Tactile Haptics: A Study of Roughness Perception in Virtual Environments

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2009

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.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis presents the design of a tactile device that can be used to display varying magnitudes of roughness. The device is designed to be attached to an existing force feedback device in order to create a package that is able to display both macro-level (force feedback) and micro-level (tactile feedback) information to the users. This device allows the users to feel a simulated texture by placing an index finger on an aperture. The stimulus is created with a spiral brush made of nylon bristles. The brush is attached to a DC motor and the speed and direction of rotation of the brush are used to generate textures at the fingertip through the aperture.

Three psychophysical experiments are conducted to study the effects of speed and direction on the roughness perception. The first experiment is designed to investigate the sensitivity to a change in the speed of the brush. This experiment is conducted for two levels of base speed and it is found that as the base speed increases, the just noticeable difference (JND) with respect to speed decreases.

In the second experiment, it is found that this tactile device is able to represent textures of rough nature, such as sandpaper. It is also found that the human roughness perception cannot be described in a unique manner. Two opposite definitions of rough textures are identified in this experiment. While some users relate an increase in the speed of the brush to increasing roughness, others relate it to decreasing roughness. Further, the results show that the effects of direction are insignificant on the roughness perception for both groups of users.

In the third experiment, the effects of direction are studied more closely by presenting the two directions successively with a time gap of $0.5s$. It is found that with this small time gap, the users are able to discriminate between directions, unlike in the previous experiment. The roughness perception is affected by the change in direction when the time gap is small.

These findings open further areas that need to be investigated before a robust tactile device can be designed.

Acknowledgements

I would like to thank my supervisor, Professor David Wang, for his invaluable guidance and support throughout this research. I would also like to thank my readers, Professor Carolyn MacGregor and Professor Christopher Nielsen for their time and valuable input.

I thank the Natural Science and Engineering Research Council (NSERC) and my industrial partner, Quanser Consulting Inc., for providing me financial support to complete my degree. Quanser also provided me with their real time control software that has been an invaluable resource for my research.

I thank Mehrdad Hosseini Zadeh for guiding me through the design of all the experiments and providing direction. Thank you to Professor Jeanette O'Hara Hines at the department of Statistics and Actuarial Science for helping me with the statistical analysis.

This research would not have been possible without all of the volunteers that participated in my experiments. Their time and input is the sole of this thesis. I would also like to thank all my friends in my lab, who have made the last 2 years an enjoyable experience for me.

I must thank Willem Petersen, for spending endless hours with me in the machine shop and helping me enormously with the mechanical design. Most of all, I must thank him for providing encouragement and a positive attitude towards my research.

Finally, I would like to thank my parents and Preet and Navi for their continuing patience and support over the course of my degree.

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Chapter 1

Introduction

The sense of touch is a crucial aspect of information gathering. Through touch, we are able to gather information about an object that may not be possible otherwise. This includes our ability to detect surface stiffness, temperature, texture, weight etc. In order to convey realism, it is important to include the sense of touch in virtual environments. A virtual environment that conveys the sense of touch is called a haptic system. A haptic system consists of 4 major units:

1. A virtual environment
2. A haptic device
3. A haptic process
4. A human operator

The haptic device is used by a human operator to interact with the virtual environment and receive force feedback from it. A haptic process links the haptic device and the virtual environment and communicates information between the two. The block diagram of this system is shown in Figure 1.1. The human operator uses the haptic device to navigate the virtual environment. The haptic process uses the position and orientation of the haptic device and the objects in the virtual environment to perform a number of tasks. These may include, for example, updating the position and orientation of an avatar according to the operator's manipulation of the haptic device, detecting a collision between the avatar and an object in the virtual world and then calculating the reaction forces that are be generated by the contact. These forces are translated into motor torques that are then fed back to the haptic device to be displayed to the user.

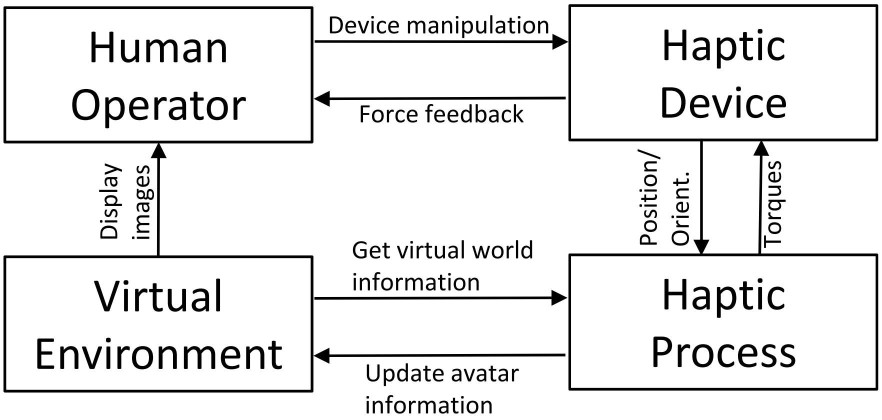


Figure 1.1: Block diagram of the haptic system

Various industries are exploiting haptic feedback to improve performance of virtual reality tasks. Including haptic touch in computer-aided-design (CAD) has shown to improve performance while designing 3D models [Liu et al., 2004, Dachille Ix et al., 2001]. Moreover, surgical residents who use haptic feedback in a medical simulator have shown to perform significantly better than those who performed the same tasks without haptic feedback [Ström et al., 2006]. Haptic feedback has also been shown to improve performance in human computer interfaces [Dennerlein et al., 2000], where a force feedback mouse was shown to reduce movement/steering times by as much as 52%.

These are all examples of a kinesthetic haptic feedback - sensations in muscles, tendons and joints. It belongs to a class known as proprioceptive that includes not only the kinesthetic sense but also the cutaneous and vestibular senses. The vestibular sense, relating to the positioning of the head, is outside the scope of the current research. However, the cutaneous sense, which relates to touch through skin is of high importance. It includes the ability to sense pressure, temperature and pain. The ability to sense pressure is more specifically known as the tactile sense, which also allows us to determine surface textures [Oakley et al., 2000]. The focus of this thesis lies in the tactile sense and the perception of rough textures.

1.1 Tactile Feedback

In a virtual environment, tactile feedback is just as important as kinesthetic feedback. Without tactile information some of the key properties of surfaces, such as texture, remain unexplored in virtual environments. One of the challenges of haptic feedback is to match the perception of touch in a virtual environment to a real environment. The perception of texture and how we perceive roughness of different magnitudes is a complex topic that has been studied by psychophysics for decades.

There are various applications in virtual reality where the performance or the learning curve can be improved by providing tactile feedback. Palpation with finger pads is a commonly practiced technique for early detection of breast cancer. However, breast cancers can range in size from being microscopic to 8cm [Klimberg et al., 1998]. Given this range, smaller tumors may be detectable via touch by an expert doctor only. Providing a virtual environment with haptic devices that can display tactile feedback, may be an important aspect of training for doctors. In fact, similar training environments are already available for laparoscopic procedures [Basdogan et al., 2001]. While 3D texture maps are applied to the visual displays to create realistic effects, realism cannot be achieved until the touch feedback is complete. Medical simulators are focused on providing force feedback. However, the tactile feedback is still missing.

Other applications of tactile feedback include machining or handcrafting such as pottery modelling [Lee et al., 2008]. Attention allocation [Sklar and Sarter, 1999], where different tactile cues are used to capture attention in human-machine communication, is another use of tactile feedback. Tactile feedback can also be used to interact with touch screen displays [Lee et al., 2004].

While the kinesthetic force feedback devices are well developed, tactile feedback devices are in a primitive stage. This thesis presents the design of a tactile device that aims to display various magnitudes of rough textures. However, roughness perception is a subjective measure. To determine if this tactile device is able to meet its objectives and how the various control variables affect roughness perception, several psychophysical experiments are conducted. These experiments are designed to study the effects of relative speed and direction of motion of a surface underneath the fingertip.

1.2 Thesis Outline

Chapter 2 of this thesis presents the literature review relevant to this research. It begins with a review of different aspects of touch that affect the touch perception followed by a discussion on how textures can be simulated. Several different designs of existing force feedback devices and tactile devices are also presented. At last, psychophysical methods that are used to quantify sensations are discussed.

Chapter 3 presents the design of the tactile device including the design considerations and constraints that dictated the design.

Chapter 4 presents some of the preliminary work that is necessary for doing user testing with this device. The key areas of psychophysical interest are presented in this chapter as well.

In Chapter 5, a study of the just noticeable difference (JND) with respect to the speed of the surface is presented. It presents a detail analysis of how the JND changes for different levels of base speed.

Chapter 6 presents the types of textures that this tactile device is able to represent. Furthermore, the effects of the speed of the surface and the direction of motion on roughness perception are also studied in this chapter.

Chapter 7 presents the effects of direction of motion in more detail by controlling the time gap between stimuli. The effects of speed of the surface are re-confirmed in this chapter as well.

Chapters 8 presents the main conclusions derived from the experiments and the future considerations that may be used to further explore roughness perception by using this tactile device.

Appendix A presents the results tables from the statistical analysis. Appendix B presents background information on the statistical analysis used in this thesis. Appendix C presents the design specifications of the tactile device. At last, Appendix D shows the CAD drawing of the tactile device.

Chapter 2

Background

2.1 The History of Haptics

The earliest known work in haptics seems to have started with the findings of Ernst Heinrich Weber, a professor at the University of Leipzig, between 1818 and 1871 [Prytherch and McLundie, 2002]. Weber was interested in studying different aspects of sensations. While his research spanned various fields, he was mostly interested in studying the haptic aspects of sensations. In various experiments, he studied how different parts of the body respond differently to touch sensations. He designed his experiments using the two-point threshold where a touch organ is touched at two closely spaced points. The goal is to determine how far apart the two points have to be in order to recognize that there is a spatial separation between them. Weber found that for touch organs that were highly sensitive, the distance between the points was less than for touch organs that were less sensitive. Furthermore, his experiments concluded that we can perceive spatial separation much better when the sensations are provided along the transverse axis of the body rather than the longitudinal axis [Ross and Murray, 1978].

Weber further investigated the cross-modality of vision and touch. Weber argued that in order for us to accurately perceive spatial separation, we need information from both touch and vision. According to Weber, vision is more sophisticated and more developed than touch. However, he did report that with practice, touch can be made more sensitive. Furthermore, Weber reported that in the absence of vision, varying the amount of applied force on objects can change our perception of their properties [Prytherch and McLundie, 2002].

His fundamental study about the threshold of sensitivity generated a lot of enthusiasm in sensory psychology. Weber found that in order for us to detect an increase in stimuli, the change must be above the threshold of sensitivity of that sense [Prytherch and McLundie, 2002]. This led to the concept of just noticeable difference (JND). The JND of a particular sensation is the smallest possible increment or decrement in stimulus that can be detected. This concept will be investigated further in Section 2.5.3.

Most of these topics will be discussed in more detail in the sections to follow where it will become apparent that the work of Weber was truly the basis of much of the human factors research in haptics being conducted today. All of his work was originally published in his two books *De Tactu* (1834) and *Der Tastsinn und das Gemeingefuhl* (1851) and has been translated to English.

2.2 Touch Perception

There are various ways in which we touch objects and ways in which our sense of touch is affected. These factors are important to review in order to conduct any experiments to study the sense of touch.

2.2.1 Active vs. Passive Touch

David Katz may be called another pioneer in the field of studying touch. Katz may have been the first one to study the effect of relative motion of a sense organ and the object to be touched. Like Weber, Katz's research spanned various fields. However, his main interest remained in studying the microstructure (texture) of objects rather than the macrostructure (form). Katz studied the effect of relative motion of a sense organ and the object to be touched. He argued that finger motion across a surface is necessary in order to fully identify surface properties such as material, stiffness and roughness [Katz and Krueger, 1989]. He explained that simply resting a finger on a rough or smooth surface is insufficient to fully judge the properties. Although he did not give a name to this phenomenon, it was later called the concept of active and passive touch. Active touch refers to the case of a finger moving over the surface of an object, thus creating relative motion whereas passive touch creates relative motion by moving the object over a stationary finger. As Gibson [1962] later put it, the difference lies in the act of touching (active touch) or being touched (passive touch).

Gibson believed that active touch is better for perceiving two dimensional shapes than passive touch. To prove his hypothesis, he conducted an experiment in which he chose six different cookie cutter shapes to be presented to his subjects. They were not allowed to look at the objects. However, they were given a picture of the six objects that were going to be presented to them. Their task was to match the object in their hand to one of the drawings. The objects were presented in a random order. In the passive case, the subjects were asked to place their hand palm up on the table and an object was placed on their palm. In the active case, the subjects were allowed to explore the object in any manner including the use of their fingers. Gibson confirmed his hypothesis since subjects answered correctly 49% of the time in the passive touch condition and 95% of the time in the active touch condition.

In a similar setup, Gibson studied the effect of static vs. moving contact for the passive case. In the static passive case, the cookie cutter shapes were simply placed on the subjects' hand as in the previous experiment. In the moving passive case, however, the cookie cutters were twisted clockwise and counter-clockwise on the hand. Gibson found the performance of the moving case to be significantly better than that of the static case — 72% vs. 49%. This leads to a similar conclusion discussed earlier by Katz — that relative motion is necessary in order to fully grasp the properties of an object. At this point, it is important to mention that Gibson did not make any conclusions from this study. In fact, he mentioned that the test setup of the active and the passive case were not the same, since in the active case, the subjects explored with their fingers while in the passive case the palm of their hand was used. Differences in sensitivity of the palm and the fingers may have resulted in different results. However, it is still worth noting that performance for the passive case improved significantly for the moving case than the static case.

In order to create a test scenario where exploration using active and passive touch was as similar as possible, Cronin [1977] conducted a set of experiments similar to those of Gibson's. Although he did not use cookie cutters as stimuli, they were still outline shapes such as a circle, square, pentagon etc. Like Gibson, Cronin studied the effects of active and passive touch on object identification. In the case of passive touch, he conducted two different tests: the case of a moving object and a still object. To avoid the ambiguity faced by Gibson by allowing the use of fingers in the active touch case, Cronin conducted all his experiments with the palm of the hand only. For the case of the active touch, the subjects were allowed to explore the object with the palm of their hand only and they were not allowed to bend their hand. They were also not allowed to feel the sides of the object to keep it consistent with the passive touch test. The results showed that in the case of the moving object, active touch and passive touch did not produce significantly different results. This contradicts Gibson's results. However, Cronin did report that passive touch was significantly better in the case of the moving object than the still object, which is in agreement with Gibson.

Many researchers have found similar results to Gibson and Cronin [Vega-Bermudez et al., 1991, Heller and Myers, 1983, Heller, 1984, Schwartz et al., 1975]. In a surprising case, Magee and Kennedy found that passive touch was better for the identification of raised-line drawings.

