Effectiveness of Vibration-based Haptic Feedback Effects for 3D Object Manipulation

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

This research explores the development of vibration-based haptic feedback for a mouse-like computer input device. The haptic feedback is intended to be used in 3D virtual environments to provide users of the environment with information that is difficult to convey visually, such as collisions between objects. Previous research into vibrotactile haptic feedback can generally be split into two broad categories: single tactor handheld devices; and multiple tactor devices that are attached to the body. This research details the development of a vibrotactile feedback device that merges the two categories, creating a handheld device with multiple tactors.

Building on previous research, a prototype device was developed. The device consisted of a semi-sphere with a radius of 34 mm, mounted on a PVC disk with a radius of 34 mm and a height of 18 mm. Four tactors were placed equidistantly about the equator of the PVC disk. Unfortunately, vibrations from a single tactor caused the entire device to shake due to the rigid plastic housing for the tactors. This made it difficult to accurately detect which tactor was vibrating. A second prototype was therefore developed with tactors attached to elastic bands. When a tactor vibrates, the elastic bands dampen the vibration, reducing the vibration in the rest of the device. The goal of the second prototype was to increase the accuracy in localizing the vibrating tactor.

An experiment was performed to compare the two devices. The study participants grasped one of the device prototypes as they would hold a computer mouse. During each trial, a random tactor would vibrate. By pushing a key on the keyboard, the participants indicated when they detected vibration. They then pushed another key to indicate which tactor had been vibrating. The procedure was then repeated for the other device. Detection of the vibration was faster ($p < 0.01$) and more accurate ($p < 0.001$) with the soft shell design than with the hard shell design. In a post-experiment questionnaire, participants preferred the soft shell design to the hard shell design.

Based on the results of the experiment, a mould was created for building future prototypes. The mould allows for the rapid creation of devices from silicone. Silicone was chosen as a material because it can easily be moulded and is available in different levels of hardness. The hardness of the silicone can be used to control the amount of damping of the vibrations. To increase the vibration damping, a softer silicone can be used. Several recommendations for future prototypes and experiments are made.

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Chapter 1
Introduction

During the creation of virtual objects in 3D virtual environments, one of the most common functions performed is object manipulation. The control elements used for object manipulation are translation (moving the object vertically or horizontally), zooming (moving the object closer or farther away), and rotation. Professionals who frequently use 3D environments (e.g. 3D CAD software) often use a non-dominant hand input device that allows them to translate, zoom, and rotate objects that they have created, while using the dominant hand to make fine detail adjustments to the design.

After several virtual objects have been created, it is often necessary to put them together to form a larger, more complex assembly. During this phase of the design process, difficulties may arise that are not present when the user is manipulating a single object. With multiple objects in the environment, it is possible for one object to impede the movement of another object. This problem is exacerbated by the lack of depth perception cues in a typical 3D virtual environment.

In a typical virtual environment, 3D space is represented using a conventional 2D monitor that lacks stereoscopic graphics. Because of the lack of stereoscopic vision, the ability of users to perceive depth is greatly reduced. In real world environments, the left and right eyes perceive slightly different images. This allows the brain to judge the distance from the eyes to an object. In virtual environments that lack a stereoscopic display, the left eye and the right eye receive exactly the same image, which prevents the user from being able to accurately estimate depth.

The inability to accurately estimate depth makes moving virtual objects through a virtual environment much more difficult than its real-world corollary. The lack of depth perception prevents the user from being able to determine the exact location of the object in 3D space. As a result, it can be difficult to prevent objects from colliding as they are moved about to form an assembly. An assembly is a collection of two or more integral 3D parts that are joined together to form a larger, more complex object.

Furthermore, when a real-world object collides with another object, such as a wall, the person holding the object feels a force that resists the motion of their hand. If they rub the object along the wall, they feel the force of friction resisting their hand motion. They also feel minor vibrations as the object rubs against the wall. The forces and vibrations applied to their hand are both forms of haptic feedback, defined by Tan (2000) as “sensing and manipulation through the sense of touch.” In a typical virtual environment, no haptic feedback is provided.

When a user manipulates a virtual object, there is no direct mapping between the location of their hand and the location of the on-screen object. Many non-dominant hand input devices, such as the Spaceball™, the SpaceMaster™, and the Space Mouse™, use rate control to specify the position of the object on the screen (Zhai, 1998). In rate control devices, the position of the input device relative to its null position controls the rate of motion of the virtual object. This means that the user’s hand does not move from its resting position as they move the object through the virtual environment, completely removing any mapping between their hand location and the location of the virtual object. For example, if they push the input device slightly away from its null position, the on-screen object will move in the direction that they push the device. If they maintains the non-null position of the input device, the virtual object will continue to move, despite the fact that their hand is not moving.

There is also no feedback of force information from the virtual environment to the user's hand. The object could hit a wall and the user would feel no force against their hand. These limitations of virtual environments make virtual object manipulation much more difficult than real-world object manipulation. For example, in a review of literature on rotating 3D virtual objects, Ware and Rose (1999) found that the time to complete virtual object rotation tasks was of the order of 10 seconds, whereas the time for real object rotation tasks was of the order of 1 to 2 seconds.

To improve the performance of virtual object manipulation, feedback about the forces being exerted on the virtual object should be provided to improve the "control feel" (Zhai, 1998). There are five senses by which humans can perceive information: vision, hearing, touch, smell, and taste. Smell and taste are very difficult to use as feedback mechanisms in computer systems. The task of 3D object manipulation is inherently a visual task, so it would be counter-productive to add more information to the visual channel. Auditory feedback could be used, but it is generally reserved for high priority warnings and alerts (Jacko and Sears, 2003). The haptic channel is very well-suited to the task of providing force feedback to the user. In the real world, forces are sensed using the sense of touch, so it is intuitive that force feedback should be provided using this modality.

1.1 Document Overview

This thesis describes the research and design development of a device to provide haptic feedback in virtual environments. The goal of the device is to enhance user performance when conducting object manipulation tasks.

The first chapter introduces 3D virtual environments and describes the difficulties involved with object manipulation within these environments. Some of the benefits of haptic feedback in virtual environments are described.

The requirements for the device are described in the second chapter. This work builds on previous research conducted at the Usability and Interactive Technology Lab at the University of Waterloo. The truncated sphere shape of the device was chosen to achieve continuity with previous research.

The third chapter includes a literature review of background research on haptic feedback and the biophysical processes involved in the sensation of vibration. Previous research on haptic feedback devices is explored to provide guidance for the new device. The methods by which the human hand senses vibration are also researched to aid in the development of the device.

The implementation of the haptic feedback device is described in the fourth chapter. The design decisions that were made in the development of the device are described and justified. Four pager motors were used as tactors to provide vibration-based haptic feedback. The pager motors were placed evenly about the equator of the device. Two prototypes are described. The hard shell prototype has tactors attached directly to a rigid plastic shell. The plastic was chosen to match the type of plastic that is commonly used in the construction of computer input devices. However, the rigid plastic transmits vibrations very well, which may make it difficult to determine which tactor is vibrating. In response to this potential problem, a soft shell prototype was developed. The soft shell prototype has tactors attached to rubber bands, which act as mechanical dampers to dampen the vibration of the tactors. It was hypothesized that the damping effect of the elastic bands would result in an increase in accuracy in localizing the vibrating tactor.

The fifth chapter describes an experiment to compare user performance in terms of signal detection of the tactors using the two prototypes.

An apparatus that will be used to develop future prototypes is described in the sixth chapter. A mould was built to allow for the rapid creation of haptic feedback devices using silicone. Silicone was chosen as a material as it can be easily moulded to a customized shape. Silicone is also available in different levels of hardness, allowing for the adjustment of the amount of mechanical damping of the vibrations.

The seventh chapter describes future work that can be done to continue the research described in this thesis. Modifications are proposed for the procedure of future experiments comparing different haptic feedback devices. It is also suggested that different configurations of tactors to be built and compared. Additionally, the hardness of the silicone should be varied in a controlled way to more accurately explore the impact of material hardness and damping effects on the accurate detection and localization of haptic feedback in handheld devices.

Chapter 2

Haptic Requirements for a 3D Input Device (veBall)

2.1 Previous Research

This work builds on the work of Rex Xu in the development of the veBall (Xu, 2004), a non-dominant hand input device for 3D virtual environments. The veBall was developed jointly by Rex Xu and Professor Carolyn MacGregor in the Usability and Interactive Technology (Use-IT) Lab at the University of Waterloo (Xu and MacGregor, 2004).

The veBall is a transformable device with two distinct modes. In rotation mode, it has the shape of a sphere, with a diameter of 68 mm. As the veBall is rotated, the virtual object rotates to match the orientation of the veBall. This provides a very natural and intuitive mapping between the veBall and the virtual object. The user can then push a button to transform the shape of the device which also changes the function to translate/zoom mode. In translate/zoom mode the bottom quarter of the sphere then retracts inside the device, leaving a truncated sphere with a flat bottom (see Figure 1). The flat bottom can be placed on a flat surface, such as a desktop, and the veBall acts like a mouse. In translate/zoom mode, moving the veBall causes the on-screen object to translate. By pushing a button on the side (not pictured) and moving the veBall up and down, the user can zoom in and zoom out. The panning and zooming functions of the veBall are very intuitive, as they use mouse motions that are familiar to all users of personal computers.

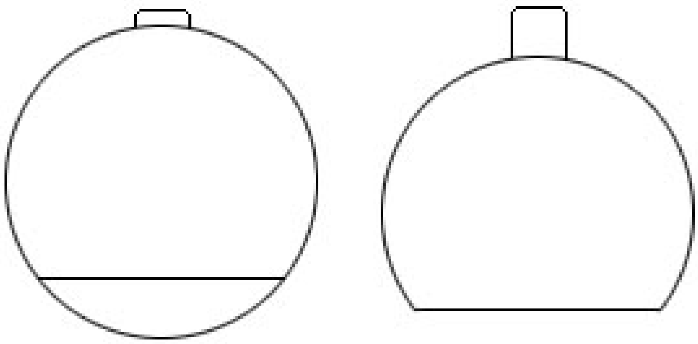

Figure 1: Simplified view of the veBall in rotation mode (left) and translate/zoom mode (right)

Unfortunately, as with most handheld 3D input devices, the veBall suffers a lack of haptic feedback when moving objects through virtual environments. The lack of haptic feedback makes the interaction more difficult and less natural than real-world object manipulation (Bloomfield and Badler, 2003).

The goal of this research and design development work and accompanying experiment is to develop haptic feedback for a handheld, mouse-like device that will enhance user performance when manipulating objects in virtual environments or other 3D applications (e.g. 3D computer aided drafting). For the purpose of this work, the veBall input device already under development in the Use-IT Lab is used as the starting point for the device form and configuration.

To understand how haptic feedback can be successfully integrated into an input device, it is necessary to understand the research that has been conducted in the field of haptics. The research must be examined from a cognitive ergonomics perspective to understand the impression (or feeling) that the user experiences when they perceive the haptic feedback. This will make it possible to integrate the research into the development of a haptic device which effectively communicates information about the virtual environment to the user. Beyond the field of haptics, it is also necessary to understand how the body senses haptic feedback. The background information presented in the following chapter will be used to guide the design and development of a haptic feedback device for virtual environments.

Chapter 3
Background

3.1 Haptic Feedback

Haptic feedback generally falls into two broad categories: force feedback and vibrotactile feedback (Jacko and Sears, 2003). Force feedback is used to exert a variable force on the hand of the user, whereas vibrotactile feedback uses vibration to deliver feedback to the user.

3.1.1 Force Feedback

Force feedback requires an armature attached to a fixed base. The fixed base can be either fixed to the earth (as seen in Figure 2) or to another part of the user. An example of the latter case is an exoskeleton with the fixed base attached to the user's arm. In both cases, the fixed base allows reaction forces to be exerted against the user's hand. The other end of the armature is attached to an input device. The armature can then provide force feedback to the input device by using actuators to oppose the motion of the device. The result is a sensation that accurately mimics the forces exerted on the human hand during object manipulation. However, torques and vibrations are not typically included in the feedback, reducing the realism of the feedback.

A popular force feedback system is SensAble Technologies' PHANTOM® Omni™ (see Figure 2). The PHANTOM® Omni™ has a fixed base to which a stylus is attached.

Figure 2: PHANTOM Omni. Image source: SensAble Technologies (2007).

The retail price of the PHANTOM® Omni™ is approximately $3900 US [Engineering Systems Technology, 2004]. This is significantly more expensive than a typical mouse-like computer input device. As the veBall is a mouse-like computer input device, the cost of implementing force feedback is prohibitive.

3.1.2 Vibrotactile Feedback

3.1.2.1 Vibrotactile Feedback Transducers

There are several transducers that are commonly used to provide vibrotactile feedback in handheld devices. The most common are described below.

3.1.2.1.1 Voice-coil Transducers

Voice-coil (shaker) transducers were some of the first transducers used to create vibrohaptic feedback (Cholewiak and Wollowitz, 1992). Voice-coil transducers work on the same principal as acoustic speakers. A coil is placed inside a strong magnetic field and oriented such that a current passing through the coil causes the coil to move along its axis. By rapidly changing the direction of the current, the coil can be made to oscillate rapidly. This means that the transducer must be operated with alternating current (AC). A contactor is placed directly on the skin. The coil strikes the contactor at one extreme of its range of motion (see Figure 3), causing a vibration to pass through the contactor to the skin. A voice coil transducer can produce vibrohaptic feedback at frequencies ranging from 0.1 Hz to 300 Hz (Cholewiak and Wollowitz, 1992). Gescheider et al. (1985) found that the detection of vibration occurred most strongly at frequencies of up to 400 Hz, so it appears that voice coil transducers can take advantage of much of the innate vibration detection capabilities of humans.

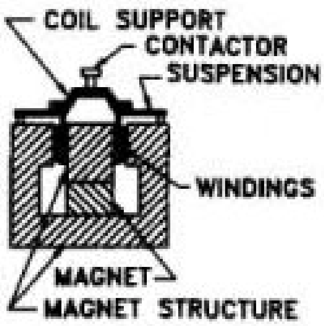

Figure 3: A voice-coil transducer. Image source: Cholewiak and Wollowitz (1992).

A voice-coil transducer that is commonly used in research is the C2 Tactor, produced by Engineering Acoustics, Inc.

