Design and Control of a Wire-driven Haptic Device: HapticPen

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Abstract: In this paper, analysis, design, control and prototype construction of a wearable wire-driven haptic interface called HapticPen is discussed. This device can be considered as a wire driven parallel mechanism which three wires are attached to a pen-tip. Wire tensions are provided utilizing three DC servo motors which are attached to a solid frame on the user's body. This device is designed as input as well as output device for a wearable PC. User can write letters or figures on a virtual plate in space. Pen-tip trajectory in space is calculated using motor encoders and force feedback resulting from contact between pen and virtual plate is provided for constraining the pen-tip motion onto the virtual plane that can be easily setup by arbitrary non-collinear three points in space. In this paper kinematic model, workspace analysis, application analysis, control and prototype construction of this device are presented. Preliminary experiments on handwriting in space show feasibility of the proposed device in wearable environments.

Keywords: Haptics, wire-driven, wearable

1. INTRODUCTION

Force feedback devices play a very important role in human-computer interaction. Several haptic interfaces have been developed. Most of them are very heavy, bulky and because of rigid links that used in their design they are not dexterous enough to make user feel comfortable. Another problem with rigid links is that they are relatively unsafe; if they collide to user's body they can cause very bad injuries. To solve the above mentioned problems wire-driven haptic interfaces have been proposed. They are very light, low-cost and safe mechanisms. Because of their light weight they are a very good choice for wearable and mobile applications.

There are several wire-driven haptic interfaces which had been developed since 1980. We can categorize them into two groups, portable and desktop. In application area, all of them have been designed for applications different from augmented reality, i.e. mostly virtual reality application.

There are three samples of desktop wire-driven haptic interfaces which were developed. Two stringed haptic interfaces have been built and tested, the *Texas 9-string* [1] and the *SPIDAR* [2]. The Texas 9-string device was too bulky, suffered from cable interference, and failed to provide small feedback forces due to large actuator friction. Also, the bandwidth was low, which resulted in large time delays and jerky motion. The *SPIDAR* system was developed with four strings to give force-reflection to a single operator's finger tip (like the *PHANToM*). It was extended to eight strings to include thumb feedback. The first version of SPIDAR allowed user to touch object via a single contact point. However, in daily life we usually need to hold, grasp, and move objects to interact comfortably with the surrounding environment. To impart user with such ability another version of SPIDAR called SPIDAR II provides two end points attached to the thumb and index fingers. Another version of SPIDAR [3] was designed for using two hands simultaneously. The new system was named both-hand SPIDAR. The last version of SPIDAR was named SPIDAR-G. SPIDAR-G [4] allows users to interact with virtual objects naturally by manipulating two hemispherical grips located in the center of a device frame. Besides 3D haptic interfaces which reviewed above a planar 2D interface was also developed [5]. The device can exert 2D force to the user's hand using 4 strings.

In the case portable wire-driven haptic interfaces there are two mechanisms which were developed till now, WireMan and HapticGear. WireMan ([6], [7], [8]) was basically designed for helping blind people to know about obstacles in their way. Two stereo cameras were attached to user's head, and whenever there is something in the way a haptic force is exerted to the user's hand. In WireMan, three motors are connected to user's back; a string is connected to each motor. A thimble is attached to the other end of strings and user can feel force using that thimble.

Another wire-driven haptic interface is HapticGear [9] and [10] that is a backpack-type device that transmits applied forces to the wearer by using a wire-tension mechanism. HapticGear was designed as an artificial force display for immersive projection displays (IPD) such as CAVE or CABIN. When user touches a virtual object appropriate force feedback is exerted to the user's hand.