All of these researches have either studied active and passive touch with outline shapes using the palm of the hand or with raised-line drawings or letters. One common factor between all of these is that, for the case of the passive touch, the experimenter has been involved in the stimulation process. In the case of outline shapes, the experimenter has moved the objects on the subjects' hand; in the case of raised-line drawings, the experimenter has guided the subjects' hand along the contour. It is possible that inconsistent presentation of the object from subject to subject may have altered the results. Lederman [1981] designed her experiments to study active and passive touch without any involvement from the experimenter. Her experimental setup consisted of a balance apparatus and eight aluminum plates with linear gratings. The procedure allowed for the subjects to apply a constant force on the plates while moving back and forth at a pace that would be the same for both active and passive cases. The stimuli were presented to the middle finger only. Once again, her results showed that there is no significant difference between the active and the passive case. It made little or no difference whether the subjects moved their finger on the metal gratings or the metal gratings moved underneath their stationary finger.

2.2.2 Exploratory Procedures

The fact that many researchers have argued over the effectiveness of object identification using touch alone has not discouraged research in this area to continue. Although some results with raised-line drawings and "nonsense" shapes have shown that touch is insufficient at object identification when compared with vision [Cashdan, 1968, Rose et al., 1972, Brynat and Raz, 1975, Magee and Kennedy], Klatzky et al. [1985] disagree. Klatzky et al. argue that such stimuli do not necessarily represent real objects and are often missing some of the key properties of real objects such as texture, size etc. Especially in the case of raised-line drawings, it becomes necessary to identify the shape of the object and imagine how it would look visually, thus defeating the original purpose of the experiment. In order to demonstrate their point, they tested a number of subjects with 100 objects both visually and haptically. As expected and forewarned by other research, all of the objects were correctly identified when presented visually. In the haptic case, a surprising 96% of the objects were identified correctly under strict naming conventions and of those 94% were correctly identified within 5 seconds. Klatzky et al. have shown that haptic identification of real objects is not only possible but also fast and accurate.

Encouraged by these results, Lederman and Klatzky [1987] began to study the hand motions that people use to identity objects via touch. They were interested in determining which hand motion, called an exploratory procedure (EP), was used to identify a property of the object and which of the EPs were most optimal at exploring a specific property. They created a set of experiments in which they observed the hand movements that the subjects used to explore a certain property of the object such as hardness, texture, temperature etc. They studied seven properties of each object: texture, hardness, temperature, weight, volume, general shape and exact shape. The hand movements that they observed were classified into six categories as shown in Table 2.1.

Table 2.1: Descriptions of exploratory procedures.

EP	**Description**
Lateral Motion	Rubbing motion
Pressure	Normal forces or torque about an arbitrary axis
Static Contact	Remain stationary on the surface
Unsupported Holding	Lift an object
Enclosure	Molding of the hand to wrap the object
Contour Following	Trace the outline of the object

The relationship between each EP and the object properties is shown in Table 2.2. S indicates that the EP is sufficient at determining the corresponding property, O indicates optimality and N indicates necessity. A blank space indicates that the particular EP was not used to explore the corresponding property.

An important observation to examine here is the EP used for texture. Although all of the mentioned EPs are sufficient for determining texture, lateral motion is the only optimal one. This may seem obvious since we generally rub our fingers back and forth on an object in order to identify its texture. However, if we generally hold the object in our hand or simply rest our hand on it, we may still be able to gather some texture information. This observation is reconfirmed in their more detailed analysis in Lederman and Klatzky [1990].

Table 2.2: Relationship between EPs and object properties [Lederman and Klatzky, 1987].

EP	**Tex.**	**Hard.**	**Temp.**	**Wt.**	**Vol.**	**Gen. shape**	**Ex. shape**
Lateral Motion	O	S	S				
Pressure	S	O	S				
Static Contact	S		O		O	O	
Unsupported Holding		S	S	O	S	S	
Enclosure	S	S	S	S	S	S	
Contour Following	S	S	S	S	S	S	N

2.2.3 Adaptation

One major issue in trying to study any of the senses of the human body is its ability to adapt to constant stimuli. Just as we might adapt to a constant audible tone such that its presence is not noticeable after some time, the sense of touch is also highly adaptive. This is by no means a drawback. In fact, it serves a very useful purpose. Without this adaptive feature, we would be constantly aware of the chair we are sitting on and the clothes we wear. It is a natural phenomenon likely developed to rid us of these discomforts. Since the ideal goal of research in haptics is to replicate reality or make it as real as possible given the various limitations, it is apparent that adaptation of the sensory system must be studied and it has been a topic of interest for researchers for decades.

In the context of cutaneous sensation, adaptation refers to one's diminishing sensitivity to touch [Scharf et al., 1975]. In other words, it refers to the phenomenon which makes us unaware of the presence of objects that we are constantly in touch with (e.g. the shoes we wear). This is not to say that once adapted, the object cannot be felt anymore. The feeling is quickly restored when the object in touch is moved [Schiffman, 1976]. Even Katz believed that adaptation occurs quickly in a touch organ [Katz and Krueger, 1989]. He strengthened his earlier argument regarding active touch being better than passive touch by saying that adaptation occurs significantly faster for a motionless contact than with a moving contact. Katz does not provide any experimental data to support his argument.

Many researchers have conducted experiments in order to find some way to quantify the time it takes for adaptation to occur, how quickly it can be restored and the factors that affect it. DiZio and Lackner [2000] have shown that adaptation does not have to occur in the presence of visual feedback only. In fact, in their experiments, they showed that congenitally blind and sighted subjects could adapt to coriolis forces. This experiment was conducted in a manner such that the subjects had to extend their arm and point at a target while they were seated at the center of rotation of a slow rotation room (SRR). According to their results, adaptation to coriolis forces occurred within 10 reaches to the target. After resting for $2min$ at $0deg/s$, the effects of this adaptation disappeared within another 10 reaches. However, They did not mention how much time it took on average to complete 10 reaches.

In a different setup, Scheidt et al. [2000] tried to study adaptation for another reaching task where the subjects were asked to move the end effector of a robot from one point to another. They were subjected to three different effects:

1. A null field — zero forces applied to the hand. The subjects moved from point A to point B freely.
2. A perpendicular force field (also called the adaptation phase)— damping force perpendicular to the hand motion and proportional to the hand velocity was applied as the subjects moved from point A to B.
3. A channel field — The hand was guided along a stiff virtual guide. The virtual guide was made of two stiff walls that were 1mm apart. The stiffness of the walls was $6000N/m$. The guide constrained the subjects to move in a straight line from point A to B.

First, the performance of the subjects was measured using the null field to record their pre-adaptation behaviour. Then they were subjected to the perpendicular force field until adaptation occurred. Full adaptation occurred when subjects had learned to apply an equal and opposite force against the perpendicular force. After adaptation, one set of subjects was provided null and channel fields on alternating trials to allow for kinematic errors during the null field trials. The other set was provided only the channel field. This was the disadaptation phase used to determine how long it takes to lose adaptation to the perpendicular force and return to the pre-adaptation behaviour. The results show that adaptation to the perpendicular field occurs within 5 to 10 trials. The disadaptation, on the other hand, was different for the two groups. The first group that received null and channel fields on alternating trials took less time to return to pre-adaptation behaviour (approximately 8.5 trials) than the the second group that was allowed to move in the channel field only (approximately 138 trials). This data shows that, in the case of reaching movements, disadaptation occurs much more quickly when kinematic errors are allowed.

With an intent to determine adaptation to pressure, Zigler [1932] found that if objects of different weights were placed on a part of the body, then adaptation occurs more quickly for lighter weights than heavier weights. For instance, a $50mg$ weight placed on the back of the hand may take only $2-5s$ to be adapted to while a $2000mg$ weight can take $9-20s$. They also showed that the size of the object also played a role in adaptation. The larger diameter objects were more quickly adapted than smaller diameter objects that had the same weight.

Thus, it is clear that it is crucial to consider adaptation of the cutaneous sense when studying the human tactile behaviour.

2.2.4 Perceived Roughness

If someone is asked to determine the texture of a fabric, they will usually respond by running their fingers back and forth on the fabric. This agrees with the observations made by Lederman and Klatzky [1987] that lateral motion is the most optimal EP to determine texture. However, the discrimination of different textures is a complicated procedure. It is affected by many variables — especially for the case of rough textures. More researchers are interested in conveying rough textures rather than smooth ones mostly because the absence of a rough surface is interpreted to be smooth. Hence, the focus has been laid upon finding how to convey different levels of roughness and the factors that change the human perception.

Fingertip Force

Lederman and Taylor [1972] speculated that the force with which one pushes down on a rough surface changes the perception of how rough the surface actually is. In other words, pushing down harder on a surface may make the surface feel rougher than just lightly rubbing a finger on it. To test their theory, they created an apparatus that allowed them to control the force with which the users would press on the surface. Their results showed that the perceived roughness increased as the applied fingertip force increased. They re-confirmed these results in a similar setup where the subjects were allowed to choose the amount of force they applied on a surface [Lederman, 1974]. They found that regardless of who set the force limit (the experimenter or the subjects themselves), perceived roughness increased with increasing force.

Rate of Hand Motion

Lederman [1974] conducted an experiment to determine if the rate at which the fingers pass over a grooved surface affects the perception of roughness. They asked their subjects to rub their fingers over the surface at specified rates. Initially, their results indicate a significant dependency of perceived roughness on rate of hand motion. It shows that as the rate of hand motion increases, so does the perceived roughness. However, upon a closer look, they conclude that the perceived roughness does not increase as significantly as the hand motion had to increase to cause the effect. For instance, the hand motion had to increase by 25 times as much in order to feel a $1dB$ increase in roughness magnitude. On this basis, they argue that the rate of hand motion does not play a significant role and other factors such as fingertip force are more effective. They had found that if the fingertip force increased by nine times, then the roughness magnitude increased by $1dB$ to $2dB$.

Geometry of the Surface

Continuing on their interest to determine the factors that affect perceived roughness, Lederman [1974] and Lederman and Taylor [1972] focused on finding how different levels of grooved surfaces can change the roughness perception. They were interested in studying if the groove width and land width played any role in roughness perception. Groove width is the width of each groove while land width is width of the flat region between each groove. They found that increasing groove width was strongly correlated with increasing roughness magnitude while increasing land width not only has less of an effect, it has an inverse effect — that is increasing land width decreased the perceived roughness. This make sense intuitively because as the width of the flat regions grows, the plate becomes more smooth than rough. Even then, the land width is more effective than the rate of hand motion. One might also say that perceived roughness may be a function of the friction between the finger and the object such that increasing friction may increase the roughness magnitude. This is generally the result found by Ekman et al. [1965]. They mostly used different sandpapers to derive their results. However, they do not describe how the coefficient of friction was measured. This is true for grip forces as well. Lowering the coefficient of friction while maintaining the same texture and roughness of the object is shown to increase the grip forces [Cadoret and Smith, 1996]. In any case, these results contradict those of Taylor and Lederman [1975] who found that the effect of coefficient of friction is insignificant in roughness perception. They used grooved plates and used liquid detergent to lower the coefficient of friction. No strict conclusion can be made from these contradictory results since they used different experimental setups.

Rigid Link vs. Direct Skin Contact

Many haptic devices allow users to feel virtual objects through some sort of a physical object interposed between the hand and the virtual object, e.g. a probe or a stylus. However, in a real environment, we rarely try to feel objects by using a pen or a stick even though it is possible to be able to feel the stiffness of a table with a stick. The haptic devices that use a probe or a stylus rely on this concept to be able to present force feedback. Although this approach appropriately conveys the surface stiffness and roughness, it is not hard to imagine that exploration with bare fingers where there is direct contact between the skin and the object is more effective. This is shown by Klatzky and Lederman [1999], where different densities of dot patterns were explored by direct finger contact, a large probe and a small probe. The results indicate that subjects tended to rate the roughness the highest when the surface was explored with the finger and the least when explored with the small probe. This indicates that probing with a larger diameter probe gathers more information about the surface as it brings the roughness magnitude closer to that which is felt directly by the finger. Similarly, exploration with bare fingers produces more accurate results than exploration with gloves [Klatzky and Lederman, 1999]. Further, it has been shown that users exert more force to explore a surface when using a probe rather than a bare finger [Klatzky et al., 1999]. This is also intuitive because less information about the surface is gathered through a probe and by applying more force, users try to compensate for this lack of texture information.

2.3 Stimulating Texture

As shown so far, much has been studied about the human tactile behavior in terms of the factors that affect touch perception and roughness perception. One major aspect that has been common in all of these experiments is that they used real materials. Whether it is sandpaper, raised line drawings or dot patterns, the forces on the finger tip are a result of direct contact with a real material regardless of the use of a probe or a finger. This research is important as it affects the design of tactile actuators where these forces are generated artificially. The question is how can phenomenon studied be incorporated into the haptic technology and make it a part of a virtual reality environment? Is it possible to give the same touch and roughness perception to virtual objects as to real materials?

While many force feedback haptic devices have been developed in the past, some of which will be discussed later in Section 2.4, not many stimulate texture. Many researchers have devised various ways to simulate the texture on virtual surfaces. Generally speaking, there is one major category in texture perception - roughness versus smoothness.

2.3.1 Height Fields

One way to simulate haptic textures is through the use of height fields. Generally this implies that an irregular height field is mapped on top of a smooth continuous surface as shown in Figure 2.1. The height field creates hills and valleys to represent irregular bumps on the surface. Height fields can be created by mapping 2D images onto 3D objects [Ho et al., 1999], by using fractal surfaces [Costa and Cutkosky, 2000] or noise textures [Perlin, 1985].

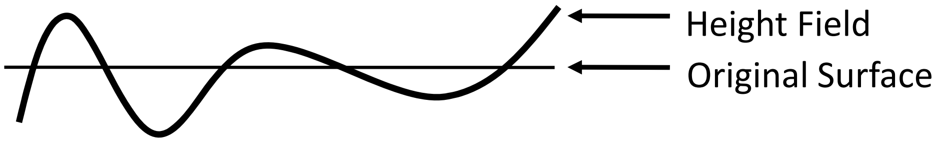
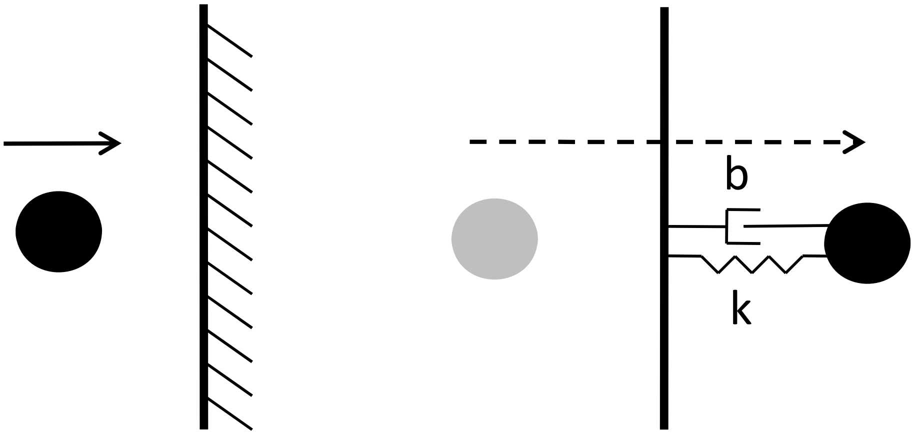


Figure 2.1: Height field mapped onto a smooth surface [Ho et al., 1999]

Before understanding how the force magnitudes and directions are calculated for textured surfaces, it is easier to look at an example of a smooth surface first. In the most simple case, the force to be applied to the user on a smooth surface is calculated using a spring damper model and the depth of penetration. An avatar is the representation of the user in a virtual environment. This could be in the shape of a mouse cursor, a dental tool when the virtual world is an application of a dental procedure or any other form appropriate to the application. The position of the avatar is constantly monitored to check for collision. Whenever there is no collision, the force output is zero. This is only true in the ideal case since the user generally has to support the weight of the end effector and the inertia of the device along with uncompensated friction effects of the joints and actuators. When a collision is detected, the depth of penetration of the avatar along with the spring and damper coefficients are used to calculate the force magnitude. The direction of the force is normal to the surface, henceforth referred to as the surface normal. For the 1D case, this scenario is shown in Figure 2.2a and Figure 2.2b. The force magnitude



(a) Without Penetration (b) With Penetration

Figure 2.2: Penetration into a smooth surface

for the two cases is given by

$$F = 0 \qquad \mathit{Penetration} = 0 \tag{2.1}$$

$$F = kx + bv \qquad \mathit{Penetration} > 0 \tag{2.2}$$

where F is the force magnitude, x is the depth of penetration, k is the spring stiffness, b is the damping coefficient and v is the velocity of the avatar. The direction of the force is normal to the surface.