3.1.2.1.2 Inertial Transducers

An inertial transducer consists of a coil attached to a spring inside a sealed case (Cholewiak and Wollowitz, 1992). The coil is suspended in a magnetic field, so that when an alternating current is applied to the coil, the coil vibrates. Like the voice-coil transducers described previously, inertial transducers must be powered using alternating current (AC). The vibrating coil causes the entire sealed case to shake. The frequency range of inertial transducers is identical to the frequency range of voice-coil transducers, as they both use the same technology to produce vibration. However, because the entire sealed case shakes, inertial transducers produce a less localized vibration than voice coil transducers, which have a small vibrating contactor (see Figure 3).

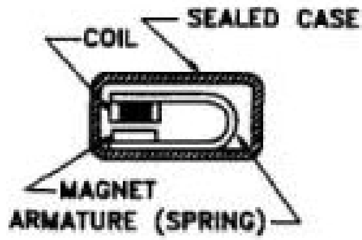

Figure 4: An inertial transducer. Image source: Cholewiak and Wollowitz (1992).

3.1.2.1.3 Eccentric Rotating Mass Motors

Perhaps the most commonly used transducer for vibrohaptic feedback is an electromagnetic motor with an eccentric rotating mass (ERM). A mass is mounted eccentrically on the shaft of a DC motor (see Figure 5). When the motor spins, the entire unit vibrates. ERM motors are frequently called pager motors because they are used extensively for haptic feedback in pagers and cellular phones.

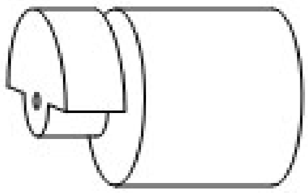

Figure 5: A DC motor with an attached eccentric rotating mass. Image source: Haywood and MacLean (2007).

ERM-based transducers generally operate using direct current (DC), which means that the frequency of vibration cannot be directly controlled. To increase the frequency of vibration, the supply voltage must be increased. However, as the supply voltage increases, both vibration frequency and amplitude increase (Holbein and Zelek, 2005). The design implications of the relationship between vibration frequency and amplitude are discussed in Section 3.1.2.3.4.

Brown and Kaaresoja (2006) performed an experiment where they varied the rhythm and intensity of the vibration of pager motors and C2 Tactors, a type of voice-coil transducer. They found that the overall vibrotactile signal recognition of human study participants using a pager motor was nearly identical to the participants' signal recognition using a C2 tactor. This result is promising, as it suggests that the pager motors may provide the same performance in terms of recognizing and identifying vibratory signals as much more expensive tactors.

3.1.2.1.4 Piezoelectric Transducers

Piezoelectric transducers take advantage of the fact that some substances contract and expand when a voltage is applied to them. In an example given by Bliss et al. (1970), two strips of lead zirconate are coated with thin layers of conducting nickel, and a thin sheet of conducting brass is placed between the two layers (see Figure 6). When a voltage is applied between the nickel and the brass, the upper layer of zinc zirconate contracts longitudinally and the lower layer expands longitudinally. As a result, the mechanism bends upwards, causing the stimulator pin to rise. When the opposite voltage is applied, the mechanism bends downwards, and the stimulator pin falls. By rapidly applying opposing voltages, it is possible to create vibrations. This means that piezoelectric transducers must be powered by alternating current (AC) in order to create vibrations. However, piezoelectric transducers tend to be used for more static applications. A grid of piezoelectric transducers can be used to generate Braille characters by raising and lowering the appropriate stimulator pins, as demonstrated by the RBD Braille interface (Benali-Khoudja et al., 2004).

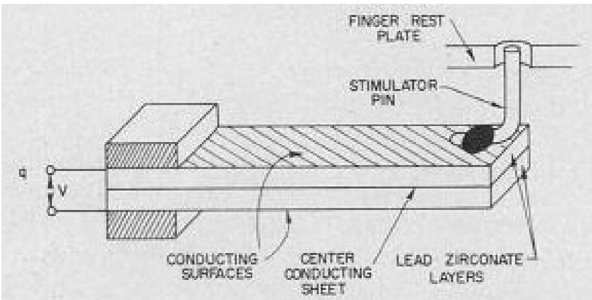

Figure 6: A piezoelectric transducer. Image source: Bliss et al. (1970).

3.1.2.2 Existing Vibrotactile Feedback Devices

There have been many devices that attempt to incorporate haptic feedback. Generally, the devices fall into one of two broad categories: single tactor devices and multiple tactor devices.

3.1.2.3 Single Tactor Vibrotactile Devices

As the name implies, single tactor haptic feedback devices use only a single tactor to transmit information to the user. Single tactor devices tend to be handheld devices, such as cellular phones or video game controllers. Significant amounts of research have been devoted towards maximizing the information that can be transmitted from an electronic device to its user using a single tactor. This research is summarized below.

3.1.2.3.1 Duration

By modifying the duration of a vibration, it is possible to change how the vibration feels to users. Gunther (2001) found that subjects perceived vibrations lasting less than 0.1 seconds as taps or jabs, whereas longer vibrations were perceived as vibrations.

Possibly the simplest form of single tactor haptic feedback is a design like the Rumble Pak™ by Nintendo™. The Rumble Pak is an attachment for the controller on the Nintendo 64™ game console. It consists of an ERM motor that vibrates when certain in-game events occur, such as firing a gun or being shot. The Rumble Pak™ provides very limited feedback, as it has only two states (on and off). This limited feedback makes signal detection easy, as the amplitude of vibration is very large and therefore the vibration is unlikely to be missed. The duration of vibration is used to transmit information to the user. For example, if the user's in-game character is shot with a small gun, the Rumble Pak™ might vibrate for a short duration. However, if the in-game character is shot with a rocket, the Rumble Pak™ might vibrate for a longer duration. The meaning of the information is very obvious and requires very little cognitive processing to understand. As anyone who has used it can attest, the Rumble Pak™ increases the sense of immersion that the user feels while playing the game.

While the duration of a vibration can be used as a signal, researchers have tended to favour combining multiple vibrations of different durations to forms rhythms (Brewster and Brown, 2004).

Duration is a parameter that can be adjusted for all types of vibrotactile transducers.

3.1.2.3.2 Rhythm

By combining vibrations of various durations with pauses, it is possible to create rhythms. These rhythms can then be used to form a tactile Morse code which can be used to encode complex information.

Brown, Brewster, and Purchase (2005) examined the ability of study participants to detect the rhythm of various tactons (tactile icons). Tactons were coded with either a 2, 4, or 7-note rhythm (see Figure 7). Notes and pauses were either very short (1/4 beat), short (1/2 beat), long (1 beat), or very long (2 beats). The 7-note rhythm consisted of two short notes, a short pause, a short note, two very short notes, a short note, and lastly a long note. The 4-note rhythm consisted of a long note, two short notes, and another long note. The 2-note rhythm consisted of a short note, a short pause, and lastly a very long note. All three rhythms were coded with the same tempo, but the authors did not specify the duration of each note. Participants had a single tactor attached to the index finger of their non-dominant hand. They were presented with one of the three rhythms and were then asked to identify which rhythm had been presented. Participants correctly identified the tacton rhythm with 93% accuracy.

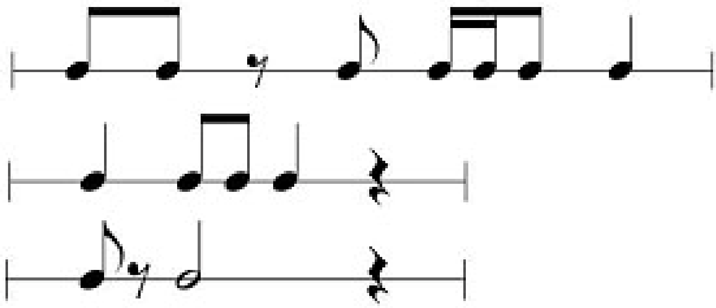

Figure 7: 7, 4, and 2 note rhythms. Image source: Brown, Brewster, and Purchase (2005).

When the experiment was repeated using three tactors mounted on the wrist and forearm (Brown, Brewster and Purchase, 2006), the researchers found that the rhythms were correctly identified with an accuracy of 96.7%.

Like duration, rhythm can be adjusted using all types of vibrotactile transducers.

3.1.2.3.3 Frequency

By modifying the frequency of vibration, it is possible to change the user's perception of the "roughness" of the vibration. A very low frequency sinusoid feels "rough", whereas a high frequency sinusoid feels "smooth" (Hoggan and Brewster, 2007).

Tan et al. (1999) found that human participants could categorize vibrations as either slow (up to about 6 Hz), rough (from 10 Hz to 70 Hz), and smooth (above approximately 150 Hz). Following up on this research, Hoggan and Brewster (2007) asked study participants to attempt to distinguish between a smooth sinusoid (250 Hz), a rough sinusoid (70 Hz), and a very rough sinusoid (6 Hz). The participants had a success rate of 81%.

Gill (2003) recommends that no more than nine distinct frequencies be used in tactons. However, it is unclear how he arrived at that recommendation. In light of the results from Hoggan and Brewster, it appears that Gill was overly optimistic in this recommendation.

For voice-coil, inertial, and piezoelectric transducers, the frequency of vibration can be controlled independently of the amplitude by changing the frequency of the AC supply. However, for ERM transducers, increasing the frequency of vibration increases the amplitude of vibration (Holbein and Zelek, 2005).

3.1.2.3.4 Amplitude

In general, large amplitude vibrations are easier to detect than small amplitude vibrations. From a signal detection perspective, this is an expected result, as large amplitude vibrations generate more activity from the skin's fast acting (FA) and slow acting (SA) units, increasing the separation between signal and noise. This increases the user's sensitivity and allows them to detect large amplitude vibrations more easily than small amplitude vibrations.

For voice-coil, inertial, and piezoelectric transducers, the amplitude of vibration can be independently controlled by increasing the amplitude of the AC supply current. A drawback to using amplitude as a parameter for tactons is that amplitude and frequency are not independent for pager motors (Holbein and Zelek, 2005). Because pager motors are the most commonly used commercial tactor, it has been suggested that amplitude and frequency be combined into a single parameter for tacton design (Brewster and Brown, 2004). However, it does not appear that any further research has yet been done on this as-yet-unnamed single parameter.

3.1.2.3.5 Waveform

Generally, modifying the waveform of the vibration changes the perceived "roughness" of the vibration (Hoggan and Brewster, 2007). This effect is very similar to the effect of frequency.

Gunther (2001) claims that human study participants can distinguish between a sine wave and a square wave, but that it would be difficult to distinguish between more subtle variations. He states that participants perceived a sine wave as "smooth" and a square wave as "rough". Hoggan and Brewster (2007) found that participants could distinguish between a sine wave, a sawtooth wave, and a square wave with an accuracy of over 94%. The sine wave was described as "smooth", the square wave as "very rough", and the sawtooth wave as "rough".

Brown et al. (2006) tested a signal that either increased or decreased in amplitude with time. They found that participants were able to correctly identify linearly or exponentially increasing signal amplitude 100% of the time. The participants were also able to identify an unchanging stimulus 95% of the time, and linearly or exponentially decreasing signal amplitude 92% of the time. These results imply that increasing or decreasing the signal amplitude is an effective method of encoding information to transmit it haptically.

Another type of complex waveform that has been attempted is amplitude modulation. Amplitude modulation is achieved by multiplying a sine wave by a sine wave of a different frequency. Brown, Brewster, and Purchase (2005) examined the ability of study participants to detect the waveform of various tactons, using a C2 tactor attached directly to the index finger. Using a pure 250 Hz sine wave, a 250 Hz sine wave modulated by a 50 Hz sine wave, and a 250 Hz sine wave modulated by a 30 Hz sine wave, participants were able to correctly identify the waveform 80% of the time. The researchers describe the pure sine wave as "smooth", the sine wave modulated by a 50 Hz sine wave as "rough", and the sine wave modulated by a 30 Hz sine wave as "very rough". This is very similar to the sense of roughness that was induced by using sine waves, sawtooth waves, and square waves.

When this experiment was repeated using three C2 tactors mounted to the wrist and forearm (Brown, Brewster, and Purchase, 2006), the identification rate dropped to 50.2%. This reduced accuracy in identifying the signal can be attributed to the fact that there are significantly more FA and SA units in the fingertips than in the forearm. The researchers then removed the 250 Hz sine wave modulated by 50 Hz from the procedure. When asked to discriminate between a pure 250 Hz sine wave and a 250 Hz sine wave modulated by a 50 Hz sine wave, participants had an accuracy rate of 80.6%.

In a follow-up experiment by Hoggan and Brewster (2007), using the three original amplitude modulated tactons and a C2 tactor attached to the index finger, test participants correctly identified the waveform 94% of the time. These results imply that the forearm and wrist are significantly worse at identifying degrees of roughness than the fingertips.

It is possible to change the supply waveform for voice-coil, inertial, and piezoelectric transducers. However, ERM transducers require a constant DC voltage, eliminating the potential to modify the waveform.

3.1.2.4 Multiple Tactor Vibrotactile Devices

Multiple tactor devices tend to be wearable arrays of tactors, such as a suit or sleeve. In a tactile suit, an array of tactors is mounted onto a suit. This allows a wide variety of body locations to be independently stimulated with vibrations.

When multiple tactors are used in a single device, two more parameters for haptic feedback become available. These parameters are the location of the vibration and spatiotemporal patterns as conveyed to the user via the input device, which are explained in the following sections.

3.1.2.4.1 Vibration Location

Many wearable tactile devices that have a grid of tactors distributed about the body have been created. Van Erp, van Veen, and Jansen (2005) describe the development of a tactile waist belt. The belt has eight pager motors, mounted equidistantly around the participant’s waist. A group of pilots was asked to move around a triangular course. The correct direction of navigation was indicated either by oral instructions from the co-pilot or by vibrating the pager motor that was closest to the correct direction. Performance was judged by the average deviation from the course. There was no difference in performance between tactile and oral instructions. Furthermore, the participants found the tactile direction indication to be “clear and useful”. This suggests that using a matrix of tactors provides a very natural mapping between the vibrotactile feedback and the physical world.

