Human Kinematic Factor for Haptic Manipulation: The Wrist to Thumb

Keehoon Kim Y. Youm W. K. Chung

Dept. of Mechanical Engineering, Pohang University of Science and Technology, Pohang, Korea
Tel : +82-54-279-2844, Fax : +82-54-279-5899, E-mail : {khk,youm,wkchung}@postech.ac.kr

Abstract

The range of human kinematic motion as well as force resolution should be known for design of a haptic device. In addition, a haptic interface can be designed more easily when master and slave devices are the same kinematically. However, human kinematic factors have not been analyzed and applied deeply because of their complexity. Although calibration techniques have been developed, there is a limit to describe the dexterous motion. In this paper, haptic manipulation which uses the tactile sensing more often than the visual sensing is defined and analyzed. During haptic manipulation, thumb and the wrist are the most important. Thumb model stated in this paper has only two variables to be calibrated and successfully expresses opposition which is a unique thumb motion of human. Through this model, the workspace of thumb and three finger grasping haptic manipulation are determined. Especially, this result can be a criterion to design a haptic device which expresses human dexterous motion.

1. Introduction

A haptic device is a bridge between an operator and virtual reality. In other words, a haptic device should have abilities to cover the workspace and the range of force of an operator and to transmit tactile sensing to an operator. Therefore, human factor should be considered to design an optimal haptic device.
First of all, the range and the resolution of human force is needed to select actuators. Human force factors have been studied in [1] and [2]. The range and resolution of shoulder, elbow, wrist, and fingers are investigated in [1]. They can be criteria for design of a haptic device.
Human kinematic factors are also needed for design of a haptic device. However, complexities of human motion, especially thumb and the wrist motion make it difficult to analyze human kinematics and many haptic devices are designed without considering them. Therefore, calibration of a human motion for a haptic device becomes an important part. In [6], mapping and calibration of a human hand for their own system have been tried. However, their trapezo-metacarpal joint model which has three joints to express the three modes of thumb is far from the real human’s. In [7], though the accurate calibration techniques for each individual person have been developed, the results are only for the fingers except thumb which have planar motion.
In this paper, the motion to be covered by a haptic device to guarantee dexterity of a hand is defined as haptic manipulation. Homogeneous transform from the wrist to thumb is developed for haptic manipulation. The three motion of flexion-extension, adduction-abduction, and opposition is obtained by the proposed trapezo-metacarpal joint model which has two calibration factors. This paper is organized as follows: Section 2 classifies human motions during manipulating an object and defines haptic manipulation. In section 3, kinematics of wrist and thumb is shown to find the motion of haptic manipulation. In section 4, the proposed model is applied to find the workspace of thumb TFG haptic manipulation. The workspace is objective under the fact that bony ratio is fixed. Therefore, results can be applied to every normal person.

2. Haptic Manipulation

The workspace of human is so large that it is difficult for a haptic device to cover it. However, since the motion with tactile sensing is small, a haptic device which includes whole workspace of human is not needed. In this section, haptic manipulation which is the motion with tactile sensing is defined in the anatomical viewpoint. When human manipulates an object, there are two kinds of grasplings as shown in Figure 1. Manipulation with power grasping is stable and strong, but not dexterous. On the other hand, precision grasping is used in dexterous job like writing, soldering, or micro surgery. Since haptic display is for transmitting tactile information and human uses visual sensing more often than tactile sensing during manipulation with power grasping, only precision grasping can be haptic ma-
why human uses only fingers and the wrist during haptic manipulation in Figure 2(d). The fact that the resolution of a manipulator is dependent on the joint of the worst resolution is fundamental in robotics. Haptic manipulation can be defined as follows from the reasons stated above.

Definition 1. Haptic manipulation is a set of motions which are composed of the movement of carpals, metacarpals, and phalanges.

3. Characteristics of hand

If the analysis of haptic manipulation defined above is investigated through experiments, the result is dependent on the experimenter’s criterion and the size of hand. Therefore, the motions will be analyzed from the viewpoint of statistical data from anatomy. This approach is reliable under the fact that bone to bone bony ratio is fixed for every normal person as shown in Table 1. For example, if the length of distal phalanx of thumb is known, lengths of other bones of thumb are also known.

3.1. Kinematics of wrist

Though motions of wrist bones are very complex, important kinematic characteristics of the wrist are clarified by [4]. Following property will be applied to analyze haptic manipulation.