Now for the textured case, determining both the depth of penetration and the direction of the force are complicated by the irregular geometry. Ho et al. [1999] present an approach to determine the depth of penetration by looking at the Haptic Interface Point (HIP) and the Ideal Haptic Interface Point (IHIP). HIP is the location of the end effector in the virtual world. This is allowed to penetrate solid objects. IHIP is location of the end effector on the surface of the object if it were not allowed to penetrate. Once the depth of penetration is calculated, the force magnitude can be calculated using a spring damper model. The direction of the force is determined using the surface normal which is also more complicated for the textured maps. Ho et al. build upon the techniques of Max and Becker [1994] to calculate the surface normal based on the original smooth surface normal and the local height gradients. Costa and Cutkosky [2000] define the direction of the force to be normal to the surface tangent that has to be precomputed.

The depth of penetration and the direction of the surface normal changes continuously as the IHIP traverses the surface. In this way, irregular forces (both in direction and magnitude) are presented to the user to convey the feeling of different textures.

2.3.2 Lateral Forces

The previous approach employed the use of normal forces to display textures. This seems intuitive. However, researchers have shown that the use of only lateral forces can also be effective in texture display. Minsky et al. [1990] used a joystick to apply lateral spring forces to the user's hand. They argue that these lateral forces can give the user a feeling of hills and valleys because users relate a downward gravitational force towards the valley with a spring force towards its rest point. This concept is shown by them in Figure 2.3. This technique also relies on the texture height maps. When the user is moving uphill, the direction of the force is against the motion in order to provide the feeling that it is harder to go uphill and when the user is moving downhill, the direction of the force is along the user's motion to make it easier to go downhill.

Similar to the earlier discussion in Section 2.2.4 that an increasing downwards force increases the perception of perceived roughness, experiments with lateral forces also show similar results. That is, increasing the magnitude of the lateral force increases the roughness perceived by users [Minsky and Lederman, 1996].

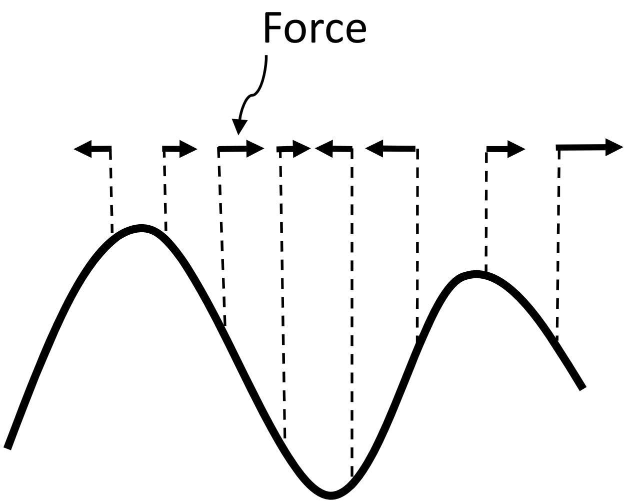


Figure 2.3: Use of lateral forces in texture display [Minsky et al., 1990]

2.4 Haptic Devices

2.4.1 Existing Force Feedback Devices

There are many haptic devices in the market that will transmit kinesthetic forces. Each one is designed with a different set of constraints. These could include fidelity, workspace, cost, force output, application just to name a few. However, most of these devices can be categorized in one of the following four ways:

1. Stylus
2. Glove
3. Free hand
4. Air Pressure

Stylus

Many haptic devices use a stylus (the end effector of the haptic device) to explore the virtual world. The users hold on to the stylus and use it to navigate their avatar

(a) The PHANTOM Omni® © Copyright SensAble Technologies, Inc. [Sensable Technologies, 2009]

(b) The Haptic Wand [Quanser Consulting Inc, 2009]

Figure 2.4: Stylus haptic devices

on the visual display. The stylus itself can be designed to resemble a specific tool, e.g. a scalpel for a surgical simulator. The force is transmitted to the user through the stylus. Examples of this type of device are the PHANTOM Omni® shown in Figure 2.4a and the Haptic Wand shown in Figure 2.4b. The PHANTOM Omni® is a six degree of freedom (DOF) device with three serial links and a stylus that is held by the user. Only the first three joints are actuated. The Haptic Wand on the other hand is a 5-DOF device consisting of two planar manipulators connected by a vertical rod that the user holds on to.

These type of devices rely on the concept of distal attribution to allow users to feel as if they are present in the virtual environment. Loomis [1992] described distal attribution as the experience of "being in touch with" the virtual environment. These devices are well suited for tasks where the use of a tool would be required, whether the task is performed in a real or simulated environment. However, it is obvious that for tasks that rely on information gathered directly from touching the objects, the use of a stylus is insufficient. Indirect surface interaction using the

(a) CyberGlove® [Cyber Glove Systems LLC, 2009a]

(b) CyberGrasp [Cyber Glove Systems LLC, 2009b]

Figure 2.5: Glove type haptic devices

stylus has been shown to be less efficient than direct finger interaction for tasks that involve tracing [West and Cutkosky, 1997]. This finding leads to designs that attempt to convey the object information through the use of the entire hand.

Glove

Haptic gloves are meant to be more versatile than a stylus haptic device. The concept behind the design of these devices is that the users should be able to "hold" the virtual objects in their hand. One example of a haptic glove is the combination of CyberGlove® and CyberGrasp by CyberGlove Systems LLC as shown in Figure 2.5a and Figure 2.5b. The CyberGlove® provides position and orientation information of the hand to display the motion on a virtual display in real-time. The CyberGrasp is an exoskeleton mounted on top of the CyberGlove® to provide push and pull forces to each of the five fingers through a network of tendons.

The applications for such devices are more obvious in CAD and in remote handling of hazardous materials [Cyber Glove Systems LLC, 2009b]. In CAD, users can grasp the objects in their hand and feel their weight, surface properties etc. In remote handling of hazardous materials, this device would have to be coupled with a slave robot that would perform the same actions as its master. Moving from stylus type devices to haptic gloves gives a greater degree of freedom in object manipulation. However, it still does not solve an underlying problem that comes with the design of haptic devices — making the free space feel free. In both of these designs, the haptic device is always in touch with the user's hand. In a real environment, when the user's hand is in free space, the user does not feel any external mass or inertia. However, when using these devices, there is always the inherent mass, inertia, friction and even surface properties of the device that are in contact with the user's hand. Moreover, these devices are expensive and generally do not convey realism.

Free Hand

Free hand exploration is of great interest in the haptic community. The idea behind this concept is that the user should feel an external effect only when the user's hand comes in contact with a virtual object, otherwise the hand should be freely moving without being connected to anything. This led to the design of a Touch/Force Display System shown in Figure 2.6 by Yoshikawa and Nagura [2001].

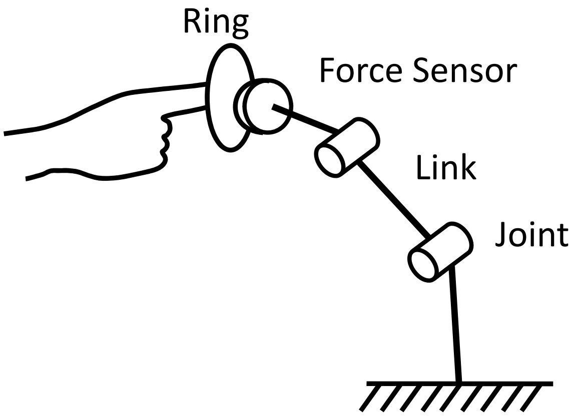


Figure 2.6: Haptic Ring [Yoshikawa and Nagura, 2001]

They designed a serial manipulator with a ring attached at the end. The users insert their finger in the ring. When the user is not in contact with a virtual object, the ring tracks the position of the finger and moves with the finger without coming in touch with it. However, as the users touch a virtual object, the ring slides in from the corresponding direction to touch the users' finger providing a distinct difference between contact and non-contact states.

2.4.2 Air Pressure

Suzuki and Kobayashi [2005] have designed a device that does not constraint the movements of the user in any way. They designed a device consisting of air nozzles and an air receiver. The design is shown in Figure 2.7. The user holds on to an air receiver generally equipped with a handle. It can be made in any shape appropriate for the application. The air jets from the nozzles hit the air receiver and apply forces on the user's hand. The purpose of the receiver is to act as an interface for receiving the air jets. The user could place their hand in the air jet. However, then the sensation feels like wind rather than an applied force.

The virtual display is projected onto the surface from a projector. The user wears 3D glasses with markers that are tracked by cameras to keep track of the user's viewpoint. The markers are also placed on the air receiver to track its position and orientation relative to the virtual display. The advantage of this device is that the user is not tethered to anything with wires or rigid links.

2.4.3 Texture Display Devices

To capture the microlevel detail of objects, researchers are now focusing on developing tactile devices that focus on capturing texture information. Unlike the force feedback devices, there are no commercially available tactile devices. However, researchers have developed various different types of tactile devices.

Pin Array

The most common type of tactile device is the pin array type. These devices generally have a grid of pins that push up on the finger tip according to the surface

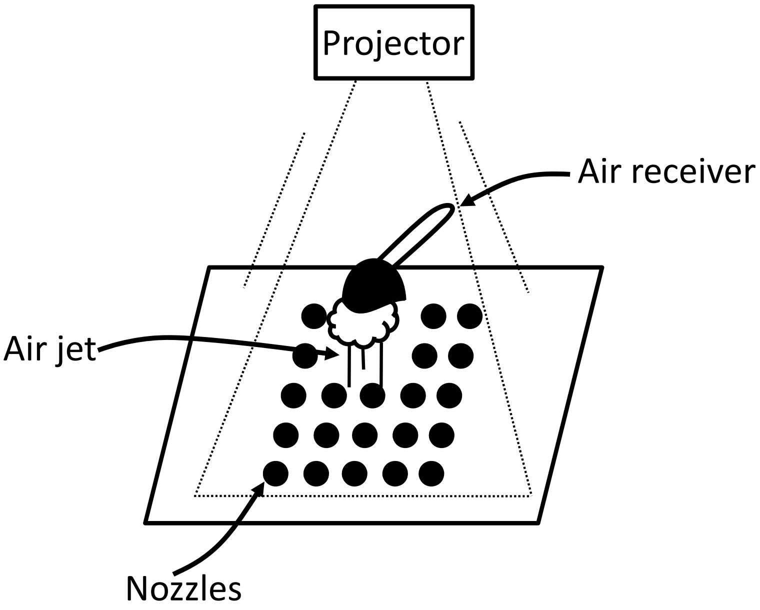


Figure 2.7: Force feedback device using air pressure [Suzuki and Kobayashi, 2005]

that is meant to be simulated. Such a device is constructed by Kontarinis et al. [1995]. They created a 6x4 array of pins that are actuated by shape memory alloy (SMA) wires. SMA wires are actuated using electric current. The temperature change of the wire causes it to shrink causing further tension or go back to its original length which is the rest position. Each pin has its own actuator resulting in 24 actuators. The design of their device for one pin is shown in Figure 2.8. Originally, the rest position of the SMA wire is such that the pins are at rest and the user feels a smooth surface. The spring is used to keep the wire at the initial tension. When the wires are heated through current, the SMA wire shrinks causing the lever to lift up and push the pin against the finger. All pins are actuated independently to create various patterns. The actuation of the pins is decided by the pressure distribution of the finger on the touch pad. The pressure distribution is measured using a capacitive tactile array sensor.

Moy et al. [2000] created a pin array device that is actuated pneumatically. They argue that in the flat top devices such as the one discussed above, not all of the raised pins come into contact with the skin. This is naturally because of the

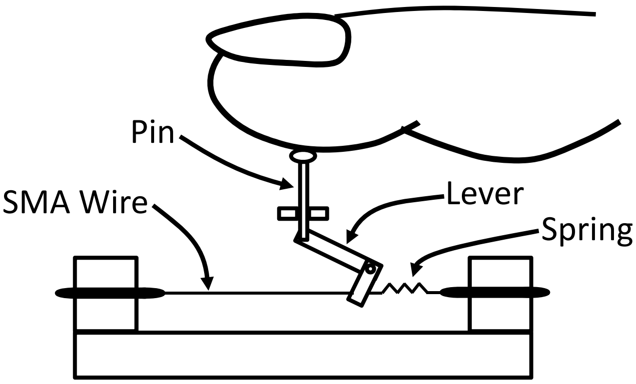


Figure 2.8: Tactile display using pins actuated using SMA wires [Kontarinis et al., 1995]

shape of the finger. Their pneumatically actuated device molds around the finger so that different areas of the skin can be stimulated. An illustration of their device is shown in Figure 2.9. It is a 5x5 array of pressurized chambers. The silicon tubing is used to control the pressure in each chamber.