Van Erp and van Veen (2003) created a tactile vest, covered in a matrix of tactors, designed to be worn by astronauts on the International Space Station. The vest was intended to create an artificial gravity vector by always having a single tactor vibrating. The location of the vibration indicates the “down” direction on the space station. By using a dense matrix of tactors, van Erp and van Veen were able to provide very precise vibrotactile feedback of the “down” direction. In-flight tests with astronauts were planned to determine the effectiveness of the tactile vest in a zero gravity environment.

Bloomfield and Badler (2003) developed a tactile sleeve for use in virtual environments. Twenty-four pager motors were mounted on a skin-tight sleeve. The participants used a motion-tracking device, attached to their right arm, to control a virtual arm. They had to control the virtual arm so that the hand would touch a virtual ball without colliding with any of the virtual objects in the scene. The participants were split into two groups. Both groups received visual feedback about collisions. The virtual arm would turn magenta at the site of any collision. One group of participants also received haptic feedback. To provide haptic feedback, the tactor closest to the location of a collision would vibrate. The group with both haptic and visual feedback experienced 21% fewer collisions than the group with only visual feedback, indicating that haptic feedback significantly improved the performance of the participants.

One of the objectives of this research is to provide feedback to users of virtual environments about collisions that occur between virtual objects. The results of the study by Bloomfield and Badler (2003) indicate that an array of tactors can be an effective mechanism for providing the desired feedback.

3.1.2.4.2 Spatiotemporal Patterns

Brewster and Brown (2004) suggest that spatiotemporal patterns may be a more effective way to provide feedback using multiple tactors. Rather than simply having tactors vibrate to indicate a collision or a direction, tactors are vibrated in a specific pattern to generate more detailed information. If there is a 3-by-3 array of tactors located on the user's back, lines and patterns can be "drawn" by vibrating tactors in turn (see Figure 8). For example, to "draw" the letter L, tactor 1 would be activated, followed by 4, then 7, 8, and finally 9.

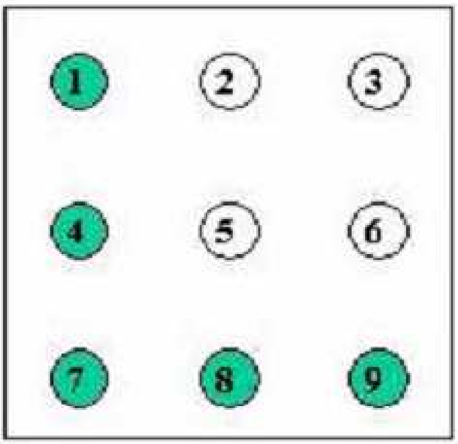

Figure 8: A 3-by-3 array of tactors. Image source: Brewster and Brown (2004).

Similarly, Saida et al. (1978, as quoted by Yanagida et al., 2004) found that a 10-by-10 pin array on the back could be used to accurately present letters haptically. Japanese letters were presented using either a static or dynamic presentation. For a static presentation, all the pins to represent the letter were activated at once. For a dynamic presentation, the pins were activated one at a time, in the order that they would be written by hand.

Using a static presentation of the letters, participants identified the letters with less than 50% accuracy. However, when the letters were "traced", as if they were being written by hand, the accuracy jumped to 95%. These results can be explained by the different cognitive processes that must occur to detect and interpret each type of presentation.

During the static presentation, a large number of pins must be simultaneously detected, after which they are interpreted to form a whole. This requires the bottom-up processing of a large number of items into a single whole, a process which is fraught with difficulties. With a dynamic presentation, only a single pin must be detected at any given time. Additionally, there is a strong expectancy that the next pin will be located beside the current pin, indicating that the "pencil stroke" is continuing. If the next pin is not beside the current pin, it indicates that a new stroke is beginning. After the dynamic presentation is complete, the participant has a mental image of the strokes that were performed. These strokes can then be relatively easily integrated into a whole letter.

Yanagida et al. (2004) followed the research of Saida et al. by creating a 3-by-3 array of pager motors mounted on an office chair. Participant had to wear thin shirts so that their clothing would not significantly affect their ability to detect vibrations. The researchers traced numbers and English letters on the backs of test subjects using the tactor array. The researchers found an overall character recognition rate of 87%.

Kohli et al. (2004) created an arm-mounted array consisting of three tactor rings. Each tactor ring had 5 voice coil tactors evenly spaced around it, providing a total of 15 tactors (see Figure 9).

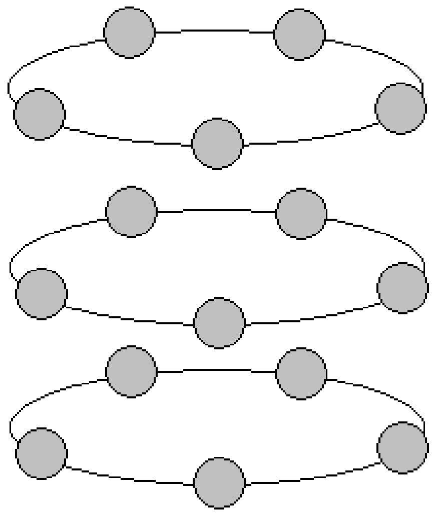

Figure 9: Arm-mounted array of rings of tactors.

Four patterns were presented: clockwise, counter-clockwise, up, and down. For the clockwise and counter-clockwise patterns, the tactors vibrated in either a clockwise or counter-clockwise direction. For the up and down patterns, the rings vibrated in order, either from top to bottom (down), or from bottom to top (up). The patterns were also presented in one of three speeds: slow (190 ms signal onset asynchrony), medium (110 ms signal onset asynchrony), or fast (64 ms signal onset asynchrony). Pattern identification was 94% for a down pattern at medium speed, 98% for a down pattern at fast speed, and 100% for all other combinations of pattern and speed. Participants correctly identified the speed as slow 97% of the time, but the speed recognition rate was only 80% for fast, and 79% for medium. These results indicate that humans are good at distinguishing the spatial location of a vibrating stimulus. Therefore, tactors located in different spatial locations can be an effective method for providing haptic feedback.

3.2 Biophysical Background

To design a device for haptic feedback, it is necessary to understand the mechanism by which the human hand senses vibration. There are approximately 17,000 mechanoreceptor nerve endings in the glabrous (hairless) skin of the human hand, with a disproportionate number located at the fingertips (Johansson & Vallbo, 1979). The nerve endings are almost evenly split between two categories: slow acting (SA) and fast acting (FA) (Johansson & Vallbo, 1983). SA units respond to a step indentation of the skin with a constant discharge. This means that as an object is pushed and held against the skin, SA units will fire continuously. FA units respond only to the onset and removal of the stimulus. As such, they are effective at detecting high frequency vibrations (greater than 20 Hz), where an object is repeatedly pushed against and removed from the skin (Caldwell, Lawther and Wardle, 1996). The nerve endings can be sub-divided into type I and type II units. Type I units (fast adapting type I, or FA I, and slow adapting type I, or SA I) have small, well-defined fields of sensitivity, whereas type II units (fast adapting type II, or FA II, and slow adapting type II, or SA II) have larger fields with ill-defined borders. FA I units are sometimes referred to as rapid adapting (RA) units. Type I units have uniform sensitivity throughout their fields of sensitivity. They are also very sensitive to edge indentations of the skin and disproportionately present in the fingertips, which aids in object manipulation. When moving an object around in the hands, the fingertips are the part of the hand that is primarily used to grasp the object. This makes type I units very important to the task of object manipulation.

Type II units have a much higher sensitivity to vibration than type I units. Type II units are defined by a single point of maximum sensitivity, with gradually reduced sensitivity further away from that point. Unlike the type I units, type II units are relatively evenly distributed throughout the hand (see Figure 10). Furthermore, their field of sensitivity is very large, often covering an entire finger.

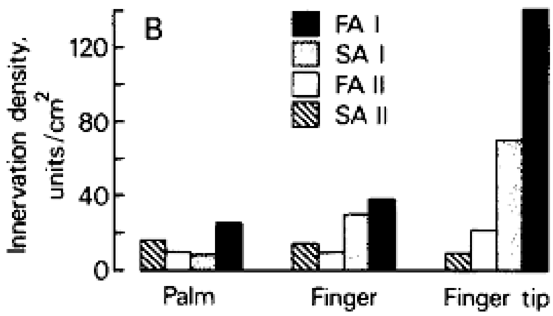

Figure 10: Density of FA I, SA I, FA II, and SA II units within the hand. Image source: Johansson and Vallbo (1983).

FA I fibres react most strongly to vibrations that occur at a frequency of 10 to 100 Hz (Bolanowski et al., 1988). According to Gescheider et al. (1985), SA II and FA II fibres both have peak sensitivity to frequencies of about 15 to 400 Hz. However, they found that SA II units have a much lower sensitivity to vibration amplitude than FA II units. Lastly, SA I units are most sensitive to frequencies between 0.4 Hz and over 100 Hz (Bolanowski et al., 1988), with a sensitivity similar to SA II fibres.

As a result, the human hand responds well to vibrations that occur in a frequency range from about 0.4 Hz to 400 Hz.

Chapter 4
Design Rationale and Implementation

4.1 Research and Design Objectives

The main objective of this research is to provide haptic feedback to the user of a 3D virtual environment. This objective will be accomplished by developing a device incorporating vibrotactile transducers. The vibrotactile transducers would respond to events in the environment, such as collisions, and vibrate to relay information about the events back to the user.

Using the background research as a starting point, a design was developed to transmit information through haptic feedback. The information to be transmitted haptically concerns collisions between virtual objects. Because the information to be transmitted to the user is primarily spatial in nature, the literature indicates that multiple tactors may be effective in relaying the information (van Erp et al., 2005; Bloomfield and Badler, 2003).

The scope of this research does not include the detection of collisions within the virtual environment. This research does not comment on which tactor (or combination of tactors) should vibrate in response to a virtual collision. Like the tactile waist belt developed by van Erp et al. (2005), it may be possible to accurately transmit collision information by vibrating a single tactor. Alternatively, it may be preferable to encode the information rhythmically, as suggested by Brown, Brewster, and Purchase (2005). This research makes no claims about the preferable haptic encoding mechanism for collision information.

This research is concerned solely with the development of a device to transmit vibration information to the user. As such, the device relies on the mechanoreceptors in the fingers and in the hand to perceive the vibration. The information must then be correctly interpreted by the user to determine the location of the tactor that is vibrating. If the user can successfully determine which tactor is vibrating, the device can be used as a basis for future research into a haptic encoding mechanism for providing feedback about collisions occurring in 3D virtual environments.

In summary, it is the goal of this research to design and evaluate a multiple tactor haptic device that can vibrate in response to commands from a host computer. Users of the device should be able to determine, rapidly and with a high degree of accuracy, which tactor is vibrating.

4.2 Physical Form of the Device

Input devices for virtual environments are typically handheld, meaning that the user's hand completely surrounds the device. Because it is a typical embodiment of 3D input devices, the veBall was chosen as the starting point for this research. Therefore, the overall dimensions of the haptic input device will mirror those of the veBall.

The veBall has two forms: spherical and truncated. In its spherical form, the veBall has the shape of a sphere with a radius of 34 mm. In its truncated form, the top half of the veBall is a semi-sphere with a radius of 34 mm. The bottom half, however, is a truncated semi-sphere. The semi-sphere has a radius of 34 mm, but the bottom 17 mm of the semi-sphere has been removed, leaving a flat surface (see Figure 1 on Page 4 for a simplified diagram of the veBall in each mode). It was decided that the haptic input device would have dimensions that mirror the veBall in its truncated form. There was no anticipated practical difference between using the two forms. However, in the spherical form, the veBall tends to roll around when placed on a flat surface. Using the truncated form would eliminate this annoyance during the development and testing of the prototype.

4.3 Number of Tactors and their Locations

Four tactors should be placed equidistantly around the equator of the device: on the front, on the rear, on the left, and on the right of the device. This configuration is analogous to the tactile waist belt (van Erp et al., 2005) that was effective at providing spatial feedback to the user. Four tactors should be used because it allows for an intuitive mapping between the tactors and egocentric directions (left, right, front, back). Using fewer than four tactors would create a mapping that does not accurately match the users' mental model of geographic navigation. The four tactors allow information regarding the "heading" of the collision to be relayed to the user. For example, if the rear tactor vibrates, it indicates that a collision occurred at the back of the object.

The user's fingertips will naturally be placed near the equator due to the shape of the device. By placing tactors at the equator of the device, they will be near the user's fingertips, which are very sensitive to vibration due to the large number of mechanoreceptors that are present (Johansson & Vallbo, 1983).

Tactors should be placed on the top and bottom of the device. These two tactors can give the user information about the "elevation" of the collision. For example, if the bottom tactor vibrates, it means that the bottom of the virtual object being manipulated collided with another object. Once again, the mapping between the tactor location and the user's egocentric view of the virtual environment is very natural.

When the veBall is in rotation mode, it has the form of a sphere. In this configuration, the bottom tactor can provide information about collisions that occur on the bottom of the device. When the veBall is in pan/zoom mode, it has the form of a flattened sphere. In this form factor, it is uncertain whether the bottom tactor would provide useful feedback. It is possible that the user would be able to discriminate the vibrations from the bottom tactor. However, it is likely that the vibrations would propagate throughout the entire device, making localization difficult.

The resulting configuration with 6 tactors is shown in Figure 11. The tactors are represented as dots at the intersection of the ellipses.

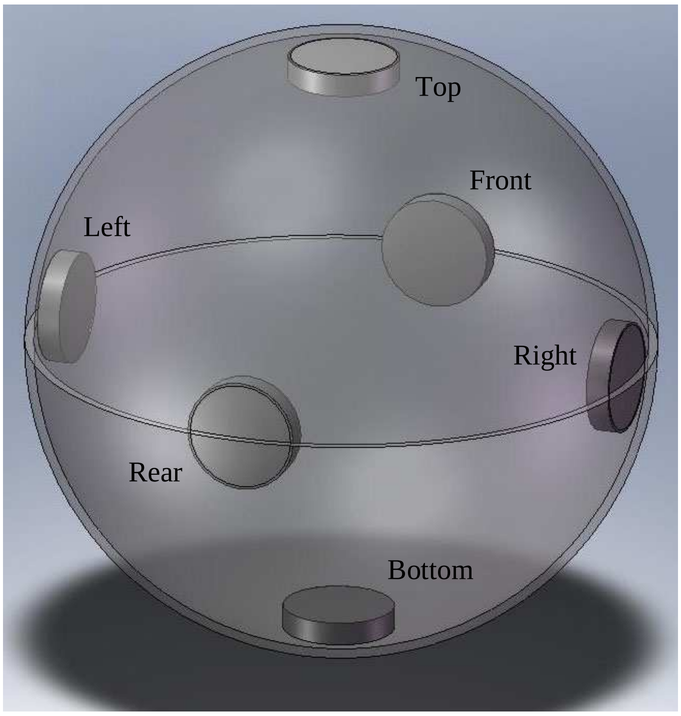

Figure 11: Location of the tactors.

