{B}_f^o]$ may be changed from positive to negative or zero. Therefore, operational stiffness elements should be considerably specified in consideration of the grasp geometry.

Generally, the problem of computing the fingertip stiffness for a given operational stiffness can be transferred a linear programming problem of the form; find K_{ff} from the following linear matrix equation given by

$$K_{oo} = [\boldsymbol{B}_f^o]\, K_{ff}, \tag{8}$$

subject to $K_{ff} \geq 0$.

Consequently, we can obtain the independent finger stiffness elements K_{ff} by solving the linear programming problem given in (8).

3. Writing Task Using Multi-Fingered Hands

When a character is written by a pen grasped by multi-fingered hands as shown in Figure 2, the pen should be stably picked up and simultaneously, it should be handled effectively to write characters. Sometimes, we should use the combination of arm and hand to draw some large characters or pictures.

Figure 2: Writing a character by human hand.

Usually, the normal writing task is classified into three control modes. The first control mode is to approach to the preparatory grasp position which ensures that grasping is achieved as easy as possible. In this approaching mode, all arm and hand joints are position-controlled. The second control mode is grasping and picking up the pen as shown in Figure 3. In this mode, thumb and other fingers are force-controlled. Finally, the third control mode is manipulating in

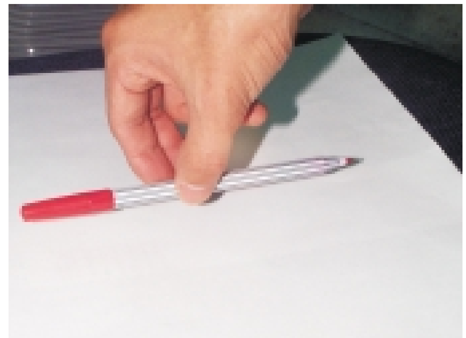
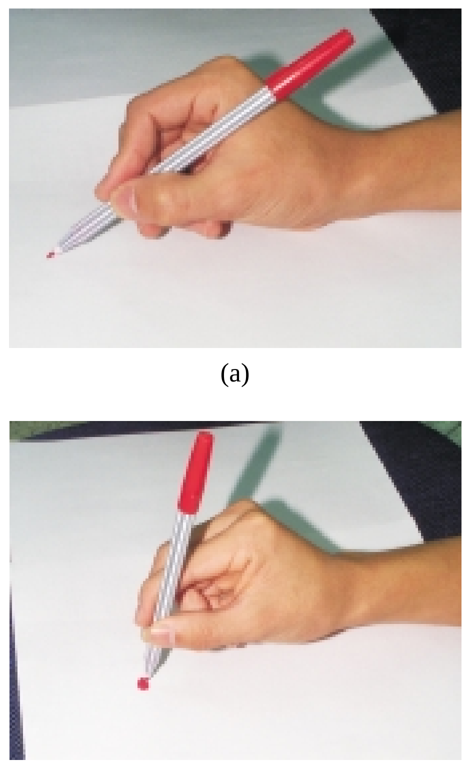


Figure 3: Picking up a pen using multi-fingered hands

the free and constrained spaces(Figure 4). Here, compliant motion control is necessary for dextrously manipulating the pen and exactly writing the given character.



(a)

(b)

Figure 4: Grasp styles of a pen by multi-fingered hands

For writing a character with a pen, there exists various grasp styles as shown in Figure 4. However, selection of a useful grasp style is very important to stably write a character. Most people prefer the grasp style of Figure 4(a) when they write a character with a pen. In Figure 4(a), since the tail of the pen is constrained on the saddle between thumb and index finger, we can intuitively find that the motion of the grasped pen can be easily balanced during writing a character. In this viewpoint, the saddle supporting the pen can be modeled as virtual finger with one passive degree of freedom.

On the other hand, the grasp configuration shown in Figure 4(b) has no constrained surface. Usually, the grasp style of Figure 4(a) is more adequate to write a precision character than the grasp style of Figure 4(b).

In this paper, we consider the writing task using fingers as shown in Figure 4(a) in a quasi-static state. Also, we assume that the contact style of each fingertip is point contact with friction and the grasp points cannot change during writing task.

