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Transparency Improvement for Haptic Interfaces

by

Samuel Thomas McJunkin

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APPROVED, THESIS COMMITTEE:

Dr. Marcia K. O’Malley, Chair
Assistant Professor of Mechanical
Engineering and Materials Science

Dr. Satish Nagarajaiah
Professor of Civil and Environmental
Engineering

Dr. Angelo Miele
Professor Emeritus of Mechanical
Engineering and Materials Science

HOUSTON, TEXAS
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Abstract

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Haptic interfaces are robotic systems designed to provide information to a user regarding a remote or virtual environment via the sense of touch; these robotic systems accomplish this feat through force feedback. Designers of haptic interfaces desire to produce an interaction using the haptic interface wherein the virtual or remote environment feels indistinguishable from the actual environment; however, it is difficult to define when a haptic interaction feels the same as the real interaction it is reproducing. This thesis discusses transparency as a measure that quantifies the performance of a haptic device by comparing the desired environment to be displayed to the actual environment displayed. In order to demonstrate the utility of transparency as a performance measure, haptic interactions are defined by the causality relationship between the user and the device. These interaction types are introduced as active and passive user interactions. In the active user interaction, the user is treated as an energy source and the environment is a dynamic system without a source of energy; the passive user interaction is the opposite case wherein the environment is an energy source and the user is a dynamic system without a source of energy. Methods of improving transparency, and hence performance, of a haptic device are compared against the definitions of haptic user interactions. These comparisons show that transparency for purely active user interactions is dependent on the user, and that for passive user interactions, transparency is dependent on the user and the haptic interface. In addition, other performance improvement methods often rely linear assumptions which are not general.
This thesis proposes a method for improving transparency while maintaining stability without regard to assumptions of linearity.
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Chapter 1

Introduction

1.1 Introduction and Motivation

Haptics\(^1\) is a burgeoning field within the disciplines of cognitive science, computer science, electrical engineering, and mechanical engineering. This field of study is unique in that it provides a means of displaying forces, geometries, and other physical phenomena intuitively by allowing a user to feel them either in a proprioceptive or a tactile sense. Generally, these sensations are communicated via a mechanical manipulator that the user physically interacts with; the manipulator displays motion or force based on computer algorithms that model the phenomena of interest as in figure 1.1. These devices can be simple - a pager

![Diagram of a user interacting haptically and visually with a virtual environment.](image)

**Figure 1.1:** Diagram of a user interacting haptically and visually with a virtual environment.

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\(^1\)Greek *haptikos*, from *hapesthai*, to grasp, touch
vibrator motor communicating surface texture - or complex - an arm exoskeleton simulating complex motion and force interactions. The range of possible uses are limited only by the ability to model and render phenomena, which makes haptics readily useful for training, design, or remote interaction. These uses are already realized in simulation of surgical procedures, virtual sculpting, and master-slave robots used in extreme environments.

The utility of haptic interfaces relies on the ability to faithfully render phenomena within the perceptible limits of a human operator. As a result, it is critical that each component of a haptic display system operate in a consistent manner with respect to other system components. For example, if the computer controller commands a 5 N force to the endpoint of the manipulator, the electrical and mechanical components ought to respond by displaying the commanded force accurately. An inability to accomplish this goal undermines the goal of exact display of a virtual environment.

1.2 Statement of the Problem

Haptic devices display forces to a user resulting from interactions with virtual dynamic elements such as inertia, compliance, viscosity, or non-linear dynamic elements such as those used to model biological tissue. Not only must a haptic device display these types of forces, but it must display them singularly, or combined, over a the range of frequencies a user can excite or feel. However, most haptic manipulators attenuate displayed forces as frequency increases in the linear domain, and there is no quantitative measure of display quality.

1.3 Objective

The objective of this research is the development of display and control techniques that maximize the accuracy of a simulation relative to the actual interaction being modeled, and develop a quantifiable definition of display quality. This objective shall be accomplished
by development of a force controller that utilizes a parameter estimator control law and means of qualitatively measuring simulation accuracy.

1.4 Significance

Haptic manipulators are enabling users to intuitively interact with computer-generated environments that simulate physical phenomena or provide another mode of interpreting data. Therefore, any improvement in the display of environments and the control of manipulators allows for a greater range of possible uses. In addition, force control has not achieved great success in the field of haptics; an attempt to apply adaptive force control would spur further development. Finally, this work would illustrate that linear display and control methods cannot be applied to most haptic manipulators, and as such, the haptics community would see the need to reevaluate current definitions and concepts that reflect the general non-linear nature of haptic systems.

1.5 Organization of Thesis

The organization of this thesis is as follows: haptics background; environment display techniques; definition of transparency for evaluating display performance; compensator development; and adaptive compensation. Chapter 2, haptics background, will discuss the man-machine interface, virtual and remote environments, applications, and performance criteria. Chapter 3, performance criteria, defines different measures of performance for haptic interfaces and the environments that are displayed. Chapter 4, environment display techniques, will introduce methods for display of virtual environments. Chapter 5, transparency, will present a linear definition of transparency with motivation towards a controller that can take advantage of full-state feedback. Chapter 6, controller development, will examine previous efforts to improve the feel or presence of simulations along with their advantages and disadvantages. Chapter 7, adaptive compensation, will develop
the notion of an adaptive algorithm that attempts to cancel manipulator dynamics while also showing the stability of the said compensator. Chapter 8 will present and discuss data relating to the nature of man-machine interface and the relative performance of two compensation methods. Chapter 9 will present conclusions and implications for future work.
Chapter 2

Haptics

In the development of virtual reality, the sense of touch has become an important part of computer-generated environments; the sense of touch in computer generated environments is known as haptics. Haptics comes from the greek word, hapthai, meaning to touch. This is exactly what happens in haptic simulations; users touch and feel simulated environments so as to gain additional information about the data they are using and interacting with. The areas of research in haptics are varied and cover diverse fields of study including: psychology, computer science, electrical engineering, mechanical engineering, and control theory. Within these disciplines, researchers are attempting to answer questions regarding: the nature of interactions between men and machines, how to display and interact with data, and which applications could benefit from haptics and how the tool of haptics should be used. This section will examine the current state of research in these areas and will introduce the problem of defining and improving fidelity of haptic interactions.

2.1 Man-Machine Interaction

In the context of haptics, it is very important to define how a user and a machine work together for the purpose of interpreting data and accomplishing tasks. At first glance, the notion of man-machine interaction seems simplistic since man has developed machines specifically for his own use; hence, interactions with machines almost goes without saying. Upon consideration, however, it becomes necessary to define assumptions about how users and machines interact to properly exploit human and machine capabilities for the goal of data interpretation or task assistance. One approach to the question of man-machine
interaction is to treat both the user and the machine as dynamic systems. Specifically, we can see the interaction between man and machine as flows of power between the two; using this approach, it becomes possible to model and control the overall interaction and hopefully improve performance using deterministic control techniques.

Power flow between dynamic systems defines causality meaning that the force/potential response of a system element is determined by the velocity/current imposed on it by another system element and vice versa. Bond graphs provide a means of visualizing these relationships and assist in the formulation of equations governing the system dynamics. Figure 2.1 shows a simple, one-port bond graph [1] defining a flow source, $S_F$, with an environment impedance, $Z_{ENV}$. In this case, the block can be viewed as a spring wherein

$$S_F \rightarrow Z_{ENV}$$

**Figure 2.1:** Diagram of interaction with a real, passive environment with bond graph notation explaining the interaction.

pressing deeper into the block results in a larger force. These interactions are commonplace. The water in a swimming pool imposes a body force on a swimmer that is directly proportional to his velocity; the seat of an automobile imposes a reaction force in response to the acceleration of the drivers mass. It is also possible to define an inverse interaction wherein the human reacts to an externally imposed force. Figure 2.2 shows another simple one-port bond graph defining an effort source, $S_E$, with the admittance, $Y_H$, of the human. Again, these interactions are commonplace; the palpation of the human pulse and the purr of a kitten are good examples. In the context of man-machine interactions, we can assume that the human and machine are two dynamic systems with a one port flow relationship between the two systems where one is an admittance and the other an
Figure 2.2: Diagram of interaction with a real, active environment with bond graph notation explaining the interaction.

impedance. The assumption of how to treat the human and the machine governs how a haptic interaction is displayed and will be discussed below.

2.2 Haptic Rendering of Virtual Environments

Haptic rendering of virtual environments is relatively simple in principle; Hogan [2] states that this simplicity stems from the fact that any natural environment or dynamic system can be recreated by some other dynamic system. In controlled dynamic systems, the behavior of the system is altered via the controller to meet desired performance characteristics. In the case of haptic rendering, all that is necessary to display a virtual environment is a model of that environment and a physical system capable of rendering that model.

Haptic manipulators that perform the task of displaying virtual environments are often electromechanical systems that rely on a position-velocity controller or a force-acceleration controller. Figure 2.3 illustrates the overall concept of displaying virtual environments where a user sees a virtual object on a graphical display, and the manipulator completes the effect by output of interaction forces. Generally, any passive, natural environment can be modeled as an impedance, $Z_E$, where a user velocity input, $V_H$, to the environment yields a force output, $F_E$, as in Equation 2.1.

$$F_E = Z_E V_H$$  \hspace{1cm} (2.1)

Haptic displays that utilize this method are termed impedance-based displays; most com-
Figure 2.3: Diagram of interaction with a real, passive wall environment with graphical description of causal inputs and outputs to the system.

Commercial haptic displays use this method of display. Alternatively, it is possible to display the same kind of passive, natural environment as an admittance, $Y_E$, wherein a user force input, $F_H$, to the environment yields a velocity output, $V_E$, as in Equation 2.2.

$$V_E = Y_E F_H$$

These displays are termed admittance-based displays. The necessity of force and acceleration sensors makes these manipulators cost-prohibitive, and digital integration, required to calculate the end-effector position from sensed forces, is undesirable. Impedance-based displays are typically less expensive since they use position sensors, but limitations on the torque output of most actuators make it difficult to display environments realistically due to the higher than expected compliance a user feels.
2.3 Applications

Haptic interactions are a field of study unto themselves and have many applications that are used for manipulation, training, and data interpretation. The fields of application are diverse, but they all have the sense of touch as a common element. Application of haptic interactions is a relatively new concept and is still an open area of research. This section will merely mention the areas of application and research to give context for the specific research of this dissertation.

2.3.1 Training and Rehabilitation

Training and rehabilitation are everyday tasks, which are repetitive and often require supervision from experience personnel. For example, stroke patients often times need to relearn motor behaviors such as reaching or grasping. Generally, a physical therapist designs tasks for the patient that train through repetition. However, these tasks can be dull, and it may not be obvious to the patient as to how well he is performing the task; these factors can lead to discouragement and attrition. Haptic feedback can overcome these problems by giving the therapist a tool that they can reconfigure for different tasks using the same instrument. In addition, it is possible to measure performance in such a way that the patient can see improvement immediately which can help the patient set performance goals and maintain their interest. Haptic interfaces are also used for training purposes. One of the most well known examples is aircraft simulators. Aircraft simulators are life-size mock-ups of an aircraft flight deck that are mounted on a hydraulically powered Stewart platform; the windshield is replaced with monitors that simulate the view from outside the aircraft. The platform moves to simulate the orientation of the aircraft in flight and thereby by creates a realistic simulation so that pilots can learn how to control the aircraft without fear of damaging, or destroying, an actual aircraft. This idea of training on haptic simulators is also being applied to the area of surgical training; surgeons can now learn how to perform laparoscopic procedures virtually before operating on actual patients[3].
These advances have made it possible to change the way people learn to perform tactile tasks and could lower the costs and shorten the time associated with training.

