THREE CABLE HAPTIC INTERFACE (TCHI)

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Abstract

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THREE CABLE HAPTIC INTERFACE (TCHI) (81 pp.)

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A simple Three Cable Haptic Interface (TCHI) based upon the WireMan configuration developed by Bonivento et al., is developed, simulated, built and tested in this thesis. Cable systems cannot push on the user but only can provide positive tensions. This TCHI is further limited due to no actuation redundancy and further, forces can only be applied within the tetrahedron formed by the finger tip point and base cable attachment points.

The inverse pose kinematics is straight forward for this parallel manipulator configuration and the forward pose kinematics are derived using William’s Three Spheres intersection algorithm [23]. A pseudo-statics solution is derived to calculate the required cable tensions to provide the desired force-feedback. Three different control strategies are developed for to perceive soft, hard and both soft and hard combinations of the virtual walls.

Approved:

Robert L. Williams II

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Chapter 1 Introduction

1.1 Statement of Purpose

The purpose of this thesis is to develop a three cable haptic interface concept based on the design of WireMan configuration developed by Bonivento et al., 1993. The goal is to perform complete modeling, both kinematics and statics, for the proposed three cable haptic interface (TCHI), simulate the TCHI and derive the feasibility of forces, to build the three cable haptic interface for experiments and develop the controlling schemes for haptic perception.

1.2 Literature Review

According to American Heritage® Dictionary of English Language, the etymology of the word “Haptics” is the Greek word “haptikos”, which means to grasp, touch [4]. The haptic interfaces are the devices by which the users can feel the virtual environment provided in the computer by touch. There are many commercial devices available in the market. Most of them are expensive in spite of having many disadvantages like being heavy and cumbersome. Popular commercial device PHANToM is a dexterous device and it costs around $64,000. To develop alternatives for such expensive devices active research is going on to develop cable based systems as in robotics. Cable based systems have lower masses and are relatively easy and cheaper to build. Cable based systems are parallel type manipulators but have lower stiffness than rigid link parallel manipulators for the same workspace. Also Cable based systems have larger workspaces. The early
cable haptic devices developed are the Texas 9-string (Lindemann and Tesar, 1989), the SPIDAR (Ishii and Sato, 1994), the 7-cable master (Kawamura and Ito, 1993) and the 8-cable haptic interface (Williams, 1998). According to its authors, the Texas 9-string device (Figure 1-1) apart from being heavy and cumbersome, severely suffered from the cable interference. They also observed that perception of smaller forces is not possible due to heavy actuators like air cylinders. Also, there is a time delay in the perception of forces and the human movement due to lower band width. The initial SPIDAR (Figure 1-2) system has only four strings and the haptic force feedback is provided only on a fingertip. It was then improved to provide feedback on thumb too, using eight strings instead of four (Walairacht et al., 1999). Kim et al., 2002, developed another version of SPIDAR called SPIDAR-G (Figure 1-3), which gives 7 degrees of freedom. With SPIDAR-G users not only can grip a virtual object but also can feel its width.
Figure 1-1 Texas 9-String (Lindemann and Tesar, 1989) [15]
Figure 1-2 SPIDAR (Ishii and Sato, 1994) [11]

Figure 1-3 SPIDAR-G (Kim et al.) [14]
Williams, 1998, developed a Cable Suspended Haptic Interface (Figure 1-4) design to provide wrenches on human hand with only positive cable tensions. He found that cable interference dominates in this device. He suggested that the cables should connect to opposite corners (as in Charlotte Robot hardware, Campbell et al., 1992) to provide correct torque moments at the wrist. Also, Williams along with Gallina (2002) developed a dynamic model to determine the wrench-exertion workspace (with only positive cable tensions) and a method to control for only positive cable tensions.

Gallina et al. (2001) claims that the end-effector configuration used by Williams (1998), planar 4-cable haptic interface decreased the manipulability and to increase the manipulability index, developed a different configuration for the end-effector than that of Williams’s. Manipulability indicates the easiness of the kinematic structure movement of in any direction. T. Yoshikawa,1983, has defined it for rigid link manipulators [24]. Manipulability is found by mapping the input joint velocities space which forms a sphere to the output task space (Cartesian velocities) which gives an ellipsoid. The Major and Minor axes gives the measure of easiness to which direction the kinematic structure can
move. The cable systems can only pull but cannot push i.e. the actuation is only one direction. So Gallina re-defined manipulability for cable systems and developed some theorems, proved them and based upon those theories they proved their system is manipulable. They developed Feriba-3 (Figure 1-5), a 4-wire mechanism with a circular end-effector spool. Each wire is fixed to the lateral side of the spool and can wind around the spool. They claim that their particular geometric configuration made the system manipulable inside a large workspace and the kinematic forward and reverse pose solutions closed-form.

Figure 1-5 Feriba-3 (Gallina et al., 2001) [9]

All of the above systems have actuation redundancy, i.e. they have more active cables than the number of degrees of freedom they provide. Bonivento et al. (1997) developed a cable driven haptic interface without actuation redundancy, the WireMan
(Figure 1-6). This is a three-wire-driven haptic interface allowing three Cartesian translations with three Cartesian forces for the exploration of virtual surfaces. The WireMan is a portable haptic interface as shown with a thimble for the operator’s finger. With this sort of configuration it is possible to apply Cartesian forces only which are directed inside the tetrahedron formed by the three wires and base. They also evaluated a performance index for this device which is 3D space defective due to the lack of actuation redundancy. Other 3-Cable configurations developed are HapticGEAR (Hirose et. al, 2001) and HapticPen (Farahani and Ryu, 2005). Both these devices are wearable and are developed inspired by the WireMan. Hirose et. al developed HapticGEAR to displaying force in immersive projection displays like CAVE and CABIN where as Farahani and Ryu (2005) developed HapticPen to write or draw figures on a virtual plate.
Figure 1-7 HapticGEAR (Hirose et. al, 2001) [11]

Figure 1-8 HapticPen (Farhani and Ryu, 2005) [8]
The current thesis presents our three-cable haptic interface (TCHI) designed and built at Ohio University, based on the concept of the WireMan (Figure 1-6). This work draws its inspiration from the WireMan and the past work done on the cable based systems by Williams. Williams et al. (2003) developed a Cable-based Metrology for sculpting assistance, in which six cables are connected in parallel from ground-mounted string potentiometers to the moving object of interest. They developed a 3-Spheres Intersection Algorithm to obtain the closed-form forward pose kinematics to determine the Cartesian pose for feedback control. The author used this method to derive the forward pose kinematics for the current Three-cable haptic device project. Though the TCHI forces are limited due to lack of actuation redundancy, the kinematics and statics Jacobian solutions are easily derived in closed-form. Also, the feasible forces directed toward the user make this TCHI potentially suitable for application in the Virtual Haptic Back Project at Ohio University (Williams et al., 2004).