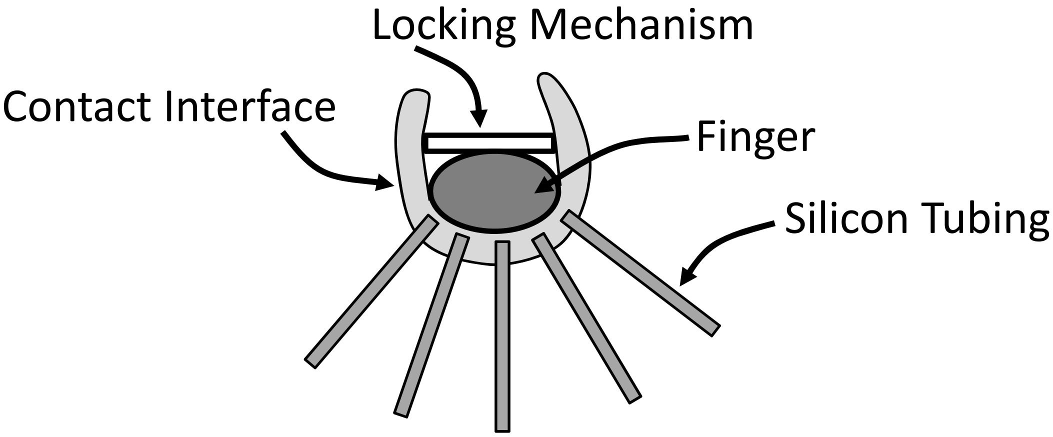


Figure 2.9: Tactile display using pneumatically actuated pins [Moy et al., 2000]

Although the actuation of pins may differ, the underlying concept for both devices is the same.

Vibration

Researchers have also used vibratory information to portray the feeling of texture. Campbell et al. [1999] modified the IBM™ TrackPoint In-Keyboard Pointing Device to produce vibrations at the tip. They outfitted the TrackPoint with a current coil and a ferromagnetic slug as shown in Figure 2.10. When a current is supplied to the coils, the magnetic field pushes the slug upwards to hit the cap. By supplying a pulsing current, the slug can be made to move up and down and the frequency of the pulse can be used to control the frequency of vibration. The users rest their finger on the cap and feel the vibration created by the slug moving up and down. In a mouse steering task, they showed that such tactile feedback can be used to enhance performance.

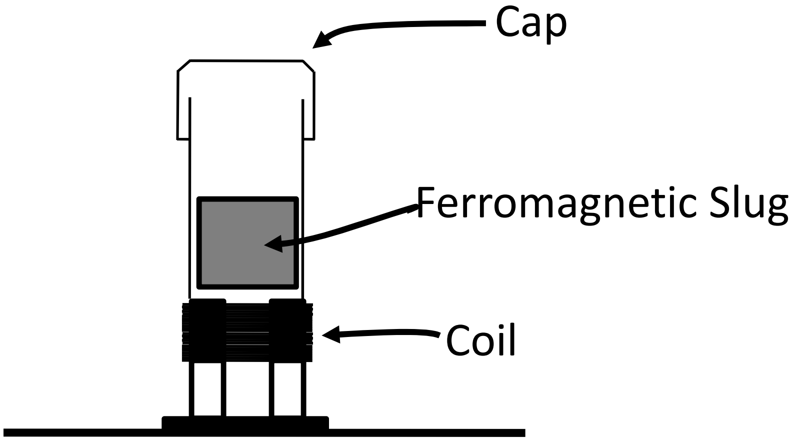


Figure 2.10: Tactile display using vibration in a TrackPoint [Campbell et al., 1999]

2.5 Psychophysical Methods

The validity of haptic devices has to be checked via user testing. To estimate how well these devices meet their objectives and how well users relate them to real life, various psychophysical methods can be employed.

The focus of this thesis is to study the texture perception. There needs to be some way of quantifying the touch sensations, whether it is done by scaling the different stimuli as they are perceived by the fingers or by using other ways to detect the thresholds of the fingertip. The measurement of sensation is an area studied by psychophysicists for over a century. Some of the most relevant psychophysical methods to this research are presented in the sections to follow.

2.5.1 Magnitude Estimation

Magnitude estimation is a part of psychophysical methodology in which subjects estimate their sensations on a number scale. This phenomenon utilizes the fact that given different magnitudes of the same stimuli, we are able to scale them using numbers in a rather consistent manner [Stevens, 1956]. Most of the research in magnitude estimation has been done using sound where the subjects are asked to scale different magnitudes of loud stimuli.The method of magnitude estimation described by Stevens [1956] looks at a few different ways of determining how different intensities of the loud stimuli correspond to a number scale. In his initial experiment, Stevens provided his subjects with a standard tone and assigned the number 10 to it. He then asked various subjects to compare the standard tone to many variable tones and assign a number to the variable tones based on their judgment. For instance, if the subjects felt that the variable tone was twice as loud as the standard, then they were asked to call it 20. In this way, he presented tones that were of lower and higher intensities than the standard tone. His results have shown that subjects could relate the loudness of each stimuli consistently to a number scale. In further experiments dealing with roughness and smoothness perception, he found that the curves for roughness and smoothness were reciprocals of each other [Stevens and Harris, 1962]. He used different grits of emery, chose a standard (set to 10) and asked the subjects to base the rest of their judgments according to this standard. Interested in determining how the performance of each subject would differ if no standard was presented, he conducted another experiment in which he asked the subjects to call the first stimulus whatever number they thought was appropriate. He found that the subjects' response was more consistent when no standard was presented. Connor et al. [1990] preformed experiments where they asked the subjects to judge the roughness of dotted patterns. They asked the subjects to give any number that was appropriate for the roughness of the patterns. Using this magnitude estimation technique, they tried to determine the effects of dot spacing and dot size on roughness perception.

The type of scaling used by Stevens is based on a ratio scale that requires the multiplication of the number assigned to the standard tone by a constant. Another type of estimation which relates numbers directly to psychological magnitudes is called the absolute scale. This method does not require the subjects to compare the magnitude of the current stimuli to any of the previous ones. Subjects are generally asked to assign any number that best describes the stimuli according to their own perception. In fact, it has been shown that subjects tend to drift towards the absolute scale rather than the ratio scale when asked to estimate the magnitudes of stimuli [Zwislocki and Goodman, 1980].

Similar magnitude estimation techniques have been used by various researchers as a way to quantify the touch perception [Minsky and Lederman, 1996, Lederman and Taylor, 1972].

2.5.2 Signal Detection Theory

Study of the touch perception also involves an analysis of the sensitivity of touch. It is necessary to determine the factors that affect our touch sensation. In order to accomplish this task, psychophysicists have devised further ways to measure the sensitivity of senses. Some of these methods will be discussed in the following sections. It is important to note that these methods are not specifically designed to study the sense of touch. These are general methods that can be applied to study sensitivity of any sense.

The Yes-No Procedure

This yes-no procedure is typically employed to check if the subjects are able to detect the presence or absence of a signal [Gescheider, 1997]. A signal could be any stimulus. If the study is being conducted on the auditory sense, then the signal could be the presence of a certain frequency beep. In the case of the visual sense, the signal could be addition of a new colour in a colour pallet. In this procedure, the subjects are required to detect the presence of the signal and respond by saying *"Yes"* or *"No"*, implying the signal was detected or not respectively. The proportion of trials that the signal is present are referred to as the signal plus noise (SN) trials and the remainder of the trials are referred to as the noise (N) trials [Gescheider, 1997]. The noise in this case does not have to be the typical ambient noise. It could be anything that distracts or affects the attention of the observer. For instance, noise could be the fatigue that subjects might feel as the experiment progresses, it could be the presence of white noise in the audio case etc. In addition, the decision made by the subjects during each trial have costs (for incorrect answers) and values (for correct answers) associated with them. The proportion of SN trials and the value of correct and incorrect answers are decided by the experimenter in advance. For each type of trial, there are two decisions that the subjects may make. In an SN trial, the subjects may detect the signal and say yes (hit) or they may not detect the signal and say no (miss). In a N trial, the subjects may think the signal was presented and say yes (false alarm) or recognize that the signal was absent and say no (correct rejection). These responses are normally categorized in a table as shown in Table 2.3. The sensitivity of the subjects is measured using the hit rate (H) and the false alarm rate (F) [Macmillan and Creelman, 1991]. This is because for perfectly sensitive subjects, the hit rate should be 1 (100%) and the false alarm rate should be 0. On the other hand for a completely insensitive subjects, the hit and false alarm rate are equal because these subjects are unable to distinguish between SN and N and make guesses that bring their probability close to the chance probability.

Table 2.3: The Outcomes of the Yes-No Procedure.

	Yes	**No**
SN	Percentage of Hits	Percentage of Misses
SN	Percentage of False Alarms	Percentage of correct rejections

The signal detection theory (SDT) can be used to measure the sensitivity of the subjects using H and F values [Macmillan and Creelman, 1991]. The measure of detectability, d', is used in SDT to quantify subjects' sensitivity level. It is the difference between the z-scores of H and F as shown in Equation (2.3). Detailed derivation of d' is provided in Section B.3 in Appendix B.

$$d' = z(H) - z(F) \tag{2.3}$$

Consider an example where H = 0.8 and F = 0.4. Then,

$$\begin{aligned} z(H) &= z(0.8) = 0.842 \\ z(F) &= z(0.4) = -0.253 \\ d' &= 0.842 - (-0.253) = 1.095 \end{aligned}$$

When d' is approximately 1, the performance is considered satisfactory. When the subjects are completely insensitive, $H = F$ and $d' = 0$. For completely sensitive subjects, H = 1, F = 0 and $d' \approx 4.65$ [Macmillan and Creelman, 1991].

Forced Choice Procedure

In the forced choice procedure, the subjects are generally provided two intervals, one of which contains the signal and the other does not. Their task is to identify which of the two intervals contains the signals. Since one of the intervals always contains the signal, the subjects are forced to choose one. A procedure with two intervals is referred to as the two-alternative forced-choice (2AFC) design. There could be multiple intervals for choice - procedures are referred to as mAFC designs where m refers to the number of alternatives the subjects have to choose from. Another scenario of a forced-choice procedure could be the presentation of two stimuli and the subjects' task is to indicate the order of the stimuli. For instance, in an audio case, they could be presented with two beeps of two different intensities and be asked to determine which of the two beeps was louder. Here, they are once again forced to make a choice. For example, suppose the order of presentation is (high, low) or (low, high). In that case, the hit rate (H) is the percentage of response that are (high, low) when the stimuli is also (high,low) and the false alarm rate (F) is the percentage of responses when the response (high,low) is received when in fact the stimuli was (low, high).

This procedure is considered easier than the yes-no procedure [Gescheider, 1997]. The advantage of this procedure over the yes-no procedure is that the yes-no procedure places memory demands on the subjects. The subjects' imperfect memory may lead to a higher number of no responses - a factor known as the response bias. Each trial in the forced-choice procedure is independent of the previous trials and the subjects do not need to remember the stimuli of the previous trials. They need to compare only the stimuli presented in the current trial. The disadvantage of this procedure is that the experimenter needs to define what is meant by *"same"* and *"different"*. The subjects may not share the same definition as the experimenter leading to of response bias. The measure of sensitivity for this procedure is also given by d' as in the yes-no procedure. However, since this procedure is considered easier, the value of d' has to be adjusted down by a factor of $\sqrt{2}$. For reasons why this factor should be $\sqrt{2}$, see [Gescheider, 1997]. So for the example shown in Equations (2.4) to (2.4), d' is calculated as

$$d' = \frac{1}{\sqrt{2}} * 1.095 = 0.774$$

The Same-Different Procedure

To overcome some of the shortcomings of the yes-no procedure and the forced-choice procedure, there is the same-different procedure. In this procedure, the subjects are presented with two stimuli within the same trial. These two stimuli may be the same or different and it is the subjects' task to determine which of these two outcomes it is. The advantage of this procedure over the forced choice procedure is that the experimenter need not explain to the subjects how the stimuli will differ. In some cases, when the difference in stimuli is verbally difficult to explain, this procedure serves well. Hit and false alarm rates in this case are calculated as before. H is the percentage of trials where the subjects say *"different"* when the stimuli are different and F is the percentage of trials when the subjects say *"different"* when in fact the stimuli are same.

This procedure is considered more difficult than the yes-no procedure and the forced choice procedure [Macmillan and Creelman, 1991] because the analysis is more complicated. The experimenter does not know which decision rule the subjects choose to classify same and different stimuli. It becomes even more difficult for the subjects and the experimenter when there are more than two stimuli. Nevertheless, two different techniques are presented in Macmillan and Creelman [1991] to carry out the analysis. One is the independent-observation strategy in which it is assumed that the subjects independently compare the two stimuli to a criterion. The other is the differencing strategy in which it is assumed that the subjects compare the two stimuli against each other and call it different when this difference exceeds a preset threshold. Macmillan and Creelman recommend that the independent-observation strategy be used when there are only two different stimuli. If there are more than two stimuli, then the differencing strategy should be used. It is easy to imagine that the task becomes increasingly more difficult with a higher number of stimuli and thus the differencing strategy generally produces a higher d' value for a given set of H and F values than the independent-observation strategy. According to Table A5.3 in Appendix 5 of [Macmillan and Creelman, 1991], $d' = 1.095$ calculated earlier, would be changed to 1.84 for the independent-observation strategy. For the differencing strategy, the value of d' would be 2.35 according to Table A5.4 of Appendix 5 in Macmillan and Creelman [1991]. This result is consistent with the earlier argument that differencing strategy, generally employed for more difficult tasks with more than two stimuli, results in a higher d' value.

2.5.3 Just Noticeable Difference

In the previous sections, the procedures were generally concerned with determining the sensitivity of the subjects to different intensities of a stimulus. These procedures are generally used to measure the threshold of sensitivity. In other words, they are used to determine the smallest level of stimulus that is detectable. However, it is sometimes important to determine a difference threshold. The difference threshold refers to the smallest incremental or decremental change in stimulus intensity that is detectable by the subjects. It is also known as the Just Noticeable Difference (JND). This concept relies on the fact that, at the difference thresholds, the subjects will sometimes detect the change in stimulus and not at other times. Some methods of determining the JND are discussed below.

Method of Constant Stimuli

In the method of constant stimuli, the subjects are provided two stimuli and are asked to determine which of the two has a larger intensity. In this way, a standard stimulus and a comparison stimulus are presented in the same trial. The standard stimulus is the same in every trial while the comparison stimulus changes either in the direction of higher intensity than the standard or in the direction of lower intensity. The value of the comparison stimuli is presented randomly in a increasing and decreasing order. The two stimuli are presented either simultaneously to two different areas of the sense organ or successively to the same area. In haptics, this could mean that the texture feedback is presented to two different fingers simultaneously or to the same finger successively. Both of these techniques are acceptable. However, each one has its drawbacks.

A space error occurs when the stimuli are presented simultaneously because different sensitivities of different areas may affect the results. These errors can be reduced by presenting the standard stimulus on one area for half the trials and to the second area for the other half of the trials.

In a similar way, time error occurs when the stimuli are presented successively because this places memory demands on the subjects that have to remember the first half of the trial to use as comparison for the second half. This can be accounted for by presenting the standard stimulus first on half of the trials and second on the other half of the trials [Gescheider, 1997].