4. Compliance Planning for Character Writing

In this section, we analyze the compliance characteristics for character writing tasks as shown in Figure 5. Consider the grasp configuration presented in Figure 5, where we assume that the stiffness characteristics in the operational space of the pen are symmetric. Figure 6 shows the grasp posture shown in the section $A - A'$. Specifically, we can find that the tips of thumb and index finger are usually lying on the surface of the second and first quarter of the pen, respectively, and also middle finger contacts on the fourth quarter. In Figure 5, note that the motion constraint by the saddle is very important to guarantee the stability of a pen during writing a character.

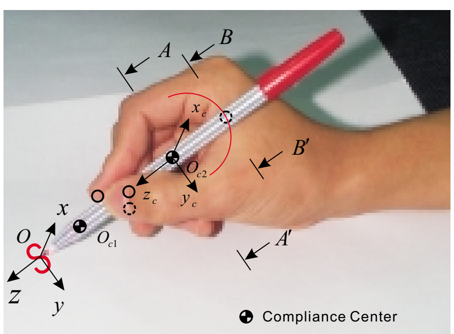


Figure 5: Writing task with a pen using multi-fingered hand.

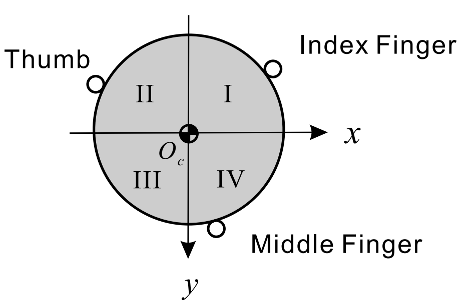


Figure 6: Grasp posture viewed in the section $A - A'$.

In this paper, we define the motion constraint as a virtual finger with passive compliance characteristics. Specially, we modeled the contact point between the pen and the virtual finger as a joint which is capable of sliding in the z-direction and rotating in the x- and y-directions. Here, the model of the

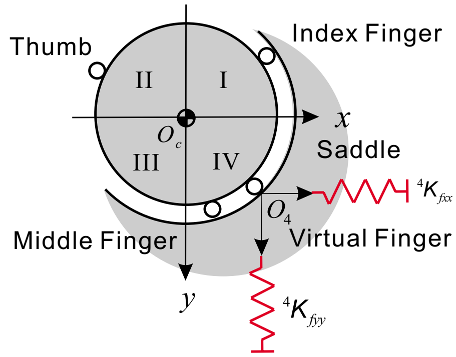


Figure 7: Virtual finger model viewed in the section $B - B'$.

defined virtual finger as shown in Figure 7 is very important to analyze the defined writing task as shown in Figure 4(a). Through the above analysis, the given writing tasks can be modeled as a manipulating problem by four-fingered hands.

Now, using the independent finger-based compliance control scheme[4], we analyze the stiffness characteristics for the defined writing task in Figure 5. Generally, to write a character, the translational and rotational motions of the grasped pen are necessary. And we can observe the following features of character writing task in Figure 5. The translational motions for x- and y-directions of the grasped pen is constrained by the saddle between thumb and index finger, and thus the horizontal(x-direction) motion of the grasped pen is modulated by combination of the translational motion in the z-direction and the rotational motion in the y-direction. Also, it is natural that the vertical(y-direction) motion of the grasped pen is modulated by combination of the translational motion in the z-direction and the rotational motion in the x-direction. The rotational motion for the z-direction is usually unused during writing characters. In this viewpoint, the other directional motions can be induced by the combination of the three motions.

As the above analysis, if the compliance center lies in the $\boldsymbol{O}_{c1}$ position which is located in the range between the tip of the pen and the firstly becoming grasp point from the tip, the 6×6 stiffness matrix in the operational space of the pen can be planned as