2.3.2 Alternative Computer Interface

Haptic manipulators are an alternative computing interface that may provide a more informative and intuitive means of working with a computer. Computers have used a variety of interfaces over the course of their development, but the most ubiquitous interface devices are the keyboard, mouse, and monitor. These devices use only the sense of sight for input and interpretation of data, which is limiting when one considers the other four senses humans use. Auditory communication devices are becoming more commonplace, and it seems unlikely that smell and taste will be integrated into computer peripherals. Touch has largely been unused until the advent of commercial haptic manipulators. Haptic manipulators offer the opportunity of designing and interacting with objects or data that engages the sense of touch. There are many applications for haptic manipulators as alternative computer interfaces that range from design and data interpretation to assistance devices for the visually impaired. Sensable Technologies has developed a design and modeling tool known as virtual clay where a user interacts with an object that has been modeled after the properties of actual clay. The user has virtual tools that a sculptor would use with real clay to construct models or objects. This allows a user to quickly build a model electronically with geometries that are not easily defined by conic sections; this model can be exported for finite element analysis or printed in a rapid prototyping printer. Immersion Corporation licenses haptic technology for many haptic interfaces including haptically enabled mice and game controllers. A haptic mouse can generate a distinctive vibration that simulates the feel of rolling over different textures. This may help a user to understand the different textures of a material virtually rather than having the actual material; it can also be a spatial cue to a user indicating their position based on a particular vibration.
Video game makers have made use of rumble packs for several years to enhance game play by playing a vibration through the joystick indicating that the player has been injured or is attempting an illegal game maneuver such as running through a wall. In addition haptic cues and modeling, haptic interfaces have been used to explore datasets that were previously examined by visual feedback only. In medicine, CT scans and ultrasound machines provide a 3-dimensional view of body structures but until recently were only seen. It is now possible to feed that 3-dimensional data into haptic rendering software that makes it possible to feel the shape, texture, and material properties of biological structures virtually. For instance, it is now possible to create a haptic model of a baby in utero from ultrasound data; parents and doctors can then touch the model of the baby via a haptic interface. It also possible to interact with large scale acoustic data sets; in particular, sonar data used to visualize structures in the ocean and in the seabed can now be felt. This may provide a human the means of finding undersea structures by touch instead of inversion models. In short, haptics manipulators provide an alternative means of interacting with digital data, and the applications are only limited to the imagination of the designer.

2.3.3 Teleoperation

Master-slave robot systems, otherwise known as teleoperators, marked the beginning of haptics and teleoperation research. The first teleoperator systems were used by the nuclear power industry to handle dangerous material from a safe distance. These systems were initially direct kinematic linkages. The rigidity of the linkages allowed for users on the master side to have a very accurate feel of the forces applied on the slave side of the mechanism. The idea of transmitting force and velocity has now been implemented in other areas as well. Fly-by-wire flight systems have extended the original teleoperator idea by transmitting forces and velocities digitally instead of through direct kinematic or hydraulic linkages. Now, the forces measured on a control surface of an aircraft are transmitted to the pilot through motors attached to the control levers that simulate the
feel that a pilot would normally feel from the shudder normally felt in hydraulically linked aircraft controls. This advancement has enabled the development of larger aircraft with lower weight due to internal control architecture. In addition, the military has funded research for telerobotic surgery so that soldiers could be operated on near the battlefield without endangering surgeons. This has culminated in the da Vinci® Surgical System [4] which surgeons have used to perform transatlantic telerobotic surgery. In addition, the da Vinci® allows surgeons to perform sophisticated procedures far less invasively since it allows a surgeon to scale down his movements and use smaller instruments in a laproscopic surgical setting as in figure 2.4. Teleoperation may also find application in exploration of remote, dangerous, or inaccessible environments in space, battle zones, or at the nanoscale. However, bilateral teleoperation, where the forces and velocities of the master and slave are transmitted, has difficult challenges that need to be overcome. These include time-delay and force-scaling; both are a current area of research.
Chapter 3

Performance Criteria

Haptic devices are varied in their design and purpose, which can make comparisons between different devices difficult. Parameters such as workspace dimensions, sensor resolution, or maximum output force may be sufficient for choosing a device for a particular virtual display. However, most users want to know the range of virtual environments they could display with a particular device. As a result, performance measures for haptic devices have been an active area of research and will be discussed below.

3.1 Definitions From Robotics

Haptic interfaces are a specialized class of robots, and therefore, it makes sense to begin with a consideration of their performance from the point of view of robotics. In the field of robotics, generally there are many performance criteria which can be considered, but three will be considered here, degrees of freedom, workspace dimensions, and force precision.

The number of degrees of freedom in a haptic interface determines, in part, its versatility, hence, the greater the number of degrees of freedom, the more versatile the interface. The degrees of freedom of robot depends on whether the robot is of a serial or parallel structure. For serial robots, the number of joints determines the number of degrees of freedom assuming that each joint is constrained to have only one degree of freedom; this applies to both planar and rotational joints. For parallel robots, the number of degrees of freedom depends on the number of link and the degrees of freedom of joints between each link. However, the most common parallel linkage is a five-bar planar linkage which has two degrees of freedom. Designers of haptic interfaces must often choose which type
of robot to build when considering degrees of freedom, however, an either-or approach is often insufficient. In the case of serial robots, the inertia of actuators at each joint limits the efficacy of the device because it will either require the user, or the robot’s joint actuators, to support the device which will either lead to fatigue for the user or limited force output. On the other hand, parallel robots usually place their actuators near the base of the robot which allows the base to support the robot instead of the human or the actuators themselves; the primary drawback of a parallel robot is a workspace limited by the kinematic singularities of parallel robots. As such, most designers use a combination of serial and parallel robots. A good example is the PHANTom haptic interface as seen in figure 3.1 [5]. The PHANTom has a five bar parallel linkage attached to a serial rotational actuator at its base. The design of the linkage makes it possible to treat the linkage as serial mechanism rather than a parallel mechanism. However, the degrees of freedom of an interface only determine, in part, the versatility of an interface. For example, if an interface has many degrees of freedom, it may be that this is a design feature that is implemented to overcome singularities in the kinematics of the interface. Therefore, it is necessary to examine the workspace of a device as well.
The workspace dimensions of a haptic device are the same as that of a robot; it is determined by the joint ranges of the robot in relation to its kinematics also known as the reachable workspace [6]. For example, a simple two degree of freedom robot consists of two rotational joints at its base and elbow as seen in figure 3.2 [7]. The workspace dimensions of this robot are simple as it is basically a torus. For more sophisticated interfaces, a "bubble" of the reachable workspace in figure 3.3 [8] gives a user an idea of the interface's workspace, however, the bubble does not necessarily account for the orientation of the human user who is interacting with the interface at a particular position. This means that a large workspace may not be useful to a user who would be required to contort himself to reach the boundaries of the workspace; the reachable workspace of the interface may be limited by the reachable workspace of the human. In addition, the force output of an interface may vary from point to point within its reachable workspace. This means that the force resolution and absolute output force are limited by the workspace dimensions as well. Therefore, it is necessary to consider the resolution of the device in regards to force and position.

Hayward and Astley [9] give a good review of mechanical and electrical performance measures for haptic interfaces including many of the features listed above. However,
Figure 3.3: Y-Z workspace limits at X = 0m of the PHANTOM Premium 1.0 haptic interface

they also introduce other measures which may be important for a designer who is choosing/designing a haptic device. These include inertia and damping, peak acceleration, and structural response. Inertia and damping affect perception of a virtual environment since these dynamics will be included unless they are otherwise compensated for; in addition, these dynamics affect the overall stability of a virtual environment. Peak acceleration is important because interactions with natural environments are often characterized by rapid velocity changes during contact; as a result, the peak acceleration a device can achieve affects the overall realism of an interaction. Finally, they note that the structural response of a device can ‘color’ the perception of a virtual environment. This idea is closely related to the inertial and damping characteristics, but it likely is more of measure of the stiffness of the haptic manipulator’s structure. Thus, the overall dynamics affect, or filter, the dynamics of the virtual environment.

3.2 Definitions From Psychophysics

Haptic interfaces have fundamental limitations in ability to display virtual environments; to overcome these limitations, researchers are exploiting human sensory strategies to design
environments such that a user perceives an environment that is different from the one that is actually displayed. This kind of display strategy relies on the psychophysics of human perception; it might also be thought of as a perceptual illusion. Since the strategies employed do not try to display the actual environment, it becomes necessary to query the user to discover how accurately the virtual environment portrays the actual environment.

Generally, the measure that is used in these type of psychophysical display techniques is a scoring scheme wherein a user either interacts with a real environment, or a virtual environment where they know exactly what the correct feel should be. The user then uses their experience with the 'control' environment to identify the correct virtual environment. For example, Kuchenbecker et al [10] asked users in their study to tap on variety of real surfaces as a control and then tap on virtual surfaces that were rendered using an "event-based haptics" approach. This technique basically plays a pre-recorded force interaction over a virtual environment. The users were then asked to identify the surface based on their experience with a real environment, and the percentage of correct scores were correlated to the types of surfaces rendered. In other studies, these scoring studies help to validate new rendering methods that depend on device parameters. Lawrence et al [11] devised a type of rendering method where virtual wall forces did not depend on the displacement penetration in the normal direction of the wall, but rather on the velocity. Equation 3.1 defines the so-called "rate hardness".

\[
HR = \frac{\text{initial force rate of change (N/s)}}{\text{initial penetration velocity (m/s)}}
\] (3.1)

This measure couples the performance of the device with the hypothesis that humans perceive the stiffness of an environment based on initial changes in force over time with the velocity of contact. The reason that velocity and force change at contact is chosen over simply the displacement and force is that humans can perceive velocity and force changes better than the actual force and displacement. In summary, psychophysical performance measures assess human perception accuracy, but these measures can help to validate new rendering schemes that do not necessarily reproduce the natural environment.
3.3 Definitions From Haptics and Teleoperation

Researchers in haptics and teleoperation recognize the need for unique definitions of interface performance that are not dependent on the qualitative perception of a user or the design of an interface since either may be an artful interpretation rather than a unbiased qualitative evaluation. These qualitative measures provide a means of evaluating how well any haptic interface displays an environment. The measures of z-width and rate hardness, which define environment display bounds, and transparency, which defines how well an environment was displayed will be discussed.

3.3.1 Z-Width, Quantization, and Structural Distortion Ratio

One means of measuring the performance of a haptic interface is to define the bounds of environments an interface might display. The maximum stiffness that an interface can display has been one of the more accepted means of defining performance. However, it is not necessarily general, and it does not address the fact that a haptic display will display other environment parameters such as damping. One solution has been proposed that combines both stiffness and damping is Z-width [12] in equation 3.2.

\[
K_{\text{max}} < \frac{2(b-|B|)}{T} \tag{3.2}
\]

Colgate and Brown devised this measure such that the environment would be passive, which is to say that the net energy in the system is negative. In addition, this measure considers the fact that haptic interfaces are discrete systems. In so doing, this measure allows a designer of a virtual display using a particular haptic interface to know a priori what range of environment parameters can be displayed while guaranteeing that the display will be passive. Abbott and Okamura [13] extend this work by examining the effect of sensor quantization.

\[
K_{\text{max}} < \min \left( \frac{2b}{T}, \frac{f_c}{\Delta} \right) \tag{3.3}
\]
Their result in equation 3.3 shows that the maximum stiffness is minimum of either the effect of loop rate and viscous damping or the coulomb friction and the resolution of position sensors in the device. However, these measures have the disadvantage in that they are useful only for environments that use stiffness and damping to render an environment. Another alternative measure is the structural deformation ratio (SDR) [14] as in equation 3.4.

\[ S(\varepsilon) = \frac{V_m}{V_{th}} \quad (3.4) \]

It is basically a measure of the flexibility of the device when an impulse is applied where \( V_m \) is the measured velocity at the joints of a manipulator and \( V_{th} \) is a theoretical velocity as seen below.

\[ V_{th} |_{t=\varepsilon} = \frac{P}{m} \]

\[ P = \int_{t=0}^{t=\varepsilon} F(t) dt \]

\( P \) is the impulse momentum and \( \varepsilon \) is the duration of the impulse. The closer the measure is to unity; the more rigid the device is reckoned to be for a particular impulse. The rigidity of the device determines where the energy of the impulse will be absorbed or transmitted. In general, most of these measures are concerned with the maximum stiffness a device can display, and do not necessarily consider the other environments that a user may encounter.