1.3 Team Contributions

In this section the contributions made by others to this project are introduced. The team for the TCHI project comprises of R.Williams II, Professor in Mechanical Engineering at Ohio University, the author and F. Giacometti, undergraduate student at University of Padova, Italy. Early mathematical derivations and simulations are contributed by Williams. F. Giacometti identified a flaw in the derivation of force feasibility conditions used for early simulations and re-derived those conditions. Giacometti helped the author in recording the current signal-to-force mapping for all the
three motors. She recorded the data for all the control schemes developed. She also submitted an undergraduate thesis at University of Padova titled “Three Cable Haptic Interface: Implementation and Evaluation”.

1.4 Thesis Objectives

The overall goal of this thesis work is to develop a three cable haptic interface. The specific objectives of this thesis are as follows:

- Perform complete modeling and analysis for a 3-cable haptic interface (TCHI).
- Build and program the portable 3-cable haptic interface.
- Make a comparison with existing commercial devices like the PHANToM®.

1.5 Thesis Organization

The current thesis presents the complete modeling both kinematics and statics, simulation, design, construction and the controlling schemes of the three cable haptic interface. Chapter 2 describes the three cable haptic interface concept. Kinematics and Statics modeling are presented in the chapter 3. In Chapter 4, three control schemes developed for this TCHI are discussed. Chapter 5 presents the experimental set up and the Hardware and software components required for this device. Experimental results are presented in Chapter 6. Following it are the conclusions, references and appendix.
Chapter 2 Three Cable Haptic Interface Concept

This section describes our Three-Cable Haptic Interface (TCHI) concept, inspired by WireMan (Bonivento et al., 1997). For now our system is fixed to the table. As mentioned earlier we used the PHANToM® 3.0 haptic interface for design specifications. Figure 2-1 shows our TCHI diagram. The base Cartesian reference frame is \( \{0\} \), attached and directed as shown. Each of the three cables is passed through the ground link at the fixed-base cable points \( ^0\mathbf{B}_1 = \{-L_z, 0, 0\}^T \), \( ^0\mathbf{B}_2 = \{0, 0, 0\}^T \), and \( ^0\mathbf{B}_3 = \{0, 0, -L_z\}^T \). The active cable lengths are \( \mathbf{L} = \{L_1, L_2, L_3\}^T \). The vector \( ^0\mathbf{P} = \{x, y, z\}^T \) gives the position of finger tip with respect to the \( \{0\} \) origin, expressed in \( \{0\} \) coordinates. The active cable tensions are \( \mathbf{T} = \{t_1, t_2, t_3\}^T \) and the resultant Cartesian fingertip force is \( ^0\mathbf{F}_r = \{f_x, f_y, f_z\}^T \). The finger thimble is located at \( ^0\mathbf{P} \) and the three tensioning motors reels are mounted at \( ^0\mathbf{B}_n \) controlling the active cable tensions \( \mathbf{T} \) to achieve the desired Cartesian fingertip force \( ^0\mathbf{F}_r \) for haptic feedback.

There is no actuation redundancy since there are three active cable tensions for three Cartesian force components. Hence we can exert only \( ^0\mathbf{F}_r \) contained within all three positive cable tensions; that is, within the tetrahedron \( B_1B_2B_3P \) since cables may exert only tension. This force limitation is configuration-dependent. The largest force magnitudes can be directed back towards the user. Generally smaller force magnitudes are possible in transverse directions. The large forces required by the Virtual Haptic Back project at Ohio University (Williams et al., 2004) are normal. So, the TCHI’s
limited haptic feedback is well suited for most haptic needs in the Virtual Haptic Back project.

Figure 2-1 Three Cable Haptic Interface Diagram
Chapter 3  Kinematics and Statics

This section presents our closed-form kinematics and statics modeling and solutions for simulation and control of the three-cable haptic interface (TCHI).

3.1 Kinematics

Kinematics modeling is concerned with relating the Cartesian position of the fingertip to the three cable lengths.

3.1.1 Inverse Pose Kinematics

The inverse pose kinematics (IPK) problem is stated: Given the desired finger tip position \( ^0P \), calculate the three active cable lengths \( L \). Like most Cable Suspended Robots (CSRs) and Cable Suspended Haptic Interfaces (CSHI), the inverse pose kinematics problem is straight-forward since the cable lengths are simply the Euclidean norms of the cable vectors connecting each base point with the fingertip:

\[
L_i = \| ^0B_i - ^0P \| \quad \text{where } i = 1,2,3 \quad (3.1)
\]

\[
L_1 = \sqrt{x^2 + y^2 + z^2 + L_i^2 + 2L_x x} \\
L_2 = \sqrt{x^2 + y^2 + z^2} \\
L_3 = \sqrt{x^2 + y^2 + z^2 + L_z^2 + 2L_z z} \quad (3.2)
\]

Substituting the specific cable base point parameters in \( \{0\} \), we see the IPK solution (3.2) is simple. The IPK solution may be used in simulation; it is not required for on-line operation of the TCHI.
3.1.2 Forward Pose Kinematics

The forward position kinematics (FPK) problem is stated: Given the three active cable lengths \( L \), calculate the Cartesian position of the fingertip \( ^0P \). This position is then implemented in real-time for haptics applications. That is, as the human moves, the motor encoders read \( L \), and FPK sends the user position \( ^0P \) to the virtual world.