Because of the natural mapping between the tactors and the location of the collision, it is doubtful that the number of tactors could be reduced while still providing an adequate level of feedback. However, it is possible that increasing the number of tactors would provide richer feedback. For example, eight tactors could be placed around the equator of the device. With a 4-tactor configuration, if a collision occurs exactly midway between two tactors, the feedback would indicate a direction that is wrong by 45 degrees. With an 8-tactor configuration, the maximum error would be 22.5 degrees. However, it is important to examine the physiological mechanisms for vibration detection. Type II mechanoreceptors, the primary detectors of vibration, have fields of sensitivity that can be as large as an entire finger (Johansson and Vallbo, 1983). It is therefore possible that eight tactors would provide a level of resolution greater than the ability of the human hand to perceive.

4.4 Transducers

An important decision is the type of transducer that should be used. The following is a summary of commercially available vibrotactile feedback transducers.

4.4.1 Voice-coil Transducers

The most common voice-coil transducer is the C2 tactor by Engineering Acoustics Inc. It costs approximately US $230 (Brown et al., 2005). The form factor of the C2 tactor is a disk shape, with a diameter of 1.2” (30.5 mm) and a height of 0.31” (7.9 mm) (Engineering Acoustics, Inc., 2007). The data sheet recommends using a driver capable of delivering at least 2 V RMS and 0.5 A RMS.

Two C2 Tactors can be seen in Figure 12.

Figure 12: C2 Tactor. Image source: Engineering Acoustics, Inc. (2007).

4.4.2 Inertial Transducers

A popular inertial transducer is the TACTAID VBW32 transducer, manufactured by the Audiological Engineering Corporation. It costs approximately US $80 (Brown et al., 2005). It is 1” (25.4 mm) long, 0.73” (18.5 mm) wide, and 0.42” (10.7 mm) thick (Audiological Engineering Corp., 2007). It typically consumes 200 mW at 2.5 V RMS, resulting in a current consumption of approximately 80 mA.

Figure 13: TACTAID VBW32 tactor. Image source: Brown et al. (2005).

4.4.3 Eccentric Rotating Mass Transducers

The VPM2 (vibrating pager motor 2) is an eccentric rotating mass tactor that comes in the form of a vibrating disk measuring 12 mm in diameter and 3.4 mm thick (see Figure 14). It costs under US $4 per unit and consumes less than 80 mA at 3 V RMS (Solarbotics, 2007).

Figure 14: VMP2 tactor. Image source: Solarbotics (2007).

4.4.4 Piezoelectric Transducers

An extensive search uncovered no commercial manufacturer of piezoelectric transducers for vibrotactile feedback.

4.4.5 Transducer Choice

The VPM2 pager motor was chosen as the transducer to provide haptic feedback due to its small form factor. Voice-coil and inertial transducers all have much larger form factors than the VPM2. As the design calls for six tactors contained within a sphere with a radius of 34 mm, the pager motor is the only tactor that could fit.

An additional benefit of the VPM2 is that it uses a DC supply current. Electronic equipment operates on DC voltage. If one of the other types of vibrotactile transducers were used, specialized electronics would be required to convert the direct current to alternating current. Using VPM2 pager motors allows the transducer to be powered using the same power supply as the electronics. This greatly simplifies the electronic design of the device.

4.5 The Input Form Housing

4.5.1 The Plastic Shell

During the construction of the original veBall, the only appropriately sized plastic shell that could be obtained easily and economically was a 2-piece plastic sphere that originally served the purpose of containing vending-machine toys. The plastic is brittle, so it is easily cracked or chipped if dropped.

The shell is comprised of two identical semi-spherical shells, each with two protruding rods and two receptacles. The rods from one semi-sphere are pushed into the receptacles of the other semi-sphere, resulting in a single sphere (see Figure 15).

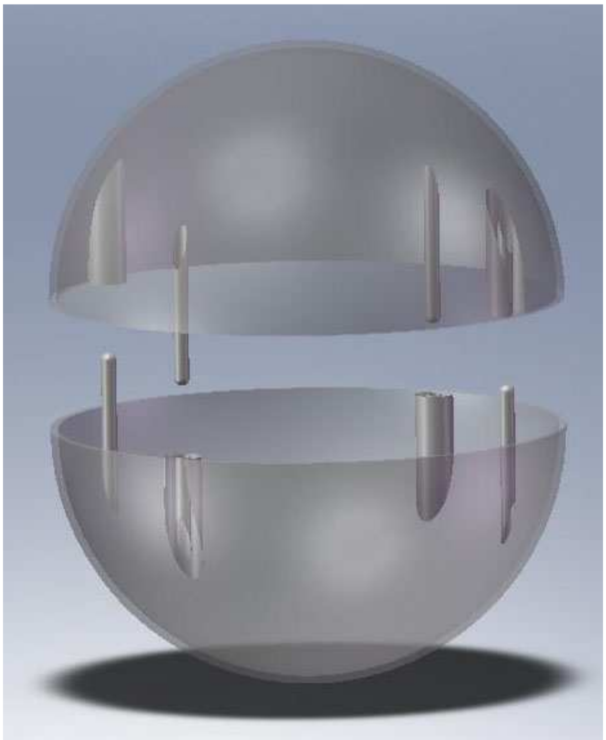

Figure 15: Two-piece plastic sphere.

The most practical method for securely mounting the tactors to the shell would be using glue or epoxy. However, the ease with which the plastic shell can be broken makes it undesirable to attach the tactors directly to the shell. If the shell were to crack, it would be very difficult to remove the tactors and attach them to a new shell.

4.5.2 Improved Shell Design

A prototype was developed with a puck-shaped PVC plastic disk as the base (see Figure 16). PVC was chosen as the material because it is very similar to the plastic that would be used in a commercially produced product. The disk has a diameter of 68 mm and a height of 18 mm. This nearly matches the dimensions of the bottom half of the veBall in its truncated form (see Figure 17).

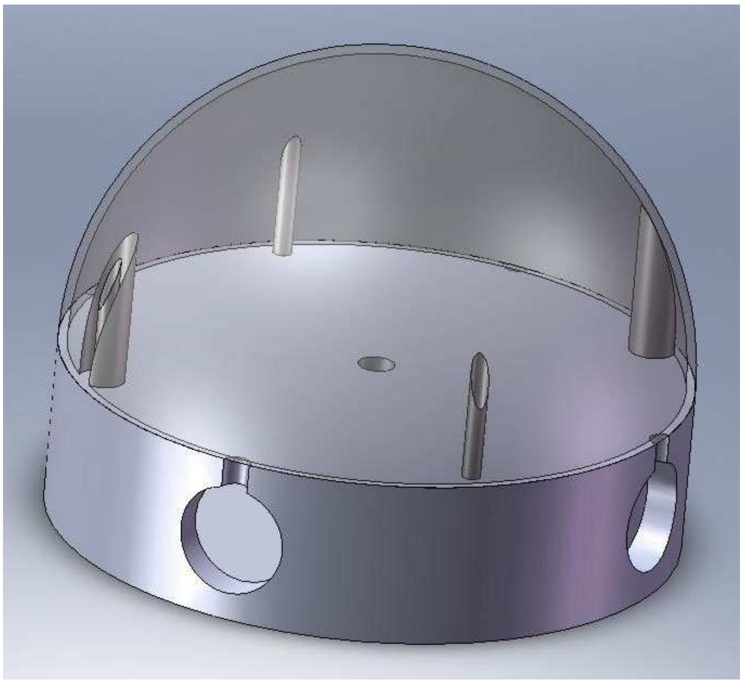

Figure 16: Hard shell prototype (not shown: tactors and wires).

Ideally, the disk would have been rounded to exactly match the dimensions of the bottom half of the veBall. Unfortunately, the disk was made using a manually operated lathe, therefore it was not feasible to accurately reproduce the rounded shape of the veBall in its truncated form.

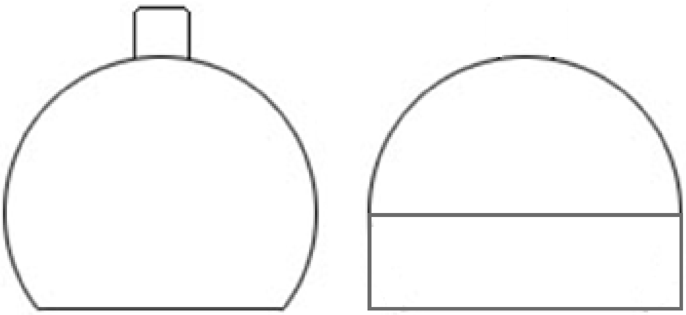

Figure 17: Simplified depictions of the veBall in truncated form (left) and the tactile feedback prototype (right)

The PVC disk contains two receptacles into which the rods from the semi-sphere can be inserted. Spaced equidistantly around the disk are holes into which the tactors can be inserted. A hole was drilled through the middle of the disk to allow room for the wires connected to the tactors. CAD drawings of the PVC disk can be found in Appendix A.

There are several advantages to this design. The design uses the same plastic shell as the original veBall, so results obtained with the prototype should, for the most part, be transferable to the original veBall. The design also has the same form factor as the original veBall in its truncated form, with a minor variation. The top half of the design is identical to the original veBall, but the bottom half has straight edges, rather than the rounded edges of the veBall in its truncated form (see Figure 17).

There are no components mounted directly to the plastic shell, so the shell can easily be replaced if it cracks. In fact, during the data collection as part of the experiment trials, the shell broke and was replaced twice. This did not affect the collection of data, as the replacement shells were identical to the original.

Unfortunately, this design eliminates the tactors on the top and bottom of the device. The top tactor was removed because of the previously mentioned difficulties in mounting tactors directly to the plastic shell. The bottom tactor was removed for simplicity.

A second drawback of this design is that the pager motors are located 9 mm below the equator of the device, instead of exactly on the equator, as was the original intent. To mount the tactors at the equator of the device, the tactors would have had to have been embedded in the upper half of the PVC disk. The bottom half of the tactors would have been embedded in the PVC disk, with the upper half rising above the disk and occupying the empty space within the plastic shell. To account for the curvature of the plastic shells, the tactors would have to be countersunk within the PVC disk (see Figure 18). This is undesirable, as it would prevent the user from comfortably placing their fingertips against the tactors.

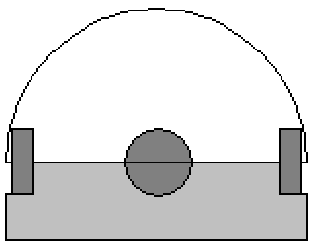

Figure 18: Simplified diagram of a hypothetical design.

4.5.2.1 Limitations with the Hard Shell Design

When the PVC-disk prototype was built, a significant problem was quickly discovered. Because the entire device is made of rigid plastic, vibrations are transmitted very easily throughout the entire device. It was apparent that the stiffness of the material of the housing could have a direct effect on the ability of the user to localize the vibrating tactor. This effect is very similar to the effect of the Nintendo™ Rumble Pak™. When the Rumble Pak™ vibrates, the entire controller vibrates. It is very difficult to detect the exact location of the vibration because the hard plastic of the controller transmits vibration very well.

Because the usefulness of vibrotactile feedback is dependent on the user’s ability to detect and discriminate between the locations of the vibrations, it was decided that a second prototype for testing would be needed to compare the effects of propagated vibrations on signal detection and discrimination performance versus the effects of non-propagated vibrations for the same tasks. The new prototype design for testing would need to prevent a single tactor from causing the entire device to vibrate.

4.5.3 Soft Shell Design

In the second prototyped design for testing vibrotactile feedback for the veBall, a mechanical damper was added between each tactor and the device shell. The goal of the dampers was to minimize the vibration of the device when any given tactor is vibrating.

To implement the dampers, a PVC disk with a height of 2 mm and a diameter of 68 mm was constructed. Protruding from the PVC disk were four sets of three posts, each 14 mm tall (see Figure 19). Like the hard shell prototype, there was a hole drilled through the middle of the disk to allow the wires to connect to the tactors.

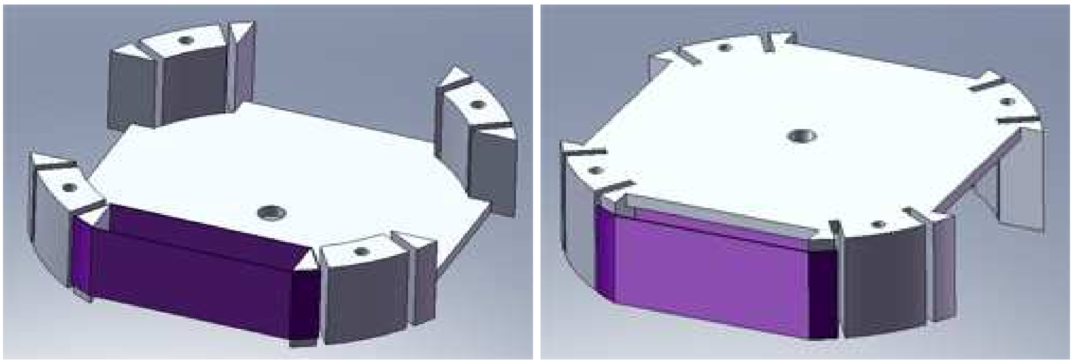

Figure 19: PVC disk for the soft shell design. The disk on the right is inverted to show bottom details.

There was a gap of 30 mm between the posts. Rubber bands were looped between the posts. The rubber bands had a thickness of less than 1 mm and a width of 14 mm. The elastics were chosen such that they fit between the posts without being stretched too tightly. The tactors were attached directly to the elastic bands with the adhesive that came pre-attached to the rear of the tactors (see Figure 20).