### 3.3.2 Transparency

In addition to haptic definitions of device performance, Lawrence [15] defined a performance measure for teleoperated systems by examining the ratio of transmitted to remote impedance. Figure 3.4 shows how a teleoperator interacts with a remote environment that has some impedance, \( Z_e \) which is defined by the force, \( F_e \), over velocity, \( V_e \); the human side receives a force, \( F_h \), and outputs a velocity, \( V_h \) which in turn defines an impedance on
Figure 3.4: Block diagram of teleoperation interaction

the human side.

\[ Z_e = \frac{F_e}{V_e} \]  \hspace{1cm} (3.5)

\[ Z_h = \frac{F_h}{V_h} \]  \hspace{1cm} (3.6)

Instead of examining whether the velocities or forces alone were properly transmitted, the ratio of impedances in equation 3.7 gives a measure of how well the impedance of the remote environment was transmitted where a value of unity for \( G_T \) is ideal.

\[ G_T = \frac{Z_h}{Z_e} \]  \hspace{1cm} (3.7)

In chapter 5, this measure will be examined for its usefulness as a performance measure for haptic interfaces.
Chapter 4

Environment Display Techniques

Haptic interfaces display information about a remote or virtual environment by giving the user feedback in the form of force and velocity. However, the means of accomplishing that goal can vary greatly in terms of the rendering approach. For instance, a designer may choose to model the environment to be displayed by implementing exact models of the environment. However, a designer may note that a user can only perceive a limited bandwidth, and as such, would display an environment with similar bandwidth in comparison to the user’s perception bandwidth that does not exactly model the actual environment. Yet again, a designer may implement a force playback approach wherein dynamic information recorded during a previous interaction with a real environment is played back to the user.

The methods of rendering could go on as designers become more artful in their approach, but haptic display techniques will be presented here from two different viewpoints, active user interactions (AUI) and passive user interactions (PUI). In terms of the examples listed above, the two methods of choosing environment models are examples of the general AUI while the playback method is an example of the general PUI. This chapter will define these two rendering strategies and illustrate the similarities and differences between them.

4.1 Impedance Methods and AUI

The AUI is simply an interaction where the user is a flow source and the environment is an impedance that generates a force determined by the displacement vector. Figure 2.1 shows
an AUI with a rigid block and a Bond graph model of the interaction. AUIs are relatively simple to model and display on an impedance-based haptic device. Figure 4.1 shows a user who is pushing a haptic manipulator modeled as a spring, a dashpot, and a mass that is also connected to an effort source, $S_E$; as the user attempts to push manipulator, the manipulator senses the position of the physical endpoint, calculates the velocity, and displays a force based on the stiffness and dissipation of the virtual environment. The

![Diagram](image)

**Figure 4.1:** Diagram of a human user interacting with a simple haptic manipulator where the human is an active input.

The figure shows the human as a flow source, $S_F$, which is to say the human is a velocity input to the system, the cart itself has an impedance, $Z_C$, and finally, the manipulator is connected to an effort source, $S_E$ which is supplying a force based on the velocity input by the human. Figure 4.2 shows the Bond graph of the interaction if the effort source were disconnected from the manipulator. However, figure 4.3 shows the Bond graph of the same system with the effort source connected to the manipulator. The key differences are the existence of a transformer element, $T_{FM}$, and an virtual impedance, $M_V$, $B_V$, and $K_V$. The transformer element is merely the Jacobian of the manipulator, but the manipulator impedance shows that the manipulator dynamics can affect the display of the virtual environment. The design of the manipulator determines the degree to which its own dynamics play a part in
Figure 4.2: Bond graph of an interaction with a simple haptic manipulator where the human is an active input.

Figure 4.3: Bond graph of an interaction with a simple haptic manipulator.

the display of a virtual environment. For this reason, manipulators are designed to have elements with small inertia, low friction, and high stiffness [12]. It is not the purpose of this paper to quantify those terms, but note, most commercial and research manipulators are constructed from aluminum, carbon fiber composites, and/or plastic linkages with ball bearing joints which have the recommended characteristics of high stiffness, small inertia, and low friction. By doing so, the poles and zeros of the linearized manipulator transfer function are significantly left of the poles and zeros of the virtual environment, ensuring that the manipulator acts as an observer. Therefore, the rendered environment dynamics will not be greatly affected by the manipulator dynamics.
4.2 Event-Based Methods and PUI

A PUI is an interaction where the manipulator is an effort source and the user and manipulator are an admittance. Figure 2.2 shows a PUI with an example of a vibrating cellular phone, and a Bond graph model of the interaction. For clarity, the human admittance, $Y_H$, is the inverse of human impedance $Z_H$; this convention is adopted to define the differences between elements in terms of causality. Therefore, an impedance receives a flow input and imparts an effort; an admittance receives an effort input and imparts a flow.

Figure 4.4 This interaction is not all that different from the AUI interaction described above, but the key difference is that the human user is now a passive system element, $Y_H$. As a comparison to figure 4.3, figure 4.5 shows the Bond graph of the interaction. Just as in figure 4.3, there are elements that account for the cart dynamics, the transformer element, and an effort source, $S_E$ which will generate the forces that the human feels, however, the effort source is now an active system element. In the AUI, the effort source is actually a function of the user input, but if the user is not moving, the effort source does not generate a force. In a PUI, the effort source must provide a force independent of the user's input since the user is a passive element meaning that the user is just sensing force and movement. As a result, the PUI is generally a cue-based interaction that gives
Figure 4.5: Bond graph of an interaction with a simple haptic manipulator where the user is a passive system element.

the user high frequency tactile information. For instance, the vibration that someone feels while tapping on a rigid surface is the impulse response of the hand and the tapping instrument and not the result of the human vigorously tapping at the frequency that the human feels [16]. PUIs have been applied in event-based haptic interactions wherein events that are not directly coupled to the impedance of the environment are displayed when the user spatially or temporally interacts with objects that may not be well modeled by impedance methods. Table 1 includes a summary of the causality relationships defined here and clearly illustrates that the only difference between real and virtual interactions is the use of a manipulator to recreate the feel of an environment. In short, AUIs are

Table 4.1: Causality relationships for real and virtual AUIs and PUIs

<table>
<thead>
<tr>
<th>Interface</th>
<th>User</th>
<th>Manipulator</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUI(real)</td>
<td>Velocity Input</td>
<td>N/A</td>
<td>Impedance</td>
</tr>
<tr>
<td>AUI(virtual)</td>
<td>Velocity Input</td>
<td>Impedance</td>
<td>Impedance</td>
</tr>
<tr>
<td>PUI(real)</td>
<td>Admittance</td>
<td>N/A</td>
<td>Force Input</td>
</tr>
<tr>
<td>PUI(virtual)</td>
<td>Admittance</td>
<td>Admittance</td>
<td>Force Input</td>
</tr>
</tbody>
</table>

interactions where the user is the input to the interaction and has closed-loop control of
the interaction; PUIs are interactions where the user senses the input effort of another system element and does not have closed-loop control of the interaction.

4.3 Event-Based Haptics

Event-based methods of rendering are conceptually easy to understand, but it is necessary to examine the underlying fundamentals of why an event playback will feel very similar to a natural interaction it is meant to model in comparison to tradition impedance-based methods. Fundamentally, event-based methods take advantage of the fact that human users can sense vibrations up to 500 Hz [17] while they can only directly excite vibrations up to 5 Hz [16]. Therefore, human sensory bandwidth exceeds human actuation bandwidth which also means that the maximum closed-loop control bandwidth is limited to 5 Hz. However, haptic computation loops are generally run at, or above, 1000 Hz to maintain stability for reasonably rigid environments. It is natural to ask why it is necessary to have high loop rates that are more than 200 times greater than the closed-loop control bandwidth of the user interacting with the environment. On the basis of Nyquist sampling criteria, a haptic loop running at 10 Hz or even 25 Hz would be sufficient. The answer is found in the performance criterion known as z-width proposed by Colgate [12] where it is shown that the maximum stiffness displayed by a haptic device is determined, in part, by the haptic loop rate. Specifically, Colgate shows that the passivity of the device and the environment it is rendering is determined by the haptic loop rate. Even still, the maximum displayable stiffness if far below the stiffness of everyday objects humans interact with leading some to call haptically rendered environments a "Nerf World" that refers to the compliant and dissipative feel they experience. This particular computational constraint has lead to researchers adopting the use of real-time operating systems to increase haptic loop rates, but the maximum displayable stiffness will then be limited by other factors including the electromechanical bandwidth of the haptic device. In short, traditional, impedance-based methods of rendering are limited in the range of environments that can
be displayed. Event-based methods on the other hand do not require high closed-loop bandwidth. Instead, a reasonable loop rate that ensures a displayed environment stiffness that provides a kinematic constraint coupled with a force playback of higher frequency information between 5-500 Hz have generated a variety of virtual environments that users are easily able to distinguish in comparison to traditional impedance-based methods [10].

In [10] realistic display of tapping on, and interacting with, rigid surfaces has been viewed as a qualitative performance measure [11], and devices that enable a user to distinguish between environments of comparable stiffness are regarded as being high-fidelity. Event-based haptic methods enable users to distinguish between similar environment stiffnesses. In addition, event-based haptics has been used to display forces that are difficult model accurately [18].
Chapter 5

Transparency

5.1 Definition

When designing virtual environments, it is important to consider the performance of the haptic manipulator that transmits the virtual environment; this is often a subjective measure that depends on human perception rather than a deterministic one. Therefore it is proposed here to use transparency as a performance measure to better define a deterministic measure of performance. Transparency was first presented in the context of teleoperation, but it is possible to redefine the transparency to evaluate virtual environment performance [19]. Transparency, $G_T$, is defined as the ratio between transmitted (measured), $Z_M$, and environment impedance, $Z_E$, [15] where the ideal ratio is unity for a desired bandwidth as in Equation 5.1.

\[ G_T = \frac{Z_M}{Z_E} \]  

(5.1)

Bandwidth is defined as 3dB crossover frequency from 0dB for the transparency function, which is the ratio defined above. From the users perspective, a transparent system enables haptic sensation of the natural environment without sensing manipulator dynamics. Equation 5.2 substitutes the impedances with velocity-force relationships derived by Equation 2.1.

\[ G_T = \frac{F_M V_E}{F_E V_M} \]  

(5.2)

Virtual environments displayed on impedance-based manipulators assume that the transmitted (measured) velocity, $V_M$, the environment velocity, $V_E$, and the human velocity,
$V_H$, are the same. As a result, transparency for virtual environments on an impedance-based manipulator reduces to Equation 5.3, wherein transparency is now a ratio of the actual transmitted force, $F_M$, to the desired virtual force, $F_E$.

$$G_T = \frac{F_M}{F_E} \tag{5.3}$$

In this study, the transparency measure is quantified and discussed for both AUI and PUI interactions.