The FPK solution consists of finding the intersection point of three given spheres, with the centers \( ^0B_1, ^0B_2, \) and \( ^0B_3 \). Let a sphere be referred as a vector center point \( c \) and scalar radius \( r \): \((c, r)\). The unknown point \( ^0P \) is found as follows:

\[ ^0P \text{ is the intersection of } ( ^0B_1, L_1 ), ( ^0B_2, L_2 ), \text{ and } ( ^0B_3, L_3 ) \]

Now the equations and solution for the intersection point \( ^0P = \{x, y, z\}^T \) of the three above spheres are derived for our specific TCHI parameters. The equations of the above three spheres are:

\[
\begin{align*}
(x + L_x)^2 + y^2 + z^2 &= L_1^2 \\
x^2 + y^2 + z^2 &= L_2^2 \\
x^2 + y^2 + (z + L_z)^2 &= L_3^2
\end{align*}
\]

Equations (3.3) are coupled nonlinear equations in the three unknowns \( x, y \) and \( z \). The solution will yield the intersection point \( ^0P = \{x, y, z\}^T \). The solution approach is to first expand the first and third terms of the first and the third equations of (3.3). Then subtract the second equation from first and third equations to find \( x \) and \( z \). Then \( y \) is found from second equation of (3.3), once \( x \) and \( z \) are known. In this way we obtain the solution \( x, y \) and \( z \) as follows:
Mathematically there are two solutions to the intersection of two spheres in general. \((X, z)\) is unique but there are two \(y\) values as shown in (3.4). However in the design shown in Figure 2-1, only the \(+y\) solution will be useful. Therefore, we have a unique FPK solution. Williams et al. (2004b) discuss the multiple solutions, algorithmic singularities, and imaginary solutions for the general three-spheres intersection algorithm. For the TCHI, imaginary solutions could be a problem only if the cable lengths are not sufficiently long to intersect at point \(0P\). If the cable length sensing is good this will not happen. The algorithmic singularities may easily be avoided by proper choice of coordinates for the base cable points (Williams et al., 2004b). Due to the simple structure of the TCHI, our algorithmic singularities are simply \(L_x = 0\) and \(L_z = 0\), which are avoided by design.

So, the FPK derivation is straight-forward and a unique solution always exists assuming good cable sensing and non-zero \(L_x\) and \(L_z\). This FPK solution is less computational intensive in the sense that it is closed-form and pretty straightforward to calculate than any other numerical algorithms like Newton-Raphson method used to solve the FPK for the parallel systems, which is really critical for the real-time haptic interface implementation.
3.2 Statics

Since the cable and finger thimble mass is very small and assuming that human fingertip velocities and accelerations are relatively small, the TCHI may be controlled in a pseudostatic manner. In this subsection statics modeling is presented. These equations are used to simulate and program the TCHI to provide desired Cartesian forces to the fingertip.

3.2.1 Static Equilibrium

For the system to be in static equilibrium, the sum of tension forces exerted on the fingertip thimble must be equal to the resultant force exerted on the finger tip (the human finger must exert an equal and opposite force on the thimble for pseudostatic equilibrium). The statics equations are:

\[ \sum_{i=1}^{3} t_i = \sum_{i=1}^{3} t_i \hat{L} = 0 F_r \]  \hspace{1cm} (3.5)

Gravity is ignored because the weight of the fingertip thimble and cables are very small compared to the tension and resultant force levels. In equations (3.5), \( t_i \) is the cable tension applied to the \( i^{th} \) cable by its motor (in the cable length unit direction \( \hat{L}_i \) directed from \( P \) to \( B_i \) because \( t_i \) must only be in tension); and \( F_r \) is the resultant vector force exerted on the fingertip by the haptic interface. Substituting the above terms into (3.5) yields:

\[ \hat{0} F_r = \hat{0} AT \]  \hspace{1cm} (3.6)
where \( \mathbf{T} = [t_1 \ t_2 \ t_3]^T \) is the vector of scalar cable tensions, \( ^0\mathbf{F}_r \) is the resultant vector force (expressed in \{0\} coordinates), and the 3x3 statics Jacobian matrix \( ^0\mathbf{A} \) (expressed in \{0\} coordinates) is:

\[
^0\mathbf{A} = \begin{bmatrix} ^0\mathbf{L}_1 & ^0\mathbf{L}_2 & ^0\mathbf{L}_3 \end{bmatrix}
\]

The statics Jacobian matrix for the TCHI of Figure 2.1 is:

\[
^0\mathbf{A} = \begin{bmatrix}
-\frac{L_x - x}{L_1} & \frac{-x}{L_2} & \frac{-x}{L_3} \\
\frac{-y}{L_1} & \frac{-y}{L_2} & \frac{-y}{L_3} \\
\frac{-z}{L_1} & \frac{-z}{L_2} & \frac{-L_z - z}{L_3}
\end{bmatrix}
\]

(3.8)

It is well known from the mechanics of parallel robots that given the statics Jacobian matrix, we can easily find the velocity kinematics that maps cable length rates into the Cartesian velocity of point \( P \), \( ^0\mathbf{X} = ^0\mathbf{J} \dot{\mathbf{L}} \):

\[
^0\mathbf{J} = -^0\mathbf{A}^T
\]

(3.9)

### 3.2.2 Pseudostatics Solution

The determinant of the statics Jacobian matrix \( ^0\mathbf{A} \) is:

\[
\left| ^0\mathbf{A} \right| = \frac{-L_x L_z y}{L_1 L_2 L_3}
\]

(3.10)

Assuming non-zero \( L_x \) and \( L_z \), the only statics singularity condition is \( y = 0 \); when the fingertip is on the \( XZ \) plane (\( y = 0 \)), it is impossible to exert \( f_y \).
The statics equations (3.6) can be inverted (as long as \( y \neq 0 \)) in an attempt to exert general Cartesian forces \( \mathbf{F} \), with cable tensions \( \mathbf{T} \):

\[
\begin{bmatrix} \mathbf{T} \end{bmatrix} = \left[ \mathbf{A}^{-1} \right] \begin{bmatrix} \mathbf{F} \end{bmatrix}
\]

(3.11)

where

\[
\mathbf{A}^{-1} = \begin{bmatrix}
-\frac{L_1}{L_x} & \frac{L_1 x}{L_x y} & 0 \\
\frac{L_2}{L_x} & -\frac{L_2 (L_z x + L_z z + L_z z)}{L_z y} & -\frac{L_2}{L_z} \\
0 & \frac{L_3 z}{L_z y} & -\frac{L_3}{L_z}
\end{bmatrix}
\]

(3.12)

So we have a closed-form solution to the cable tensions \( \mathbf{T} \) given \( \mathbf{F} \):

\[
\begin{align*}
t_1 &= \frac{-L_1}{L_x} f_x + \frac{L_1 x}{L_x y} f_y \\
t_2 &= \frac{L_2}{L_z} f_x - \frac{L_2 (L_z x + L_z z + L_z z)}{L_z y} f_y + \frac{L_2}{L_z} f_z \\
t_3 &= \frac{L_3 z}{L_z y} f_y - \frac{L_3}{L_z} f_z
\end{align*}
\]

(3.13)

The above solution is closed form. The tensions in the above equation must always be positive to feel the required resultant force \( \mathbf{F} \), because cables can only pull, cannot push.