Property 1. The trajectories of the hand during radial-ulnar deviation and flexion-extension, when they occur in a fixed plane, are circular and the rotation in each plane takes place about a fixed axis. The center of the rotation lies on the one-quarter point of the capitate.
Property 1 shows that the wrist motions\(^2\) are independent to other motions of fingers. This property is very important because haptic manipulation can be decoupled to the wrist motion and other motions.

### 3.2. Kinematics of thumb

Fingers are needed to handle an object. Moreover, human is the only one who can manipulate something by using precision grasping among animals which have fingers, since human has thumb which can be in opposition to other four fingers. In other words, it is possible to manipulate an object on the range where thumb can reach.

When human manipulates an object, the range of other four fingers incudes that of thumb. Therefore, the manipulability and the workspace of manipulation are dependent on thumb. The motion of thumb should be known to find the motions of haptic manipulation. From now, kinematics of thumb will be found except other four fingers since they consist of simple rotary joints.

Thumb has 5 degrees of freedom: 2 D.O.F in trapezometacarpal joint, 2 D.O.F in metacarpophalangeal joint, and 1 D.O.F in interphalangeal joint\(^5\). However, the range of deviation of metacarpophalangeal joint is so small that thumb can be assumed to have 4 D.O.F as shown in Figure 3.

Assumption 1 The thumb has four degrees of freedom: two D.O.F in the trapezo-metacarpal joint, one D.O.F in the metacarpophalangeal joint and one D.O.F in the interphalangeal joint.

The most important part is the trapezo-metacarpal joint to analyze kinematics of thumb. Though other parts can be modelled by 1 D.O.F rotary joint, trapezo-metacarpal joint is a strange saddle joint which is usually not used in engineering. Besides, four actuators which move the joint are attached on a metacarpal as shown in Figure 4. Though many models of thumb have been suggested, it is difficult to be implemented. Moreover, opposition can not be described exactly. In this section, trapezo-metacarpal joint will be modelled by two rotary joint. This model has advantage to be implemented or simulated easily with rotary joint. In addition, it shows opposition.

The link from the wrist to distal phalanx of thumb has 6 D.O.F. according to Assumption 1 including 2 D.O.F of the wrist. Figure 5 shows coordinate systems from the wrist to thumb. The 0th and the 1st coordinate frames are on a quarter point of capitate by Property 1 and rotation axes of them are orthogonal in the neutral position. The 2nd and the 3rd coordinate frames are on trapezo-metacarpal joint and their rotational axes are orthogonal in the neutral position. The 4th and the 5th coordinate frames are on metacarpal joint and interphalangeal joint. The 6th coordinate frame represents the end effector of the link. First of all, the relationship between the 1st and the 2nd coordinate frames should be found out to analyze the link. Finally, transformations from the wrist to the end of thumb will be determined.

To find the direction of the 2nd and 3rd coordinate frame, a cubic model as shown in Figure 6 will be applied. □OABC is the palmar plane parallel to \(x_1 − z_1\) plane of the 1st coordinate frame. □OCFG is Medial plane. Medial plane is defined as following. Figure 7 shows medial plane.

Definition 2 (Medial plane) The Medial plane is a plane

\(^2\)flexion-extension and radial-ulnar deviation
which includes the capitate and the third metacarpals and is orthogonal to the palmar plane.

$OC$ is parallel to $x_1$ axis and $OE$ represents $x_2$ axis of the 2nd frame. $\triangle OEH$ is on the plane $x_2 - z_2$ and orthogonal to the axis $y_2$. Followings are the transformations from the wrist to the end of thumb.

\[
0T_1 = R_z(\theta_0)R_x(90^\circ)
\]
\[
1T_2 = R_z(\theta_1)T(l_0, -l_2, -l_1)R_y(20^\circ)
\]
\[
2T_3 = R_z(-\alpha)R_y(\beta)
\]
\[
3T_4 = R_z(\theta_2)T(l_4, 0, 0)R_x(-10^\circ)
\]
\[
4T_5 = R_z(\theta_3)T(l_5, 0, 0)R_y(90^\circ)R_z(90^\circ)
\]

\[4, 5\] are referred for next constraints of joint angles.

\[-37^\circ < \theta_0 < 20^\circ\]
\[-50^\circ < \theta_1 < 45^\circ\]
\[-30^\circ < \theta_2 < 45^\circ\]
\[-10^\circ < \theta_3 < 20^\circ\]
\[-70^\circ < \theta_4 < 0^\circ\]
\[-80^\circ < \theta_5 < 0^\circ\]

Therefore, if angles $\alpha$ and $\beta$ are calculated, the 2nd and the 3rd frame are known. In order words, angle $\alpha$ and $\beta$ are the calibration factor. For example, these angles can be determined by $\angle BOC$, $\angle COF$ and $\angle COH$ in Figure 6(b),(c) and (d) with following method.