### 5.2 Teleoperation

Transparency and stability are of critical importance in teleoperation systems. It is the goal of teleoperated systems to first be stable, and second be transparent in the desired frequency range. Teleoperated systems face unique challenges related to communication lag, unknown human interaction forces, and the fact that their environment is not always well characterized. In short, the teleoperation system is generally a nonlinear, time variant system, which is not a trivial system to control. As such, most of the techniques used to improve stability rely on compensators of some type. Linear compensators of the lead-lag type have been shown to extend transparency bandwidth in simulation [20]. Other compensators use adaptive control laws to optimize for a given performance criteria, usually transparency or stability [21] [22]. In addition, it has been observed that unity transparency between the remote and the transmitted environment impedances is not always desirable [23]; Colgate observes that indeed it may be desirable to shape impedances to achieve stability and transmit impedances that are more meaningful to the user. Cases would include magnifying impedances in micro-scale teleoperation or minimizing impedances in macro-scale teleoperation.
5.3 Virtual Environments

In virtual environments, the goals are similar to that of teleoperation, maintain display stability and increase transparency bandwidth. In these virtual environments, the approach to increase transparency bandwidth and stability has been either with closed loop feedback [24] or open loop linear compensators [25]. Eom et al. have taken an approach to examine stability from a non-linear perspective where a disturbance observer is included in the haptic loop, and use Lyapunov stability criteria to verify stability [26]. This is a step closer to actually examining the general haptic interface, which is typically nonlinear in its kinematics, and therefore, dynamics.

5.4 Transparency as a Transfer Function

The transparency function is intended to measure performance of a teleoperated system in terms of how well it transmits information, in this case, proprioceptive information, but in the case of a haptic interface, the device doesn’t truly transmit information from a remote location to a local one. One might conclude that transparency function is a type of transfer function. In a strict sense, it is not a transfer function since the transparency function does not relate the velocity input to the force output. For a haptic interface, the transparency function shows how well force was transmitted from the theoretical model to the measured output force; in this sense, the transparency function shows how the haptic interface filters the force output. As such, the transparency function can give a haptic environment designer a means of how to design a digital filter to correct for the manipulator and human dynamics.
Chapter 6

Controller Development

Haptic interfaces are designed to have small inertia, low friction, and high stiffness, but this design goal has its limits. The dynamics of a haptic interface will influence the transmitted impedance of a remote or virtual environment, however, designers of haptic interfaces and virtual environments want to minimize the dynamic effects of the interface to ensure that only the remote or virtual environment is transmitted to a user. There are two approaches to solving this problem: redesign of the haptic interface to minimize manipulator dynamics [27], or controller solutions that "reshape" manipulator performance to meet the goal of a transparent transmission of a remote or virtual environment [23]. In this chapter, different control approaches will be presented along explanations of their advantages and disadvantages.

6.1 User Considerations

Any controller that is used to improve the display of a haptic environment must consider how a user affects display performance and what means, if any, will be used to compensate for a user. The reason for such consideration is that a user is an element in the resulting dynamic system of the haptic manipulator and virtual environment. Interactions with the natural environment can provide a clue as to how this problem can be addressed. In general, humans will interact with the environment in one of two ways: as a passive element or an active element imposing either a force or a position to the environment. Chapter 4 defined the two basic haptic interactions, AUIs and PUIs; a brief discussion below will comment on how users can affect these interactions.
6.1.1 AUI

In AUIs, users are a causal input to the manipulator and the virtual environment that the manipulator is rendering, but the response of the manipulator and virtual environment do not depend on the human dynamics. The reason for this lies in the fact that the human is a causal input to the system. For instance, when humans swim, their muscles are primarily working in an isotonic mode, that is to say, the human outputs force that are proportional to the velocity of the body traveling through the water. The water imposes a force based on the velocity of the human traveling through the fluid; this is an impedance type of interaction. Alternatively, a human pushing a box on a floor with friction in an example of an admittance interaction. The human applies a force until he overcomes friction at which point the box moves at a constant velocity. In each instance, the human is an active input to the system, and the system itself is passive.

In the same way, the haptic manipulator and passive virtual environments are indistinguishable from passive natural environments. The type of causality depends on the manipulator and the environment rendered. Specifically if the environment uses impedance methods for rendering, the user provides a velocity (position) input, and the haptic manipulator and virtual environment respond with a force output. Alternatively, the environment could be rendered with the human as a force input, and the manipulator and the virtual environment respond with a velocity (position) output. These two examples define most of the rendering methods used in haptics to date. The difference is the causality relationship between the user, the haptic manipulator, and the virtual environment. In natural environments, humans unconsciously perform these two types of active interactions, but it remains true that the human is a causal input and the dynamics of the environment, natural or virtual, defines the response to the input not the human dynamics, and therefore, it is not necessary to compensate for their dynamics.
6.1.2 PUI

In PUIs, the manipulator and the virtual environment impose a causal input to user; the user is a passive element that will respond to the causal input with a force if the system imposes a velocity or a velocity if the system imposes a force. Here, the dynamics of the user do affect the performance of the manipulator since the user has now become a passive natural environment as seen in AUIs. Consider a physician palpating a patient for a pulse; the doctor must learn to adjust the stiffness of his fingers when feeling for the pulse. If his fingers are too stiff, the doctor may impede blood flow in the artery he is palpating; alternatively, if his fingers are too compliant, the doctor may effectively damp out the pulse. In each case, the doctor is not a causal input to the system, rather he is a passive observer whose own dynamics affect the perception of an active environment. It is for this reason that doctors and healthcare personnel must learn to appropriately palpate to perceive a patient’s vital signs [28]. Moreover, the patient’s own passive dynamics such as the amount of adipose (fat) tissue, skin turgidity, and muscle tone affect palpation dynamics.

In the same way, a haptic manipulator that displays an active virtual environment must consider the dynamics of the user and the manipulator to ensure that the correct force or velocity is transmitted to the user. If care is not taken to consider these dynamics, active virtual displays must be tuned for each individual user [29] and [30]. This is not a simple task as users will vary from person to person and a user can change their own dynamics, such as muscle tension, and thereby affect the performance of the overall system response. Therefore, it is necessary for PUIs to compensate for both manipulator and human dynamics.
6.2 Force Control with Transparency as Equilibrium Condition

The definition of transparency for a haptic interaction is basically the ratio of the measured force to the desired force. A straightforward approach might be to simply use the force error as a basis for a linear force controller. Alternatively, one could use a the transparency function, in the frequency domain, as a means of designing a compensator. Both of these control solutions require sensors that can measure the position, velocity, and acceleration, and force output of the haptic manipulator; with such rich sensor feedback, either of these approaches should work. However, this section details why such a controller is not advisable for haptic manipulators.

6.2.1 PD and PI Force Controllers

The first controller solution that one might use with a load cell as a force would be traditional linear control laws such as a PID implementation. However, practical sensor issues hamper the ability to do so.

Consider a proportional-derivative control law using the load cell to calculate force error. The proportional control law is simple to construct and implement, but the derivative poses a difficulty primarily due to the noise of the load cell signal. The derivative control law requires taking a numerical derivative of the load cell signal which will then amplify the noise because the time between sampling intervals is usually small as seen here as $\Delta t$ gets smaller the noise from the load cell, $\Delta F$, is amplified.

$$\dot{F}_m = \frac{F_m(i+1) - F_m(i) \pm \Delta F}{\Delta t} \tag{6.1}$$

It is possible to lower the sampling rate, but that would affect the performance of the virtual environment where a haptic loop rate of at least 1000 Hz is required for environment displays to be stable while generating stiffnesses that enable a human user to distinguish between objects. It is also possible to filter the load cell signal, but this is an issue itself
and will be discussed in the open loop control methods section. Moreover, the noise from
the derivative will be felt in the display of the environment, and this too is an undesirable
effect of the controller.

A proportional-integral control law has also been proposed as a means of improving
transparency [24], but this too has practical difficulties when it comes to implementation.
The proportional-integral control law was designed to correct for steady state error in a
system; the integral term also served as a way of averaging the noise from a sensor, and
thus, limiting its problematic effects. However, the PI control was designed for use where
the system will reach a steady state, but a user who explores a haptic environment will
not generally maintain static contact with an object indefinitely. The practical limitation
is that there are not steady state interactions. If one were to implement a PI force control,
the controller would begin to exhibit strange effects; namely, the controller would generate
forces that the user could not account for in terms of the environment he sees visually dis-
played. It is possible to periodically zero the integral term to ensure that these saturation
limits are not exceeded, but it would require that a scheduling law that zeroes the integral
term which could lead to the ineffectiveness of the integral term over short time intervals.

6.2.2 Force Control as a Virtual Environment

Perhaps more important than any other factor is that a simple force controller becomes an
element in the virtual environment, simply stated, the load cell is essentially a spring that
has a much higher stiffness than the achievable stiffnesses defined by passivity criteria.
Consider how a load cell operates; it is basically a well designed and calibrated spring
element with strain gauges attached to the spring to measure deflection. The force-strain
relationship is indistinguishable from the force-displacement relationship of a spring. An
and Hollerbach [31] state this explicitly when they consider an impedance controller such
as one that could be used for haptic displays. However, this is also obvious when one con-
siders the causality of haptic interactions. Any dynamic system will either have a velocity
or a force input and have a force or a velocity output; the impedance or admittance of
the system itself determines the relationship between velocity and force. Haptic interac-
tions are no different since the haptic manipulator attempts to display an impedance by
responding with a force proportional to a velocity input or vice versa. A proportional force
controller changes the impedance, or admittance, of the system by adding an additional
spring. A user no longer feels only the effects of the virtual environment but that of the
force controller as well.

6.2.3 Open Loop

In contrast to the closed-loop force control methods mentioned above, it is possible to
design an open loop controller based measurements from the load cell and the position
sensors. In the case of a virtual environment, the transparency measurement basically
shows how the haptic manipulator filters the force that the user was supposed to feel from
the model, however, this method has drawbacks as well.

It is possible to use the transparency function as a means of designing open loop
controllers, or filters, that can correct the filtering effects of the haptic manipulator. It
is also possible to do this for teleoperated systems as well, although it is not explicitly
stated as a filter, this is effectively what these control solutions do. Tanner and Niemeyer
[32] design a gyrator which modulates the effort and flow between the two manipulators
in a teleoperator system. In this scheme, power is conserved, but the gyrator introduces
damping to ensure stability due to lag in the teleoperator; this leads to the teleoperator
having a very damped feel. Abbott and Okamura [33] create "guidance fixtures" to assist
an operator in maintaining a desired trajectory in the remote environment; just as with
the gyrator, the fixtures introduce significant damping into the system to ensure stability.
Kuchenbecker and Niemeyer [34] take a slightly different approach wherein they estimate
the parameters of a model of the manipulator; they then use this model to cancel the effects
of the actual system. It is effective, but it is a model that designed about a particular
operating point. The drawback is that it is unknown if this type of compensator would be effective in other areas of the workspace, or different types of environments.