The upper limen, L_u, is the intensity larger than the standard which is detected 50% of the time. The lower limen, L_l, is the intensity smaller than the standard which is detected 50% of the time. The JND is then half of their difference [Scharf et al., 1975]. It is given by

$$JND = \frac{L_u - L_l}{2} \tag{2.4}$$

Method of Limits

Similar to the method of constant stimuli, in the method of limits, the subjects are again provided two stimuli in a given trial. Initially, the comparison intensity is set to be at a level much higher or much lower than the standard so that there is no ambiguity about which stimuli is higher. Suppose that the initial comparison intensity is set to be much larger than the standard. In that case, on successive trials, the experimenter decreases the intensity by the smallest possible value. This series of trials are referred to as the descending series. In each trial, the subjects are required to say whether the comparison stimuli is greater than, equal to or less than the standard. At the beginning, their response will be *"greater than"* for a few trials. Once the discriminability approaches zero, their response becomes *"equal to"* and then eventually to *"less than"*. L_u is the average of the two trials when the response changes from greater to equal. L_l is the average of the two trials when the response changes from equal to less. The series of trials when the initial value of the comparison stimuli is set well below that of the standard is referred to as the ascending series. A number of ascending and descending series are performed in an alternating fashion to get a set of L_u and L_l values. The means of the L_u and L_l, $\overline{L_u}$ and $\overline{L_l}$ respectively, are used to determine the JND [Gescheider, 1997]. It is given by

$$JND = \frac{\overline{L_u} - \overline{L_l}}{2} \tag{2.5}$$

It is important to note that space and time errors discussed earlier must be accounted for in similar ways. An example of an ascending and descending series is shown in Table 2.4. For the ascending series (A), L_u is the average of stimulus intensities 8 and 9 because the response changes from equal to (E) to greater than (G). L_l is the average of stimulus intensities 3 and 4 because the response changes from less than (L) to equal to (E). Similarly, the upper and lower limen are calculated for the descending series. The problem with this method is its systematic order. Two types of errors that occur with this method are the error of habituation or the error of expectation. Habituation occurs when the subjects keep responding with the same answer because the comparison stimulus is changing slowly. Expectation occurs when the subjects change the response after a number of trials because of the awareness that at some point the answer is expected to change [Scharf et al., 1975]. These errors can be avoided by restricting the size of the trials so that the subjects do not tend toward any habit and by changing the starting value of each series so that it is harder to expect when the response should change.

Staircase Method

The staircase method, otherwise referred to as the variations in the method of limits, is derived from the method of limits. The subjects are initially presented with a stimulus intensity which is either far below or far above the intensity of the standard stimulus. For illustrative purposes, assume that the stimulus intensity is far below that of the standard. In the ascending series, the intensity of the comparison stimulus will be increased in steps until the subject's response changes from *"less than"* to *"equal to"*. At this point, the series is reversed. An example of

Table 2.4: Ascending and Descending series of the Method of Limits

Stimulus Intensity	**A**	**D**
13		G
12		G
11		G
10		G
9	G	E
8	E	E
7	E	E
6	E	E
5	E	E
4	E	L
3	L	
2	L	
1	L	
$\mathbf{L}_u$	**8.5**	**9.5**
$\mathbf{L}_l$	**3.5**	**4.5**

this method is shown in Figure 2.11. The points at which the subject's response changes is called a transition point. The experiment is continued until a number of transition points are obtained. The JND is taken to be the average of these transition points. This method generally requires fewer trials than the method of limits because intensities that are far below or far above the standard intensity are not presented [Gescheider, 1997].

Method of Adjustment

The method of adjustment is different from all of the previous methods because in this method, the intensity of the comparison stimulus is controlled by the subjects

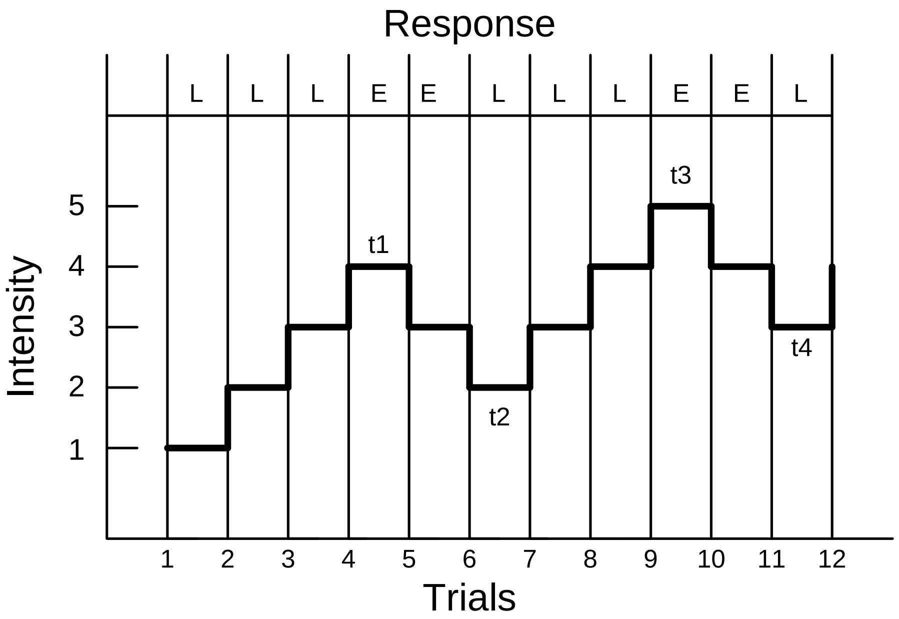


Figure 2.11: The staircase method

rather than the experimenter. The subjects are provided with a standard stimuli and a variable comparison stimuli. Their task is to adjust the intensity of the comparison stimuli until it matches the standard. The idea behind this concept is that the subjects will sometimes overestimate the intensity and at other times, underestimate it. This information can be used to define thresholds [Gescheider, 1997]. However, this method has been criticized as being invalid for defining the JND [Scharf et al., 1975]. First, for this method to work properly, the comparison stimulus has to be continuously variable which may not be the case for some studies. Second, the two stimuli have to be presented simultaneously which may not be possible. If the stimuli are presented in successive order with the standard presented first, then the time errors described earlier cannot be corrected [Gescheider, 1997].

Interweaving Staircase Method

In the staircase method, the experiment can still have errors introduced in it due to subjects' habituation and expectation. To overcome this issue, the interweaving staircase method is developed in which an ascending and a descending series may be presented in a random order to the subjects. In fact, the two series are intertwined such that each series does not have to be terminated before the other one begins. This scenario is presented in Figure 2.12 for successive presentations of the standard stimulus followed by the comparison.

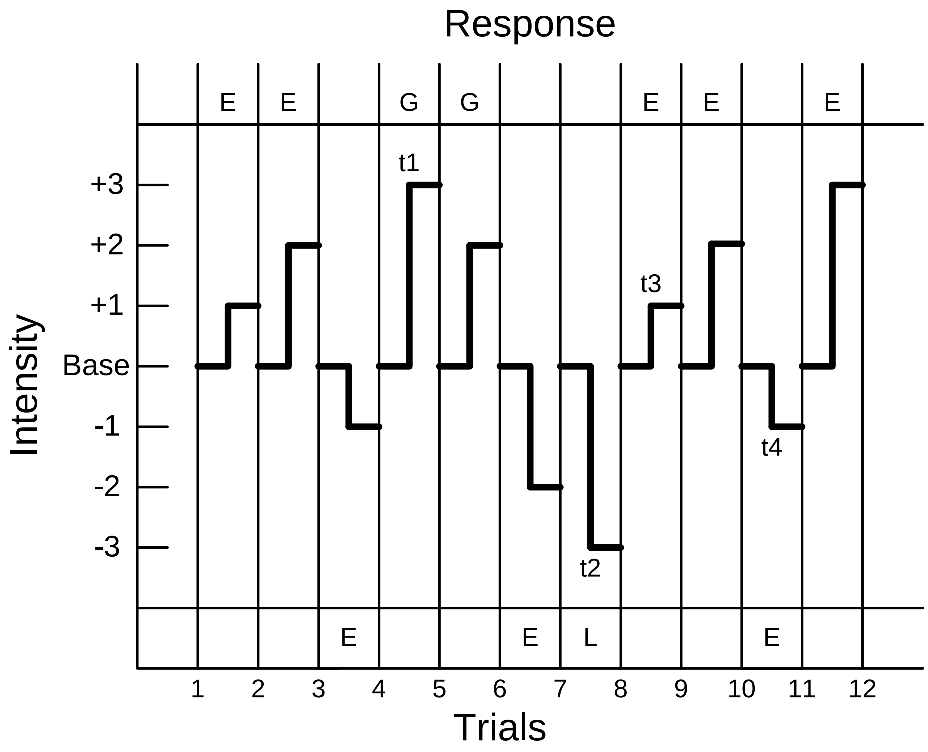


Figure 2.12: The interweaving staircase method

In this case, the subject is initially presented with a comparison stimulus intensity that is greater than the standard by 1 incremental unit. The subject is asked to determine if the response is greater than, less than or equal to the standard. If the subject responds with *"equal to"*, then the value of the comparison response is increased by another unit in the next trial. Without waiting for this ascending series to terminate, in the following trial, the value of the comparison stimuli is decreased by 1 unit. In this way, the ascending and descending series are intertwined. A transition point occurs, when the response of the subject changes for a series. The JND once again is the average of the transition points. In this case, an upper limen and a lower limen JND can be calculated individually by taking the average of the the ascending and descending series respectively. So in the example shown, the upper limen JND is the average of points t1 and t3 and the lower limen JND is the average of points t2 and t4.

Chapter 3

Tactile Device

3.1 Motivation and Design Considerations

As discussed earlier, haptic feedback is comprised of two parts: the kinesthetics and the tactile. Hence, a haptic device needs to be able to transmit both types of information. The goal of this research is to combine these two effects at a macro and a micro level scale. Designs of force feedback devices have been well studied. Research in this field started with the transmission of large forces. However, now researchers are focusing more on the tactile aspect. The interest in the current project began with the idea of designing a tactile device that can be attached on an existing force feedback device. In this way, the kinesthetic force information would be provided by the force feedback device and the tactile information would be provided by the tactile device.

It is important to determine what type of tactile information should be considered. Much of the literature in studying the tactile sense is concerned with the ability to distinguish different roughnesses. As discussed in Chapter 2, roughness is of prime interest over smoothness because the absence of a rough texture can be interpreted as smooth. Therefore, the tactile device should be able to portray different roughnesses. In Section 2.2.2, it was discussed that people detect texture best by rubbing their fingers laterally on a surface. This piece of information is important in the design of a tactile device because to imitate reality, the hand movements of the users should be as natural as possible. Furthermore, the roughness should be portrayed via direct finger contact instead of using a probe since direct contact gathers the most information. Such a design places further constraints:

1. The device must be attached to an existing force feedback device, thus it must be compact and light to reduce loading on the force feedback device.
2. The existing force feedback device must be chosen such that the user can perform lateral motions that are required to detect textures.
3. The device must be able to portray different magnitudes of roughness without changing the stimulus mechanically.
4. Direct contact with the hand and fingers requires that the device must have smooth edges and feel comfortable to the users.
5. To increase comfort, the users hand must not be tied to the device so that they can let go of it whenever they wish.

Several ideas using pin arrays, magnetorheological (MR) fluids and SMA springs were formed. However each one of these violated one or more constraints. The pin array devices are generally bulky and heavy due to large number of actuators that are required. A design using MR fluids introduces much more complexity. For texture display, several spikes in the fluid need to be created and this is not possible. SMA springs have the same problem as pin array devices. A matrix of springs would need to be used and a fine resolution of the display may not be achieved due to physical limitations.

The design of the device to be studied in this thesis allows users to place their fingertip on an aperture and a stimulus is created on the finger through the aperture at different speeds. The stimulus is created by using a spiral brush. This employs one actuator and one spiral brush. A chassis is designed so that the actuator and brush can be overlayed on top of an existing force feedback device. In this way, this tactile device meets all of the above constraints. The force feedback device to be used is the PHANTOM Omni® due to its ease of use with the software that will be discussed later in Section C.2. For the purposes of this research, joints 2 and 3 of the device, as shown in Figure 3.1, are locked in fixed positions so that the only motion possible is the radial motion due to revolute joint 1. A more detailed description of the device and its components is provided in the following section.

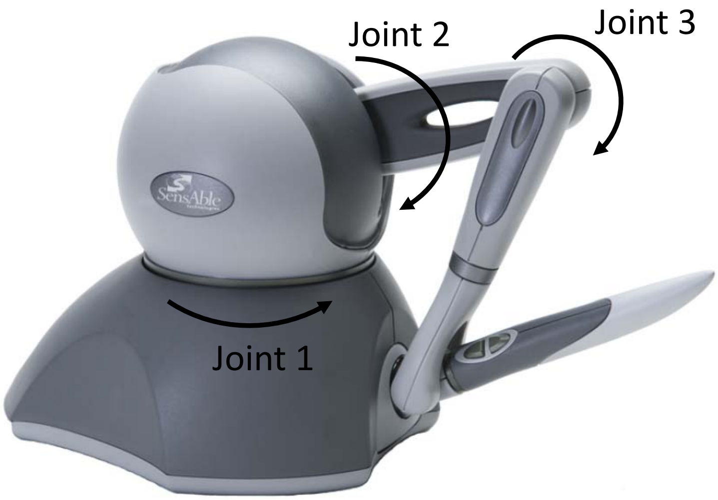


Figure 3.1: Joints 1 to 3 of the PHANTOM Omni®. © Copyright SensAble Technologies, Inc [Sensable Technologies, 2009]

3.2 Device Description

The tactile device is a one degree of freedom device consisting of a DC motor and a spiral brush. The brush is attached to the motor and the speed of the brush is varied to provide different stimuli. The motor and brush combination is inserted into the chassis as shown in Figure 3.2. A small aperture is cut out at the top of the chassis. The subjects place their index finger on the aperture and can feel the brush rubbing against their finger. The device is designed to be able to fit on top of the PHANTOM Omni®. This is achieved by removing the end cap of the stylus of the Omni and inserting the tactile device in its place. The complete design is shown in Figure 3.3.