Let $OC = 1$.

\[
HC = \tan \angle HOC = \tan 20^\circ = 0.364 \quad (3)
\]
\[
BC = \tan \angle BOC = \tan 40^\circ = 0.839 \quad (4)
\]
\[
CF = \tan \angle FOC = \tan 35^\circ = 0.700 \quad (5)
\]
\[
OE = \sqrt{BC^2 + OC^2 + CF^2} = 1.481 \quad (6)
\]
\[
EH = \sqrt{(BC - HC)^2 + BE^2} = 0.846 \quad (7)
\]
\[
OC \cos \angle HOC = 1.064 \quad (8)
\]
\[
OC \cos \angle COF = 1.305 \quad (9)
\]
\[
(OE \cdot \cos \beta - OH)^2 + (OE \cdot \sin \beta)^2 = EH^2 \quad (10)
\]
\[
\beta = \cos^{-1}\left(\frac{OE^2 + OH^2 - EH^2}{2OE \cdot OH}\right) = 34.085^\circ \quad (11)
\]
\[
\cos \alpha = \frac{\triangle OBO}{\triangle OEB} \quad (12)
\]
\[
\alpha = \cos^{-1}\left(\frac{OB \cdot \sin \angle BOC}{OE \cdot \sin \beta}\right) = 57.477^\circ \quad (13)
\]

Now, $\alpha$ and $\beta$ are found in the proposed model.

### 3.3. Motion of the Proposed Thumb Model

In this section, the characteristics of the proposed model, the shape of workspace and opposition will be shown. Figure 8-10 show the workspace of thumb using simulation.
Figure 8. $x_1 - y_1$ plane of 1st frame when distal phalanx of thumb has unit length. Horizontal axis : $x_1$, Vertical axis : $y_1$

Figure 9. $x_1 - y_1$ plane of 1st frame when distal phalanx of thumb has unit length. Horizontal axis : $y_1$, Vertical axis : $z_1$

Figure 10. $x_1 - y_1$ plane of 1st frame when distal phalanx of thumb has unit length. Horizontal axis : $z_1$, Vertical axis : $x_1$

Figure 11. The trajectory of $-x_6$ axis during opposition; Horizontal axis : $y_1$, Vertical axis : $z_1$

The workspace of thumb is difficult to represent in a plane because it is a complex 3 dimensional. From the figures, the workspace of thumb can be included roughly by hexahedron which is 3.5 on $x_1$ axis, 5.0 on $y_1$ axis, and 7.0 on $z_1$ axis.

Opposition is the rotation of thumb during flexion-extension or adduction-abduction. Figure 11 shows the change of the unit vector on $-x_6$ direction when $\theta_1 = 0.0^\circ$, $\theta_3 = 20.0^\circ$, $\theta_4 = -30.0^\circ$, and $\theta_5 = -30.0^\circ$ and $\theta_2$ changes from $45.0^\circ$ to $-30.0^\circ$. Since the change of the unit vector on plane $y_1 - z_1$ means opposition, the suggested model of thumb can follow opposition successfully.

4. The Workspace of TFG Haptic Manipulation

Haptic manipulation with precision grasping needs at least two fingers. Three fingers are needed to control an object stably. There are many kinds of haptic manipulation which are distinguished by the number of fingers or methods. Three-finger grasping haptic manipulation will be considered among haptic manipulations with thumb, index finger, and middle finger. TFG(Three Finger Grasping) haptic manipulation is usually used in micro-surgery, soldering, and writing.

Definition 3 (TFG haptic manipulation) The three-finger haptic manipulation is a set of motions which are composed of the movement of carpals, metacarpals, and phalanges and are constrained distal phalanges of thumb, index, and middle finger to manipulate an object.

Though three fingers are used in TFG haptic manipulation, thumb plays the most important role. The deviations of index finger and middle finger are very small during TFG
haptic manipulation. Besides, metacarpal bone of middle finger directly represents the motion of the wrist as shown in Property 1. In conclusion, an object which is manipulated by three fingers is always on a plane parallel to medial plane. Since the range of the index and the middle finger are larger than that of thumb on medial plane, we can assume the following.