Mechanical configuration of the HapticPen is similar to two other wearable haptic devices which are already named WireMan and HapticGear. In application area HapticPen is designed as input device for wearable PC. User first of all defines a virtual plate in space by clicking over three points in space. After that user can write commands to wearable PC over the defined virtual plate. As user touches the virtual plate by pen a force feedback is provided

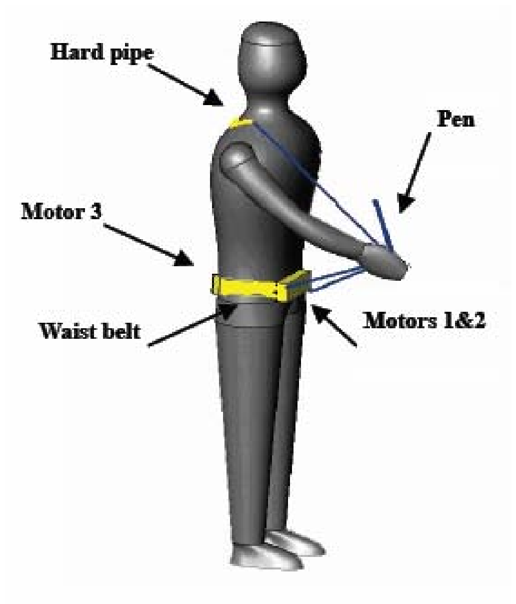


Fig. 1.HapticPen

to pen by stretching wires using motors which are attached to user's body. (see Figure 1)

In this paper kinematic analysis, workspace analysis, control and experimental setup and some preliminary results are presented.

2. KINEMATIC ANALYSIS

In this device for tracking pen-tip by utilizing wire lengths we need to solve forward kinematics. Considering 3 wires are connected to the pen-tip. Consider *{0},{1},{2}* as reference frames that are attached to wire extraction points, and S_0^1, S_0^2 as coordinates of origins of *{1}* and *{2}* with respect to *{0}*. (see Figure 2). Notice that non-collinear three wire extraction points form a plane in space.

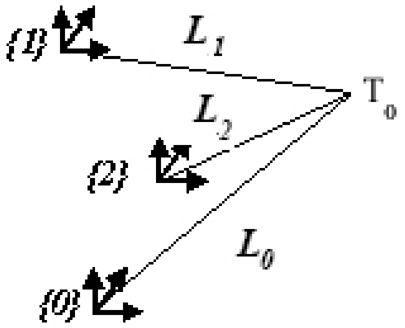


Fig. 2. Coordinate systems and wires

L_0, L_1, L_2 : wire lengths

T_0 : pen-tip coordinated with respect to *{0}*

$$T_0 = [x, y, z]$$

$$S_0^1 = [s_{1x}, s_{1y}, s_{1z}] \ = constant$$

$$S_0^2 = [s_{2x}, s_{2y}, s_{2z}] \ =constant$$

we can write

$$\begin{aligned} L_0 &= \lVert T_0 \rVert \\ L_1 &= \lVert T_0 - S_0^1 \rVert \\ L_2 &= \lVert T_0 - S_0^2 \rVert \end{aligned} \qquad (1)$$

System of equations (1) can be solved easily for T_0 considering the fact that we can construct a linear system of equations with respect to ***x,y*** and ***z*** by calculating $L_1^2 - L_0^2, L_2^2 - L_0^2$ and $L_1^2 - L_2^2$. Solving resultant linear system of equations gives us ***x,y*** and ***z*** position of pen-tip. So we can track pen-tip position in space very easily. Details solution for forward kinematics and closed from solutions for ***x,y*** and ***z*** can be found in appendix.

Inverse kienmatic problem is very straightforward. Consider pen-tip position as ***[x,y,z]*** in inverse kinematics we have to calculate wire lengths having pen-tip position.

$$\begin{aligned} L_0 &= \sqrt{x^2 + y^2 + z^2} \\ L_1 &= \sqrt{(x-s_{1x})^2 + (y-s_{1y})^2 + (z-s_{1z})^2} \\ L_2 &= \sqrt{(x-s_{2x})^2 + (y-s_{2y})^2 + (z-s_{2z})^2} \end{aligned} \qquad (2)$$