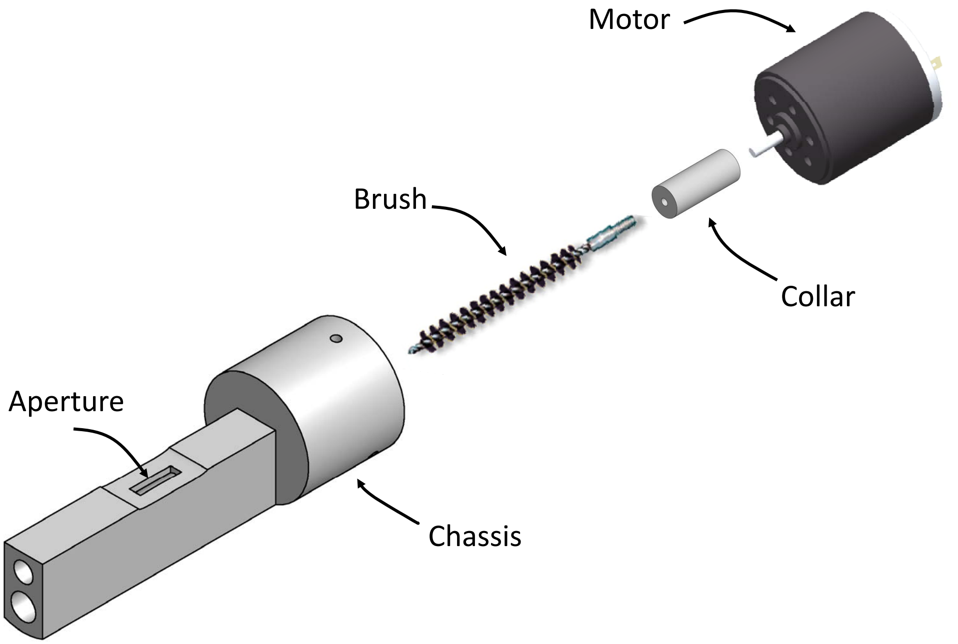


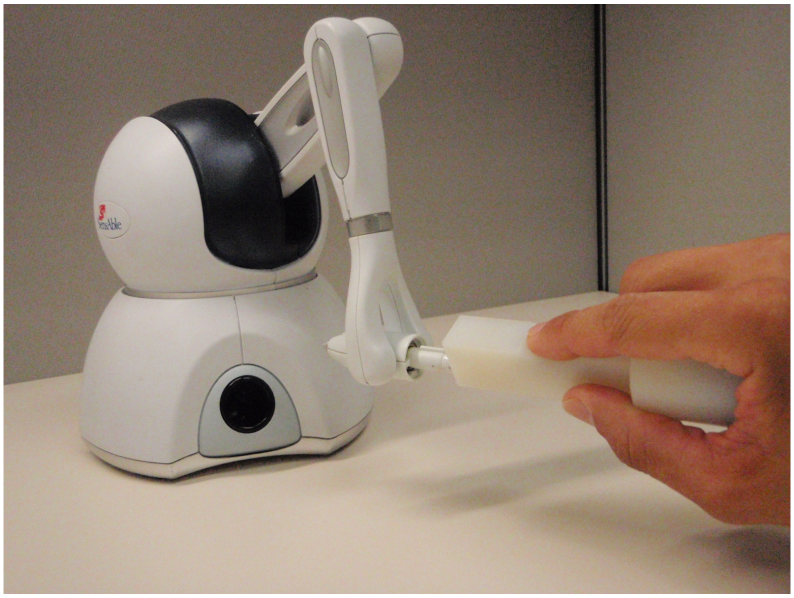
Figure 3.2: Exploded view of the tactile device

3.2.1 DC Motor and Spiral Brush

The tactile device should be as small as possible and as lightweight as possible in order to reduce loading on the force feedback device. Consequently, the DC motor inherits these specifications as well. For speed control, the motor has to be equipped with an encoder. The motor has to be bi-directional. It must have low friction in order to mitigate any non-linearities. From preliminary prototypes with hobby motors, it is found that the motor stall torque has to be at least $0.014Nm$. The specifications of the DC motor that meet these constraints are given in Table C.1 in Appendix C

Since only a small part of the brush comes in contact with the fingertip, the length and diameter of the brush can be arbitrary. The only requirements for the

(a) Attached to PHANTOM Omni®



(b) Tactile device in use

Figure 3.3: Tactile device

brush are that it must not be painful to the user and that it stiff enough so that the forces generated on the fingertip are noticeable. On one end, the brush is attached to the motor shaft while the other end is unsupported. This cantilever design requires that the brush should be rigid to reduce deflection when it brushes against the finger. This is required in order to decrease the friction that is created if the brush comes into contact with the inside walls of the chassis. A bent brush also creates unwanted vibrations. It is not necessary for the brush to be spiral. This happened to be the case because the only commercially available brushes in small quantities that have a rigid structure are the twisted-in-wire spiral brushes as shown in Figure 3.4. The bristles of this brush are made of nylon. The end of the brush is threaded for ease of installation. This is one of the strong features of this brush because the brush can be easily coupled to the motor shaft via a collar. The motor shaft is friction fit into the collar whereas the brush is twisted in using the coupling.

Figure 3.4: Spiral Brush [Torrington Brush Works, 2009]

3.2.2 Chassis

The chassis of the device is made of plastic. The motor and the brush combination are fitted into the chassis. Any unnecessary material is removed in order to reduce the weight. The aperture size of the chassis is approximately 1*cm* x 0.3*cm* rectangular. This size was chosen through user testing with various prototypes. The size was meant to be as small as possible and still be able to provide contact with the brush. Male and female subjects with various different finger sizes were used to decide the final size of the aperture. The chassis has three holes, labeled A, B and C on Figure 3.5. Hole A is for the motor, hole B for the brush and hole C is for the stylus of the PHANTOM Omni®. The stylus is friction fit, whereas the motor is secured with three equally spaced set-screws. The hole diameter for the brush is slightly bigger than the diameter of the brush itself in order to prevent the brush from rubbing against the inside walls. Detailed measurements of the chassis are provided in Appendix D.

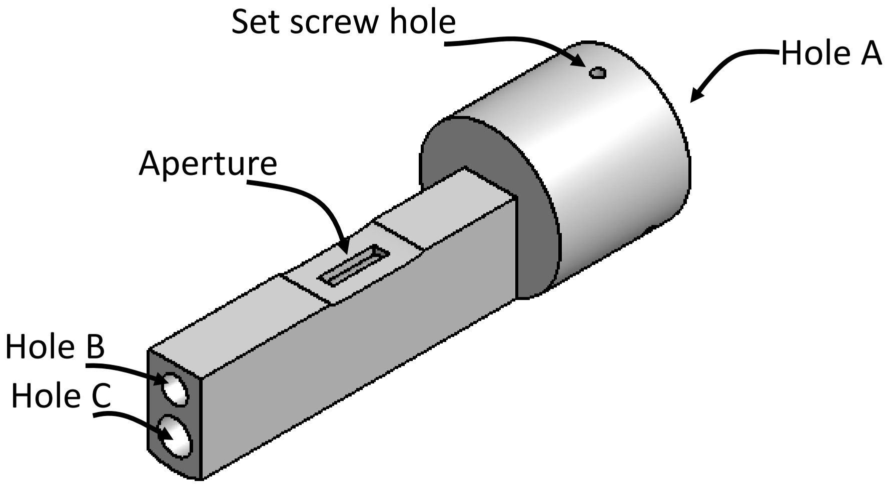


Figure 3.5: Chassis design

3.3 Control

PD control is used to control the speed of the motor. A block diagram of the control is provided in section C.5 in Appendix C. To give the subjects the feeling that they are feeling a stimulus as they are moving their hand back and forth on a surface, the motor is turned on only when the users start moving their hand at the beginning of each trial. As soon as the motor starts, it runs independently of the motion of the subject's hand. This is to ensure that the speed of the motor remains constant. The speeds chosen for the experiments, in revolutions per second (RPS), are $20RPS$, $40RPS$ and $60RPS$. Once again, these are chosen experimentally as speeds that are most comfortable to the subjects while covering a wide range. The step response of the motor to these speeds is shown in Figure 3.6.

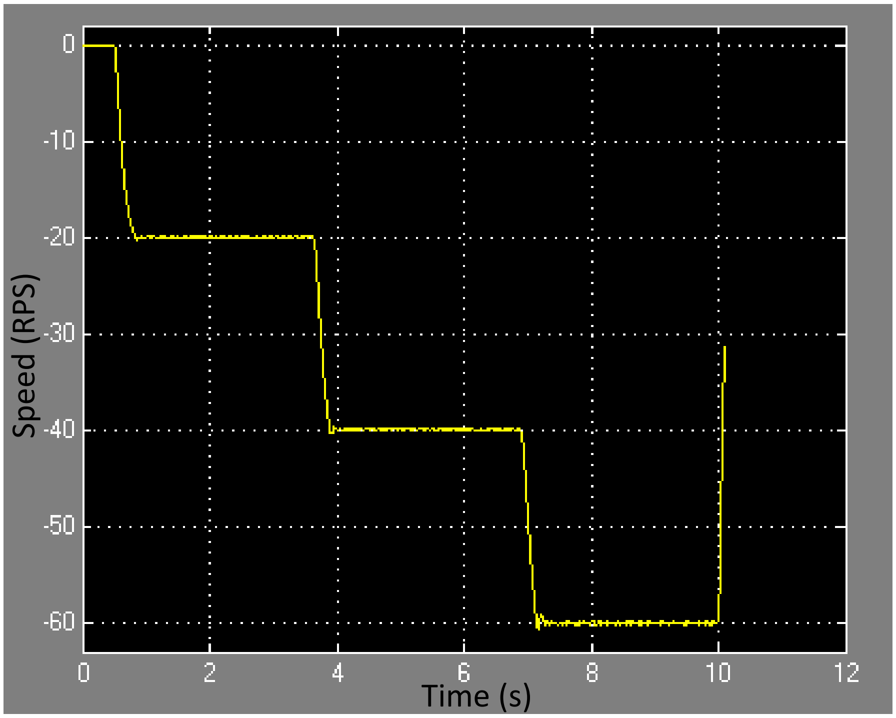


Figure 3.6: Step Response to three different speed levels

There are no kinesthetic forces applied to the subjects through the PHANTOM Omni® device. This device is used only to monitor the position and velocity of the user's hand for graphical purposes and to provide a proof of concept that this tactile device can be overlayed on an existing force feedback device.

Chapter 4

Design of Experiments

The experimental setup consists of a desk with two chairs on opposite sides for the subject and the experimenter. On the desk, the tactile device is placed inside a large box with a large opening on the experimenter's side and a smaller opening on the subject's side. There are two monitors as well - one facing the subject and the other facing the experimenter. The subject's monitor shows a graphical display only while the experimenter changes the control variables. In this way, the subject cannot see what parameters the experimenter is changing.

4.1 Graphical Interface

The general format of the experiments is for the users to place their index finger on the aperture while moving the entire tactile device in a horizontal motion (left-right-left...). To complete the loop between vision and touch, their hand motion is also shown to them on a graphical display using a spherical avatar. As the subjects move back and forth with the device, the avatar represents their motion on the interface. The subjects watch the avatar move on a planar surface so that they feel the virtual texture of the planar surface. The mapping between their hand motion and the avatar is one-to-one. In other words, $5cm$ displacement of their hand corresponds to $5cm$ displacement in the same direction of the avatar.

The size of the planar surface in the x-dir, as shown in Figure 4.1, is $10cm$. The avatar movement is 1-DOF; it moves in the x-dir only. The subjects are asked not to move past the side boundaries of the surface, thus their hand motion is approximately $8cm$. Due to the base revolute joint of the PHANTOM Omni® and the fact that joints 2 and 3 are locked, pure x movement is not possible. There is a small z component, which is ignored for simplicity. The maximum value of the z component is $1.5cm$.

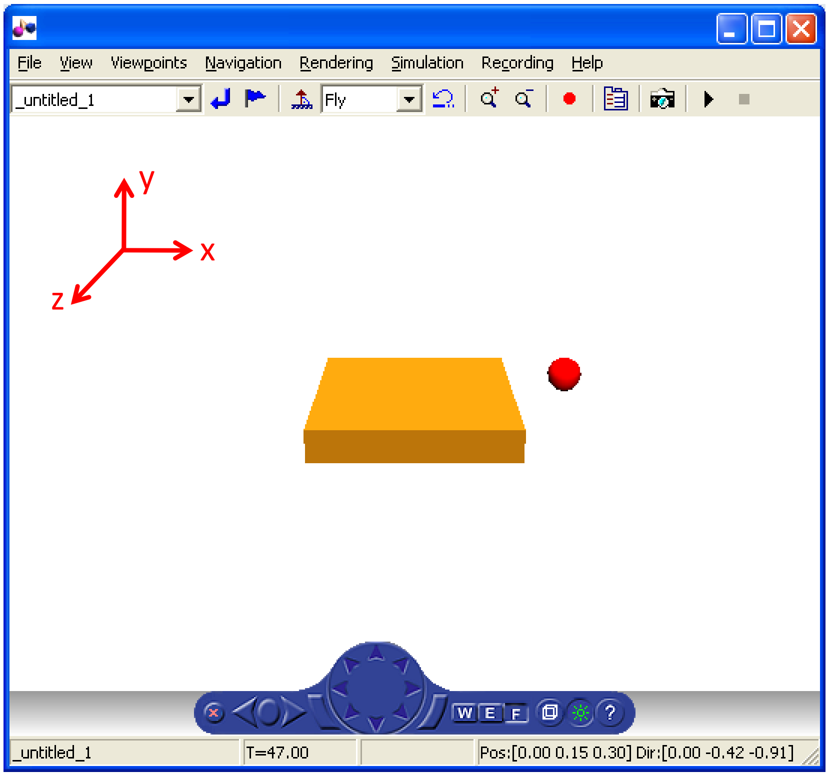


Figure 4.1: Graphical interface

The graphical display is designed to be simple and easy to understand for the subjects. The graphics are created in V-Realm Builder and incorporated into Simulink® using the Virtual Reality Toolbox. The graphics are rendered at 30 frames/sec. The colour of the planar surface is arbitrary. However, the colour of the avatar is not. To maintain consistency in the rate of hand motion between all subjects, their lateral speed has to be constrained. The subjects are told that there is a range of speed that they should try to stay within. When they are in that range, the colour of the avatar is green, otherwise it is red. This range is chosen by experimenting with various subjects and finding the range that is most achievable. This range is between $1cm/s$ to $3.5cm/s$ inclusive. To ensure that the ball stays green at the end points, the moving average over the previous $0.5s$ of their speed is used to check if the speed is within the given range or not. This is necessary because at the end points, when the subjects change the direction of movement, the speed drops to zero. Taking instantaneous speed would cause the colour of the avatar to turn red. To avoid distracting the subjects, the average of the speed over the last $0.5s$ is used to control the avatar colour since it does not change abruptly.

4.2 Training Subjects

At the beginning of each experiment, subjects are trained how to use the tactile device. First of all, since all subjects are experimentally naive and many have not had any previous experience in haptics, they are given a brief description of haptics. Then, they are explained how lateral motion plays an important role in texture perception. Following this, the experimenter tells the subjects that the tactile device they will be using is hidden inside the box. They are not allowed to look inside the box in order to ensure that their response is not biased by the appearance of the device. The experimenter gives a demonstration of what the subjects will be required to do. They are told how to keep the ball green and are asked to keep a light pressure on the aperture.

Once the subjects have adjusted their chair to a comfortable position, the experimenter, helps them place their index finger on the aperture. The subjects then move their hand from the elbow in a sideways motion while trying to keep the ball green. With speed regulation turned off, the speed of the motor is used as an indication of how much load the subjects are applying. Free running, the speed of the motor is approximately $24RPS$ at $2V$. The subjects are asked to adjust their finger pressure until the speed is approximately $22RPS$ as shown in Figure

4.2. They are asked to practice at this pressure and rate of motion until they are comfortable. Then they are asked to switch hands and repeat the procedure with the other hand.