In addition to teleoperator systems, haptic interfaces can also utilize a filter technique for compensation. Sirithanapipat [24] does this using a lead-lag compensator, or filter; the difficulty with this method is that, in an effort to improve transparency, it is possible to introduce non-passive effects into the virtual environment. This can happen due to the lead effect of the lead-lag filter; if the lead cutoff frequency is near the cutoff frequency for the actuation bandwidth of human user (5 Hz), the user will feel the effects of the lead filter as the system being energetic rather than being passive. For this reason, a lead-lag filter can be useful for PUIs where the user is expecting an energetic output anyway, but it is not generally useful for AUIs where the user expects the environment to be passive.
Chapter 7

Adaptive Compensation

Current transparency extension methods attempt to use linear compensation, however, these methods have limited functionality. These methods suffer from a lack of practicality. In the case of open-loop methods, the haptic device is modeled about a particular operating point that is only valid about that point. Closed-loop methods use force data as state feedback for a proportional controller alone. It is not possible to use derivative controllers in this case because of transducer noise, and integral control is not practical since haptic interactions generally do not have steady state equilibrium. All of these controllers change the system dynamics as they are a system element, which is not desirable when attempting to display another dynamic system via a haptic device. Ideally, a compensator should cancel the dynamics of the manipulator and not affect display of the virtual environment. The following section will show the development of a controller that cancels the manipulator dynamics by estimating those dynamics and simply subtracting the forces from the force determined by the virtual environment.

7.1 Estimation of Human-Machine Dynamics

As stated in Chapter 4, haptic interactions can be divided into two classes: active-user interactions (AUI) and passive user interactions (PUI). In an AUI, the user provides the motion input to the system and the response of the virtual environment is displayed through the manipulator; in a PUI, the manipulator plays a force through the manipulator while the user merely holds onto the manipulator. Both interaction types can be represented by the equations of motion for the system to be displayed; this can be expressed generally
as in Equation 7.1 where \( f \) is the force output of the desired environment, and \( g \) is the function defining that environment as a function of time, \( t \), and space, \( x \).

\[
f(x, t) = g[x(t)]
\]  

(7.1)

These types of interactions are displayed on impedance-based manipulators; so named because this manipulator measures the velocity as the state input and force is the system output. AUIs are a subset of this general interaction; figure 7.1 shows the block diagram of this interaction. Here, \( X_h \) is the measured velocity input, \( Z_E \) is the environmental

\[ \begin{align*}
  V_H & \rightarrow Z_E \rightarrow F_D \rightarrow G_T \rightarrow F_M
\end{align*} \]

**Figure 7.1:** Block diagram of Active User Interaction (AUI)

impedance, \( F_D \) is the desired force, \( G_T \) is the transparency transfer function and \( F_M \) is the measured force transmitted to the user. The human is assumed to be a velocity source, and the environment is assumed to passive. PUIs are the more general of the two interactions since a PUI doesn't require that the environment be passive. Figure 7.2 shows a block diagram of a PUI. Here, \( F_C \) is the commanded force and is not passive since it can contribute energy into the interaction. \( Y_H \) is the human-machine admittance,

\[ \begin{align*}
  F_C & \rightarrow \sum \rightarrow F_D \rightarrow G_T \rightarrow F_M \rightarrow Y_H \rightarrow V_H \rightarrow Z_E
\end{align*} \]

**Figure 7.2:** Block diagram of Passive User Interaction (AUI)

which means that the measured force is treated as an effort source and the human and the manipulator are modeled as passive elements.
7.1.1 Least-Squares Based Controller

One way of correcting the force error due to unknown human-manipulator dynamics is to develop a means of estimating those dynamics as a function of the force output error and then use that estimate to correct the commanded torque to the manipulator. First, define the desired end-point force, \( f_D \), as

\[
f_D = f(\ddot{x}_H, \dot{x}_H, x_H, t)
\]

where \( x_H \) represents the human motion input. The force due to manipulator dynamics, \( f_P \), is defined as the difference between the desired force and the measured force, \( f_M \),

\[
f_P = f_D - f_M
\]

By multiplying the manipulator dynamics by the Jacobian, it is possible to formulate the equations of motion in terms of the generalized coordinates where

\[
J^T f_P = \tau_p
\]

and \( \tau_p \) is the torque due to the manipulator. The Lagrangian derived by Cavusoglu et al [35], which defines the PHANToM 1.5A manipulator dynamics is

\[
\tau_p = M\ddot{\theta} + V(\dot{\theta}, \theta) + B\dot{\theta} + K\theta + G(\theta)
\]

The matrices defining the compliant, \( K \), and dissipative, \( B \), dynamics are assumed to be symmetric, positive definite, passive, and decoupled because they occur at the joint. The inertial and gravitational forces and forces due to Coriolis and centrifugal forces are usually non-linear. In addition, the manipulator in this study is a PHANToM 1.0 Premium, but the Lagrangian derived by Cavusoglu et al provides the correct form since the differences between the two manipulators are scalars of manipulator parameters including: masses, moments of inertia, and link lengths. To define the parameter update law, let us begin by defining an alternative form of the Lagrangian for convenience. The vector of torques due to the dynamics of the manipulator is a function of the velocity vector, its derivatives,
and inertial, dissipative, and compliant elements. We can define this torque vector as a regressor matrix and coefficient vector

\[
\tau_p = Y(\ddot{\theta}, \dot{\theta}, \theta)\Psi
\]

\[
\Psi^T = [\psi_1 \psi_2 \cdots \psi_r]
\]

(7.6)

(7.7)

where \(Y\) is an \(n \times r\) matrix of known functions, and \(\Psi\) is an \(r \times 1\) vector of coefficients of the manipulator dynamics. The parameter space is not unique and the dimension, \(r\), of the space depends on the choice of coefficient composition. The dimension, \(n\), depends on the number of actuated degrees of freedom of the manipulator. This formulation has the dimensional size of the parameter space by identifying parameters in the Lagrangian that share common functions of the generalized coordinates. The formulation of the regressor and the parameter vector can be found in the appendix. To estimate the parameter vector, \(\Psi\), a least-squares method is utilized. The torque estimate can be written as

\[
\tilde{\tau}_p = Y(\ddot{\theta}, \dot{\theta}, \theta)\hat{\Psi}
\]

(7.8)

It is then possible to create a cost function based on the torque error between the manipulators actual torque and its estimate. In this case, a quadratic cost function is used

\[
J(\tau_p) = \frac{1}{2}(\tau_p - \tilde{\tau}_p)^T(\tau_p - \tilde{\tau}_p)
\]

(7.9)

The necessary condition is that the derivative of the cost function with respect to \(\Psi\) be zero defined as

\[
\frac{\partial J(\tau_p)}{\partial \Psi} = (Y^TY\hat{\Psi} - YT\tilde{\tau}_p)^T = 0
\]

(7.10)

Then, the estimate of \(\Psi\) can be defined as

\[
\hat{\Psi} = Y^T(Y^TY)^{-1}\tilde{\tau}_p
\]

(7.11)

where the right pseudoinverse is used because \(Y\) is generally an underdetermined system of equations. Using the parameter estimate, it is now possible to define the controller in terms of the commanded torque, \(\tau_c\), as

\[
\tau_c = \tau_d + K_C Y\hat{\Psi}
\]

(7.12)
where $K_C$ is a diagonal, positive definite gain matrix and acts as a proportional controller. The block diagram of the system can be seen in figure 7.3

![Block diagram of an adaptive controller for Passive User Interaction (AUI)](image)

**Figure 7.3:** Block diagram of an adaptive controller for Passive User Interaction (AUI)

### 7.2 Stability and Passivity

The controller described above is designed to estimate the admittance of the human-machine system, however, there is no comment on the stability of the controller. The reason for a lack of comment is that it may not make sense to discuss stability, or passivity for that matter, because the environment is active. That is to say, the PUI adds energy to the system and does not necessarily approach an equilibrium, and it is for this reason that neither a passivity or stability analysis is applied.
Chapter 8

Results and Discussion

Throughout the investigation of transparency, experiments were conducted to collect data for the purpose of understanding transparency of the haptic interface, the nature of the interaction between the human user and the haptic interface, and finally, an evaluation of the efficacy of the proposed control solution. This chapter will provide details about the experimental setup, the virtual environments and control methods, and discussion of the results.

8.1 Experimental Setup

In this study, the PHANTOM 1.0 Haptic interface by Sensable Technologies is the haptic manipulator that is used in this study. Kinematically, the PHANTOM is a combination of both serial and parallel robotic elements as in figure 8.1, however, the design has kinematic constraints which allow the manipulator to be considered as a serial manipulator with the advantage that joint actuators are placed near the base of the robot. The links are constructed of aluminum tubing which makes the manipulator both rigid and lightweight when compared to the rigidity and mass of the user or any environments that the manipulator is likely to display. The actuators may be approximated as Maxon RE-025-055035 model DC brush motors [8] with optical encoders with a resolution of 4096 ticks/revolution. The actuators are connected via capstan transmission with a 11:1 ratio for the base capstan and 8:1 ratio for the parallel mechanism capstans and are driven using Copley model 303 PWM amplifiers [36]. The encoder and motor control signals are han-
Figure 8.1: Simplified diagram of PHANToM 1.0 haptic interface detail location of parallel and serial joint mechanisms.

died by a proprietary PCI controller based on an Altera FPGA that is controlled by the GHOST API. The API allows a designer to create sophisticated virtual environments by using predefined environment primitives such as walls, prisms, spheres, or a user-defined mesh by reading position and velocity and specifying force output based on the impedance of the predefined environment. It is also possible to create textures, force fields, active forces, and user-defined environment primitives by allowing the designer to directly read position/velocity values and specify the force output.

In addition to the PHANToM’s own encoders, the PHANToM 1.0 A is modified to measure force and acceleration at the interface point. A Nano-17 load cell by ATI Inc is mounted in a specially designed alternative end-link and measures force and torque at the end point, and three ADXL-35 single axis accelerometers are mounted to the link to measure acceleration. Figure 8.2 shows a photograph of the PHANToM with the sensors mounted to the PHANToM used for experiments. The load cell measures the actual force output of the PHANToM, which is then used as the error basis for the adaptive controller; the accelerometers enable measurement of the accelerations of the joints which is used for the adaptive model. Both the load cell and accelerometers are interfaced to the PC via a National Instruments PCI-6035E card using the NI-DAQ API and driver libraries. The NI-DAQ functions are called within the haptic loop to ensure that encoder, acceleration, and force measurements occur concurrently; however, data acquisition of the accelerometer
and the load cell happens at 200 Hz compared to the 1000 Hz haptic loop. Experience has shown that the reason for this mismatch is that it is not possible for the thread running the haptic loop to execute reliably at 1000 Hz due to operating system interrupts; this lack of reliability results in the GHOST API temporarily disabling the amplifiers. Since the purpose of this study is to examine transparency as a means of enhancing performance based on human-machine interaction dynamics, thread reliability is not considered in this study, however, it is an important problem that is being addressed through the use of real-time controllers and operating systems that are designed to overcome the problems of operating system interrupts.

8.2 Virtual Environments and Control Methods

8.2.1 AUI/PUI: Multiple Users with Constant Environment

In order to experimentally evaluate the proposed transparency transfer functions, a user was asked to interact with a virtual environment via the PHANToM Premium 1.0 A. The virtual environment was simply two springs oriented along a principle axis while constraining the other two axes with the stiffest environment possible, 300 N/m; figure 8.1
shows the orientation of the PHANToM Premium in these directions. For each interaction type (AUI and PUI) and constraint axis (X, Y, and Z), the user was asked to perform ten trials. A total of six right-handed male subjects aged 20 to 27 participated in the experiment. In all the trials, the subjects were instructed not to rest their elbow to prevent the introduction of any bias by those resting versus not resting their elbow; rather, they were instructed hold the stylus in such a way that the shoulder was the mechanical ground point for the user. In addition, users were allowed to practice with the device before the tests to familiarize themselves with the device. In order to calculate transparency, displacement, force, and time are measured. In these tests, the environment impedance is a set of virtual springs.