Considering u_0, u_1 and u_2 as unit vectors in direction of wires, tension in wires which is necessary to produce force ***f*** on the pen-tip can be calculated considering P as vector of wire tensions

$$\begin{aligned} f &= p_0 u_0 + p_1 u_1 + p_2 u_2 = J^{-T} P \\ J &= [u_0, u_1, u_2]^{-T} \end{aligned} \qquad (3)$$

so ***J*** is Jacobian of WiredPen and we can write

$$P = J^T f \qquad (4)$$

3. WORKSPACE ANALYSIS

To determine if a particular point belongs to the workspace or not we have to compare two things: the force which is needed to be exerted to the user's hand and the maximum force-set which can be generated by the haptic device in that point. If required force belongs to the maximum force-set it means that point is a member of workspace.

To formulate the above mentioned idea we need to define two concepts of attainable force set and required force set.[11]

Attainable force set (AF) is the set of all possible forces which the haptic device can exert on the pen-tip at a particular position given the range of wire tensions. (see Figure 3)

Required force set (RF) is the set of all net forces which the user or task requires the haptic device exert on the environment for a particular position.

Workspace can be defined as set of all points where RF is a subset of AF.

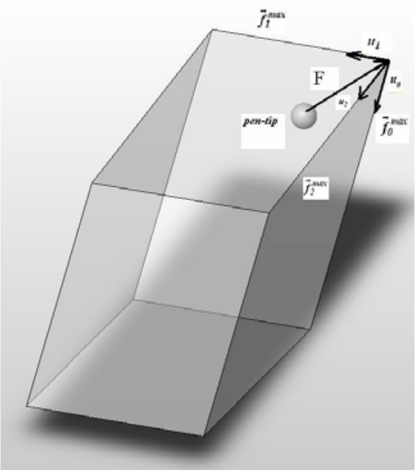


Fig. 3. Attainable force set

For calculating AF consider f_i^{max} as maximum permissible tension of wire *i* . If we consider the force which the user exert to the pen-tip as *F* we can derive AF as bounded positive span of wire tension vectors which is translated by *F*.

$$AF = \{ \sum_{i=0}^{2} a_i \vec{f}_i^{max} : 0 \le a_i \le 1 \} \oplus F \tag{5}$$

Geometrically $\{ \sum_{i=0}^{2} a_i \vec{f}_i^{max} : 0 \le a_i \le 1 \}$ is a parallelogram formed by $\vec{f}_0^{max} + \vec{f}_1^{max} + \vec{f}_2^{max}$. So AF is the mentioned parallelogram shifted by ***F*.*(***see Figure 3)

RF must be defined according to application scenario of the haptic device. For example consider an application scenario which the user must write on a vertical virtual plate, it is obvious that the reaction force from virtual plate to user's hand is in the direction of the pen, as user can hold the pen in any arbitrary direction then the reaction force in each point of the virtual plate can change its direction on a hemisphere over virtual plane. In the above mentioned application scenario RF is a hemisphere, we can numerically calculate distance between pen-tip and parallelogram plates. In every point where this distance is less or equal to required force then that point belongs to workspace.

Based on the above mentioned method a numerical simulation has been done. Figure 4 is one of simulation results. It is workspace view in a plane perpendicular to user's body, with $F = [0, -1] N$ and RF is a hemisphere with radius 4 N.

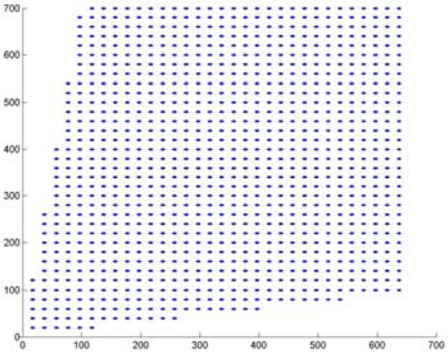


Fig. 4.Workspace of HapticPen in xy-plane

4. CONTROL

Direction of reaction force onto the tip of the HapticPen is always perpendicular to the virtual plate based on the assumption of no friction on the virtual plane. Figure 5 shows the normal force to the virtual plane. The resultant normal force is generated by three wire tensions as in Eq. 4

