Haptic Interface with 7 DOF Using 8 Strings : SPIDAR-G

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Abstract

Because of the continuous development of computers it is now possible to construct various environments. As a result, human interfaces that allow users to manipulate virtual objects in an intuitive manner, as in the real world, are being demanded. In this paper, we present a 7 DOF tension-based haptic interface that allows users to not only pick the object but also to sense its width. We have developed a system to utilize the physical action of gripping to display grasp manipulation in virtual environments. We also present a method to calculate the position and display force associated with this gripping mechanism. In addition, we show the possibility of its application to virtual reality. Finally, we refer to the characteristic of this device and its validity through examples.

Keywords

7DOF, Tension based haptic interface, SPIDAR-G.

1. Introduction

The development of computer technology is enabling users to interact with various virtual environments. When users want to interact with virtual objects in a manner similar to those in the real world, an intuitive haptic interface with multiple degrees of freedom (DOF) becomes a necessity. In general, the physical act of gripping (or grasping) allows human beings to perform several important functions including using instruments to puncture, cut, rotate, and hit objects. Before doing the above-mentioned tasks, we select the necessary instruments by grasping it. Depending on the size and shape of the object, we can generally grasp an object using our thumb and our other fingers. So far haptic interfaces have presented users with simple ways of representing this grasping function, such as pushing a button in a mouse or keyboard. We believe that an effective haptic interface should not only provide feedback on the differential sense of width. Such an "intuitive" haptic interface has not been developed yet. The purpose of this paper is to realize such a tension-based 7 DOF haptic interface that can allow users to not only pick an object, but to also sense the width of an object as in real life object manipulation.

2. Related work

We can divide the haptic interfaces that have been developed so far into two categories: ground-based type and body-based type. LRP data glove by LRP[1], Cybergrasp force feedback glove by Virtual Technologies Inc[2], and Rutgers Masters (RM-II)[3],[4] developed at Rutgers University are well-known examples of body-based haptic interfaces. Body-based haptic interfaces have the advantage of allowing the user to grasp an object, but also present the disadvantage of not being able to represent the weight of an object. Recently, developers have tried to overcome this demerit in Vti by fixing the Cybergrasp force feedback glove to a serial link manipulator. Still, this device has the disadvantage of not being efficient in displaying rotational force. Furthermore, the overall structure is complex in that is cumbersome to put on the users hand and is difficult to maintain.

Ground-based haptic interfaces can generally be classified as link type, magnetic levitation type, and tension based type. Link type haptic interfaces have the disadvantage of exhibiting backlash, backdrive friction and inertia, and limited work space. The PHANToM is an example of a successful link type haptic interface. However, since it has 6 DOF, it is impossible to grasp virtual objects using a single PHANToM. When 2 PHANToMs are used to grasp virtual objects, only 2 fingers are displayed in the virtual environment (thumb and index finger). This setup also suffers from limited workspace, due to inertial effects. Recently, a haptic group at MIT succeeded in integrating the Immersion Impulse Engine, a recent invention by Immersion Corporation[5], and 3 DOF PHANToM[6] (made by Sensable Technologies)[7] for laparoscopic surgery simulation[8]. The system utilized a 5 DOF simulation software with the PHANToM as the laparoscopic tool [9]. Therefore it did not provide feedback of rotation force to its users. The Haptic Master [10] is another well-known parallel-link type haptic interface. Because this device uses a gear, it has backlash and backdrive friction while displaying only 6 DOF.

CMU's magnetic levitation type haptic interface [11], [12] has the advantages of non-contact actuation and sensing, high control bandwidths, high position resolution and sensitivity, but has disadvantages of small workspace (motion range:15-20 degrees rotation, 25mm translation) and only 6 DOF display.

Tension based haptic interfaces [13], [14], [17], [18] have the advantages of fast reaction speed, simple structure, smooth manipulation, and scalable work space (since tension based types do not affect backlash, backdrive friction and inertia). The SPIDAR-G has 7 DOF, users can manipulate virtual objects with 6 DOF and can grasp them simultaneously. SPIDAR-G stands for SPace Interface Device for Artificial Reality with Grip.