8.2.1.1 Experimental Determination of AUI Transparency

In the active tests, subjects were instructed to move the stylus along the constrained axis in a sinusoidal manner that increased in frequency similar to a chirp sine sweep. Subjects were visually cued by attempting to keep a solid sphere inside a larger wire frame sphere, which oscillated according to the desired chirp signal. The spring stiffness specified for these tests was 50 N/m, which is a typical stiffness that will not fatigue users. The length of the visual chirp was 10 seconds and used a hyperbolic ramp as in Equation 8.1 that ended at 30 Hz.

\[ X_{\text{cue}} = X_{\text{amplitude}} \sin\left(2\pi f_{\max} \frac{1}{1 + t_{\text{duration}} - t}\right) \quad (8.1) \]

\( X_{\text{cue}} \) is the displacement, in mm, of the wire frame sphere providing the visual cue to the user, \( X_{\text{amplitude}} \) is the amplitude of the cue sweep in mm, \( f_{\max} \) is the maximum frequency desired in Hz, \( t_{\text{duration}} \) is the length of the sweep in seconds, and \( t \) is the time in seconds. Finally, forces were sampled at a rate of 100 Hz with a haptic thread update rate of 1000 Hz.
8.2.1.2 Experimental Determination of PUI Transparency

In the passive tests, the same compliant environment was used but here the force chirp was applied directly as the desired force with an amplitude of 2N. During the test, the subject gripped the stylus and remained passive as forces were displayed. In addition, the user did not need any visual cue as the manipulator moved; the user simply maintained his/her grip. The length of the force chirp was 25 seconds with a linear ramp as in Equation 8.2 that ended at 50 Hz.

\[ F_C = F_{\text{amplitude}}\sin(4\pi t^2) \] (8.2)

\(F_C\) is the input force as in figure 7.3, \(F_{\text{amplitude}}\) is 2N, and \(t\) is time in seconds. The forces were sampled at a rate of 200 Hz with a haptic thread update rate of 1000 Hz. In this case, a linear ramp was chosen because it did not affect the users performance; the user is passive in PUI tests. The reader will note that some aspects of the two tests are not the same; in particular, the type of chirp sine sweep and their duration are different. The type of chirp sine sweep does not affect the result of the transparency measurement; it merely distributes the frequency sweep temporally. In addition, the sweep in the AUI tests is ramping the visual cue frequency to the user while the sweep ramps the force input frequency of the manipulator in the PUI tests. In the AUI tests, the hyperbolic function controlling the visual cue frequency increase was chosen because it allowed the user to track the lower frequencies for a longer duration of the test and put the saturation frequency towards the end of the test; this was implemented mainly as a comfort feature for subjects. The length of the test was chosen so as not to fatigue subjects while actively moving the manipulator; the maximum frequency was set at 30 Hz because that is the maximum visual update rate for humans. The length of the ramp in the PUI case was chosen to ensure that a maximum frequency of 50 Hz was generated given the slope of the linear ramp; 50 Hz was chosen as a conservative maximum frequency due to the Nyquist criterion because in these tests because the software updating the data acquisition thread limited the maximum sampling rate at 200 Hz. If the software allowed for higher force
sampling rates, the highest frequency available via the Nyquist criterion would have been chosen.

8.2.2 PUI: Multiple Users with Varied Environment

Five right-handed subjects, ages 23 to 27, held the stylus of the PHANToM 1.0A in a PUI interaction. The subjects were instructed to not rest their elbow but hold the stylus in such a way that the shoulder was the mechanical ground point for the user. In each trial, a force chirp was displayed through a spring environment and was applied directly as in Figure 3. The desired force amplitude ranged from 2 to 6 N at intervals of 2 N and the spring stiffness ranged from 0 to 100 N/m at intervals of 50 N/m. During a given trial, the subject gripped the stylus and remained passive as forces were displayed. In addition, the user was not provided any visual cues as the manipulator moved; the user simply maintained his/her grip. The length of the force chirp was 25 seconds with a linear ramp that ended at 50 Hz; the force-sampling rate was 200 Hz with a haptic thread update rate of 1000 Hz. Subjects completed five trials for each value of force and stiffness.

During each trial, the virtual environment impedance, \( Z_E \), is known, along with the commanded force \( F_C \). To clarify, the PUI interaction in this study asks the user to determine information about an environment that transmitted to them without probing an impedance. This is the event in "event-based" haptics for this particular case. In these experiments, subjects are asked to simply maintain a grip and allow the manipulator to move them; the playback is purely temporal.

8.2.3 Loop Shaping vs. Adaptive Controller

To compare the efficacy of the proposed controller, tests were conducted that first measured transparency for the central operating point and other operating points within the PHANToM’s workspace. The purpose of the test is to evaluate the efficacy of the controller for one subject over a range of environments and operating points; the subject who
participated in this test is male, right-handed, and 30 years of age. The test points were conducted at three operating points in the workspace: near the extent of the X, Y, and Z coordinate range at 150 N/m stiffness with a 4 N force amplitude, the mid-range of the X and Y coordinate range at 100 N/m stiffness with a 4 N force amplitude, and the mid-range of the X and Z coordinate range at 50 N/m with a 2 N force amplitude.

The controller algorithm is actually a simplified version of the controller described in Chapter 7. The reason for the discrepancy is that is functionally difficult to implement the controller with the given hardware. Between samples, an estimate of velocity and acceleration from encoder data is the only available data source of velocity and acceleration between samples; this estimate is poor due to the noise from the numerical differentiation.

\[ \tau_c = \tau_D + K_C Y(\dot{\theta}, \dot{\dot{\theta}}, \theta) \tilde{\Psi} \]  

(8.3)

This results in saturation of the Y portion of the controller which, when implemented in the software for the PHANToM, results in a force error that terminates the software that executes force commands to the PHANToM. The adaptive controller can be simplified to a proportional force control if the model estimate is not used to change the force command between samples with \( \tau_p \) as the error between the measured torque and the desired torque.

\[ \tilde{\Psi} = Y^T(YY^T)^{-1}\tau_p \]  

(8.4)

\[ \tau_c = \tau_D + K_C Y Y^T(YY^T)^{-1}\tau_p \]  

(8.5)

In this way, the efficacy of the controller can qualitatively evaluated in the sense that it will show that the same controller can be used for a variety of environments with the same efficacy as a variety of filters for multiple environments.
8.3 Results

8.3.1 AUI/PUI: Multiple Users with Constant Environment

8.3.1.1 Transparency of Active User Interactions (AUIs)

In the active trials, the subject was asked to track a wire frame ball with the PHANToM in an attempt to excite the manipulator within a desired frequency. Results show that the estimated transparency function bandwidth ranged from 1-5 Hz and was about 2 Hz when averaged over all subjects. Figure 8.3 shows a typical result for a single subject. The transparency function estimates showed differences between the constraint axes where X and Y generally had a lower bandwidth than the Z-axis. The data indicate insufficient

![Estimated X-Axis Transparency Transfer Function](image1)

![Phase Angle (degrees)](image2)

**Figure 8.3:** Typical estimated transparency of X-axis interaction in an active test for measured and simulated manipulator dynamic forces

excitation above 6 Hz; therefore, the displacement as a function of frequency was also examined. Figure 8.4 shows that the displacement amplitude for the same typical test drops to below -50 dB between 2-4 Hz, which corresponds to the transparency bandwidth of the AUI trials. Comparisons to a dynamic model of the PHANToM Premium were
also made using a model by Cavusoglu et al [35]. In [35], a PHANToM Premium 1.5 is considered; therefore, parameters were appropriately scaled for the PHANToM Premium 1.0. The modeled response in figure 8.3 shows that if excitation at higher frequencies were sufficient, the manipulator would have a transparency bandwidth of 11 Hz, which far exceeds the apparent excitation range of the user.

8.3.1.2 Transparency of Passive User Interactions (PUIs)

In the passive trials, the subject was asked to simply maintain a rigid grip on the stylus while allowing their forearm to be moved by the manipulator. Figure 8.5 shows a typical result for a single subject. In these tests, the transparency function crosses below the 3dB boundary at 8 Hz and stays close to the boundary until crossing below at 50 Hz. This was not limited to a particular axis either; all constraint axes showed similar results. When analyzing the transparency frequency response plots, it is important to emphasize that the phase information cannot be used to analyze stability since the transparency function is a tool for measuring display performance; it is not a representation of the actual system dynamics. As a means of comparison, the typical displacement plot is presented in figure
Figure 8.5: Typical estimated transparency of X-axis interaction in a passive test for measured and simulated manipulator dynamic forces

8.6. The most noteworthy information is that the displacements are all above -50dB

Figure 8.6: Typical X-axis displacement in a passive test

which agrees with the active test data showing that valid results were obtained when the displacements were greater than -50dB. As in the AUI case, a comparison to a model was
made for the PUI case. The results presented in Figure 8.5 show that the transparency bandwidth of 25 Hz for the virtual dynamics is larger than that of the AUI case and matches the morphology and bandwidth of the measured transparency reasonably well, and as such, makes transparency a reasonable measure for PUIs.

8.3.2 PUI: Multiple Users with Varied Environment

Five subjects were subjected to a range of input force amplitudes (2 to 6 N) and coupling impedances (0 to 100 N/m) for PUI interaction with a compliant environment with an overlaid sinusoidal force sweep. Results for transparency and human admittance are presented in the following sections.

8.3.2.1 Transparency

Figure 8.7 shows transparency data, averaged over five trials, for a typical subject for all combinations of force amplitude and environment impedance. Note that there is not significant deviation from case to case. Figure 8.8 shows average results over five trails for

![Typical Estimated X-Axis Transparency](image)

**Figure 8.7:** Typical X-axis transparency in a passive test

each subject at one force-stiffness combination. Again, note the similarity in transparency
measures for all subjects.

![Estimated X-Axis Transparency for Environmental Stiffness](image)

**Figure 8.8:** X-axis transparency in a passive test for multiple users

### 8.3.2.2 Human-Machine Admittance

Figure 8.9 shows human admittance results averaged over five trials for all combinations of force amplitude and environment stiffness for a single representative subject. Except at frequencies of 5 to 10 Hz, there is not a significant deviation from case to case. Figure 8.10 shows human admittance measurements, averaged over five trials, for all subjects for a single force amplitude-stiffness combination. This plot illustrates the invariance admittance from user to user and case to case.