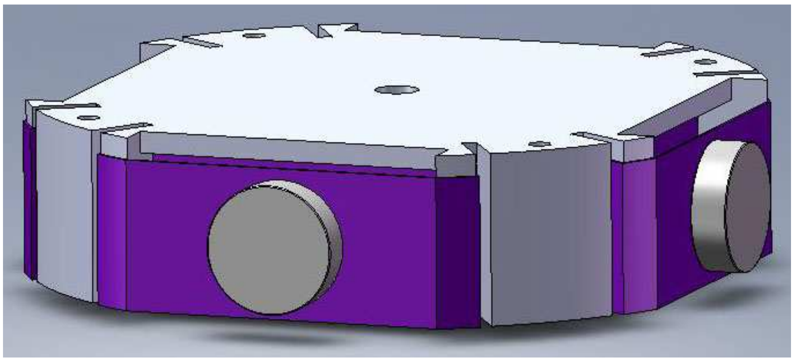

Figure 20: PVC disk for soft shell design with elastic bands and tactors.

The adhesive that was pre-attached to the tactors was not sufficiently strong to hold the tactors in place during intense vibration. To prevent the tactors from detaching from the elastic bands, a second set of elastic bands was placed over the elastic bands and tactors. To prevent the elastic bands from sliding off the posts, a plastic disk with a thickness of 2 mm and a diameter of 68 mm was attached to the bottom of the posts. This produced a disk with a diameter of 68 mm and a height of 18 mm, which is the same form factor as the hard shell prototype. The complete soft shell prototype can be seen in Figure 21.

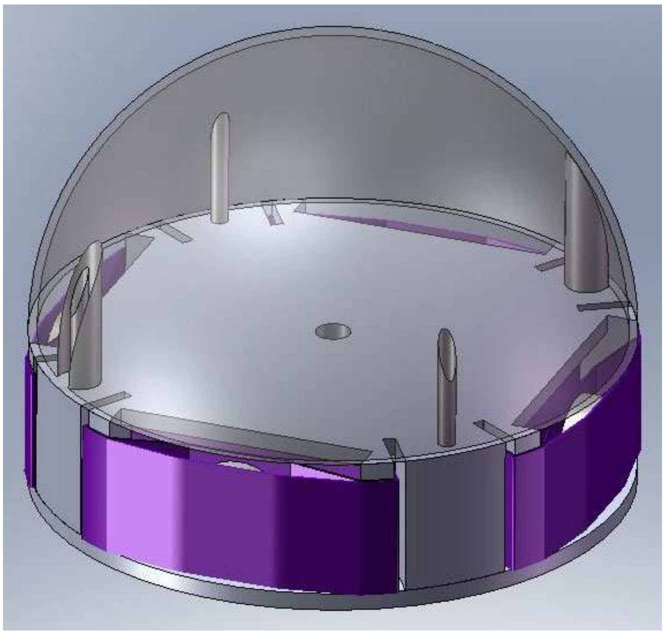

Figure 21: Soft shell prototype (not shown: wires).

Theoretically is should be easier for a user to localize the vibrating tactor using the soft shell prototype. However, to determine if the soft shell prototype results in a significant improvement in performance, a controlled experiment to compare the two prototype designs was required. The goal of this experiment was to determine which factors aid in the localization of vibrating tactors. The experiment is detailed in Chapter 5.

4.6 Electronics

To control the tactors, a Microchip PIC16F690 microcontroller was used. A Microchip PIC microcontroller was chosen because of the small size, ease of programming, and low cost. This microcontroller has a serial port to communicate with the host computer, as well as 17 digital output ports, allowing it to control up to 17 tactors (Microchip Technology Inc., 2006).

The tactors are controlled using pulse width modulation (PWM). To use PWM, a period and a duty cycle must be specified. The duty cycle specifies the percentage of time that the output should be high. The period specifies how frequently the output pattern repeats itself. For example, with a duty cycle of 30% and a period of 10 ms, the output will be high (5 V) for 3 ms (10 ms * 30%). The output will then be low (0 V) for 7 ms to complete the 10 ms period. This pattern then repeats itself indefinitely. In this manner, the output is always either 0 V (low) or 5 V (high), but the average output voltage is 1.5 V (30% * 5V). Unfortunately, the PIC16F690 only contains a single PWM output, so the built-in PWM functionality cannot easily be used to control multiple tactors.

A technique called “bit banging” is used to implement pseudo-PWM functionality. The period is fixed at 0.8 ms and the duty cycle can be any multiple of 5% (0%, 5% … 95%, 100%). The PIC16F690 firmware works by dividing the period into 20 sub-periods, each lasting 0.04 ms. For each tactor output, the duty cycle is divided by 5 to determine the number of sub-periods, *n*, during which the output should be high. For example, if the tactor has a duty cycle of 35%, the tactor output should be high for seven sub-periods (35 / 5 = 7). The tactor output will therefore be high for the first *n* sub-periods of the period. When *n* sub-periods have expired, the output level is set to low for the remainder of the sub-periods. When the next period begins, the process repeats itself. The length of the period is 0.8 ms because this is the worst case execution time for the algorithm.

The microcontroller is controlled by a host computer. The host computer communicates with the microcontroller using an RS-232 serial connection. The host sends a 1-byte packet to the microcontroller. The most significant three bits of the packet indicate the tactor for which the packet is intended: 000 indicates tactor 1, 001 indicates tactor 2, and so on. The least significant five bits indicate the duty cycle, divided by 5. For example, 00100 binary (4 decimal) indicates a duty cycle of 20% (4 x 5 = 20).

Four output ports are connected via a resistor to a transistor, and each transistor powers a single pager motor. A “free-wheeling” diode is attached in parallel to each motor to prevent inductive kickback voltages that could damage the transistors (Gottlieb, 1994). The complete schematic can be seen in Figure 22.

Table 1: Part descriptions for tactor control circuit.

Part	Description
R1, R2, R3, R4	330 Ω ¼ watt resistor
D1, D2, D3, D4	1N4001 general purpose rectifier diode
M1, M2, M3, M4	VPM2 tactor
Q1, Q2, Q3, Q4	2N3904 NPN transistor
U1	20 pin DIP PIC16F690 microcontroller

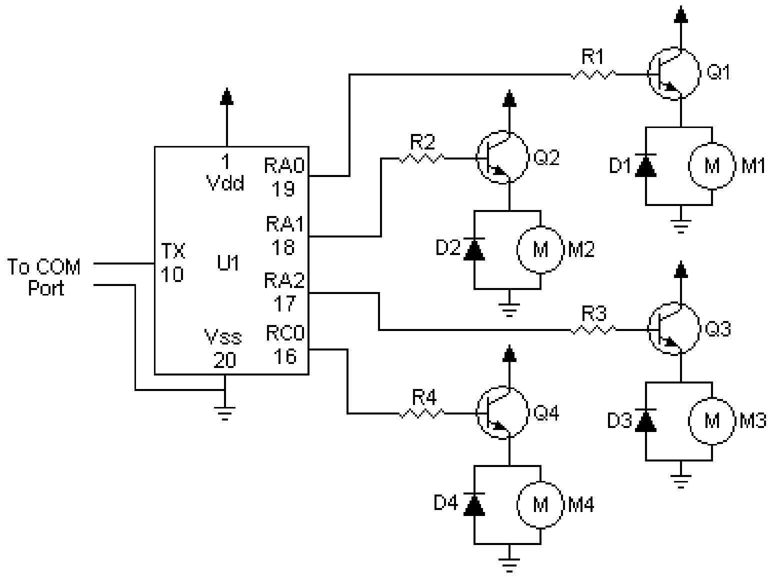

Figure 22: Tactor control circuit.

Chapter 5

Experiment (Comparison of the Two Prototypes)

5.1 Objectives

The objective of this experiment was to determine the speed and accuracy with which users can detect, identify, and localize vibrations using each of the two prototypes. The experiment compares a hard shell design with a soft shell design to determine if there are significant differences between the two prototypes.

5.2 Hypotheses

Three hypotheses were developed for the experiment.

1. **Users will be able to more accurately localize the vibrating tactor with the Soft-Shell (SS) prototype than with the Hard-Shell (HS) prototype.**

   This result was expected because the dampers in the SS prototype were expected to limit the vibration to the region immediately surrounding the vibrating tactor.

2. **Users will identify the vibrating tactor more quickly with the SS prototype than with the HS prototype.**

   The dampers in the SS prototype were expected to limit the vibration of the entire device, helping users to identify the vibrating tactor more quickly.

3. **Users will detect vibrations faster with the HS prototype than with the SS prototype.**

   The hard shell of the HS prototype was expected to propagate the vibrations throughout the entire device, increasing the area of the user's hand that was exposed to vibrations. The user was therefore expected to detect the vibration more quickly.

5.3 Experimental Design

A 2 (gender) x 2 (order) x 2 (shell-type) mixed-factor experiment was conducted. The experiment received approval from the University of Waterloo's Office of Research Ethics, and all participants signed an informed consent form prior to beginning the experiment. All relevant ethics documents are included in Appendix B.

5.4 Participants

Twelve right-handed participants (mean age 34, standard deviation (S.D.) 18) were divided into 2 equal groups, each with 3 males and 3 females. All participants performed signal detection trials using both prototypes. The first group tested the hard shell (HS) prototype first, followed by the soft shell (SS) prototype. The second group tested the devices in the reverse order. Gender and order were included in the experimental design for balance, but there was not any serious expectation of interaction effects with shell type.

5.5 Procedure

The veBall was designed to be used in the non-dominant hand. For this reason, each participant was asked to hold on to the prototype with the left (non-dominant) hand and to type responses to each trial with the right hand.

The task that each participant had to perform was a target detection and identification task. On the numeric keypad of the keyboard, the participant pushed the middle "5" key to begin a trial. After a delay that varied randomly from 1 to 3 seconds to minimize participant anticipated detection, a single tactor on the prototype would vibrate. Upon detecting a vibration, the participant pushed the "5" key to stop the timer and the vibration. The participant then had to identify which tactor had vibrated by pushing the left arrow key ("4"), the right arrow key ("6"), the up arrow key ("8"), or the down arrow key ("2"). Participants were instructed to respond as quickly as possible while trying to be as accurate as possible.

For each device, the participants were given 12 practice trials followed by 96 experimental trials. During the experimental trials, each tactor vibrated 24 times. The order of the vibrating tactors was randomly determined and varied between participants. After completing the experimental trials with one device, the participant filled out a usability questionnaire before repeating the experimental procedure with the second device.

Because the tactors make an audible noise when they vibrate, the participants listened to music on headphones during the experiment. At the beginning of the experiment, the volume of the music was adjusted such that each participant could not hear the tactor vibrating.

5.6 Recorded Measures

For each trial, three measures were recorded: detection time, identification time, and accuracy. The *detection time* was defined as the time between the beginning of the vibration and the participant pushing the "5" key to indicate that they had detected the vibration. The *identification time* was defined as the time between the participant pushing the "5" key to indicate detection and pushing the "2", "4", "6", or "8" key to indicate which tactor had vibrated. The *accuracy* was recorded as "1" if the participant identified the correct tactor. Otherwise, the accuracy was recorded as "0". If the participant pushed "5" to indicate that the vibration was detected before the tactor started vibrating, then the trial was discarded. If a user accidentally pushed the wrong key to identify the tactor, the recorded result was manually changed to reflect the intended response.

5.7 Usability Questionnaire

After using each device, participants were asked to answer 3 questions on a scale of 1 (very easy) to 5 (very difficult). Each participant was asked to rate: 1) the ease of determining if a motor was vibrating; 2) the ease of identifying which motor was vibrating; and 3) the ease they experienced in holding the device. For each device, they were asked to estimate their accuracy level, and provide any additional comments. After completing the experiment, they were asked which device they preferred. The complete questionnaire can be seen in the ethics documents in Appendix B.

5.8 Results

Using the data collection process described above, 18 trials (1.6% of all trials) were discarded for reasons of “anticipated” detection. With these trials discarded, the mean detection and identification times were calculated for each participant, using each device. If the detection time for a particular trial was more than 3 standard deviations from the participant’s mean detection time for that device, the trial was discarded. In these situations, it is possible that the participants were distracted from the task and did not respond as promptly as they would have had proper attention been paid to the task. Several participants also verbally reported that on occasion their dominant hand slipped from its intended position. As a result, they accidentally pushed “4” to indicate that they had detected the vibration, rather than pushing “5”. Upon realizing their error, they restored their dominant hand to its proper position, but the recorded times for that trial were unusually long.

Similarly, if the identification time for a trial was more than 3 standard deviations from the participant’s mean identification time for that device, the trial was also discarded. Sixty-five outlier trials were discarded, comprising 5.6% of all the trials that were conducted. The outlier trials were fairly evenly distributed amongst the study participants. With the remaining 1069 trials (92.8% of all trials), the accuracy rate, mean detection time, and mean identification time were calculated for each tactor and each participant.

5.8.1 Checking Data for Skewness and Kurtosis

To ensure the normality of the data, tests were conducted to ensure the lack of skewness and kurtosis in the data.

Using the HS prototype, there was no significant skewness for the accuracy (S = -1.057, $SE_{skewness}$ = 0.637, p > 0.09), the detection time (S = 0.243, $SE_{skewness}$ = 0.637, p > 0.69), or the identification time (S = 0.733, $SE_{skewness}$ = 0.637, p > 0.25). Using the SS prototype, there was no significant skewness for detection time (S = 1.147, $SE_{skewness}$ = 0.637, p > 0.071) or identification time (S = -0.650, $SE_{skewness}$ = 0.637, p > 0.30), but the skewness for accuracy was significant at the 0.05 level (S = 1.598, $SE_{skewness}$ = 0.637, p < 0.013). Field (2005) states that for small sample sizes, a probability level of 0.01 should be used to indicate significance of skewness, so the skewness for accuracy using the SS prototype is not considered significant.

Using the HS prototype, there was no significant kurtosis for accuracy (K = 1.662, $SE_{kurtosis}$ = 1.232, p > 0.17), for detection time (K = -0.570, $SE_{kurtosis}$ = 1.232, p > 0.63), or for identification time (K = -0.832, $SE_{kurtosis}$ = 1.232, p > 0.49). Using the SS prototype, there was no significant kurtosis for accuracy (K = 2.235, $SE_{kurtosis}$ = 1.232, p > 0.07), for detection time (K = -0.278, $SE_{kurtosis}$ = 1.232, p > 0.81), or for identification time (K = -0.457, $SE_{kurtosis}$ = 1.232, p > 0.70).