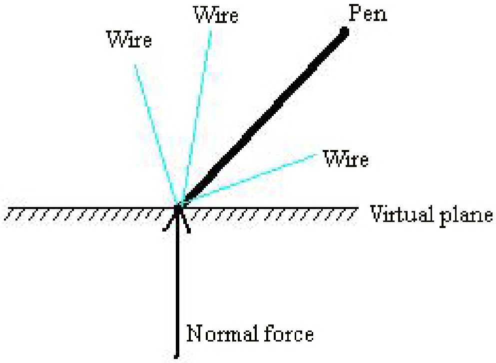


Fig. 5.Normal force to the virtual plane

Consider f(x,y,z)=0 as equation of the virtual plate, this equation can be easily derived using coordinates of three points which user selected in order to construct the virtual plate, as already mentioned in section 1.

Consider A, B, and C as 3 points over the virtual plate, these points are clicked in space by the user. ***N*** a normal vector to the virtual plate can be written as

$$N = [\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}] \qquad N = AB \times AC \tag{6}$$

For calculating Δx the penetration of the pen in the virtual plane in a point (x_0, y_0, z_0) we can use the following equation:

$$\Delta x=\frac{\left|f(x_0,y_0,z_0)\right|}{\sqrt{a^2+b^2+c^2}} \qquad (7)$$

Where a,b and c are values of $\frac{\partial f}{\partial x}$, $\frac{\partial f}{\partial y}$ and $\frac{\partial f}{\partial z}$ respectively.

Consider $\boldsymbol{K}$ as stiffness of the virtual plate. $\boldsymbol{f}$ the interaction force can then be calculated as

$$f=-K\Delta x\left(\frac{1}{\|N\|}N\right) \qquad (8)$$

For an ideal rigid object like a rigid, plane the value of $\boldsymbol{K}$ is infinite. So if we choose a bigger $\boldsymbol{K}$ users feel a harder and more realistic virtual surface. But there is a limitation, if we choose a very big $\boldsymbol{K}$ in the moment of contact and after that some unwanted vibrations due to stability problems will be produced. Using trial and error we found out for this system 50 N/m is a suitable value for $\boldsymbol{K}$.

Calculation of each wire-tension for producing $\boldsymbol{f}$ in the pen-tip then can be obtained by Eq. 4.

Controller block diagram is shown in Figure 6

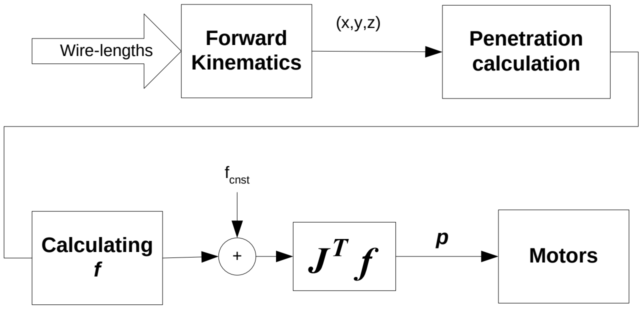


Fig. 6. Controller block diagram

As it can be inferred from Figure 6 first of all wire lengths which are measured by motor encoders are used in forward kinematic model in order to calculate coordinates of the pen-tip. Using pen-tip coordinates penetration of pen into virtual plate is calculated and then using (8) $\boldsymbol{f}$ is easily obtained. After adding constant force to $\boldsymbol{f}$ using (4) tension for each wire is calculated. Then proper commands corresponding to the required tensions will be sent to the motors.