### 8.3.3 Loop Shaping vs. Adaptive Controller

Figure 8.11, figure 8.12, figure 8.13 shows transparency data for a particular operating point at the extent of the X, Y, and Z coordinates of the workspace with a 150 N/m environment at 4 N force amplitude.
Figure 8.9: Typical X-axis admittance in a passive test

Figure 8.10: X-axis admittance in a passive test for multiple users

8.4 Discussion

8.4.1 Transparency of Active User Interactions (AUIs) and Passive User Interactions (PUIs)
The data from the active (AUI) trials indicate that transparency bandwidth is very small and user dependent, while the passive (PUI) trials indicate that transparency bandwidth is not user dependent or small. The causality arguments presented in Chapter 5 show that in AUI trials the human is the causal input; in the PUI trials, the user is a system element. In the AUI case, the excitation shown in Figure 8.3 is insufficient at higher frequencies, and leads to the conclusion that the transparency bandwidth measurements for AUIs are not reliable indicators of true transparency bandwidth. This excitation limitation is supported by prior work [16] that shows human motor bandwidth to be less than 5 Hz. Future work will address measurement of the AUI transparency by means of external, controllable excitation without a human operator. Since causality analysis shows that human dynamics do not affect AUI transparency bandwidth, this approach should provide reliable measurements. Prior work [20],[24] has predominantly used AUI techniques for determining transparency bandwidth, proposing linear compensators to improve the experimentally determined transparency bandwidth of the human-haptic system. This paper questions the validity of AUI measurements of transparency when bandwidths beyond that which can be voluntarily excited by the human user are of interest. In the passive (PUI) tests, the PUI transparency measurement technique was demonstrated to be reliable because there was sufficient system excitation. Here, the user was subjected to a commanded force that was uniformly applied while the manipulator and the user were coupled to a feedback impedance; this is an event-based haptic interaction [37],[38]. The transparency function estimates only slightly varied from user to user, which suggests that the use of a universal compensator should be sufficient to ensure that the transmitted impedance is essentially equivalent to the desired virtual environment impedance regardless of the user dynamics. The transparency transfer function can be defined explicitly as in Equation 8.1.

\[ G_T = \frac{F_M}{F_C - F_M Y_H Z_E} \] (8.6)

The denominator of this equation indicates that a range of users would feel the same commanded force, assuming a transparent manipulator, only when the environment impedance
is zero. However, it is obvious from the transparency function that the transparency bandwidth is fundamentally linked to the admittance of the user. Very low admittance on the part of the user would result in a transparency gain of unity, but this limiting case is unlikely, as it would be a large impedance that a human is not likely to emulate. A priori knowledge of user dynamics may prove useful for extending transparency bandwidth as demonstrated by [39],[40],[41],[42],[38]. However, variations in user dynamics cannot be addressed by a universal compensator, and may require other methods such as look-up tables based on physiological data (e.g. grip force, EMG, et cetera) or an adaptive control scheme. These approaches will be the focus of future work.

8.4.2 PUI: Multiple Users with Varied Environment

Figures 8.7 and 8.8 show that users generally are invariant in terms of transparency, but figures 8.9 and 8.10 show that the admittance of users does change with operators and environment. It is reasonable to assume that the manipulator admittance is invariant, and so, it is assumed that if the human-manipulator admittance changes, it is due to the human admittance. Consider for the moment, two extremes from the perspective of a user: a low force display and a high force display. The low force display will see most users as a fixed body, since the output of the display is below the maximum force output capabilities of a human operator. As a result, the smallest user has an admittance that is below the bound of what the manipulator can effectively move. The force of this manipulator is so small that the user completely arrests it regardless of their size, build, or strength. The high force display, on the other hand, would treat a user as a minor inertial error effectively moving the user about regardless of their low admittance. In the limiting cases, we see how the user can, or cannot, effectively determine the nature of human-machine interactions. Thus, these limiting cases clarify how most PUI interactions occur within a subspace human-machine admittance and operating conditions.
8.4.3 Loop Shaping vs. Adaptive Controller

The data in figures 8.11, 8.12, and 8.13 show that for a single user with a change of operating point, the transparency performance will change; this in itself is not surprising. Figure 8.13 does not have plots for transparency response with a linear filter; the reason is that the performance for that operating point initially showed that no filter was necessary. When the operating point changed, the transparency performance degraded. Table 8.1 shows the ranges where the transparency function for various operating points were within the 3dB band. Even so, the data show that linear filters can improve transparency performance even if the filter was designed for a different operating point, however, it does not always improve as well as the operating point for which it was originally designed. The closed loop force controller has similar performance to the filter which might make it seem as if the filter is as good as the force controller, however, the closed loop force controller does not require adjustment. In all cases, the proportional gain of the controller was 0.15. Moreover the closed loop controller can improve performance when a linear filter would not normally be implemented based on performance about a particular operating point. This shows that a closed loop or adaptive controller can perform as well as linear filters, but they do not require adjustment or a laborious development of a library of filters for

<table>
<thead>
<tr>
<th>Operating Point</th>
<th>Axis</th>
<th>No Compensation</th>
<th>Filtered</th>
<th>Adaptive</th>
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<td>X</td>
<td>0-9</td>
<td>0-20</td>
<td>0-20</td>
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<td>1-30</td>
<td>0.5-30</td>
</tr>
<tr>
<td>Center</td>
<td>Y</td>
<td>0.5-10</td>
<td>0-50</td>
<td>0-80</td>
</tr>
<tr>
<td>XYZ Extent</td>
<td>Y</td>
<td>50-85</td>
<td>20-70</td>
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<td>Center</td>
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<td>0-70</td>
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<tr>
<td>XYZ Extent</td>
<td>Z</td>
<td>40-50</td>
<td></td>
<td>40-50</td>
</tr>
</tbody>
</table>
different environments, users, and operating points.
Figure 8.11: Efficacy of Compensator on PUI on the X-axis
(a) No compensation, center  
(b) No compensation, XYZ extent

(c) Filtered, center  
(d) Filtered, XYZ extent

(e) Compensated, center  
(f) Compensated, XYZ extent

Figure 8.12: Efficacy of Compensator on PUI on the Y-axis
Figure 8.13: Efficacy of Compensator on PUI on the Z-axis
Chapter 9

Conclusions

This thesis investigates the transparency bandwidth of haptic interfaces by measuring transparency for two generalized interactions. Specifically, active user interactions (AUI) and passive user interactions (PUI) are studied. This work also discusses causality relationships in the natural environment and at the man-machine interface and shows that causality relationships are indistinguishable from the point of view of the human. As a result, variability in human dynamics between users has no effect on the transmitted impedance during AUI measurements; however, insufficient excitation on the part of the human makes transparency a poor performance measure in this instance, because it measures the performance of the human, not the interface. In the case of PUI measurements, the human cannot distinguish between natural and virtual environments on the basis of causality; however, the human dynamics do affect transmitted impedance. In practice, transparency is a good performance measurement for PUIs, but it is not a good performance measurement for AUIs. To address this issue for the AUI case, the use of external excitation is proposed to ensure excitation of the full frequency range of the haptic system. Finally, these data support the design of filters or compensators as an approach to improve haptic device performance in terms of transparency bandwidth.

In addition, this work shows the effect that permutations of coupling impedance and force amplitude have on transparency and the human-machine admittance during a passive user-induced (PUI) interaction. Results show that transparency and the human-machine admittance are sensitive to these changes for a low force display. Transparency is found to be a characteristic of a manipulator and the dynamics of the human operator. Results
indicate that it is possible to develop controllers to improve measured transparency for a given haptic interface. The controllers, typically implemented in the form of open-loop compensators, must be designed with the variety of users that may interact with the device, and the dynamics of the simulated environment to be displayed.

9.1 Contributions

This work has made several contributions to the body of knowledge in the field of haptic interactions. First, this work makes a case for the use of the transparency function as a performance measure for haptic interfaces; it shown in chapter 5, equation 5.3, that for haptic manipulators the transparency function reduces to ratio between the measured force to the modeled force. In addition, the transparency function effectively illustrates how the haptic manipulator affects the display of a virtual environment, that is, the manipulator is an electromechanical filter; from this observation, it is possible to create compensators as digital filters that can improve the transparency of the device. However, this work does not address the question of perception of the virtual environment on the part of the user. Secondly, a distinction is made between active and passive user interactions. Until recently, the distinction between the two types of interactions was unnecessary since practically all interactions were modeled as passive environments that do not provide a source of energy to the overall system; with the advent of event-based haptics, it becomes necessary to examine the nature of this type of interaction and develop modeling tools that designers can use for effective haptic displays. This work does not develop those tools; it merely examines the two interactions to begin to understand how to improve performance from the perspective of the haptic interface not the virtual environment. Third, this work has shown that, in AUIs, it is not advisable to try to implement compensators. The examination of AUIs shows that humans have a relatively low actuation bandwidth, but it must be stated that the transparency measurement, in the case of AUIs, is misleading since it implies attenuation by the device when it is actually due to the inability of the
user to excite higher frequencies. Compensators that are designed to correct this problem will either introduce energy into the system, as with lead-lag compensators, which lead to instability, or will significantly change the impedance of the modeled environment as with closed loop force control. Therefore, the work on designing and implementing open loop compensators as digital filters shows that transparency for PUIs can indeed be improved, however, the filters are not general solutions. Instead, filters must be designed on a case by case basis. Finally, this work establishes the idea of adaptive compensation that estimates the impedance of the manipulator and user and then uses that estimate as a basis for canceling dynamics that are due to the manipulator and the user. In particular, the closed loop force controller illustrates that a simple controller can perform as well as loop shaped methods without the laborious effort of designing and implementing a filter for individual users and environments.
Appendix A

PHANToM Equations

Developing a controller for the PHANToM 1.0 Haptic Interface requires an understanding of the device's kinematics to be able to implement the controller itself. This section shows a derivation of equations for forward kinematics and the manipulator Jacobian.

A.1 PHANToM Diagram

![Diagram of PHANToM 1.0 kinematics]

Figure A.1: Reference frames for the PHANToM 1.0.

A.2 Denavit-Hartenberg Parameters

In order to derive the forward kinematics for the PHANToM, the Denavit-Hartenberg notation [6] is used. The definitions for the variables from Craig are reproduced below,
and the values in the table correspond to the figure.

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<th>$a_{i-1}$</th>
<th>$d_i$</th>
<th>$\theta_i$</th>
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</thead>
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<td>$\theta_2$</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>$L_1$</td>
<td>0</td>
<td>$-\theta_3$</td>
</tr>
<tr>
<td>tool</td>
<td>$-\frac{\pi}{2}$</td>
<td>$L_2$</td>
<td>0</td>
<td>$\frac{\pi}{2}$</td>
</tr>
</tbody>
</table>

$a_i$ = the distance from $Z_i$ to $Z_{i+1}$ measured along $X_i$

$\alpha_i$ = the angle between $Z_i$ to $Z_{i+1}$ measured about $X_i$

$d_i$ = the distance from $X_{i-1}$ to $X_i$ measured along $Z_i$

$\theta_i$ = the angle between $X_{i-1}$ to $X_i$ measured about $Z_i$

### A.3 Forward Kinematics

The forward kinematics come directly from the Denavit-Hartenberg parameters above using a general transformation matrix also from Craig.

\[
_i^{i-1}T = \begin{bmatrix}
\cos(\theta_i) & \sin(\theta_i) & 0 & a_{i-1} \\
sin(\theta_i)\cos(\alpha_{i-1}) & \cos(\theta_i)\cos(\alpha_{i-1}) & -\sin(\alpha_{i-1}) & -\sin(\alpha_{i-1})d_i \\
sin(\theta_i)\sin(\alpha_{i-1}) & \cos(\theta_i)\sin(\alpha_{i-1}) & \cos(\alpha_{i-1}) & \cos(\alpha_{i-1})d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  \hspace{1cm} (A.1)

Using this general form of the transformation matrix, the transformation matrix from frame to frame is as follows:

$$
\begin{align*}
&_{world}T = \begin{bmatrix} 0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 \end{bmatrix} \\
&_{0}T_{1} = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & -L_1 \\
\sin(\theta_1) & \cos(\theta_1) & 0 & 0 \\
0 & 0 & 1 & L_2 \\
0 & 0 & 0 & 1 \end{bmatrix}
\end{align*}
$$
\[
\begin{align*}
\frac{1}{2} T &= \begin{bmatrix}
\cos(\theta_2) & -\sin(\theta_2) & 0 & 0 \\
0 & 0 & -1 & 0 \\
\sin(\theta_2) & \cos(\theta_2) & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \\
\frac{2}{3} T &= \begin{bmatrix}
\cos(\theta_4) & \sin(\theta_4) & 0 & L_1 \\
-\sin(\theta_4) & \cos(\theta_4) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \\
\frac{3}{\text{tool}} T &= \begin{bmatrix}
0 & -1 & 0 & L_2 \\
0 & 0 & 1 & 0 \\
-1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\end{align*}
\]