3. Force displaying using tension

One characteristic of using strings to display forces is that they can only be used to represent tension. In other words, the strings can be used to pull and not push. We can determine the number of strings needed by applying vector closure to the indispensable condition of displaying n-DOF reflective forces using strings. When generating a n-dimensional force vector $q \in R^n$, using m-strings, the force vector q added to the target object from m-strings can be shown like this.

$$q = [w_1, w_2, \cdots, w_m]\tau \qquad (1)$$

$$w_i \in R^n \quad (i = 1, \cdots, m)$$

$$\tau = (\tau_1, \tau_2, \cdots, \tau_m)^T$$

Where w_i represents a force vector, when unit tension is added to the i -th string and τ is tension vector. The following theories (1 and 2) outline the Conditions for a positive τ that can realize any q in equation (1) [15], [16].

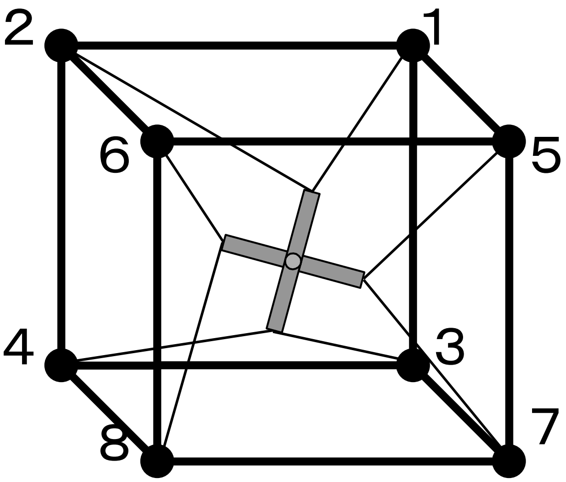

Figure 1. Basic structure of SPIDAR-G

[Theory 1]

If $A = [w_1, w_2, \cdots, w_m]$, the indispensable condition to have positive solution in equation (1) is as follows:

m>n

[Theory 2]

If $A = [w_1, w_2, \cdots, w_{n+1}]$, the indispensable condition to have positive solution in equation (1) is as follows:

1. $rank(A) = n$
2. Using remain row vector, any $w_i (i = 1, \cdots, n+1)$ have to represent as

$$w_i = -\sum_{j=1(j \neq i)}^{n+1} \alpha_j w_j \quad (\alpha_j > 0) \qquad (2)$$

However, n is the dimension of the work coordinate. Therefore, we can conclude that for the user to move an object in any direction in n-dimensional space, n+1 strings are need. Furthermore, the connection of the strings has to satisfy theory 2. In our case, SPIDAR-G needs at least 8 strings to display 7 DOF.

4. Structure of SPIDAR-G

4.1 Basic structure

Although we deduced that it was sufficient for us to use only 8 strings and that the connection had to comply with theory 2 (from vector closure), we still need to choose the best possible configuration for the connection of strings. This is because the magnitude, direction and area of force depend on the types of connection between the frame and grip. In general, we assume the users of our device would work in the central area of the frame. We choose the simplest way to display 7 DOF force in the central areas of