5. PERILIMINARY EXPERIMENTAL RESULTS

In order to test the quality of haptic sensation to the user, some preliminary experiments have been performed. In the experimental setup three brushless DC motors with gear heads are used. With just 16 mm diameter each motor with attached gearhead has stall torque equal to 170 mNm. Position is detected using incremental encoders of motors with resolution of 540 pulses per revolution. The drivers and controller are small and light relative to other commercial models makes them suitable for wearable and mobile applications. The controller board has a 16 KHz dedicated DSP chip. The controller board is connected to the PC using RS232 protocol. (see Figure 7)

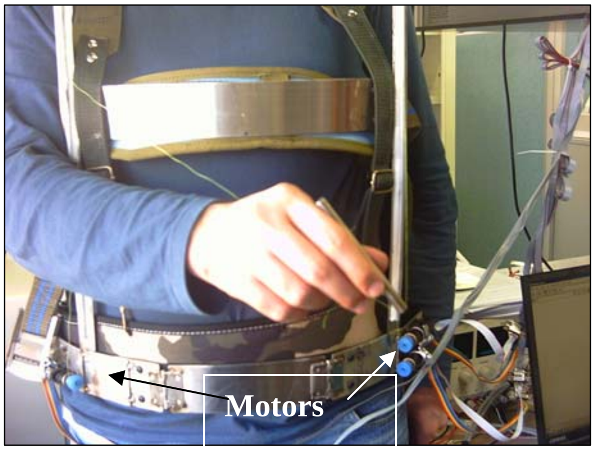


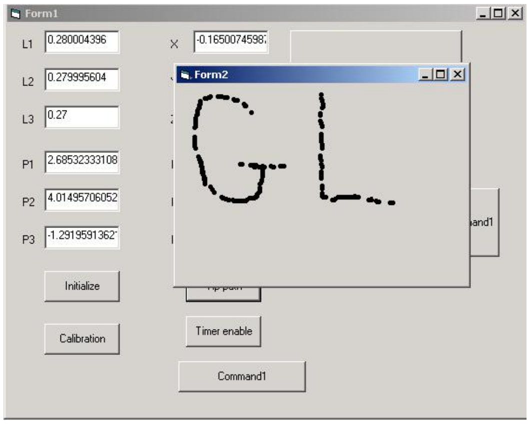
Fig. 7. Prototype

At the beginning of experiment there is a calibration procedure, user must move the pen-tip to a special point on the HapticPen frame and then push a button on the software, because coordinates of that point relative to frame are known, after that we can calculate position of the pen-tip. After calibration user chooses three points in the space to define a virtual plate. Then he will write different texts on the virtual plate. In order to keep the pen-tip on the virtual plane, force feedback is provided to the user according to penetration of pen-tip in the virtual plate.

Because orientation of pen can not be calculated, the feedback force is always in a constant direction independent of real pen direction. This constant direction can be always normal to virtual plate.

For experiment users were asked to try to write letters L and G on the virtual plate. In the preliminary prototype there is still a lot of friction which makes the user can not operate the device well. In this test user tried three times in order to perform the task.

Figures 8 shows letters which were written by a users and detected by HapticPen.



L1 0.280004396
L2 0.279995604
L3 0.27
P1 2.68532333108
P2 4.01495706052
P3 -1.2919591362
X -0.1650074598

Fig. 8. Letters which were written by a users

The discontinuities of letters in Figure 8 are due to low frequency of internal software timer because of low power of controller PC, with a more powerful PC a continues shape can be drawn on the monitor.

6. CONCLUSION

In this paper analysis, control and prototype construction of a wire driven wearable haptic device is discussed. Preliminary experiments show feasibility both in pen-tip tracking and also users perception of haptic feedback.

The existing prototype must be modified for reducing the friction between wires and frame, friction makes readings erroneous and also user feels uncomfortable with the device.

In the existing prototype, PC is used for controlling the hardware, because this device is basically a wearable device so the user must be able to move around freely while using HapticPen. The controller has a RS232 serial communication port so it can be connected to a PDA with serial port. Using windows CE programming, HapticPen can be controlled while it is connected to a PDA. Because of powerful DSP chip on the controller when PDA is used some parts of kinematic and dynamic calculation can be done on the controller so PDA resources can be used for other purposes. Another plan for future study is utilizing wireless Bluetooth technology for controlling the device.

ACKNOWLEDGMENTS

This work was supported by the smart haptic device project from the Ministry of Information and Communication.