5.8.2 Gender and Order Effects

There was no significant effect of gender on accuracy (F(1,10) = 0.568, p > 0.46), detection time (F(1,10) = 0.565, p > 0.46), or identification time (F(1,10) = 0.027, p > 0.87). There was no significant effect of order on accuracy (F(1,10) = 4.864, p > 0.051) or detection time (F(1,10) = 1.747, p > 0.2). There was a significant effect of order on identification time ($F(1,10) = 9.566$, $p < 0.02$). This will be discussed further in Section 5.9 (Discussion of Results).

5.8.3 Detection Time

The mean detection time was significantly faster ($t(11) = 3.353$, $p < 0.01$) with the SS prototype (mean = 949 ms, S.D. = 360) than with the HS prototype (mean = 1424 ms, S.D. = 485).

Paired sample t-tests were conducted to test the difference in detection times between the HS prototype and the SS prototype for each tactor location. Using paired sample t-tests will not result in an increased risk of type I errors because there are only two means that can be compared (using the HS prototype and using the SS prototype). The results of the t-tests are shown in Table 2. Results that are significant at the 0.05 level are shown in bold.

Table 2: Detection times by device and tactor location, measured in milliseconds.

Tactor	Hard shell (Plastic)		Soft shell (Elastic)		Paired-sample t test	
	Mean	S.D.	Mean	S.D.	t(11)	p
Front	1439	485	867	334	4.153	**0.002**
Back	1568	610	1031	450	3.203	**0.008**
Left	1317	528	991	436	1.873	0.088
Right	1352	443	928	327	3.033	**0.011**
All	1424	485	949	360	3.353	**0.006**

The only tactor with a significantly different detection time than the other three tactors was the front tactor for the SS prototype. The detection time was significantly faster ($t(11) = -3.412$, $p = 0.006$) for the front tactor (mean = 867 ms, S.D. = 334) than for the other three tactors (mean = 984, S.D. = 378).

5.8.4 Identification Time

There was no significant difference in the identification times ($t(11) = 1.329$, $p > 0.2$) between the HS prototype (mean = 454 ms, S.D. = 311) and the SS prototype (mean = 352 ms, S.D. = 104).

Paired sample t-tests were conducted to test the difference in identification times between the HS prototype and the SS prototype for each tactor location – none of the pairings were significantly different. The results of the t-tests are shown in Table 3.

Table 3: Identification times by device and tactor location, measured in milliseconds.

Tactor	Hard shell (Plastic)		Soft shell (Elastic)		Paired-sample t test	
	Mean	S.D.	Mean	S.D.	t(11)	p
Front	412	205	340	70	1.445	0.176
Back	430	221	385	140	0.617	0.550
Left	441	270	336	76	1.405	0.188

Right	454	311	352	104	1.328	0.211
All	422	221	349	76	1.329	0.211

5.8.5 Accuracy

There was a significant difference in the accuracy ($t(11) = 4.594$, $p < 0.001$). The accuracy when using the SS prototype (mean = 90.4 %, S.D. = 12.6) being much higher than when using the HS prototype (mean = 64.6 %, S.D. = 13.2).

Paired sample t-tests were conducted to test the difference in accuracy between the HS prototype and the SS prototype for each tactor location. The results of the t-tests are shown in Table 4. Results that are significant at the 0.05 level are shown in bold.

Table 4: Accuracy rates by device and tactor location, measured in percent.

Tactor	Hard shell (Plastic)		Soft shell (Elastic)		Paired-sample t test	
	Mean	S.D.	Mean	S.D.	t(11)	p
Front	64.9	18	95.2	9	4.917	**0.000**
Back	60.8	21	85.1	18	3.560	**0.004**
Left	74.2	22	92.4	15	2.293	**0.043**
Right	63.1	18	92.6	14	4.202	**0.001**
All	64.6	13	90.4	13	4.594	**0.001**

Examining accuracy rates, the only tactor that performed significantly better or worse than the other three tactors was the rear tactor for the SS prototype. For the SS prototype, the accuracy was significantly worse ($t(11) = 2.520$, $p = 0.028$) for the rear tactor (mean = 85.1%, S.D. = 17.7) than for the front, left and right tactors (mean = 93.4%, S.D. = 10.5).

5.8.6 Usability Data

For the SS prototype, all 12 participants gave a rating of 1 (very easy) when asked to rate ability to determine if an individual motor was vibrating. For the HS prototype, 11 participants gave a rating of 1, but 1 participant gave a rating of 2. This difference was not significant ($t(11) = -1.000$, $p = 0.339$).

Participants thought that it was significantly easier ($t(11) = -3.079$, $p = 0.010$) to determine which tactor was vibrating when using the SS prototype (mean = 2.25, S.D. = 1.138) than when using the HS prototype (mean = 3.83, S.D. = 1.115).

Participants thought that it was significantly easier ($t(11) = -2.345$, $p = 0.039$) to hold the SS prototype (mean = 2.67, S.D. = 1.073) than to hold the HS prototype (mean = 3.00, S.D. = 1.128).

There was a strong and significant correlation between the accuracy that the participants estimated and the accuracy that was recorded, both for the SS prototype (mean estimated accuracy = 80.1%, mean recorded accuracy = 90.4%, $r = 0.933$, $p < 0.001$) and for the HS prototype (mean estimated accuracy = 50.4%, mean recorded accuracy = 64.6%, $r = 0.653$, $p = 0.011$). The difference between the recorded accuracy and the estimated accuracy for the SS prototype (mean = 10.8%, S.D. = 14.1) was not significantly different ($t(11) = 0.754$, $p = 0.467$) from the difference between the recorded accuracy and the estimated accuracy for the HS prototype (mean = 14.1%, S.D. = 15.2).

Of the 12 participants, 11 preferred the SS prototype.

5.8.7 Questionnaire Comments

Three female participants commented that they were unable to grasp either device properly because the device housing was too large for their hands. One stated that the "device was made for a larger hand" and was "not very comfortable" to hold.

One participant commented that the tactor "near wrist is difficult to feel." Two participants commented that the left tactor was difficult to detect.

5.9 Discussion of Results

As predicted by the first hypothesis, the participants had significantly higher accuracy when using the SS prototype than when using the HS prototype. This higher accuracy can be attributed to the damping provided by the elastic bands, which helped to prevent a single tactor from vibrating the entire device. With the HS prototype, the participants had an accuracy rate of less than 65%. With the SS prototype, the accuracy rate was over 90%. This is a difference of more than 25%, making the SS prototype much more suitable for applications requiring the accurate localization of vibrating tactors.

Contrary to the second hypothesis, the identification time for the SS prototype was not significantly faster than the identification time for the HS prototype. In fact, there was no significant difference in the identification times between the two prototypes. The results for the third hypothesis were also counter-intuitive, as (opposite to the hypothesis) the detection times for the participants were significantly lower for the SS prototype than for the HS prototype. However, these two results can be better understood in light of the researchers' observations during the experiment.

Despite explicit instructions to the participants to push the "5" key as soon as they *detected* a vibration, the participants would frequently wait until they had *identified* the vibrating tactor before pushing the "5" key. They would then immediately push the "2", "4", "6", or "8" key to identify the tactor that had vibrated. It is therefore likely that the "detection" times reported are in fact "detection + identification" times. Similarly, the reported identification times are simply the delay between pushing the "5" key to indicate detection and pushing the "2", "4", "6", or "8" key to identify the tactor that had vibrated. As a result, the identification times reported are dubious in that they may not be reflecting true identification time. This finding also helps to explain why there is a significant effect of order on identification time. It is likely that the participants had a shorter identification time while using the second device because they learned to push the "2", "4", "6", or "8" key more quickly. As such, the effect of order on identification time is a training effect.

It is interesting that the rear tactor is perceived much less accurately than the other three tactors when using the SS prototype, but not when using the HS prototype. Several participants commented after the trials that when using the SS prototype, they would determine that the rear tactor was vibrating using a process of elimination. The participants put their fifth finger on the left tactor, their index or middle finger on the front tactor, and their thumb on the right tactor. Unfortunately, it was impossible for them to directly touch the rear tactor. This may be the reason that vibrations coming from the rear tactor were less accurately localized than vibrations coming from the other three tactors. It is suspected that this effect was not seen when using the HS prototype because the participants used the palm of their hands, rather than just the fingertips, to localize vibrations while using the HS prototype. Because the hard shell transmits vibrations more easily, their palms received higher amplitude vibrations with the HS prototype than with the SS prototype. This allowed the participants to use their palms to localize vibrations. Because they were not relying on their fingers being in direct contact with the tactors for localization, participants did not experience a penalty when attempting to localize vibrations coming from the rear tactor (which they could not directly touch).

It appears that the participants preferred the soft shell prototype. With both prototypes, participants reported having no difficulty determining that a tactor was vibrating. However, they reported that it was significantly easier to localize the vibrating tactor when using the SS prototype than when using the HS prototype. This suggests that, for future development, the hard shell design should be discarded in favour of the soft shell design. However, it may be possible to combine the two designs to form a hybrid design. Rather than attaching each tactor to an elastic (as in the soft shell design), the tactors could be attached to a hard shell. However, the hard shell could be segmented, with each tactor attached to a different hard plastic segment. The segments could be attached together elastically. This design would allow each tactor to vibrate a larger area than with the soft shell design, but, unlike the hard shell design, would limit the area that each tactor vibrates.

It is not obvious why the participants responded that it was easier to hold the SS prototype than the HS prototype. The HS prototype has a shell that is entirely solid, whereas the SS prototype has a shell that is partially elastic. One might think that the solid shell would therefore be easier to hold because, unlike the soft shell, it does not deform under the user's grip. The participants clearly thought that their accuracy with the SS prototype was low (as evidenced by the estimated accuracy values given in the questionnaire), so it is possible that the participants were adopting an uncomfortable grip to attempt to improve their performance. It is also possible that the participants were not objectively judging the devices based on ease of holding, and were giving their preferred device a better score.

The size of the device appears to be problem for female users. Of the six female participants in the study, three complained that the prototypes were too big to be comfortable for their hand size. It is possible that this problem is caused by the tactors being mounted 9 mm below the equator of the device, rather than directly on the equator. If the tactors were mounted exactly at the equator of the device, the user would need a hand spread of 106.8 mm (d$=\frac{2\pi r}{2}=\pi*34mm=106.8\ mm$) in order to touch the left tactor with the little finger and the right tactor with the thumb. The hand spread is defined as the maximum distance between the thumb and the fifth finger. Because the tactors were mounted 9 mm below the equator, the hand spread required was 124.8 mm. The maximum hand spread of the 5th percentile female is 165 mm (Pheasant and Haslegrave, 2006). However, this hand spread is obtained by stretching the fingers as wide apart as possible, which is an uncomfortable position. The functional hand spread is measured by determining the width of the largest piece of wood that can be held between the tip end segments of the ring finger and the thumb. To approximate the comfortable hand spread, the functional hand spread is likely a much better metric than is the maximum hand spread. The 5^{th} percentile female has a functional hand spread of 109 mm (Pheasant and Haslegrave, 2006), which is large enough to touch both the left and right tactors on the current device. However, if the tactors were placed at the equator, a 5^{th} percentile female would still be able to touch them.

Conversely, the 95^{th} percentile male has a functional hand spread of 165 mm (Pheasant and Haslegrave, 2006). It is possible that, were the tactors moved to lie directly on the equator, the 95^{th} percentile male would find the device uncomfortably small. In the current design, none of the six male participants complained about the size of the device. Future research is needed to determine if there is a single size which can accommodate both the 5^{th} percentile female and the 95^{th} percentile male.

Chapter 6

Developing Future Prototypes

The results from the experiment suggest that dampers should be used to isolate the vibration from each tactor. Although using elastics in the soft shell prototype worked well, elastic bands are impractical to use in a marketable product. It is suggested that silicone be used as the main shell material of the device, as it has the viscoelastic properties needed to dampen vibration. Silicone is also resistant to degradation. However, a number of practical design factors need to be further investigated before the materials and mounting of the tractors can be finalized:

a) How thick should the silicone be to maintain housing form integrity but still allow for appropriate damping of the individual tactors?

b) What is the best way to mount or embed the tactors relative to the device housing and still maintain the integrity of the housing design and desired damping effects?

c) How should the frame of the device be designed to support the housing and still leave sufficient space for the electronic and mechanical components of the input device?

To help create a series of prototypes for future testing, an aluminum mould was designed that allows silicone-based models to be cast with relative ease. The mould is designed to create prototypes in an inverted orientation, so the bottom half of the mould produces the top half of the silicone prototype (see Figure 23).

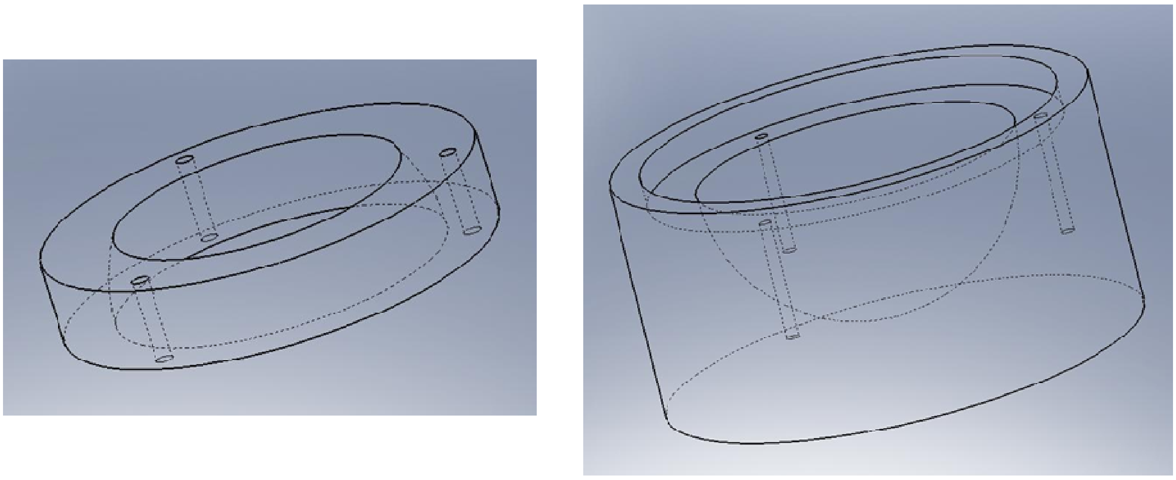

Figure 23: Top (left) and bottom (right) of the silicone mould.