### 3.3 Force Feasibility Conditions

For better visualization of what a feasible force is, we derived the force feasibility conditions and simulated. F. Giacometti has detected a flaw in our early derivations and has re-derived them [10]. As stated earlier, since this haptic interface has no actuation
redundancy in (3 active cables for 3 Cartesian force components); we can only exert $^0F_r$ bounded by all three cable tensions, within the tetrahedron $B_1B_2B_3P$, since cables may only exert tension. In theory, fingertip point $P$ can take any value (subject to cable limits, plus the $Y_0$ position component should be positive in practice), but the resultant force must be contained within the three cables. This is configuration-dependent, and the mathematical determination for TCHI feasible forces is derived below.

Since any feasible (all three cable tensions must be positive) resultant force $^0F_r$ must be bounded by all three cables, if we project the force vector $^0F_r$ from the fingertip point $P$ back to the $XZ$ plane ($y = 0$), the force will be feasible only if this intersection point is contained within triangle $B_1B_2B_3$. To derive the intersection point $P_{int}$ (see Figure 3-1), let $L_{int}$ be the vector pointing from the finger point $P$ back to the intersection point; $L_{int}$ is of (unknown) length $L$, pointing in the unit vector direction $^0\hat{F}_r$ along $^0F_r$. Please see Figure 3-1 for the intersection point geometry.
Figure 3-1 Projection of $\hat{\mathbf{F}}_r$ onto XZ Plane

The unit vector direction $\hat{\mathbf{F}}_r$ is:

$$
\hat{\mathbf{F}}_r = \begin{pmatrix}
\hat{f}_x \\
\hat{f}_y \\
\hat{f}_z
\end{pmatrix}
= \frac{1}{\|\mathbf{F}_r\|} \begin{pmatrix}
\mathbf{F}_x \\
\mathbf{F}_y \\
\mathbf{F}_z
\end{pmatrix}
$$

(3.14)

where $\|\mathbf{F}_r\| = \sqrt{f_x^2 + f_y^2 + f_z^2}$ is the Euclidean norm of the resultant force vector. To solve for the unknown length $L$ and the unknown intersection point $\mathbf{P}_{\text{int}} = \{x_0, 0, z_0\}^T$ given finger position $\mathbf{P} = \{x, y, z\}^T$ and given resultant force $\mathbf{F}_r$, we have the following vector loop closure equation:
\[ \begin{align*}
\begin{bmatrix} x \\ y \\ z \end{bmatrix} + L \begin{bmatrix} \hat{f}_x \\ \hat{f}_y \\ \hat{f}_z \end{bmatrix} &= \begin{bmatrix} x_0 \\ 0 \\ z_0 \end{bmatrix} \\
(3.15)\end{align*} \]

From the middle equation, the unknown length \( L \) to the intersection point from the fingertip point is easily found to be:

\[ L = \frac{-y}{\hat{f}_y} \]

and the remaining unknowns are found by substituting this \( L \) into the top and bottom equations of (3.15):

\[ \begin{align*}
x_0 &= x + L \hat{f}_x \\
z_0 &= z + L \hat{f}_z \\
(3.17)\end{align*} \]

The equation for the lower constraint line \( B_1B_3 \) is:

\[ Z = \frac{-L_z}{L_x} X - L_z \]

(3.18)

Again, a force will be feasible only if the intersection point \( P_{int} \) is contained within the base triangle \( B_1B_2B_3 \). Therefore, any resultant vector force \( ^0\mathbf{F}_r \) is feasible with the TCHI only if all three inequalities in (3.19) are satisfied (the force is border-line feasible if one or more inequality becomes equal, i.e. one or more cable tension will go to zero, but not negative, in these cases):
\[
L > 0 \\
- \frac{L_z}{L_x} (z_0 + L_z) < x_0 < 0 \\
- \frac{L_z}{L_x} x_0 - L_z < z_0 < 0
\]

The requirement \( L > 0 \) is necessary to ensure the force is pointing towards the \( XZ \) plane, i.e. if \( L < 0 \) then at least one negative cable tension will be required. The second two constraints are required to ensure the intersection point \( \mathbf{p}_{\text{int}} \) will lie within triangle \( B_1B_2B_3 \). The left-hand inequalities of the second two constraints are redundant, i.e. they represent the same linear equation constraint (3.18). Therefore we can simplify the force-feasible constraints as follows:

\[
L > 0 \\
x_0 < 0 \\
- \frac{L_z}{L_x} x_0 - L_z < z_0 < 0
\]

### 3.4 TCHI Simulation Examples

This section presents three related snapshot examples to demonstrate the required calculations for implementation of the TCHI. All three examples have the same TCHI at the same fingertip point (that is, with the same three cable lengths), but with different desired Cartesian forces for possible application.

The simulated TCHI design has \( L_x = 0.8 \) and \( L_z = 0.9 \) m (see Figure 2-1). The common snapshot position for all three examples has active cable lengths
\[ \mathbf{L} = \{L_1 \ L_2 \ L_3\}^T m \] and fingertip position point \( ^0 \mathbf{P} = \{-0.525 \ 0.275 \ 0.094\}^T \) (this configuration was developed using FPK but can equally serve as an IPK example).

The three examples below have this same configuration. The three Figures 3-2, 3-3, 3-4 thus have the same kinematics. The heavy blue lines indicate the base and the light red lines are the three active cables. The heavy green line is the Cartesian resultant force to apply. This green line shows whether the force is directed towards or away from the user depending upon whether the line is coming from base direction to the thimble position point or it comes from outside to the thimble position. Only example 3 turns out to be feasible since Examples 1 and 2 were designed to require negative cable tension(s).

**Example 1**

The desired resultant Cartesian fingertip force to be exerted on the human finger is: \( ^0 \mathbf{F}_r = \{0.1 \ 1.0 \ 0.2\}^T N \). This force is not feasible since the intersection length \( L \) is not greater than 0:

\[
\begin{align*}
L &= -0.282 \\
x_0 &= -0.553 \\
z_0 &= -0.149
\end{align*}
\]

The required active cable tensions are all negative:

\[
\mathbf{T} = \{-1.006 \ -0.313 \ -0.604\}^T N
\]
This case is shown in Figure 3-2. The intersection point would lie within the base point triangle, but the force is directed the wrong way, i.e. away from the user (green line comes from outside to the thimble position).