7. REFERENCES

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APPENDIX

We can rewrite Eq. (1) as below

$$
\begin{aligned}
&L_0^2 = x^2 + y^2 + z^2 \\
&L_1^2 = (x - s_{1x})^2 + (y - s_{1y})^2 + (z - s_{1z})^2 \qquad \text{(A.1)} \\
&L_2^2 = (x - s_{2x})^2 + (y - s_{2y})^2 + (z - s_{2z})^2
\end{aligned}
$$

For finding position of pen-tip we have to calculate x,y and z from system of equations (A.1). System of equations (A.1) is nonlinear with respect to x,y and z. We can construct a linear system of equations with respect to x,y and z by calculating $L_1^2 - L_0^2, L_2^2 - L_0^2$ and $L_1^2 - L_2^2$ as below:

$$
\begin{aligned}
&L_1^2 - L_0^2 = -2xs_{1x} - 2ys_{1y} - 2zs_{1z} + s_{1x}^2 + s_{1y}^2 + s_{1z}^2 \\
&L_2^2 - L_0^2 = -2xs_{2x} - 2ys_{2y} - 2zs_{2z} + s_{2x}^2 + s_{2y}^2 + s_{2z}^2 \qquad (A\quad 2) \\
&L_1^2 - L_2^2 = -2(s_{1x} + s_{2x})x - 2(s_{1y} + s_{2y})y - 2(s_{1z} + s_{2z})z + s_{1x}^2 + s_{1y}^2 + s_{1z}^2 + s_{2x}^2 + s_{2y}^2 + s_{2z}^2
\end{aligned}
$$

System of equations (A.2) is linear with respect to x,y and z as

$$
\begin{aligned}
&s_{1x}x + s_{1y}y + s_{1z}z = K_1 \\
&s_{2x}x + s_{2y}y + s_{2z}z = K_2 \qquad \text{(A.3)} \\
&(s_{1x} + s_{2x})x + (s_{1y} + s_{2y})y + (s_{1z} + s_{2z})z = K_3
\end{aligned}
$$

$$K_1 = (s_{1x}{}^2 + s_{1y}{}^2 + s_{1z}{}^2 - L_1{}^2 + L_0{}^2) / 2$$
$$K_2 = (s_{2x}{}^2 + s_{2y}{}^2 + s_{2z}{}^2 - L_2{}^2 + L_0{}^2) / 2 \qquad \text{(A.4)}$$
$$K_3 = (L_2{}^2 - L_1{}^2) / 2$$

Where system of equations (A.3) is easily solvable for x,y and z with Kramer method:

$$\Delta = det \begin{bmatrix} s_{1x} & s_{1y} & s_{1z} \\ s_{2x} & s_{2y} & s_{2z} \\ s_{1x} + s_{2x} & s_{1y} + s_{2y} & s_{1z} + s_{2z} \end{bmatrix}$$

$$x = \frac{det \begin{bmatrix} K_1 & s_{1y} & s_{1z} \\ K_2 & s_{2y} & s_{2z} \\ K_3 & s_{1y} + s_{2y} & s_{1z} + s_{2z} \end{bmatrix}}{\Delta}$$

$$y = \frac{det \begin{bmatrix} s_{1x} & K_1 & s_{1z} \\ s_{2x} & K_2 & s_{2z} \\ s_{1x} + s_{2x} & K_3 & s_{1z} + s_{2z} \end{bmatrix}}{\Delta} \qquad \text{(A.5)}$$

$$z = \frac{det \begin{bmatrix} s_{1x} & s_{1y} & K_1 \\ s_{2x} & s_{2y} & K_2 \\ s_{1x} + s_{2x} & s_{1y} + s_{2y} & K_3 \end{bmatrix}}{\Delta}$$

The condition of nondiminishing determinant Δ is that three origin points of coordinate frames **{0}** ,**{1}** ,**{2}** must be non-collinear. In addition, well conditioning of the determinant requires three origin points must be separated from each other.