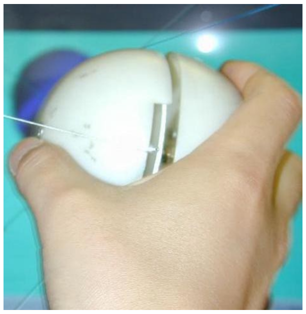

Figure 2. State of grip before grasping

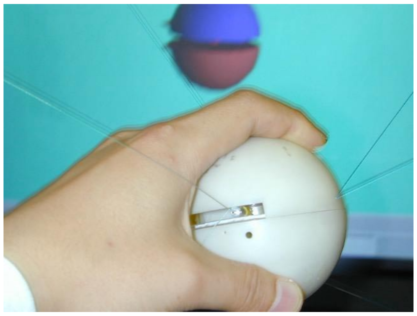

Figure 3. State of grip after grasping

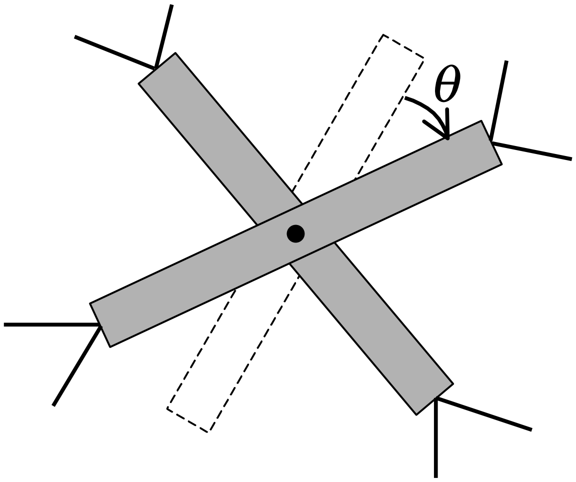

Figure 4. Grasp work

the frame by using low torque. In other words if the position vector of grip was set to $A(\in R^{7\times 8})$, the larger the result of $\det|A^T A|$, the better it was for our purpose. Using this type of an analysis we could take the best connection between a vertex of a grip and a corner of a frame, as in figure 1. At each corner of the frame, an encoder and a motor was attached. The 8 strings were connected to each of the corners of the frame. On the opposite side, the other 8 strings were connected to each of the 2 strings on the vertex of the grip as well. The encoder calculated the length of string and the motors produced tension by pulling on the string.

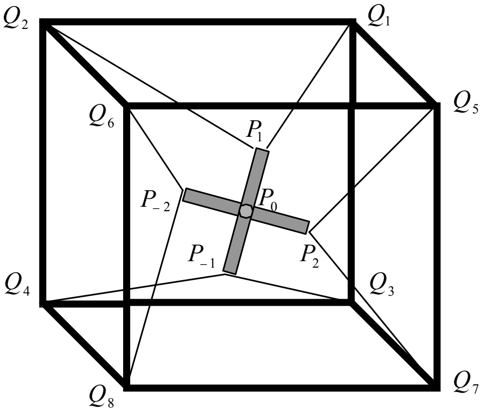

Figure 5. Definition of symbols

4.2 Structure to grasp

Human beings are naturally skilled at grasping objects using their thumb and fingers. To display feedback force on the individual fingers, we initially tried attaching strings to the tips of each finger. This approach was not successful as it provided to be difficult to display translational, rotational, and grasping forces using only 8 strings.

In this paper we suggest a new mechanism for the grip. The new grip allows its users to manipulate with 7 DOF by grasping it between the thumb and other fingers. In order to incorporate the "grasping" functionality of the grip, it is best to consider a spherical shape, In figure 2, the proposed mechanism is broken into 2 hemispherical structures. As can be seen, if the user grasps the grip using thumb and other fingers, the 2 poles rotate depending on the magnitude of the grasp force (see figure 3). Hence it is possible to control the grasp functionality of the grip. The basic structure of the cross type grip is shown in figure 4.

The crossing degree θ changes with the magnitude of the grasping force and is used to quantify the action of grasping.

5. Way to calculation position

Position (translation, rotation, and grasp) is calculated from the length of 8 strings. The shape of frame is rectangular parallelepiped and each size of X, Y and Z axis is $2a, 2b, 2c$.

We take the center of frame as the origin $(0,0,0)$. Each position vector Q_i $(\in R^3)$ in i-th extremity of frame is as follows.

$$Q_1 = (\ a,\ b,\ c) \quad Q_2 = (\ -a,\ b,\ c)$$

$$Q_3 = (\ a,\ -b,\ c) \quad Q_4 = (\ -a,\ -b,\ c)$$

$$Q_5 = (\ a,\ b,\ -c) \quad Q_6 = (\ -a,\ b,\ -c)$$

$$Q_7 = (\ a,\ -b,\ -c) \quad Q_8 = (\ -a,\ -b,\ -c)$$

Position vectors of the grip (P_0) and the 4 extremities $(P_1, P_{-1}, P_2, P_{-2})$, P_i ($\in R^3$) are defined below.