The bottom half of the mould is a semi-sphere with a radius of 34 mm, matching the dimensions of the veBall (see Figure 23). The top half of the mould has the same shape, but only extends to a height of 17 mm. Unlike the prototypes produced during this research, the bottom half of the silicone prototype exactly matches the dimensions of the veBall in its truncated form (see Figure 24). The resulting mould allows for the casting of silicone models that exactly match the dimensions of the veBall in its truncated form.

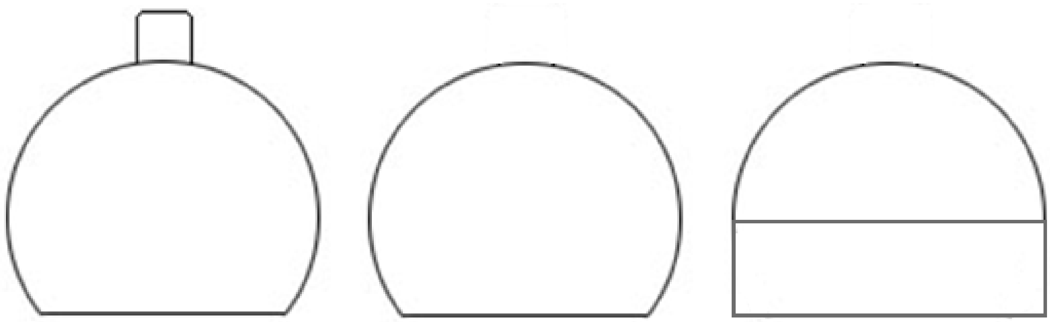

Figure 24: The veBall in its truncated form (left), the silicone prototype (middle), and the prototypes that were tested (right).

Tactors can be arranged in the mould using small pieces of 2 mm thick double-sided adhesive foam. Each tactor is held in place with a 4 mm square piece of foam. The silicone is then poured into the mould and allowed to set. Once the silicone has set, the top half of the mould is detached from the bottom. The silicone model can be removed from the bottom half of the mould. The pieces of foam are removed from the silicone model, leaving small indentations in the silicone at each tactor location. If desired, silicone can be poured into the indentations to produce a smooth surface.

The mould aids in the rapid creation of prototypes with differing properties. For example, it is possible to use types of silicone with varying degrees of viscoelasticity, thereby changing the damping properties of the material for testing. It is also possible to place tactors just beneath the surface of the device at any location to test for optimal location of tactors for signal detection and identification. The number of tactors implanted in the device can also be varied, using as many or as few as desired for testing rhythmic patterns to represent different haptic effects as suggested by Brown et al. (2005).

Chapter 7
Future Work

7.1 Modification of Procedures for Future Experiments

A slight change should be made in any future experiments to more accurately measure detection and identification times. An initial set of trials should be conducted during which participants are asked to push a button when they detect a vibration. However, the participants should not be asked to identify which tactor was vibrating. A second set of trials should then be conducted during which the participants are asked to push a button once they can identify the vibrating tactor. This would create a "detection + identification" time, from which the detection time from the first part of the experiment could be subtracted. Although this is an imperfect method for determining identification time, it would provide more accurate information about detection and identification times than was gained during the experiment described in this thesis.

There is a need to separate the measurement of detection and identification times. The alternative is to measure a single time for both detection and identification. However, there are moments during object manipulation when detection is all that is necessary. For example, if attempting to move one object past another object, the lack of depth perception makes it difficult to perceive that a collision has occurred, even with an unobstructed view of both objects. Haptic feedback can be used to relay the collision information to the user. It might be possible for the user to visually determine the location of the collision, without a need to localize the vibrating tactor. In such a situation, the detection time is relevant, whereas the identification time is not. However, in a different object manipulation task where the view of the objects is obstructed, there can be no visual feedback about the location of the collision. In such a situation, the haptic feedback will be needed both to detect the collision and to identify the location of the collision. Thus, both the detection and identification time are required.

As a final change in the recommended procedure for future experiments, the hand size of participants should be measured to determine its effect on accuracy, detection time, and identification time. This will help to ensure that the device can be used by users with hand sizes ranging from the 5^{th} percentile female to the 95^{th} percentile male. Alternatively, participants could be screened to ensure that their hand size falls within an acceptable range.

7.2 Additional Prototypes Design Factors

The aluminum mould described earlier will be used to cast silicone prototypes quickly and easily. These prototypes will allow for comparison of proposed design factors relating to silicone hardness and tactor locations in order to determine which one facilitates the best user performance for detecting and localizing vibrations.

7.2.1 Tactor Locations

Three study participants complained that the existing prototypes were too large to be comfortably held. As discussed previously, it is possible that the reason for this is that the tactors were mounted 9 mm below the equator of the device, as discussed in Section 4.5.2. A prototype should be developed with the tactors mounted exactly on the equator of the device. It is possible that this small change will improve the accuracy in identifying all tactors and especially the rear tactor. If mounting the tactors directly on the equator does not significantly improve the rear tactor detection accuracy, a prototype should be developed with the front, left, and right tactors mounted on the equator, and the rear tactor mounted above the equator so that it can be touched directly by the bottom of the palm of the hand.

Another prototype should also be developed with tactors mounted above the equator of the device. It is possible that this arrangement would allow better localization for users with small hands, as it would allow them to place their fingertips directly on the tactors.

7.2.2 Silicone

Prototypes should be made using silicone of differing levels of viscoelasticity. It is hypothesized that softer silicone will dampen vibrations more, increasing the ease of localization, whereas harder silicone will transmit vibrations more easily. However, there is a trade-off, as silicone that is too soft may not be durable enough to be used in a consumer device. Further experiments will be needed to determine an appropriate level of viscoelasticity.

7.3 Encoding of the Haptic Information

As previously mentioned, the question of how to encode collision information haptically remains unresolved. Further research is required to determine the most effective encoding mechanism.

Two possible techniques for encoding the information are discussed below.

7.3.1 Interpolation

The use of only six tactors provides less precise haptic feedback than would be provided using more tactors. For example, if a collision were to occur on the equator of the virtual object, exactly midway between the front and right tactor locations (see Figure 25), it is unclear which tactor should vibrate. Regardless of which tactor vibrates, the real-world feedback will not be a perfect reflection of the virtual environment collision.

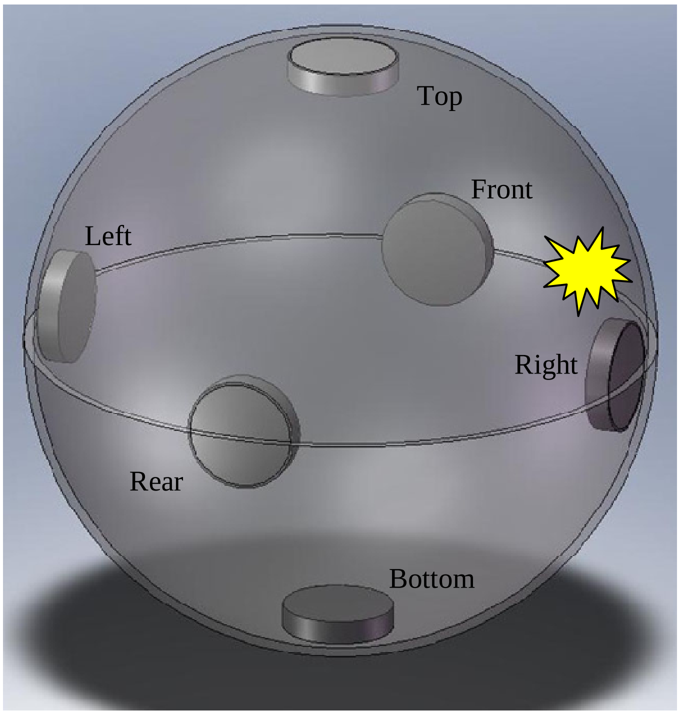

Figure 25: Collision occurring midway between the front and right tactors.

To resolve that problem, it is proposed that an interpolation system be used to provide the appropriate feedback. In the previous example, the front and right tactors would both vibrate at half of their usual intensity. It is hypothesized that the resulting sensation would be interpreted by the user to mean that the collision occurred midway between the two tactors. Similarly, if the collision were to occur closer to the front tactor than to the right tactor, the front tactor would vibrate with greater amplitude than the right tactor. This feedback would imply that the collision occurred between the front and right tactors, but closer to the front tactor.

An experiment should be conducted to examine interpolation about the equator of the device. Two tactors should be vibrated simultaneously, at predetermined amplitudes. For example, a PWM duty cycle of 50% would be applied to the front tactor, and a duty cycle of 25% would be applied to the left tactor. Participants would be told that the object they are controlling has collided with another object, and asked to identify the location of the collision. From this experiment, it is expected that a set of guidelines can be derived to represent any collision on the equator of the object using four tactors.

A follow-up experiment using interpolation would involve using tactors mounted above and below the equator of the device. These tactors would be used to represent collisions that occur either above or below the equator of the device. It is hypothesised that the top tactor will succeed in its intended function. However, it is hypothesised that the bottom tactor will not be successful because there would be no direct (or even close) contact between the bottom tactor and the user's hand.

7.3.2 Rhythm

An alternative to interpolation would be to use rhythmic patterns of vibrations similar to that proposed by Brown et al. (2005). Rhythmic vibrations could encode the exact position of a collision and transmit the information to the user haptically. It is uncertain the most effective way to encode the information in a rhythmic form. Future experiments are necessary to explore how to maximize the potential of the information that can be conveyed through vibration to the user.

Chapter 8
Conclusion

Background research supports the position that haptic feedback will help users of the veBall to localize collisions that occur in a virtual environment. The background research also indicates that pager motors are the only transducer for providing haptic feedback that fits the cost, size, and power requirements for the veBall.

The experiment showed that mounting multiple tactors directly to a plastic shell makes localization of vibration extremely difficult. By adding dampers between the tactors and the shell, it was possible to increase the accuracy of localization by over 25%. Adding the dampers also reduced the time required for detecting and localizing the vibration. However, due to the experimental design, firms conclusions cannot be made about the time required for detection or the time required for identification.

The mould for prototyping, designed as an outcome of learning from the experiment, can be used to rapidly create many additional prototypes for testing other factors, such as tactor location, relating to the design of 3D haptic input devices. These prototypes should be tested using the revised experimental procedures described in Chapter 7 in order to more objectively evaluate and compare the effect of different designs on signal detection and identification performance. Experiments should be conducted to determine the effectiveness of interpolation and rhythmic vibration patterns as a method for improving the richness of the haptic feedback.

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Appendix A
CAD Drawings

All dimensions are in millimetres and all angles are in degrees.

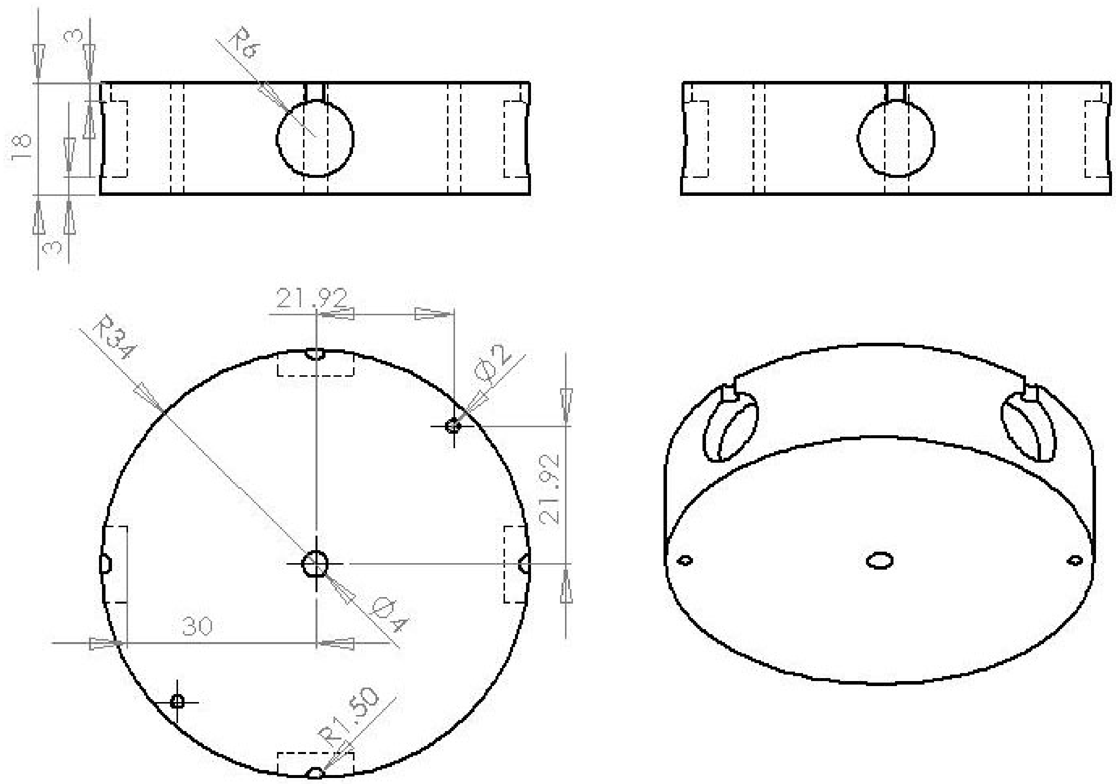

Figure 26: CAD drawing of PVC disk for hard shell prototype.