### Example 2

The desired resultant Cartesian fingertip force to be exerted on the human finger is: \(^0\mathbf{F}_r = \left[ -0.5 \quad -1.0 \quad -0.5 \right]^T N\). This force is **not feasible** since the intersection point doesn’t lie within the base triangle:

\[
\begin{align*}
L &= 0.336 \\
x_0 &= -0.662 \\
z_0 &= -0.232
\end{align*}
\]

One of the required active cable tensions is negative:

\[
\mathbf{T} = \left[ 1.206 \quad -0.187 \quad 0.938 \right]^T N
\]
This case is shown in Figure 3-3. The force is directed toward the user (see that the green line comes from the base direction to the thimble position), but the intersection point does not lie within the base point triangle (see the green dot in Figure 3-3).

![Figure 3-3 TCHI Example 2](image)

**Example 3**

The desired resultant Cartesian fingertip force to be exerted on the human finger is: $\mathbf{F}_r = \begin{bmatrix} -0.3 & -0.9 & -0.2 \end{bmatrix}^T N$. This force is feasible since the intersection length $L$ is positive and the intersection point lies within the base triangle:

$$L = 0.296$$

$$x_0 = -0.617$$

$$z_0 = -0.156$$

The required active cable tensions are all positive:

$$\mathbf{T} = \begin{bmatrix} 1.010 & 0.111 & 0.566 \end{bmatrix}^T N$$
This case is shown in Figure 3-4. We see the force is directed towards the base (see that the green line comes from the base direction to the thimble position) and the projection point (see the green dot in Figure 3-4) lies within the base point triangle.

Figure 3-4 TCHI Example 3
Chapter 4  TCHI Control Methods

The purpose of a haptic control scheme is to allow safe and proper haptic interaction to the human. As the human goes on exploring the virtual space with his finger the forces are provided by the controller on to the human finger in order to be able to feel the virtual environment. The idea is that the human has to be able to freely move in the free space and only should feel resistance when contacting a virtual object. The controller tracks the position of the human finger and based upon the position of the finger and the position of the object, it provides signals to the motors of the TCHI. The TCHI in turn provides the force on the finger so that the human finger feels the reaction force as he pushes against the object.

4.1 Control Schemes Developed for the TCHI

The control schemes developed for this project are done keeping in mind, that the control scheme should be able to provide appropriate signals to the motors with respect to the position of the human finger. In the three cable haptic device, the position is calculated from the motors encoder readings and the relative position with respect to the virtual object is obtained. Initially, this difference in the position is used to obtain the required force (spring force) to be applied on the human’s finger using the following typical haptic force equation,

\[ f = -k \Delta x \]  \hspace{1cm} (4.1)
where $f$ is the spring force applied on the operator’s finger and $\Delta x$ is the difference in the distance between human operator’s finger and the virtual object.

Initial experiments are done aiming to provide a spring force on the human finger, to feel a virtual (infinite) spring in front of the device set up (XZ plane) in y direction at a distance of 0.22 cm. The spring force equation used is

$$f_y = -k \cdot (y - 0.22) \quad (4.2)$$

The first control scheme developed was the simple force control scheme aimed to calculate required forces, check the feasibility of forces and send the mapped current signals to the motors via amplifiers. This control scheme is a traditional haptic control scheme in the sense that most haptic devices developed used this control approach. We then developed the position control scheme and Force/Position control scheme to check if the system behaves as expected.

Now, in the following sections we will look at the each control scheme, and how they are implemented in our project.

### 4.2 Force Control Scheme

This is a traditional approach of control for haptic devices in the sense that most haptic devices developed used the same approach. In this approach the force felt is the spring force and it is proportional to the distance moved into the object. The spring force follows the equation (4.1) ($f = -k \Delta x$). By varying the spring constant $k$, the kind of objects one can feel differs. For soft objects we need lower spring constant and for stiffer objects, the higher spring constant.
The following control block diagrams explain this scheme.

Figure 4-1 Force Control Concept
Figure 4-2 Detailed Force Control Blocks for TCHI

As seen in the block diagrams, real cable lengths are obtained from the Motor Encoder readings and these lengths are used in Forward Pose Kinematics to obtain the position of the human finger. In the haptics model, this position is compared to virtual objects location and the forces are calculated using the equation: Then the required tensions in the cable to generate those forces are calculated using pseudo-statics solution. These tensions are then transformed to required motor currents and these currents are sent to the TCHI. The actual implementing MATLAB/SIMULINK control diagram is shown in Figure 4-3.
Figure 4-3 Implementation of Force Control in MATLAB/SIMULINK
4.3 Position Control Scheme

This is traditional robot control scheme. We decided to check if the traditional robotic position control scheme works for TCHI. This position control scheme is adopted from the Master’ thesis work of Vadia, 2003, Ohio University, where he implemented this scheme for the run-time implementation of a Four Cable Direct Driven Robot.

![Position Control Block for TCHI](image)

Figure 4-4 Position Control Block for TCHI

Positional error is the driving force for this control scheme. The control scheme is based upon the individual joint control of the robotic systems. As seen above, the position is obtained from the encoder readings, which then used to obtain the Forward Pose Kinematics solution which gives the actual length. Based upon the actual distance and actual lengths, desired position and the corresponding desired lengths are calculated. The difference in the lengths of both actual and desired is calculated for each cable and based upon this error; the PD controller for the motor sends the necessary current signal to rotate the motor so as to provide proper tension in the cable. The cables provide
corresponding reaction forces on the thimble to stop the further movement. The actual implementing MATLAB/SIMULINK diagram is shown in Figure 4-5.
Figure 4-5 Implementation of Position Control in MATLAB/SIMULINK
4.4 Combined Force/Position Control Scheme

We developed this control scheme based upon the above two control systems. We implemented this scheme such a way that when the thimble encounters soft skin, the force felt is spring force until it encounters the stiff wall. Here at this position, position control comes into play and the thimble will be stopped. The implementing SIMULINK control diagram is shown in figure 4-6.
Figure 4-6 Implementation of Force/Position Control in MATLAB/SIMULINK
Chapter 5  Experimental Setup

We developed the Three Cable Haptic System based upon the equipment available in the ME Robotics Lab, Ohio University. All the equipment selection used for the developing the experimental setup and conducting experiments both the software and hardware is what is available in the lab. Since the project is not funded from any external source most of the times we took the material from the lab. Though the equipment selected may not be ideal, it is nevertheless turned out to be sufficient to successfully conduct the experiments and to draw enough conclusions on this concept of Three Cable Haptic Interface.