$$P_0 = (x, y, z)$$

$$P_1 = (x + x_1, y + y_1, z + z_1)$$

$$P_{-1} = (x - x_1, y - y_1, z - z_1)$$

$$P_2 = (x + x_2, y + y_2, z + z_2)$$

$$P_{-2} = (x - x_2, y - y_2, z - z_2)$$

If we set the length of each pole to $2d$, the following equation comes out.

$$x_1^2 + y_1^2 + z_1^2 = x_2^2 + y_2^2 + z_2^2 = d^2$$

If we set each extremity of grip which is connected to the i-th frame (i), we can easily know the following relation.

$$(1) = (2) = 1, \quad (3) = (4) = -1$$

$$(5) = (7) = 2, \quad (6) = (8) = -2$$

Setting the length of the i–th string, l_i can be represented with the following equation.

$$l_i = \left\| Q_i - P_{(i)} \right\| \quad (i = 1, \cdots, 8) \qquad (3)$$

To calculate translation, rotation, and grasp, we have to solve (x, y, z), (x_1, y_1, z_1), and (x_2, y_2, z_2) from the length of 8 strings. Equation 3 can be converted into the following equations.

$$(x + x_1 - a)^2 + (y + y_1 - b)^2 + (z + z_1 - c)^2 = l_1{}^2 \quad (4)$$

$$(x + x_1 + a)^2 + (y + y_1 - b)^2 + (z + z_1 - c)^2 = l_2^2 \quad (5)$$

$$(x - x_1 - a)^2 + (y - y_1 + b)^2 + (z - z_1 - c)^2 = l_3^2 \quad (6)$$

$$(x - x_1 + a)^2 + (y - y_1 + b)^2 + (z - z_1 - c)^2 = l_4^2 \quad (7)$$

$$(x + x_2 - a)^2 + (y + y_2 - b)^2 + (z + z_2 + c)^2 = l_5^2 \quad (8)$$

$$(x - x_2 + a)^2 + (y - y_2 - b)^2 + (z - z_2 + c)^2 = l_6^2 \quad (9)$$

$$(x + x_2 - a)^2 + (y + y_2 + b)^2 + (z + z_2 + c)^2 = l_7^2 \quad (10)$$

$$(x - x_2 + a)^2 + (y - y_2 + b)^2 + (z - z_2 + c)^2 = l_8^2 \quad (11)$$

Using the above equations, we can solve (x, y, z), (x_1, y_1, z_1), and (x_2, y_2, z_2). We can solve above variables using 4 arithmetical operations because of the redundancy of strings. We show the detailed algorithm in index 1.

6. Way to display reflect force

In this section, we explain how to determine tension of the 8 strings to display 7 DOF force in crossing type grip.

We define force vector $q (\in R^7)$ should be generated like this.

$$q = \left(f_x f_y f_z m_x m_y m_z, g \right)^T$$

Where f_x, f_y, f_z represent translation forces, m_x, m_y, m_z rotation forces, and g is the grasp force.

We define the tension of string $\tau_{(i)}$ $(i = 1, \cdots, 8)$, and tension vector τ as follows:

$$\tau = (\tau_1, \tau_2, \cdots, \tau_8)^T \quad \left(\in R^8 \right)$$

We set w_i as the force vector generated in the grip as the unit tension is added to i–th string. w_i is defined below.

$$w_i = \begin{bmatrix} c_i \\ r_{(i)} \times c_i \\ \delta_i \cdot n \cdot r_{(i)} \times c_i \end{bmatrix}$$