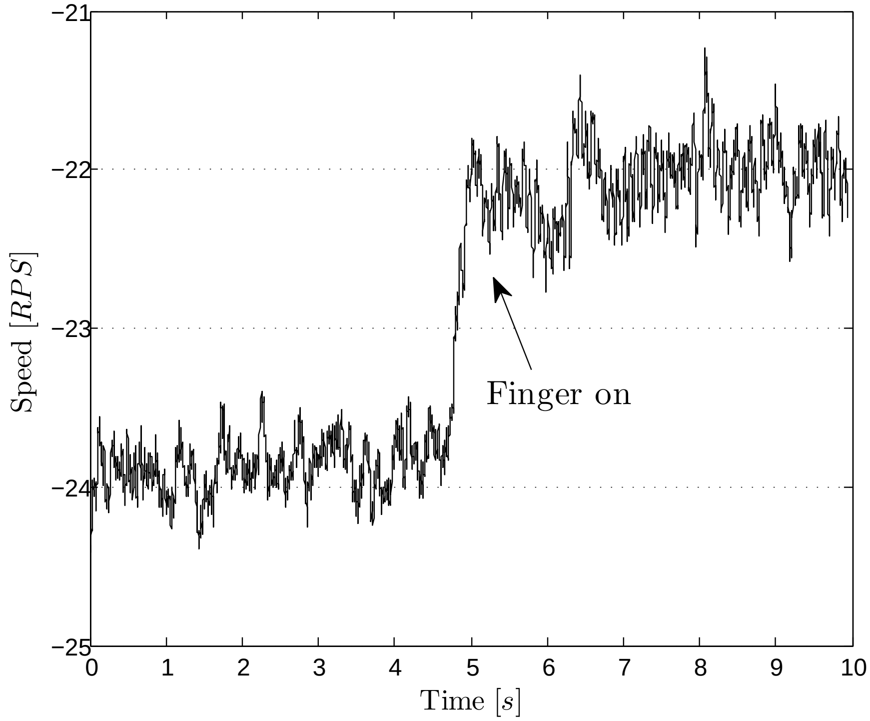


Figure 4.2: Indication of load on the motor with and without the finger in an open loop control

It is important to note that while the load on the motor can be judged in the training phase, it is not possible to judge this load during the actual testing because the motor speed is regulated automatically. During the testing, the subjects are reminded frequently about keeping the pressure light. However, it is likely that their finger pressure varies throughout the testing. This is not considered an issue here because Lederman et al. [2004] have shown that small variations in finger pressure do not affect texture perception. This may seem to contradict their earlier results [Lederman and Taylor, 1972, Lederman, 1974] that increasing fingertip forces increases the perceived roughness of grooved surfaces. However, their recent results show that while this is still the case when force variation is large (from $0.27N$ to $4.4N$ in their previous experiment), for small variations, the texture perception is not affected. They found that when the users were asked to maintain a “light” force, the variation in force throughout the experiment did not affect their perception significantly. Thus, the force is not monitored in these experiments; instead the subjects are asked to apply “light pressure”.

The subjects are asked to keep their hand motion between the side boundaries of the planar surface on their screen. Speed ranges from $20RPS$ to $70RPS$ in both clockwise (CW) and and counter-clockwise (CCW) directions are applied in the training phase for their awareness. However, they are not told the actual speeds that will be used during the experiments. Subjects are asked to focus on the sensation in their fingertip only and not in the rest of their hand.

4.3 Areas of Investigation

The purpose of the device is to be able to portray various levels of roughness. To check whether the device is capable of meeting this criterion, psychophysical experiments have to be conducted. The experiments conducted in Chapters 5 to 7 are designed to study the following factors:

- Intensity JND — How does the JND with respect to speed differ at two different levels of base speed?
- Speed — What is the effect of changing the speed of the brush on the roughness perception?
- Direction — Is the change in the direction of rotation of the brush detectable? If so, then does it affect the roughness perception?

These questions will be answered using the results from three separate experiments. The hypotheses related to each will be presented in the corresponding chapters.

Chapter 5

Experiment 1: Just Noticeable Difference

5.1 Introduction

The purpose of this experiment is to determine the just noticeable difference (JND) with respect to speed at two different levels of base speed. The levels of base speed used in this experiment are the low speed, $20RPS$ and the high speed, $60RPS$. Two levels of speed are deemed sufficient to characterize how the JND changes with speed. For similar reasons, the experiments are performed in CCW direction only. The interweaving staircase method is used to determine the JND. This method is chosen to reduce response bias, which is more common in the other methods outlined in Section 2.5.3.

5.2 Hypothesis

The hypothesis tested in this experiment is as follows:

H_1: The JND with respect to speed decreases as the speed of the brush increases.

This hypothesis is driven by the the results of Salada et al. [2004], who found that as the speed of a rolling wheel increases underneath the fingertip, the slip sensitivity to speed decreases.

5.3 Participants

There were 13 subjects (9 male, 4 female) between the ages of 18 and 32 who took part in this experiment. All subjects are different from those in experiment 2 and experiment 3. All subjects are students at the University of Waterloo. All are right-handed. None of the subjects have any neurological or physical injury that affected sensitivity of the index fingers of both hands. This experiment is approved by the office of research at the University of Waterloo (ORE # 15667). The experiment is performed according to the ethical guidelines. Each subject signed a consent letter prior to beginning the experiments.

5.4 Method

The experiment is conducted in two separate sessions with a time gap of at least 24 hours in between to prevent fatigue due to long experiment times. One of the two base speeds is tested on day one and the other on day two. For 6 subjects, the $20RPS$ level is used on day one and for 7 subjects, the $60RPS$ level is used on day one. If all the subjects are tested with $20RPS$ level on day one, then perhaps the effects of the speed used on day one could be confounded with the average results. However, by testing half of the subjects with $60RPS$ on day one, any effects introduced by the order of the speed will cancel out when the average is taken across all subjects.

For each level of speed, there are 40 trials. Half of the trials are in the incrementing direction and the other half are in the decrementing direction from the base. The incrementing and decrementing trials are randomly spaced among the 40 trials. The resolution for increment and decrement is chosen to be $1RPS$. This is chosen in part to ensure that the actual speed can be read from the motor without any overlap in the signal. Furthermore, from pilot studies, it was found to be the resolution that is low enough to be undetectable and high enough to avoid large number of trials. Figure 5.1 shows the actual speed read from the motor when the base speed is $20RPS$ and a $1RPS$ change is applied in the incrementing and decrementing directions.

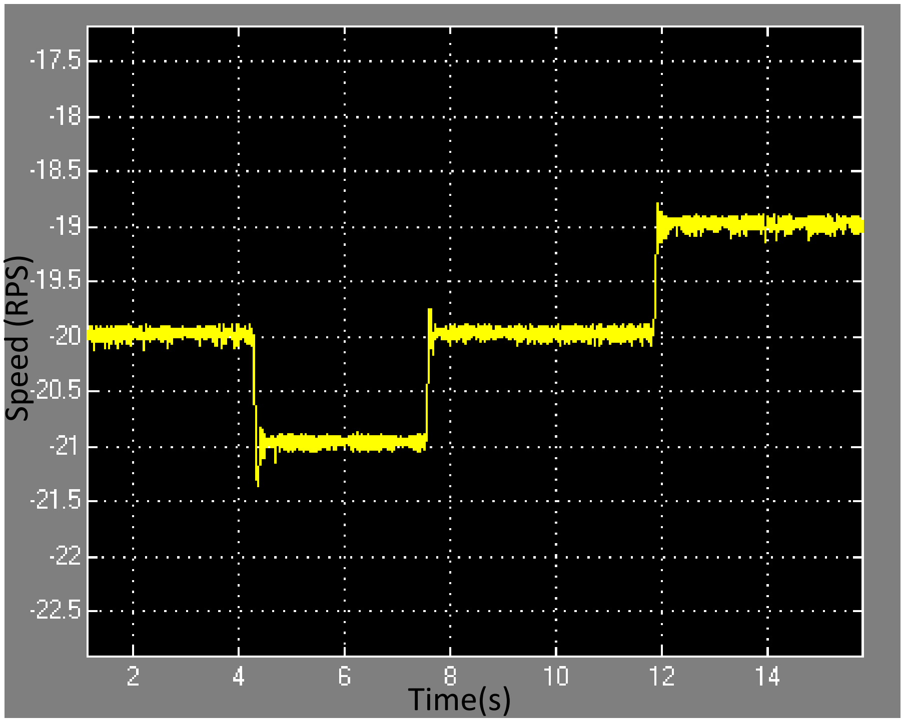


Figure 5.1: The speed of the brush shown at $20RPS$ base speed and an increment and decrement of $1RPS$

The effects of adaptation are reduced by having the subjects switch hands on alternating trials. Half of the subjects that start the experiment with $20RPS$ base speed on day one, start with their right hand and the other half start with the left hand. Same applies to the subjects that start with $60RPS$ base speed on day one. If all the subjects start the experiment with their right hand, then perhaps the effects of hand could be confounded with the average results. However, by asking half of the subjects to start with the left hand, any effects of hand will cancel out when the average is taken across all subjects. The organization of subjects can be seen in Figure 5.2.

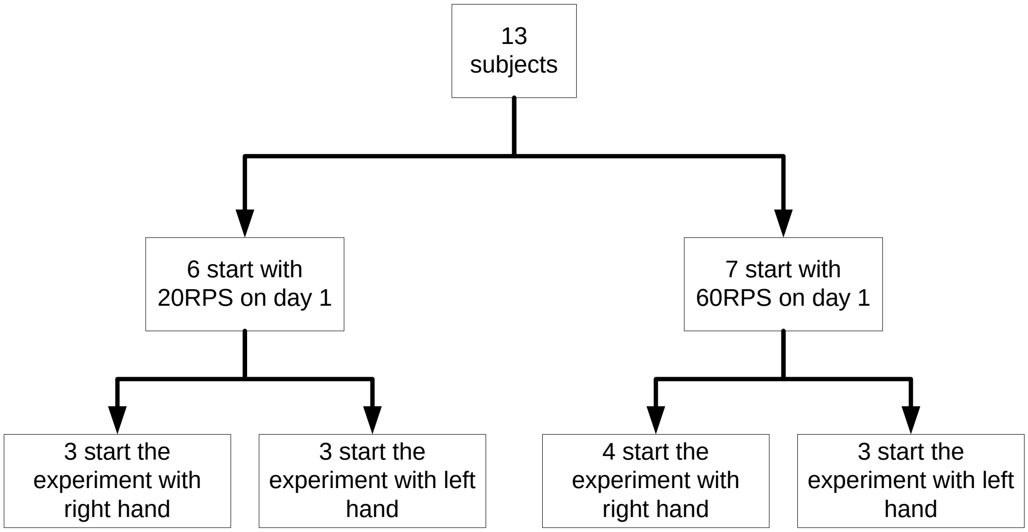


Figure 5.2: Organization of subjects

Each trial is $16s$ long. At the beginning of each trial, the base speed is applied for at least $5s$. The speed then increments or decrements automatically by the appropriate amount according to the interweaving staircase method. The speed change occurs anywhere between $5s$ to $10s$ so that the subjects do not expect the change to occur at the same time in every trial. The range $5s$ to $10s$ is chosen so that the base stimulus and the comparison stimulus are presented for at least $5s$ in every trial. Through pilot experiments, it was determined that $5s$ is enough time for subjects to grasp the stimulus. Long trial times are avoided to reduce adaptation. The stimuli are presented successively and the standard stimulus (base speed) is always presented first. This method introduces time errors discussed in 2.5.3. However, the effect of these errors is assumed to be negligible in this experiment because there is no time gap between the two stimuli.

During each trial, the stimulus begins only when the subjects start moving their hand (see Section 3.3). A “thumbs up” signal from the experimenter is used to indicate the start of each trial.

When the step changes are around $4RPS$ to $5RPS$, the noise made by the device becomes audibly different. To prevent subjects from using the change in noise as an indication of stimulus change, they are asked to wear earmuffs throughout the experiment. The training plus testing session on each day takes approximately $30min$ to finish.

5.5 Procedure

Each subject starts with a training session outlined in Section 4.2 before beginning the experiment on each day. The subjects are allowed to train for as long as necessary to get used to the hand motion needed to keep the colour of the avatar green and the applied vertical pressure light. Prior to beginning the actual experiment, a ceiling test is performed in which subjects are provided large changes (between $\pm 8RPS$ to $\pm 15RPS$) in order to ensure that they are able to at least detect these extremes. These numbers were experimentally determined from pilot studies as being detectable 100% of the time for both speed levels in both incrementing and decrementing directions. This technique also allows for the subjects to learn what type of change in stimulus to expect. They are informed that during the actual testing, the intensity of the change will be smaller and that they should pay close attention. The subjects are given the following information:

> There will be 40 trials on the first day and 40 trials on the second day. Begin the experiment with your right[1] hand. Each trial will be $16s$ long. For each trial, I will wait for you to place the index finger of the appropriate hand on the device. Once you are ready, wait for my signal to begin moving back and forth. When you begin moving your hand, the stimulus will start automatically. During the trial, there may or may not be a change in the stimulus. When you feel that the stimulus changed, immediately tell me how the signal changed. Say *"Increase"*

---

[1] Seven subjects are asked to start with their right hand and six subjects are asked to start with their left hand.

> if you feel that the stimulus frequency increased and say *"Decrease"* if you feel that the stimulus intensity decreased. Do not wait to tell me this at the end of the trial[2]. If there is going to be a change, then it will be a step change. At the end of the trial, the stimulus will stop automatically. At this point, remove your hand from the box and replace it with the opposite hand and wait for my signal to begin moving. You may ask me to repeat any trial if you feel it necessary. You must wear earmuffs throughout testing in order to reduce ambient noise and most importantly, to block audio clues from the device.

5.6 Results

The JND results for each subject are shown in Table A.1 in Appendix A. The first 20 trials for the $20RPS$ base speed for one of the subjects are shown in the interweaving staircase plot in Figure 5.3. This subject has 12 transition points in the first 20 trials. Points t1 - t4 and t6 - t7 are used to find the upper limen (L_u) JND and points t5 and t8 - t12 are used to find the lower limen (L_l) JND.

The upper limen and lower limen JND found by averaging across all subjects for the two speeds are shown in Table 5.1. The results are presented as a percentage of the base speed. The average data is shown graphically in Figure 5.4 along with the standard errors.

Table 5.1: The upper and lower limen JND for the two base speeds.

Base speed [RPS]	L_u **JND [%]**	L_l **JND [%]**
20	17.2	15.2
60	8.15	9.63

---

[2] This allows for further rejection of response bias as the subjects are not given the opportunity to guess at the end of the trial.