The final transformation matrix from that transforms a point in the tool frame to the world frame is:

\[
\begin{align*}
\frac{\text{world}}{\text{tool}} T &= \begin{bmatrix}
\cos(\theta_1) & -\sin(\theta_1)\sin(\theta_3) & \cos(\theta_3)\sin(\theta_1) & \sin(\theta_1)(L_1\cos(\theta_2) + L_2\sin(\theta_3)) \\
0 & \cos(\theta_3) & \sin(\theta_3) & L_2 - L_2\cos(\theta_3) + L_1\sin(\theta_2) \\
-\sin(\theta_1) & -\cos(\theta_1)\sin(\theta_3) & \cos(\theta_3)\cos(\theta_1) & -L_1 + \cos(\theta_1)(L_1\cos(\theta_2) + L_2\sin(\theta_3)) \\
0 & 0 & 0 & 1
\end{bmatrix}
\end{align*}
\]

The position vector that defines the endpoint of the PHANToM in the world frame is the first three rows of the fourth column of the transformation matrix.

\[
\begin{bmatrix}
X_{\text{world}} \\
Y_{\text{world}} \\
Z_{\text{world}}
\end{bmatrix} = \begin{bmatrix}
\sin(\theta_1)(L_1\cos(\theta_2) + L_2\sin(\theta_3)) \\
L_2 - L_2\cos(\theta_3) + L_1\sin(\theta_2) \\
-L_1 + \cos(\theta_1)(L_1\cos(\theta_2) + L_2\sin(\theta_3))
\end{bmatrix}
\] (A.2)

### A.4 Jacobian

The manipulator Jacobian transforms forces in the world frame into torques in joint space, and it also transforms angular velocities in joint space into rectilinear velocities in the world frame [6].

\[
J^T \vec{F}_{\text{world}} = \vec{\tau}_{\text{joint space}}
\] (A.3)

\[
\vec{V}_{\text{world}} = J^T \vec{\omega}_{\text{joint space}}
\] (A.4)
The Jacobian can be defined as the partial derivative of the position vector with respect to the joint space variables:

\[
J(\vec{\theta}) = \frac{\partial \vec{F}_{\text{world}}}{\partial \vec{\theta}}
\]  

(A.5)

\[
J(\vec{\theta}) = \begin{bmatrix}
\cos(\theta_1)(L_1\cos(\theta_2) + L_2\sin(\theta_3)) & -L_1\sin(\theta_1)\sin(\theta_2) & L_2\sin(\theta_1)\cos(\theta_3) \\
0 & L_1\cos(\theta_2) & L_2\sin(\theta_3) \\
-L_1\sin(\theta_1)(L_1\cos(\theta_2) + L_2\sin(\theta_3)) & -L_1\cos(\theta_1)\sin(\theta_2) & L_2\cos(\theta_1)\cos(\theta_3)
\end{bmatrix}
\]  

(A.6)
Appendix B

Regressor Matrix

The regressor matrix used for the adaptive controller is shown below

\[ Y = [Y_A \quad Y_B \quad Y_C \quad Y_D \quad Y_E \quad Y_F] \]

\[
Y_A = \begin{bmatrix}
0 & y_{12} & y_{13} \\
0 & 0 & 0 \\
y_{31} & y_{32} & y_{33}
\end{bmatrix}
\]

\[
Y_B = \begin{bmatrix}
0 & y_{15} & y_{16} \\
y_{24} & y_{25} & y_{26} \\
0 & 0 & 0
\end{bmatrix}
\]

\[
Y_C = \begin{bmatrix}
y_{17} & y_{18} & y_{19} \\
0 & y_{28} & 0 \\
0 & 0 & y_{39}
\end{bmatrix}
\]

\[
Y_D = \begin{bmatrix}
y_{110} & 0 & 0 \\
y_{210} & y_{211} & 0 \\
y_{310} & 0 & y_{312}
\end{bmatrix}
\]

\[
Y_E = \begin{bmatrix}
y_{113} & 0 & 0 \\
0 & y_{214} & 0 \\
0 & 0 & y_{315}
\end{bmatrix}
\]

\[
Y_F = \begin{bmatrix}
y_{116} & 0 & 0 \\
0 & y_{217} & 0 \\
0 & 0 & y_{318}
\end{bmatrix}
\]

\[
y_{12} = (1 + \cos(2\theta_3))\ddot{\theta}_1 - 2\cos(\theta_3)\sin(\theta_3)\dot{\theta}_1\dot{\theta}_3 - \sin(2\theta_3)\dot{\theta}_1\dot{\theta}_3
\]

\[
y_{13} = (1 - \cos(2\theta_3))\ddot{\theta}_1 + 2\cos(\theta_3)\sin(\theta_3)\dot{\theta}_1\dot{\theta}_3 + \sin(2\theta_3)\dot{\theta}_1\dot{\theta}_3
\]

\[
y_{15} = (1 + \cos(2\theta_2))\ddot{\theta}_1 - 2\cos(\theta_2)\sin(\theta_2)\dot{\theta}_1\dot{\theta}_2 - \sin(2\theta_2)\dot{\theta}_1\dot{\theta}_2
\]

\[
y_{16} = (1 - \cos(2\theta_2))\ddot{\theta}_1 + 2\cos(\theta_2)\sin(\theta_2)\dot{\theta}_1\dot{\theta}_2 + \sin(2\theta_2)\dot{\theta}_1\dot{\theta}_2
\]

\[
y_{17} = \ddot{\theta}_1
\]

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\[ y_{18} = (1 + \cos(2\theta_2))\ddot{\theta}_1 + 2\cos(\theta_2)\sin(\theta_2)\dot{\theta}_1\dot{\theta}_2 - \sin(2\theta_2)\dot{\theta}_1\dot{\theta}_2 \]
\[ y_{19} = (1 - \cos(2\theta_3))\ddot{\theta}_1 + 2\cos(\theta_3)\sin(\theta_3)\dot{\theta}_1\dot{\theta}_3 + \sin(2\theta_3)\dot{\theta}_1\dot{\theta}_3 \]
\[ y_{110} = 2\cos(\theta_2)\sin(\theta_3)\ddot{\theta}_1 - 2\sin(\theta_2)\sin(\theta_3)\dot{\theta}_1\dot{\theta}_2 + 2\cos(\theta_2)\cos(\theta_3)\dot{\theta}_1\dot{\theta}_3 \]
\[ y_{113} = \dot{\theta}_1 \]
\[ y_{116} = \theta_1 \]
\[ y_{24} = \ddot{\theta}_2 \]
\[ y_{25} = \sin(2\theta_2)\dot{\theta}_1^2 \]
\[ y_{26} = -\sin(2\theta_2)\dot{\theta}_1^2 \]
\[ y_{28} = 2\ddot{\theta}_2\sin(2\theta_2)\dot{\theta}_1^2 \]
\[ y_{210} = -\sin(\theta_2 - \theta_3)\dot{\theta}_3 + \cos(\theta_2 - \theta_3)\dot{\theta}_3^2 + \sin(\theta_2)\sin(\theta_3)\dot{\theta}_1^2 \]
\[ y_{211} = \cos(\theta_2) \]
\[ y_{214} = \dot{\theta}_2 \]
\[ y_{217} = \theta_2 \]
\[ y_{31} = \ddot{\theta}_3 \]
\[ y_{32} = \sin(2\theta_3)\dot{\theta}_1^2 \]
\[ y_{33} = -\sin(2\theta_3)\dot{\theta}_1^2 \]
\[ y_{39} = 2\ddot{\theta}_3 - \sin(2\theta_3)\dot{\theta}_1^2 \]
\[ y_{310} = -\sin(\theta_2 - \theta_3)\dot{\theta}_2 + \cos(\theta_2 - \theta_3)\dot{\theta}_2^2 - \cos(\theta_2)\cos(\theta_3)\dot{\theta}_1^2 \]
\[ y_{315} = \dot{\theta}_3 \]
\[ y_{318} = \theta_3 \]
\[
\begin{bmatrix}
\psi_1 \\
\psi_2 \\
\psi_3 \\
\psi_4 \\
\psi_5 \\
\psi_6 \\
\psi_7 \\
\psi_8 \\
\psi_9 \\
\psi_{10} \\
\psi_{11} \\
\psi_{12} \\
\psi_{13} \\
\psi_{14} \\
\psi_{15} \\
\psi_{16} \\
\psi_{17} \\
\psi_{18}
\end{bmatrix} = \begin{bmatrix}
(I_{axx} + I_{dfxx}) \\
\frac{1}{2}(I_{awy} + I_{dfyy}) \\
\frac{1}{2}(I_{azz} + I_{dfzz}) \\
(I_{bezz} + I_{czz}) \\
\frac{1}{2}(I_{beyy} + I_{cyy}) \\
\frac{1}{2}(I_{bezz} + I_{czz}) \\
I_{baseyy} \\
\frac{1}{8}l_1^2(4m_a + m_c) \\
\frac{1}{8}(l_2^2m_a + 4l_3^2m_c) \\
\frac{1}{2}(l_1(l_2m_a + 4l_3m_c)) \\
\frac{1}{2}g(2l_1m_a + 2l_5m_{be} + l_1m_c) \\
\frac{1}{2}g(l_2m_a + 2l_3m_c - 2l_5m_{df}) \\
b_{11} \\
b_{22} \\
b_{33} \\
k_{11} \\
k_{22} \\
k_{33}
\end{bmatrix}
\]
Appendix C

Transparency Test Psuedo Code

The software used for acquiring data and implementing controllers was developed in C/C++ using the GHOST API for haptic rendering, NI-DAQ API for data acquisition, and ATI libraries for resolving load cell gauge voltages.

C.1 Main Function

The main function, in all versions of the software, handles the initialization of different aspects of the overall program.

1. Initialize graphics using OpenGL and GLUT commands
2. Initialize the PHANToM
3. Check PHANToM for error states
4. Reset PHANToM encoders
5. Enable PHANToM amplifiers
6. Start haptic (servo) loop
7. Initialize primary haptic loop data structrue
8. Initialize global time
9. Configure data acquisition environment
10. Collect bias voltages from load cell
11. Start graphics loop
C.2 Functions

The software uses many different functions to accomplish rendering of the virtual environment. The GHOST API is responsible for many of the low-level aspects of rendering including acquisition of current PHANToM state, conversion of world frame forces into joint space torques, and maintaining loop rate integrity. This section will only detail user defined functions. For information about API specific functions please refer to the developer documentation.

**GST SCHEDULER CALLBACK** - Main thread for the haptic (servo) loop; it calls all subsequent functions in the program. This is also where data acquisition from the load cell and accelerometers occur.

**SineSweep** - Renders the virtual environment forces and implements the chosen controller.

**model estimate** - Calculates the current parameter estimate vector.

**regressor** - Calculates torque due to the estimated model for use in the compensator.

**ang velocity** - Angular velocity of PHANToM 1.0 joints.

**ang acceleration** - Angular acceleration of PHANToM 1.0 joints.

**jacobian phantom** - Jacobian matrix for the PHANToM 1.0.

**jacobian phantominv** - Inverse Jacobian matrix for the PHANToM 1.0.

**calLoadCell** - Calibrates the load cell.

**init** - Sets up the graphics environment.

**display** - Updates the graphics environment.

**reshape** - Changes view orientation of the graphics environment.

**SelectFromMenu** - Executes the choices made from the GUI menu.

**BuildPopupMenu** - Builds the GUI pop-up menu.
Bibliography


[4] Intuitive Surgical Inc. da vinci surgical system.