However,

$$c_i = \frac{Q_i - P_{(i)}}{\left\| Q_i - P_{(i)} \right\|} \quad (i = 1, 2, \cdots, 8)$$

$$r_{(i)} = P_{(i)} - P_0$$

$$\delta_i : \begin{Bmatrix} 1 & i = 1,2,3,4 \\ -1 & i = 5,6,7,8 \end{Bmatrix}$$

$$n = \frac{r_1 \times r_2}{\left\| r_1 \times r_2 \right\|}$$

If we set $A \in R^{7 \times 8}$ into $A = (w_1, w_2, \cdots, w_8)$, the force vector q, given tension vector τ, can be represented as

$$q = A\tau$$

To display force vector q to cross type grip, we have to solve the tension vector τ which satisfies the above equation. However, the tension vector is positive value vector $(\tau_i \geq 0, i = 1, \cdots, 8)$. If we solve 2 degree Optimum problem, we can obtain the tension vector.

$$\left\| q - A\tau \right\| \rightarrow \min$$

$$s.t. \ \ \tau \geq 0$$

Because SPIDAR-G uses the tension of strings to display force, according to the position of grip, there are certain location in the frame where SPIDAR-G can not display appropriate forces. However, near the center of frame, SPIDAR-G can display 7 DOF force appropriately (see index 2).

7. Development of SPIDAR-G

We show manufactured SPIDAR-G in figure 6. The length of frame is 52cm, and the radius of grip is 4.1cm. The computer which was used with the SPIDAR-G in figure 6 is Pentium 400 MHz. The encoder was a HEDS-5540 made by HP company. A DC motor made by Maxon company was used.

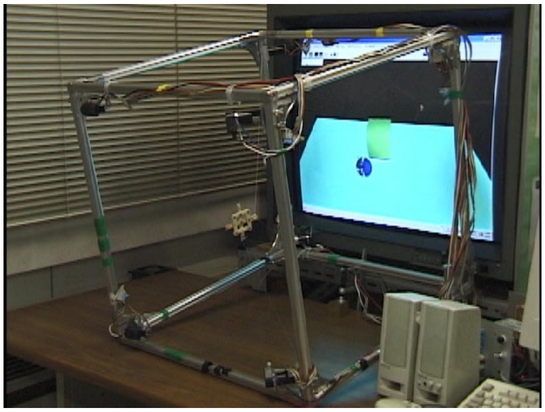

Figure 6. Manufactured SPIDAR-G

In following example, the user grasps the grip and the color of grip in the monitor turns red. On release, the color turns blue. This allows users to perceive not only force feedback but also a visual representation.

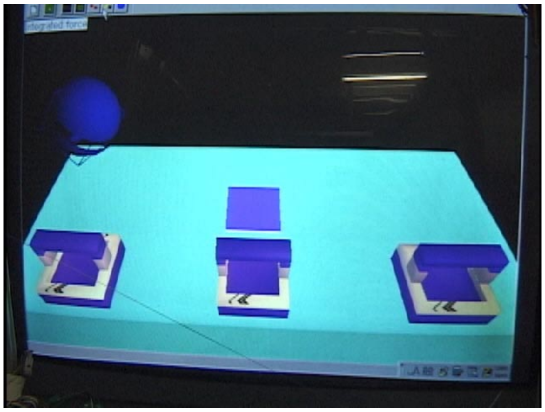

Figure 7. Example of lift up virtual object

We prepared 3 different weighted objects, and lift up each object with grasping. From this work, we could distinguish weight difference of the each object. However, it was difficult for users to perceive the same weight when far from the center of the frame. In addition, users had difficulty perceiving the width of the objects when the grip was positioned far from the center of the frame.

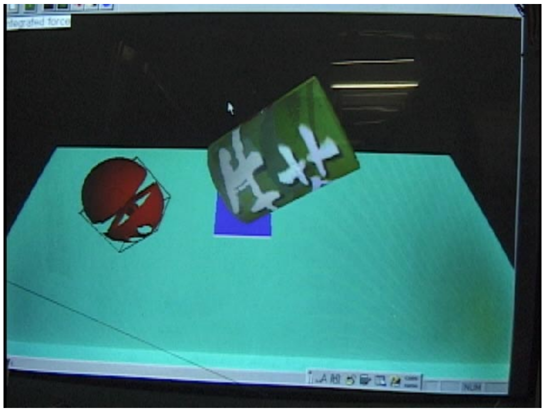

Figure 8. Example of grasp and rotation

In the demonstration represented in figure 8, users have to grasp the object and rotate into each X axis(depth direction), Y axis(vertical direction) and Z axis (horizontal direction). It was easier to manipulate from the X axis, the Y axis, and the Z axis respectively.