5.1 Experimental Setup

Figure 5-1 TCHI Experimental Setup
As the Figure 5-1 shows, a thimble is connected by the three cables to three different motors mounted upon a 2” x 2” steel channel rectangular frame. When the operator pushes the thimble with his finger, motors rotate to pull back the cables to provide reactional forces on the operator’s finger, thus providing the haptic perception. A data acquisition board (PCI Multi Quanser Board) is connected to the PC. The motor encoders are connected to the data acquisition board so that the position of the finger can be calculated at real time. Based upon the control scheme used, computer calculates the current signals based upon the position of the finger and these current signals are sent to amplifiers to amplify the current proportionately are required by the motors. An AC to DC transformer is used to convert current to DC to provide supply to the amplifiers used.

## 5.2 Hardware

The hardware components required to build a 3-Cable Haptic Device are three motors, pulleys, cable, frame upon which the motors are mounted, amplifiers, transformer and a data acquisition board for real time control. The following is the list of equipment used for the current TCHI:

- 24VDC, 5.9:1 gear ratio motors with 500 CPR encoders
- 25A8 amplifiers
- PS16L30 transformer
- 8 analog I/O MultiQ PCI Quanser board
- PC with 1GB RAM, Intel Pentium IV 2.12 GHz processor, 80GB hard disk.
5.2.1 Motors

First we used PITTMAN gear motors designated as GM14904S016, which are available in the lab. A GM14904S016 gear motor has a gear ratio of 19.7:1 and a continuous torque of 2.64N-m. We faced potential problems with this motors. Even in free space operator had to continuously apply considerable force to overcome the inertia of the motors and we couldn’t provide low forces perception required for soft materials. The problem is with the gear ratio. Then we looked for lower gear ratio PITTMAN motors. Finally we settled for GM9236S015 which has a gear ratio of 5.9:1. It would have been better if we could get the motors with even less gear ratio.

Figure 5-2 GM9236S015 PITTMAN Motor [7]
5.2.2 Amplifiers and Power Supply

Since the motors used in TCHI hardware require higher voltage and current than that supplied by the data acquisition board, we need amplifiers to amplify the current signals. A 25A8 Servo amplifier from Advanced Motion Controls is used for these purposes. This A-series amplifier is safe against most of the potential electrical problems, including over-voltage, over heating and short circuits. These amplifiers can be used to operate in either current, voltage or velocity mode. With TCHI, we use this amplifier to command the current i.e. it is operated in current mode. For each motor we use a separate 25A8 unit. Since, the controlling schemes developed for the TCHI are based upon the
control law $\tau \propto i$ i.e. output torque is proportional to the input current, a servo amplifier is a natural choice. Also, the motors we use are 24VDC motors with peak current of 10A. 12A8 amplifiers would have been an ideal choice but since 25A8 amplifiers are readily available in the lab, they have been used.

The 25A8 amplifiers require a DC supply of 30V. So, a PL16L30 transformer from AMC is used to convert the supply from 120V AC (line voltage) to 30V DC.
Figure 5-5 PS16L30 Transformer [2]

Figure 5-6 Power Assembly
5.2.3 Quanser Board

The PCI Multi-Q data acquisition board from Quanser is used to collect data from the motor encoders, to calculate the human finger position and to send the signals to command the motors. This board has eight analog I/O, four digital inputs and six encoder inputs. The analog I/O range is ± 5V and the sampling time is 1.35μs when all the 8 channels are simultaneously used. But the encoder input sample time is 4.72 μs [16]. Since we use three motors, we need three encoder inputs and three analog outputs. This board is selected because it can be integrated for real time control with MATLAB/SIMULINK software with which control schemes are easier to develop.
5.2.4 Personal Computer (PC)

The data acquisition board used can be inserted only in a PCI slot of the motherboard and the related software WINCON 4.0 we used is compatible with windows 2000/XP operating system. Hence any normal PC with the motherboard having PCI slots with the operating system windows 2000/XP can be used for this project. Considering the data acquisition board and the related software requirements, any normal PC with 512 MB RAM and Pentium III processor will do. We used Sony VAIO PC with 1GB RAM and Intel Pentium IV with 2.12 GHz speed.

5.3 Software

5.3.1 MATLAB/SIMULINK

MATLAB is an interactive, high level language. It performs intensive computational tasks faster than any other traditional high level languages like C and C++. It has a rich set of tool set that can be used for computations in a wide range of applications that pretty much cover all engineering areas. SIMULINK is a platform, integrated with MATLAB, which provides an easy tool for designing and simulating the dynamic systems. SIMULINK tool provides all necessary control blocks including S-Function blocks to interface with C code. This is necessary to generate real time code for real time control. For detailed description of the product please visit the website www.mathworks.com.
5.3.2 WINCON

WINCON Software has it potential applications in Rapid Control Prototyping (RCP) and Hardware-In the-Loop (HIL) testing. It can be used for real time control either directly interfacing with C code or through SIMULINK. It works both ways. WINCON runs on Windows and quickly implements the real time code generated automatically, via Real Time Workshop. For detailed description of the product please visit the website www.quanser.com. This software works with the PCI MutliQ data acquisition board we selected.
Chapter 6  Experimental Results and Comparisons

This chapter first presents the results of the basic experiments conducted on the three cable haptic interface built at ME Robotics Lab at Ohio University. At the end subjective comparisons are made between the control schemes and the TCHI vs. PHANToM. The main factors like tensions of the cables, forces acting on the thimble, cable lengths and the position of the thimble are recorded for all the three control schemes developed and presented here. The thimble is pushed perpendicularly away from the base of the haptic interface in a linear motion. The data is collected for both to and fro motion i.e. for the operator’s motion when he starts moving the thimble from a specific initial point, until he hits the virtual wall and then coming back to the same point. The initial position for all the experiments is the same where the initial cable lengths are 0.39m, 0.38m and 0.48m respectively and the corresponding initial thimble position in Cartesian coordinates is \{-0.26m, 0.135m, -0.24m\}^T. F. Giacometti has helped to do mapping for the electric signals sent into the data acquisition board and the final the cable tensions that come out [10]. Since we didn’t measure the cable tensions, we used this mapping to calculate the cable tensions and plotted them. These mapping is calculated by putting the weights around the pulley and noting the signal required just to balance the weight in air. She also recorded the data for this experimental setup.
6.1 Force Control Scheme

This experiment is conducted for a non-linear spring which follows the equation \( f_y = -\left[300 \cdot \Delta y + 3000000(\Delta y)^3\right] \). The constant values used in the equation are arbitrary. A non-linear equation is used because we want to simulate the compression of spring against the hard wall. The figures 6-1 through 6-5 show the plots plotted for the data recorded.