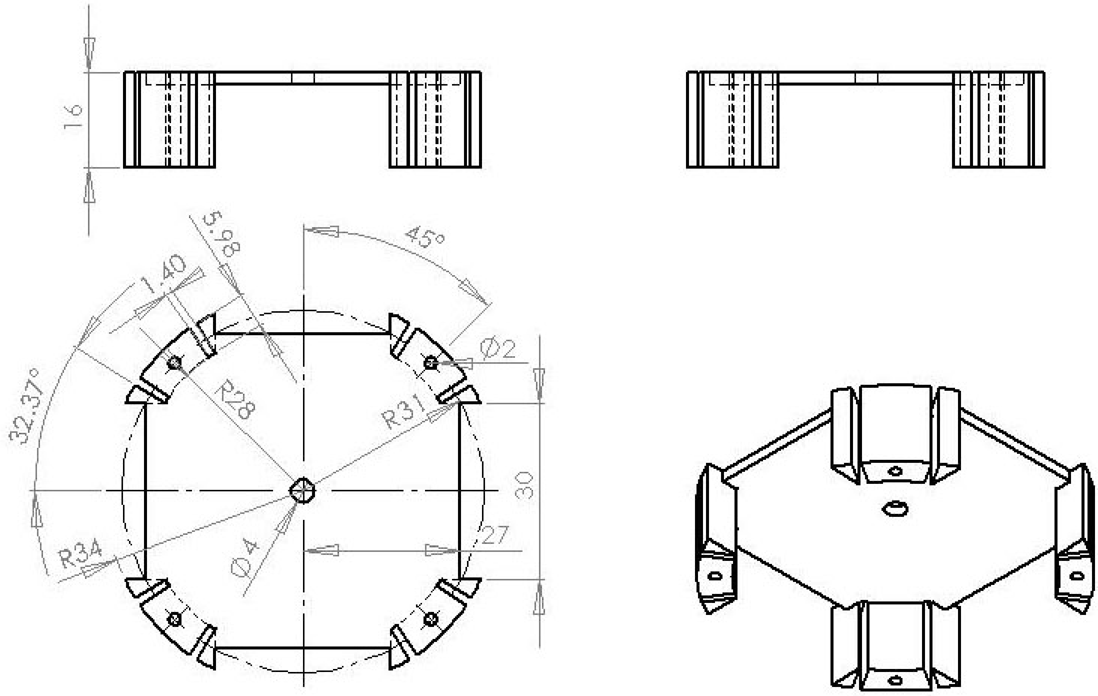

Figure 27: CAD drawing of top part of PVC disk for soft shell prototype.

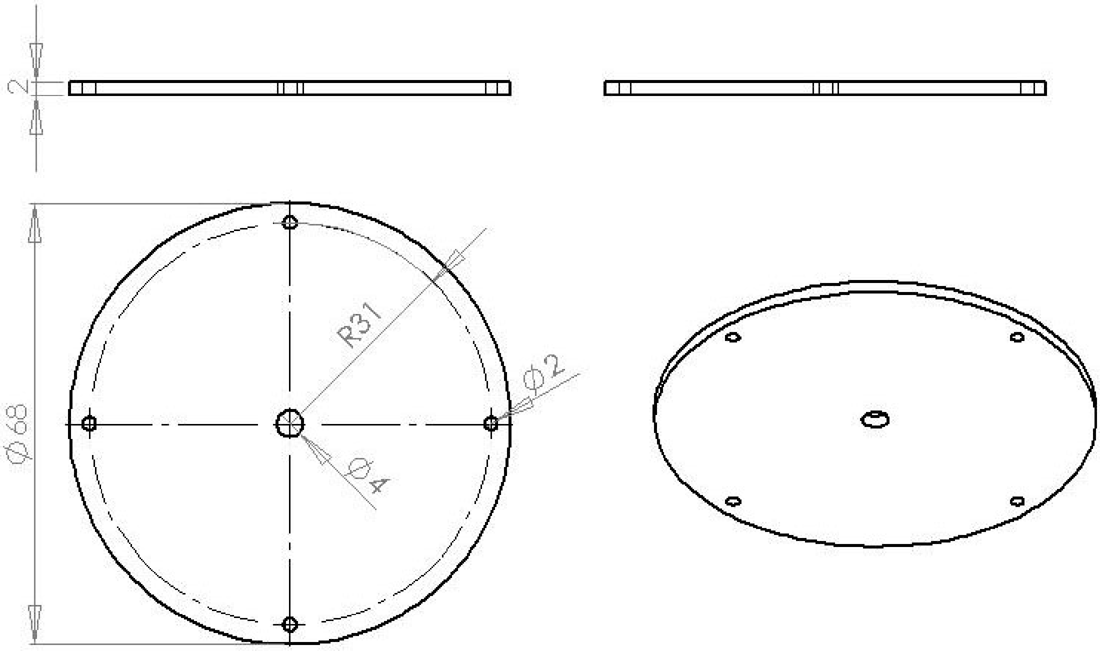

Figure 28: CAD drawing of bottom part of PVC disk for soft shell prototype.

Appendix B

Ethics Documents

ORE Ethics Approval

From: ORE Ethics Application System <OHRAC@uwaterloo.ca>
Date: Aug 13, 2007 9:58 AM
Subject: Full Ethics Clearance after provisional, no comments (ORE # 14105)
To: cgmacgre@uwaterloo.ca
Cc: krenwick@uwaterloo.ca

Dear Researcher:

The recommended revisions/additional information requested in the initial ethics review of your ORE application:

Title: Vibration-based haptic feedback.
ORE #: 14105
Faculty Supervisor: Carolyn MacGregor (cgmacgre@uwaterloo.ca)
Student Investigator: Kyle Renwick (krenwick@uwaterloo.ca)

have been reviewed and are considered acceptable. As a result, your application now has received full ethics clearance.

A signed copy of the Notification of Full Ethics Clearance will be sent to the Principal Investigator or Faculty Supervisor in the case of student research.

ADDITIONAL REVISIONS OR RESPONSES TO COMMENTS:
N/A

****
Note 1: This clearance is valid for four years from the date shown on the certificate and a new application must be submitted for on-going projects continuing beyond four years.

Note 2: This project must be conducted according to the application description and revised materials for which ethics clearance have been granted. All subsequent modifications to the protocol must receive prior ethics clearance through our office and must not begin until notification has been received.

Note 3: Researchers must submit a Progress Report on Continuing Human Research Projects (ORE Form 105) annually for all ongoing research projects. In addition, researchers must submit a Form 105 at the conclusion of the project if it continues for less than a year.

Note 4: Any events related to the procedures used that adversely affect participants must be reported immediately to the ORE using ORE Form 106.

Best wishes for success with this study.

Susanne Santi, M. Math.,
Manager
Office of Research Ethics
NH 1027
519.888.4567 x 37163
ssanti@uwaterloo.ca

Background Questionnaire

The following information will be used to analyze the data by demographic factors. Because there may be varying types and levels of expertise from participants, understanding your experience will help us perform more accurate analysis.

1. Gender
   - ❑ Male
   - ❑ Female
2. Dominant hand
   - ❑ Right
   - ❑ Left
   - ❑ Neither
3. Age: _________________
4. How many hours a week do you use a computer?
   - ❑ 0-5
   - ❑ 5-10
   - ❑ 10+

Consent Form

I have read the information presented in the information letter about a study being conducted by Dr. Carolyn MacGregor and Kyle Renwick of the Department of Systems Design Engineering at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted.

I am aware that excerpts from my questionnaires may be included in the thesis and/or publications to come from this research, with the understanding that the quotations will be anonymous.

I was informed that I may withdraw my consent at any time without penalty by advising the researcher.

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Director, Office of Research Ethics at 519-888-4567 ext. 36005.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

☐YES ☐NO

I agree to the use of anonymous quotations in any thesis or publication that comes of this research.

☐YES ☐NO

Participant Name: ____________________________ (Please print)

Participant Signature: ____________________________

Witness Name: ________________________________ (Please print)

Witness Signature: ______________________________

Date: ____________________________

Information Letter

University of Waterloo

Title of Project: Vibration based haptic feedback.

Faculty Supervisor: Dr. Carolyn MacGregor
University of Waterloo, Department of Systems Design Engineering
519-884-4567 Ext. 33742

Student Investigator: Kyle Renwick
University of Waterloo, Department of Systems Design Engineering
519-884-4567 Ext. 35607

You are invited to participate in a study that concerns the assessment of two mouse-like devices that provide vibration-based feedback for virtual environments.

As a participant in this study, you will be asked to evaluate two different devices. Each device is a semi-sphere with 4 motors mounted around the equator. You will be presented with a series of trials via a computer monitor, during which one motor will begin to vibrate. You will then identify which motor is vibrating using the keyboard.

Prior to the first trial, you will be given a questionnaire that asks for some background information about yourself. After using each device, you will be asked several questions regarding the ease of use of the device.

Participation in this study is voluntary, and will take approximately 15 minutes of your time. By volunteering for this study, you will learn about human factors research in general and the topic of this study in particular. In addition, you will receive cookies and/or donuts in appreciation of your time. You may decline to answer any questions presented during the study if you so wish. Further, you may decide to withdraw from this study at any time by advising the researcher, and will be remunerated with cookies and/or donuts. All information you provide is considered completely confidential; indeed, your name will not be included or in any other way associated, with the data collected in the study. With your permission, anonymous quotations from the questionnaire may be used in the thesis or any publications. Paper record and electronic data collected during this study will be retained for 3 years. The paper record will be stored in a locked office to which only researchers associated with this study have access. Electronic data will be encrypted with password-only access and stored in a password-protected computer accessible only to researchers associated with this study. After the 3 years the data will be confidentially destroyed. There are no known or anticipated risks associated to participation in this study.

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes at this office at (-519-888-4567 Ext. 36005.

Thank you for your assistance in this project.

Participant Feedback Letter

University of Waterloo

Dear participant,

I would like to thank you for your participation in this study. As a reminder, the purpose of this study is to provide feedback for two mouse-like devices that give vibration-based feedback for virtual environments.

The data collected during the session will contribute to a better understanding of the potential value of the designs in question and identify areas of concern necessary for development and implementation of future devices.

Please remember that any data pertaining to you as an individual participant will be kept confidential. Once all the data are collected and analyzed for this project, I plan on sharing this information with the research community through seminars, conferences, presentations, and journal articles. If you are interested in receiving more information regarding the results of this study, or if you have any questions or concerns, please contact me at either the phone number or email address listed at the bottom of the page. If you would like a summary of the results, please let me know now by providing me with your email address. When the study is completed, I will send it to you. The study is expected to be completed by August 31st, 2007.

As with all University of Waterloo projects involving human participants, this project was reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. Should you have any comments or concerns resulting from your participation in this study, please contact Dr. Susan Sykes in the Office of Research Ethics at 519-888-4567, Ext., 36005.

Sincerely,

Kyle Renwick

University of Waterloo
Systems Design Engineering
Contact Telephone Number
519 888 4567 x 35607
krenwick@engmail.uwaterloo.ca

Protocol for Running the Study

Recruiting participants & scheduling

1. After receiving permission from the Engineering Society, post the recruitment posters in the engineering buildings.
2. When contacted by interested prospective participants ask for their email address and send them the information letter. Also suggest times for the study in the email.

Setup of the Environment

1. Check that the computer is on and ready for experiment.
2. Check that the first set of trials is loaded on the computer.
3. Have the following documents printed out:
   a) Information Letter
   b) Consent Letter
   c) Description of Demo
   d) Background Questionnaire
   e) Questionnaires for Demos
   f) Feedback letter

Conducting the Study

1. Greet the participant.
2. Provide the participant with the Information Letter, and go through it with the participant, answering any questions he or she may have.
3. Ask the participant to complete the Consent Letter.
4. Ask the participant to complete the Background Questionnaire.
5. Explain what they have to do for the study. See script below:

To begin, you will be given one of the two devices to evaluate. You will hold the device in your non-dominant hand, as you would hold a mouse. The arrow on the device must be pointing forwards (away from your body). Because the device makes a noise when it starts vibrating, you will have to wear headphones with music playing so that you cannot hear the device. When the experiment begins, the on-screen experiment will ask you to push the "5" key to begin a trial. Use your dominant hand to push the "5" key. A short, random amount of time after pushing the key, a motor will begin vibrating. Once you feel the vibration, push the "5" key again. Instructions will then appear on-screen asking you to push one of the arrow keys to indicate which motor you felt vibrating. There will be a series of 12 practice trials to familiarize yourself with the device. During the practice trials, no data will be recorded. The practice trials will be followed by a series of 96 real trials, during which data will be recorded. Once the real trials have been completed for the first device, the same procedure will be applied for the evaluation of the second device. After using each device, you will be given a short questionnaire, asking specific questions relating to the device. You can take as much time as you like to answer the questionnaires. Do you have any questions before we start the practice trials?

1. Get the device vibrating. Ask the participant to put on the earphones and to increase the volume until he/she can no longer hear the device when it is vibrating.
2. Run the experiment for the first device, during which they will use the keyboard to go through the trials.
3. Ask the participant to complete the device questionnaire.
4. Repeat 7 and 8 for the second device.
5. Provide the feedback letter and thank the participant.

Device Questionnaires

Questions for Device 1

Please rate the level of difficulty to perform the following tasks.

	Very Easy				Very Difficult
Determining if a motor was vibrating	1	2	3	4	5
Identifying which motor was vibrating	1	2	3	4	5
Holding the device	1	2	3	4	5

What level of accuracy do you think you had in identifying the vibrating motor? ________ %

Do you have any additional comments?

____

____

____

____

Questions for Device 2

Please rate the level of difficulty to perform the following tasks.

	Very Easy				Very Difficult
Determining if a motor was vibrating	1	2	3	4	5
Identifying which motor was vibrating	1	2	3	4	5
Holding the device	1	2	3	4	5

What level of accuracy do you think you had in identifying the vibrating motor? _________ %

Which device did you prefer? ☐ First device ☐ Second device

Why did you prefer this device?

____

____

____

____

Do you have any additional comments?

____

____

____

____

Recruitment Poster

PARTICIPANTS NEEDED FOR RESEARCH
in Vibration Based Haptic Feedback

Department of Systems Design Engineering
University of Waterloo

We are looking for volunteers to take part in a study assessing the effectiveness of vibration as a method of providing feedback in virtual environments.

A participant in this study would be asked to use two mouse-like devices that provide vibration based feedback. The device would vibrate, and an on-screen question would appear. The user would have to indicate which part of the device vibrated using the keyboard, and provide feedback as to the usability of the devices.

The study would take approximately 15 minutes of your time. The study would take place in E2-3367, or the location of your choosing, whichever is more convenient. In appreciation for your time, you will receive cookies and/or donuts.

For more information about this study, or to volunteer for this study,
please contact Kyle Renwick at 519-888-4567 Ext. 35607 or
Email: krenwick@engmail.uwaterloo.ca

This study has been reviewed by, and received ethics clearance
through, the Office of Research Ethics, University of Waterloo.