$$\begin{bmatrix} \boldsymbol{K}_{oxx} & \boldsymbol{K}_{oxy} & \boldsymbol{K}_{oxz} & \boldsymbol{K}_{ox\gamma} & \boldsymbol{K}_{ox\beta} & \boldsymbol{K}_{ox\alpha} \\ \boldsymbol{K}_{oyx} & \boldsymbol{K}_{oyy} & \boldsymbol{K}_{oyz} & \boldsymbol{K}_{oy\gamma} & \boldsymbol{K}_{oy\beta} & \boldsymbol{K}_{oy\alpha} \\ \boldsymbol{K}_{ozx} & \boldsymbol{K}_{ozy} & \boldsymbol{K}_{ozz} & \boldsymbol{K}_{oz\gamma} & \boldsymbol{K}_{oz\beta} & \boldsymbol{K}_{oz\alpha} \\ \boldsymbol{K}_{o\gamma x} & \boldsymbol{K}_{o\gamma y} & \boldsymbol{K}_{o\gamma z} & \boldsymbol{K}_{o\gamma\gamma} & \boldsymbol{K}_{o\gamma\beta} & \boldsymbol{K}_{o\gamma\alpha} \\ \boldsymbol{K}_{o\beta x} & \boldsymbol{K}_{o\beta y} & \boldsymbol{K}_{o\beta z} & \boldsymbol{K}_{o\beta\gamma} & \boldsymbol{K}_{o\beta\beta} & \boldsymbol{K}_{o\beta\alpha} \\ \boldsymbol{K}_{o\alpha x} & \boldsymbol{K}_{o\alpha y} & \boldsymbol{K}_{o\alpha z} & \boldsymbol{K}_{o\alpha\gamma} & \boldsymbol{K}_{o\alpha\beta} & \boldsymbol{K}_{o\alpha\alpha} \end{bmatrix} =$$

$$\begin{bmatrix} \otimes & 0 & 0 & 0 & -\psi_1 & \otimes \\ 0 & \otimes & 0 & +\psi_2 & 0 & \otimes \\ 0 & 0 & S & 0, \pm\psi_3 & 0, \pm\psi_4 & 0 \\ 0 & +\psi_2 & 0, \pm\psi_3 & L & 0, \pm\psi_5 & \otimes \\ -\psi_1 & 0 & 0, \pm\psi_4 & 0, \pm\psi_5 & L & \otimes \\ \otimes & \otimes & 0 & \otimes & \otimes & \otimes \end{bmatrix} \tag{9}$$

where $\boldsymbol{K}_{oii}$ and $\boldsymbol{K}_{oij}$ denote the i-directional stiffness element and the coupling stiffness element existing between the i- and j-directions, respectively. And γ, β, and α indices denote the rotational directions for x-, y-, and z-directions, respectively. The parameters $\psi_i(i = 1, 2, \cdots, 5)$ are all positive and also, the symbol $\otimes$ means unimportant stiffness elements for writing tasks by structurally-determined motion constraints. S and L mean that small and large value of stiffness, respectively, and those elements can be determined by considering the task characteristic for each direction[5][9, 10]. Here, the procedure of obtaining (9) is omitted due to limit of space, but it is easily obtained by analyzing (7) in detail[11].

In (9), we can notice that the important stiffness elements for the writing tasks are $\boldsymbol{K}_{ozz}$, $\boldsymbol{K}_{o\gamma\gamma}$, $\boldsymbol{K}_{o\beta\beta}$, and the coupling stiffness elements relating those elements. Specially, the coupling stiffness elements $\boldsymbol{K}_{ox\beta}$ and $\boldsymbol{K}_{oy\gamma}$ in (9) can be specified as

$$\boldsymbol{K}_{ox\beta} = -{z_1}^1\boldsymbol{K}_{fxx} - {z_2}^2\boldsymbol{K}_{fxx} - {z_3}^3\boldsymbol{K}_{fxx} - {z_4}^4\boldsymbol{K}_{fxx} \qquad (10)$$

and

$$\boldsymbol{K}_{oy\gamma} = +{z_1}^1\boldsymbol{K}_{fyy} + {z_2}^2\boldsymbol{K}_{fyy} + {z_3}^3\boldsymbol{K}_{fyy} + {z_4}^4\boldsymbol{K}_{fyy} \qquad (11)$$

from (7), where z_i denotes the elements of position vectors directing from the ith finger contact position to the task position, and they are given all positive. Therefore, we can confirm that $\boldsymbol{K}_{ox\beta}$ and $\boldsymbol{K}_{oy\gamma}$ always should be specified as negative and positive values, respectively.