![Figure 6-1 Finger Tip Position for Force Control](image-url)
Figure 6-2 Cartesian Forces for Force Control
Figure 6-3 Calculated Cable Tensions for Force Control
Figure 6-4 $F_y$ vs. $y$ for Force Control
As seen in the above plots, the period during which the thimble is at the threshold i.e. when the spring compresses to the extreme limit (at $y = 0.22m$), the forces start to increase and reach the maximum, where the operator can’t move further and when he withdraws his finger, the forces decrease to zero. The force-displacement curve shows the behavior of the non-linear equation. The reaction force felt by the operator increases with the distance he compresses the virtual spring and finally causes an obstruction to his movement further. This simulates the haptic perception of compressing a non-linear spring all way up to the end, until no further movement can be made.
6.2 Position Control Scheme

With this control scheme we simulated the haptic behavior of stopping at a virtual wall. As soon as the operator reaches the virtual wall, he should feel instant force acting on the finger obstructing his further movement into the wall. The proportional and derivative gains chosen for each PID controller which controls a motor are chosen to be $K_p = 7500$ and $K_d = 1$. Figures 6-6 through 6-10 show the above behavior.

![Figure 6-6 Finger Tip Position for Position Control](image)
Figure 6-7 Cartesian Forces for Position Control
Figure 6-8 Calculated Cable Tensions for Position Control
Figure 6-9 $F_y$ vs. $y$ for Position Control
Figure 6-10 Calculated Cable Tensions vs. y for position control

As seen in the above figures, as soon as the operator reaches the threshold, there is a rise in the reaction force acting on the thimble, so high \( f_y = 2.8 \text{N approx.} \) that the operator cannot overcome the force and move the thimble forward. Figure 6-6 shows that there are no negative tensions in the cables; the condition required so that the cable are always in tension.

6.3 Force and Position Control Scheme

With this control scheme we simulated the haptic behavior of a soft wall like tissue before the operator hits the hard virtual wall i.e. the operator must be able feel the
penetration into the soft tissue and should be stopped immediately when he hits the highly stiff virtual wall. The figures 6-11 through 6-15 depict such behavior.

Figure 6-11 Finger Tip Positions for Force/Position Control
Figure 6-12 Cartesian Forces for Force/Position Control
Figure 6-13 Calculated Cable Tensions for Force/Position Control
Figure 6-14 $F_y$ vs. $y$ for Force/Position Control
As seen in figure 6-14, the force acting on the operator thimble starts increasing from zero when the operator reaches the position at \( y = -0.22\)m. The force increases linearly in a ramp fashion i.e. the force is proportional to the distance following the linear spring force law \( f = -k.y \), where \( k = 175 \). At \( y = -0.25\)m, the position at which the highly stiff virtual wall exists, the force shoots up to highest magnitude causing immobility to the human finger. The designed control system simulates the forces to be able feel a soft skin layer and the virtual wall behind it. The calculated cable tensions plot shows that there are high fluctuations in the cables where the algorithm switches from force control to position control, which is undesirable. The operator didn’t feel fluctuations in the
haptic behavior. Cable tensions are obtained from signal - force mapping we did i.e. from the known currents, known motor torque constant and known pulley radius. Though the electric system in TCHI is being able to pick up the fluctuations as we see in the plot, the mechanical system might not be able to pick it up which explains the operator not being able to sense these fluctuations. However, a thorough investigation is required to identify the problem. As of now the author couldn’t come to a conclusion about these high fluctuations in the cable tensions, but future work must concentrate upon investigating these fluctuations in the cable tensions.

6.4 Comparison between the Three Control Schemes

We implemented three control schemes to simulate a non-linear spring with Force Control scheme, a hard wall with Position Control scheme and a combination of soft wall and hard wall with Force/Position Control scheme. All these control schemes gave the haptic behavior, the way we expected. The experiments are not designed to have common factors for all the three control schemes to make quantitative comparisons. Still, the author believes that a subjective comparison can be made here basing upon the nature of the control schemes.

Looking in the broad way, in all the three control modes, we change the stiffness for the perception of different materials. For force control we change the stiffness k in the equation \( f = -k \cdot x \), which is used to calculate the forces applied. For Position Control, the stiffness is the proportional constant \( k_p \) used in the PID controller. By varying this proportional constant we will be able to simulate the haptic perception of different
materials (soft or hard). It is possible with either control schemes to obtain the haptic perception for any kind of material.

For cases like Virtual Haptic Back, where the haptic perception required is the palpation of soft skin over the hard material (bone), it is possible with either the Force control mode or the Force/Position Control. With Position control it is not possible because only one kind of haptic perception either soft or hard is achievable depending upon the $k_p$ value since it is constant. In force control a non-linear equation can be used to calculate the forces, which first gives low forces for soft skin perception and then shoot up the forces to give hard substance perception. The forces felt depends on the nature of the non-linearity so there is always a gradual shift from soft to hard, which can or cannot be for a very short distance. With Force/Position control an abrupt shift from soft materials to hard materials is possible. There are no calculated cable tension fluctuations in force control, but as plot Figure 6-15 shows there are severe calculated cable tension fluctuations in the combined force/position control which might be undesirable.

### 6.5 TCHI vs. PHANToM

Though this study is premature to make any quantitative comparison with the PHANToM, the author believes that a subjective comparison can be made between the develop TCHI and the PHANToM. The current TCHI is developed keeping in mind the commercial haptic device PHANToM. The design specifications of the PHANToM are as follows:
<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workspace</td>
<td>900 x 900 x 300 D mm</td>
</tr>
<tr>
<td>Nominal position resolution</td>
<td>&gt; 0.02 mm</td>
</tr>
<tr>
<td>Maximum exertable force</td>
<td>22 N</td>
</tr>
<tr>
<td>Continuous exertable force</td>
<td>3 N</td>
</tr>
<tr>
<td>Back drive friction</td>
<td>0.2 N</td>
</tr>
<tr>
<td>Force feedback</td>
<td>x, y, z</td>
</tr>
<tr>
<td>Position sensing</td>
<td>x, y, z (6DOF optional)</td>
</tr>
</tbody>
</table>

For the complete specifications please visit the website [www.sensible.com](http://www.sensible.com). With the current three cable haptic device, base is a 2’x2’ rectangular frame and the length of each cable is more than 1m i.e. 1000mm. Though the TCHI has potentially more workspace than that of PHANToM, the force may be limited as the thimble moves away from the base. Currently, with the motors and the pulleys available in the laboratory, the operator is able to feel the maximum force of (though it depends on the capacity of the operator) around 12N. With proper combination of the motors and pulleys the maximum force limit of PHANToM (22N) is achievable. Also, the maximum force the PHANToM gives is instantaneous but the maximum force provided by the TCHI is continuous, depending on how long the operator can withstand that force.
PHANToM can exert continuous force of 3N only, but it is observed that with the current TCHI this force is greater than that. We have seen a maximum force of 12N continuous force though it depends on the strength of the operator and the position of the thimble.