8. Conclusion and future work

In this paper, we described the tension based haptic interface with 7 DOF. We can get the precise solution for the position of grip using the redundancy of strings and the unique geometric characteristic of this system. We have also showed a new way to calculate position with a 7 DOF. Through examples using SPIDAR-G, we have demonstrated the validity of our proposed SPIDAR-G. The examples prove that our contrived SPIDAR-G provides users with not only translation and rotation but also grasp manipulation that is accurate and efficient. There are still issues with rotational force stability, which hope to address in future research.

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Index 1

From equation (4)~(11), we can get each x, y, x_1, y_2 as follows.

About x : -eq(4)+eq(5)-eq(6)+eq(7)

About y : -eq(8)-eq(9)+eq(10)+eq(11)

About x_1 : -eq(4)+eq(5)+eq(6)-eq(7)

About y_2 : -eq(8)+eq(9)+eq(10)-eq(11)

Therefore,

$$x = \frac{1}{8a}\left(-l_1^2 + l_2^2 - l_3^2 + l_4^2\right)$$

$$y = \frac{1}{8a}\left(-l_5^2 - l_6^2 + l_7^2 + l_8^2\right)$$

$$x_1 = \frac{1}{8a}\left(-l_1^2 + l_2^2 + l_3^2 - l_4^2\right)$$

$$y_2 = \frac{1}{8a}\left(-l_5^2 + l_6^2 + l_7^2 - l_8^2\right)$$

We substitute the above solutions into equation (12)~(15).

$$\mathrm{eq}(4) + \mathrm{eq}(5) + \mathrm{eq}(6) + \mathrm{eq}(7) \tag{12}$$

$$\mathrm{eq}(4) + \mathrm{eq}(5) - \mathrm{eq}(6) - \mathrm{eq}(7) \tag{13}$$

$$\mathrm{eq}(8) + \mathrm{eq}(9) + \mathrm{eq}(10) + \mathrm{eq}(11) \tag{14}$$

$$\mathrm{eq}(8) - \mathrm{eq}(9) + \mathrm{eq}(10) - \mathrm{eq}(11) \tag{15}$$

We can get 4 equations about Z. These 4 equations can be changed into 2 six degrees equations. General case, we use numeric method to solve six degrees equations. But this method requires suitable conditions, substantial time due to the iterative nature of the technique, and the results are only approximations. It is necessary to reduce the amount of calculations to maintain the haptic servo loop and we need precise results rather than approximations to earn high resolution. Numerical methodologies are therefore unsuitable.

Fortunately, in the case of using strings, we can know that the above 2 six degree equations contain the same result about z due to the redundancy of the strings. By either adding or subtracting 2 equations, we are able to get a six degree equation and a five degree equation which have a common solution about z. By dividing the high degree equation by the low degree equation, we get the result of Z. Using this, we can solve other variables (y_1, z_1, x_2, y_2, z_2).

$$y_1 = \frac{1}{2b}\{k_1 + (z-c)^2\}$$

$$x_2 = \frac{1}{2a}\{k_3 + (z+c)^2\}$$

$$y_2 = \frac{1}{8b}\left(-l_5^2 + l_6^2 + l_7^2 - l_8^2\right)$$

$$z_2 = \{\frac{1}{8}(l_5^2 - l_6^2 + l_7^2 - l_8^2) - yy_2 - ax - xx_2\}/(z+c)$$

However,

$$k_1 = x^2 + y^2 + d^2 + a^2 + b^2 - \frac{1}{4}\sum_{i=1}^{4} l_i^2$$

$$k_2 = x^2 + y^2 + d^2 + a^2 + b^2 - \frac{1}{4}\sum_{i=5}^{8} l_i^2$$

Index 2

That is to say, our system satisfies following equation in the center of the frame.

$$\sum_{1}^{8} w_i = 0$$

We can know that that equation satisfies theory 2.