However, if the compliance center moves to the $\boldsymbol{O}_{c2}$ region which denotes the inner range of the grasp configuration formed by the grasp points, $\boldsymbol{K}_{ox\beta}$ and $\boldsymbol{K}_{oy\gamma}$ can be changed as

$$\boldsymbol{K}_{ox\beta} = {z_1}^1\boldsymbol{K}_{fxx} + {z_2}^2\boldsymbol{K}_{fxx} + {z_3}^3\boldsymbol{K}_{fxx} - {z_4}^4\boldsymbol{K}_{fxx} \qquad (12)$$

and

$$\boldsymbol{K}_{oy\gamma} = -{z_1}^1\boldsymbol{K}_{fyy} - {z_2}^2\boldsymbol{K}_{fyy} - {z_3}^3\boldsymbol{K}_{fyy} + {z_4}^4\boldsymbol{K}_{fyy}. \qquad (13)$$

Thus, those coupling elements can be specified as an arbitrary values by using linear programing technology. As a result, the stiffness matrix in the operational space of the pen can be planned as

$$\begin{bmatrix} \boldsymbol{K}_{oxx} & \boldsymbol{K}_{oxy} & \boldsymbol{K}_{oxz} & \boldsymbol{K}_{ox\gamma} & \boldsymbol{K}_{ox\beta} & \boldsymbol{K}_{ox\alpha} \\ \boldsymbol{K}_{oyx} & \boldsymbol{K}_{oyy} & \boldsymbol{K}_{oyz} & \boldsymbol{K}_{oy\gamma} & \boldsymbol{K}_{oy\beta} & \boldsymbol{K}_{oy\alpha} \\ \boldsymbol{K}_{ozx} & \boldsymbol{K}_{ozy} & \boldsymbol{K}_{ozz} & \boldsymbol{K}_{oz\gamma} & \boldsymbol{K}_{oz\beta} & \boldsymbol{K}_{oz\alpha} \\ \boldsymbol{K}_{o\gamma x} & \boldsymbol{K}_{o\gamma y} & \boldsymbol{K}_{o\gamma z} & \boldsymbol{K}_{o\gamma\gamma} & \boldsymbol{K}_{o\gamma\beta} & \boldsymbol{K}_{o\gamma\alpha} \\ \boldsymbol{K}_{o\beta x} & \boldsymbol{K}_{o\beta y} & \boldsymbol{K}_{o\beta z} & \boldsymbol{K}_{o\beta\gamma} & \boldsymbol{K}_{o\beta\beta} & \boldsymbol{K}_{o\beta\alpha} \\ \boldsymbol{K}_{o\alpha x} & \boldsymbol{K}_{o\alpha y} & \boldsymbol{K}_{o\alpha z} & \boldsymbol{K}_{o\alpha\gamma} & \boldsymbol{K}_{o\alpha\beta} & \boldsymbol{K}_{o\alpha\alpha} \end{bmatrix} =$$

$$\begin{bmatrix} \otimes & 0 & 0 & 0 & 0,\pm\psi_1 & \otimes \\ 0 & \otimes & 0 & 0,\pm\psi_2 & 0 & \otimes \\ 0 & 0 & S & 0,\pm\psi_3 & 0,\pm\psi_4 & 0 \\ 0 & 0,\pm\psi_2 & 0,\pm\psi_3 & L & 0,\pm\psi_5 & \otimes \\ 0,\pm\psi_1 & 0 & 0,\pm\psi_4 & 0,\pm\psi_5 & L & \otimes \\ \otimes & \otimes & 0 & \otimes & \otimes & \otimes \end{bmatrix} \qquad (14)$$

From (14), we can notice that the coupling stiffness elements, $\boldsymbol{K}_{ox\beta}$ and $\boldsymbol{K}_{oy\gamma}$, can be specified as zero and thus, the unwanted translational motion caused by the rotational motions in the x- and y-directions can be removed. Also, we can observe that this effect can be obtained by the virtual finger from (12) and (13). Accordingly, we can recommend that the grasp configuration with the compliance center $\boldsymbol{O}_{c2}$ is useful for character writing. Additional analyses with other grasp configurations for character writing can be performed by this fundamental analysis.

5. Concluding Remarks

In this paper, we modeled a grasp configuration for writing a character and then analyzed the conditions of the specified stiffness matrix in the operational space to successfully and more effectively achieve the defined writing task. Through the analysis, it is shown that proper compliance planning considering grasp geometry is very important to write a character and also, the location of compliance center on the pen plays important role for successful character writing.

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