The PHANToM is force transparent in free space and the operator can feel a very smooth palpation. That’s because PHANToM has a very low back drive friction 0.2 N. The TCHI always requires maintaining some minimum tension in the cables. So there is always some force acting on the finger even in the free space. We estimated that to be 0.9-1 N. Also for the current TCHI, there is no friction-less guides for cables. Due to these factors there is always some considerable force acting on the human finger and this might cause wearisome to the human.

According to R. Conaster Jr., research associate of Virtual Haptic Back (VHB) team, the maximum force used in VHB application is 6N. The normal palpation range they are using is only between 1N-3N because the PHANToM’s maximum continuously exertable force is only 3N. Also, the rate at which the forces are updated is 0.001 second. The author got this information from R. Conaster Jr. Forces provided with the current TCHI are always sustainable depending upon the capacity of the operator, provided that the forces are feasible.

The force palpation range they use is limited due to the device. In case, physicians use more than that palpation range on a real human back, the current TCHI can provide that for more realistic palpation on the virtual human back. Also, in VHB the most forces used are normal. In this kind of situation where we need only normal forces TCHI is
suitable considering cost factor and also it can provide high continuously exertable forces provided the device is built such that it can provide forces to palpate through the whole virtual back. For the current TCHI we have set up the step size i.e. the rate at which it sends the signals to be 0.001 second. This matches with the rate the haptics is updated for VHB. Though the back drive friction for the current TCHI is considerably high, this can be reduced if we use motors with lower gear ratios and friction less guides. Also, the new PHANToMs can provide six degrees of freedom where TCHI can only provide three degrees of freedom.

As part of future work, a proper evaluation of the TCHI, has to be done to make proper judgments on PHANToM vs. TCHI.
Chapter 7 Conclusions and Recommendations

7.1 Conclusions

In this thesis, a complete three cable haptic interface is developed. This device is inspired by the WireMan Configuration (Bonivento et al.). The close-formed forward pose kinematics are derived using the 3-Spheres algorithm developed by Williams et al. 2004. The FPK solution is unique based upon the configuration of this haptic device and is less computational intensive compared to numerical algorithms typically used to solve FPK. The pseudo static solutions are obtained based upon the William’s earlier work on cable based systems. Having no actuation redundancy, Cartesian forces can only be applied within the tetrahedron formed by the finger tip point and base cable attachment points. Based on this, mathematical conditions required for force feasibility are derived to understand the force limitations through simulation.

We developed three control schemes, force, position and a combined force/position control schemes. The control schemes we developed gave a satisfactory performance i.e. the behavior of the haptic perception is exactly the same way as we expected.

7.2 Recommendations

It is found that even though the gear ratio (5.9:1) is low, the operator still found it wearisome while working on the cable haptic device for long time. The recommendation
is that the gear ratio should be even more less in order to be able to work for a very long time.

The cables are guided through the nearest holes available from the pulleys in the rectangular channel used to build the frame. Author would recommend having proper guides to guide the cable so that the end points are fixed, to achieve more accuracy.

The software cost involved for windows based real time control is higher than the Linux based real time control since Linux is open source software. Also, Linux based systems have faster performance compared to Windows based systems. Author recommends switching to Linux based real time control (RTX Linux drivers).

Future work should focus on commercializing this device by competing with PHANToM as this device can be built for as cheap as $1000.00 compared to $64,000 cost of PHANToM.
References


\url{www.sensable.com}

Master’s Thesis, Ohio University


Appendix – TCHI Operation Procedure

In this section the detailed guide lines for the safe operation of the TCHI and the related equipment are given.

1. Check if all connections to the MultiQ-PCI board are connected appropriately.
   Check whether all the three motors encoders are connected to digital encoder outputs, three amplifiers which power the motors are connected to analog inputs and the J1-J5 buses are connected to appropriate slots.

2. Switch on the computer and check if the LCD (red light) on the board is glowing.
   If not, first, change the 1A fuse next to the LCD and then switch on the computer.
   If it still doesn’t work, then there is a problem with the board.

3. Make sure all the connections from the transformer to the amplifiers are not short circuited anywhere. If in case short circuit happens and power blows off, replace the fuse before the transformer and check the circuit. Still if it doesn’t work then there is a problem with the circuit and it is not fit to experiment.

4. Switch on the transformer-amplifier circuit and check whether the amplifier LCDs glow green. If they glow red then there is a problem with the amplifier.

5. Start MATLAB and set the path to F:\CableHapticDevice.

6. Run Const.m file.

7. Check if encoders are working. To do this open the SIMULINK diagram called EncoderMapping.mdl and on the diagram menu go to tools, RealTimeWorkshop and do a Build Model. Once the WinCon Server startup menu shows up, click
first on the Open plot button and click on L act scope. Now click on the start button and move the motor back and forth with hand and see if the L act reading is changing. If the reading changes then the encoder is in working condition. Do this for one motor encoder at time by changing the Channel(s) to use value on the Encoder Input block.

8. Check if the motors are in working condition. To check this open the MotorTest.mdl and build a real time model as explained in step 7. While running the motor, the signal should be just sufficient (0.22) to wind the cable round the pulley, if the operator allows. Else, turn the potentiometers on the amplifier as the reference catalog suggests.

9. If any of the above steps fails, take the remedial steps before proceeding to the next steps.

10. Now open the required SIMULINK control diagram and do a real time build model on it. Before clicking on the WinCon Server start up button, make sure that power to the transformer-amplifier circuit is on.

11. After the experiment is done, click on the WinCon Server stop button to stop and switch off the transformer-amplifier circuit. Never shut down the computer before switching off the transformer-amplifier circuit. This will cause motors to run abruptly with high speeds breaking off the cables.

12. Check if everything is shut down before shutting off the computer. This completes the procedure.