**Assumption 2** During the TFG haptic manipulation, the end of the distal phalanx of the thumb is on a plane\(^3\) parallel to the medial plane. On the plane the workspace of index and mid finger includes the workspace of the thumb.

Therefore, the workspace of TFG haptic manipulation is dependent on the kinematic characteristics of thumb. In other words, whole kinematic characteristics of three fingers are not needed. In order to find the workspace of TFG haptic manipulation, the workspace of thumb will be determined and motion of wrist will be added later. This approach is valid under the fact that the wrist motion is independent to motions of other joints.

An important constraint of TFG haptic manipulation is that an object manipulated is on medial plane. The problem to find the workspace of TFG haptic manipulation with a small object can be represented by Eq.(1) and (2) with Eq.(14).

\[
\begin{align*}
\alpha &= 57.5^\circ, \quad \beta = 34.1^\circ \\
l_0 &= 0.818, \quad l_1 = 1.182, \quad l_2 = 0.833 \\
l_3 &= 2.09, \quad l_4 = 1.37, \quad l_5 = 1.00 \\
l_3 \text{ to } l_5 \text{ are from [3].} \\
l_0 \text{ to } l_2 \text{ are from x-ray pictures.} \\
\theta_0 &= \theta_1 = 0 \\
\frac{z_6}{l_1} &= -l_1
\end{align*}
\]

The calculated workspace of thumb is on medial plane. Figure 12 and 13 show the workspace of thumb for TFG haptic manipulation on \(z = -l_2\) plane of 1st frame. This plane is parallel to medial plane. The workspace is about \(2.5 \times 2.3\) when there is no wrist motion and distal phalanx of thumb has unit length. The length of distal phalanx of thumb determines the workspace due to bone to bone bony ratio. For example, if the length of distal phalanx of thumb is 2, the values in Figure 12 become double.

The whole workspace of TFG haptic manipulation can be determined by adding the wrist motion to simulation result in Figure 12 and 13. Then, \(\theta_0\) and \(\theta_1\) are not fixed values anymore.

Figure 14-18 show the workspace of TFG haptic manipulation. Figure 14 is the 3-dimensional representation.

\(^3\)This plane is one of the planes parallel to the medial plane. It is determined by the size of a grasped object and the contact type between fingers and an object.
Figure 14. The workspace of TFG haptic manipulation

Figure 15. The workspace during flexion(50°)-extension(45°)

Figure 16. The workspace during abduction(20°)-adduction(37°)(wrist deviation)

Figure 17. The workspace of TFG haptic manipulation(front view) when distal phalanx of thumb has unit length: $MG = 2.91$, $MH = 1.43$ and $AB = 9.37$. 
Figure 18. The workspace of TFG haptic manipulation (rear view) when distal phalanx of thumb has unit length: $NG = 2.91$, $NH = 1.43$, $AB = 9.37$, $NL = 0.64$, $NK = 1.62$ and $IJ = 5.67$.

Figure 15 is the workspace on the plane $\triangle OAB$. $45^\circ$ and $50^\circ$ mean the range of wrist motion in [4]. Figure 16 is the workspace on the plane $\triangle OCD$. $20^\circ$ and $37^\circ$ mean the range of wrist deviation. Figure 17 and Figure 18 represent workspace viewed from E and F. Plane of Figure 17 is orthogonal to $\triangle OAB$ and includes $AB$. Plane of Figure 18 is orthogonal to $\triangle OAB$ and includes $AB$.

5. Conclusion

The kinematic factors of a hand are important for the design and operation of haptic devices. In this paper, haptic manipulation is defined as the motions which need tactile sensing more often than visual sensing with high force resolution. A 6 DOF model from the wrist to thumb is developed to described haptic manipulation. The homogeneous transforms which have two calibration factors are derived. The opposition has been shown during thumb motion. This improves the understanding of the complex motion of the thumb. The results make it possible to follow human haptic manipulation or to apply to design of a haptic manipulator. The model is used to find the workspace of TFG haptic manipulation. The workspace can be used for every normal person under the fact that the bony ratio is fixed. In the future, the motions of the proposed model will be compared to the real human hand motion and applied to design a master device.

Acknowledgements

This work was supported by grant No. 2000-2-30200-008-3 from the Basic Research Program of the Korea Science & Engineering Foundation

References