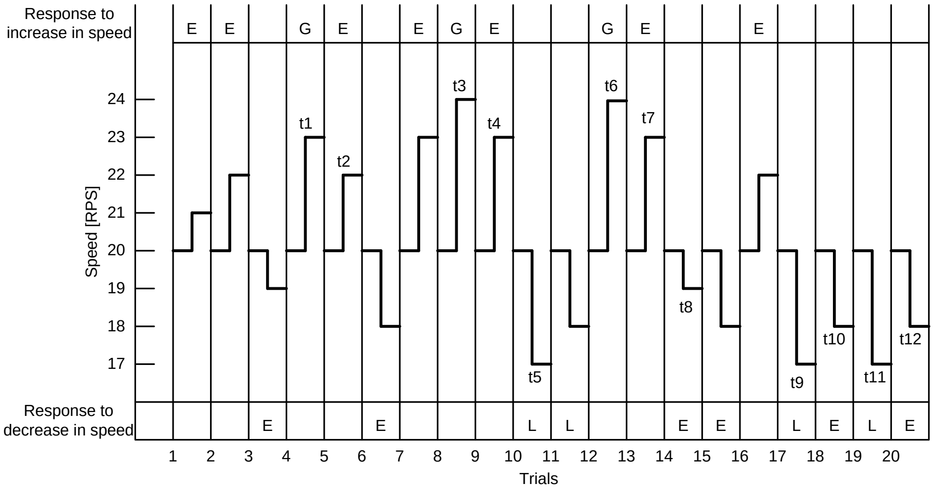


Figure 5.3: A typical test scenario at $20RPS$ base speed. (E = equal to, G = greater than, L = less than)

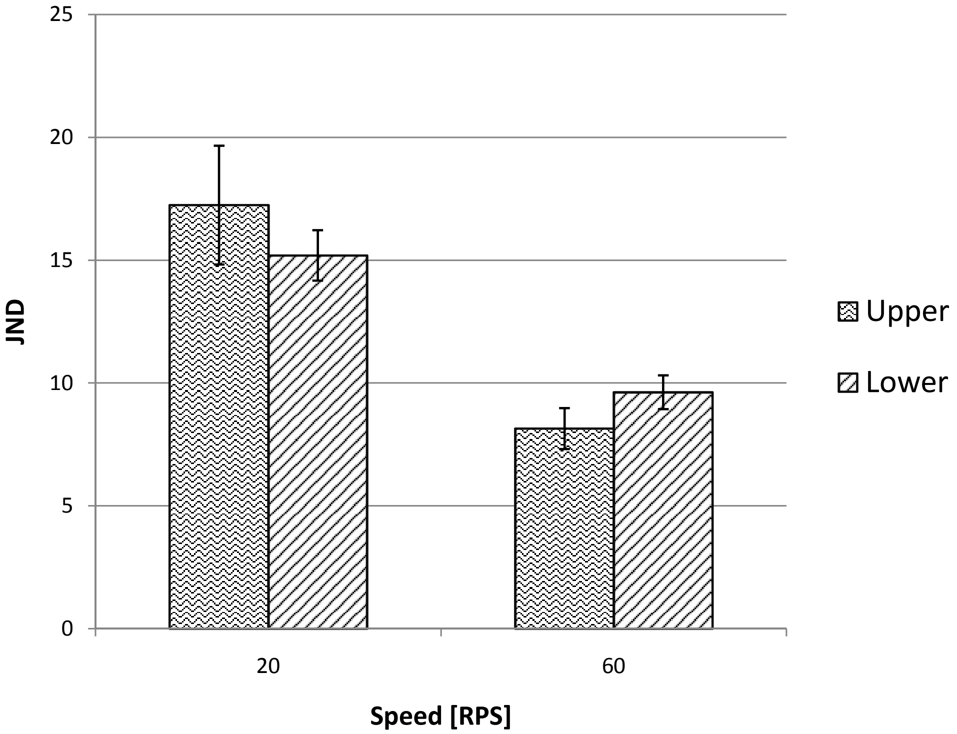
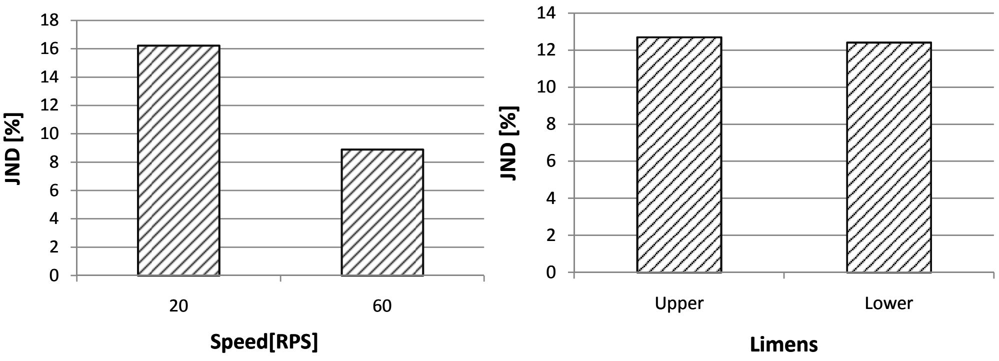


Figure 5.4: JNDs for each speed along with standard errors

Between each speed, the $20RPS$ level shows higher JNDs than the $60RPS$ level. This indicates that as the speed of the brush increases, the JND for speed decreases. The statistical significance of this difference is found by performing a 2-



(a) Across the upper and lower limens (b) Across each speed

Figure 5.5: Average JNDs

way within subject analysis of variance (ANOVA). Detailed description of ANOVA can be found in Appendix B. The two factors are the base speed and the direction of stimulus increase (upper and lower limens). The analysis is performed using SAS, a statistical analysis software. The results are based on a 0.05 rejection level. The detailed results of ANOVA are shown in Table A.2 in Appendix A.

The ANOVA results show that there is no significant interaction between the speed and direction, F(1,12)= 3.24 and p = 0.0969. The level of speed significantly affects the JND, F(1,12) = 25.04 and p = 0.0003. Consequently, Figure 5.5a shows that there is a large difference between the two levels of speed, when the upper and lower limen JNDs within each speed are averaged. The direction (upper or lower) shows no significance, F(1,12) = 0.04 and p = 0.8432. This can be observed in Figure 5.5b, where the upper and lower limen JNDs are found by averaging across both base speeds.

5.7 Conclusion

This analysis shows that as the speed of the brush increases, the upper and the lower limen JNDs decrease significantly. The upper limen JND and the lower limen JND for a single level of speed are not significantly different from each other. The upper limen JND of the low speed is significantly greater than the upper limen JND of the high speed. Similarly with the lower limen JNDs. These results are analogous to the ones found by [Salada et al., 2004].

In order to provide a change in stimulus, the speed has to increase or decrease by at least 17.2% or 15.2% respectively when the base speed is $20RPS$ and at least 8.15% or 9.63% respectively when the base speed is $60RPS$. These results will be used to determine the levels of speed that can be used to test for roughness perception in the next experiment. In order to provide distinct stimuli, the levels of speed should be appropriately far away from each other so that the change in speed is detectable.

This experiment confirms the hypothesis H_1.

Chapter 6

Experiment 2: Roughness Magnitude

6.1 Introduction

Recall that the original goal of the device is to mimic different levels of roughness. The purpose of this experiment is threefold. First, the goal is to determine if the subjects can detect roughness using this tactile device. Second, if the texture is classified as rough, then the goal is to study if different speeds of the brush can be used to convey different magnitudes of roughness. Third, the objective is to determine if the direction of rotation of the brush affects the roughness perception. Three speed levels are considered in this experiment: $20RPS$, $40RPS$ and $60RPS$. According to the results of the previous experiment, these speeds can be differentiated by all users. This range of speed also allows for a better resolution to study the effects of speed on roughness perception. The experiments are conducted using both CW and CCW directions.

6.2 Hypotheses

The hypotheses tested in this experiment are as follows:

H_2: The texture represented by the brush is rough.

H_3: The speed of the brush can be used to control the perceived roughness.

H_4: Increasing the speed of brush decreases the magnitude of roughness.

H_5: The direction of the brush does not change the magnitude of roughness.

All of these hypotheses are tested in a single experiment outlined in the following sections.

6.3 Participants

There were 17 subjects (16 male, 1 female) between the ages of 22 and 30 who took part in this experiment. All subjects are different from those in experiment 1 and experiment 3. All subjects are from the University of Waterloo. All but 2 subjects are right handed. None of the subjects have neurological or physical injury that affects sensitivity of the index finger of both hands. This experiment is approved by the office of research at the University of Waterloo (ORE # 15667). The experiment is performed according to the ethical guidelines. Each subject signed a consent letter prior to beginning the experiments.

6.4 Method

The experiment is conducted in three separate sessions with a time gap of at least 24 hours in between to prevent fatigue due to long experiment times. There are 60 trials in total split over three days (20 trials/day). To reduce the effects of adaptation, left and right hands are used on alternating trials.

Nine subjects start the experiment with left hand and eight subjects start with the right hand. If all the subjects start the experiment with their right hand, then perhaps the effects of hand could be confounded with the average results. However, by asking half of the subjects to start with the left hand, any effects of hand will cancel out when the average is taken across all subjects. The 60 trials are split into levels shown in Table 6.1. All levels are randomly distributed among 60 trials.

Table 6.1: Distribution of trials in experiment 2.

Speed [RPS]	**Direction**	**Number of Trials**
20	CW	10
20	CCW	10
40	CW	10
40	CCW	10
60	CW	10
60	CCW	10

Each trial is $10s$ long. Only one level of stimulus is presented in each trial. The $10s$ period was chosen experimentally in a pilot study to be sufficient time to grasp the stimulus. Long trial times are avoided to reduce adaptation.

During each trial the stimulus begins only when the subjects start moving their hand as explained in Section 3.3. A “thumbs up” signal from the experimenter is used to indicate the start of each trial.

The noise made by the device is audibly different at each speed. To prevent response bias resulting from this noise, subjects are asked to wear earmuffs throughout the experiment. The training plus the testing session on each day takes approximately $20min$.

6.5 Procedure

Prior to beginning the experiment on each day, subjects start with a training session as outlined in Section 4.2. The subjects are allowed to train for as long as necessary to get used to the hand motion needed to keep the colour of the avatar green and the applied vertical pressure light. The subjects are given the following information:

> There will be 20 trials on each day. Begin the experiment with your right[1] hand. Each trial will be 10s long. For each trial, I will wait for you to place the index finger of the appropriate hand on the device. Once you are ready, wait for my signal to begin moving back and forth. When you begin moving your hand, the stimulus will start automatically. During the trial, the stimulus will remain constant. At the end of each trial, I will ask you two questions:
>
> 1. What real world texture or material does the sensation remind you of?
> 2. On a scale of 1 to 100, how would you rate the sensation at your fingertip? Choose 1 as "least rough" and 100 as "most rough". Choose a number that you feel is appropriate for the sensation. You do not have to compare a trial to the previous trials. For each trial, you may give a number independent of what you said in the previous trials.
>
> At the end of the trial, the stimulus will stop automatically. At this point, remove your hand from the box and replace it with the opposite hand and wait for my signal to begin moving. You may ask me to repeat a trial if you feel it necessary. You must wear earmuffs throughout testing in order to reduce ambient noise and most importantly, to block audio clues from the device.

Subjects are asked not to compare a trial with the previous trials in order to reduce memory demands. It has been shown by Stevens and Harris [1962], that in the absence of a standard given by the experimenter, subjects perform better. Thus, in this test, the subjects are given the freedom to assign numbers on their own. The first question allows for the experimenter to determine the type of textures or materials this device represents. The second question is used to determine if the

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[1] Eight subjects are asked to start with their right hand and nine subjects are asked to start with their left hand.

device is able to represent different magnitudes of roughness. Moreover, the effects of direction on roughness perception can be derived from this question as well. Together these questions test all the hypotheses.

6.6 Results

6.6.1 Texture

This section presents the analysis derived from the first question that is meant to determine the type of textures that this setup represents. Given 60 trials and 17 subjects, theoretically there should be 1020 responses. Subjects are not expected to provide 60 unique responses. Thus, many of the responses are repetitive not only within the subjects but also between the subjects. However, not all subjects are able to give an answer for every trial because for some trials those subjects can not relate the sensation to any real world material or texture. Thus, the number of collected responses is not 1020, it is 734. Table 6.2 shows a summary of the number of response from the subjects.

Table 6.2: Number of subjects in given number of response ranges.

Number of Responses	**Number of Subjects**
60	4
50-59	8
10-19	2
< 10	3

The responses collected from all subjects are grouped into 11 main categories as shown in Table 6.3. Note that the frequency of the “Sandpaper” response is the greatest. While it seems that the next two categories follow sandpaper closely, it is important to note that sandpaper is recorded only when the subject strictly says “Sandpaper”. The other categories include various responses. For instance the “Rough Fabric” category includes responses such as “chair covers”, “corduroy” etc. Given that a response is classified under the sandpaper category under strict naming convention while the other categories are more lenient, it can be concluded that the setup resembles sandpaper more closely than anything else. Sandpaper is not only the most frequently occurring response, tied with rough fabric, it is also the response mentioned by the most number of subjects (13 out of 17). There are nine subjects that fit into the wide category of “Rock/Stone/...”.

Table 6.3: Categories of responses and their frequencies.

Texture/ Material	**Frequency [%]**	**Number of Subjects**
Sandpaper	19.1	13
Rock/Stone/Brick/Wall/ Concrete/Sidewalk/ Gravel	18.1	9
Rough Fabric	17.7	13
Regularly Spaced Bumps	9.53	9
Corrugated Steel/ Cardboard/plastic	8.58	8
Wood	7.9	6
Brush	4.36	4
Tree Bark/Plants/Fruits	3.13	7
Vibration	1.23	2
Animal Skin	0.82	2
Miscellaneous	9.54	14

All of these categories are of rough nature. Thus, it is concluded that the texture represented by this setup is rough and most like sandpaper.

6.6.2 Roughness Magnitude

This section presents the analysis derived from the second question that is meant to determine the effect of changing the speed and the direction of rotation on the roughness perception. An unexpected observation made in this experiment is that some subjects scale the stimuli such that when the speed of the brush increases, their roughness perception decreases. Other subjects think in an opposite manner. These subjects perceive roughness to increase as the speed increases. In order to classify the subjects into two groups without using the experimental data itself, at the end of each experiment, the subjects are asked the following qualitative question regarding their perception of the texture.

> Did the roughness increase or decrease with speed?

Their response can be paraphrased as follows:

> Case 1: 9 of 17 subjects mentioned that at low speeds, the surface feels like it had bigger *"bumps"*. As the frequency increases, they feel that the surface becomes more continuous. They relate continuity with roughness such that the more continuous it feels, the less rough it becomes. Thus, higher speeds decrease the roughness. These subjects are classified into the "Dec" group.
>
> Case 2: 8 of the 17 subjects mentioned that at high speeds, the intensity of the stimulus feels greater and the *"bumps"* are *"hitting the finger"* much faster. They relate bumps with roughness such that the more the bumps, the rougher the surface feels. At low frequencies, there are fewer bumps and thus it feels less rough. Thus, higher speeds increase the roughness. These subjects are classified into the "Inc" group.

The data from the 17 subjects along with their group is shown in Table A.3 in Appendix A. The results for the two groups for CW and CCW directions are shown in Figure 6.1 and Figure 6.2. The solid lines, representing the "Inc" group, have a generally increasing trend and the dotted lines, representing the "Dec" group, have a generally decreasing trend.

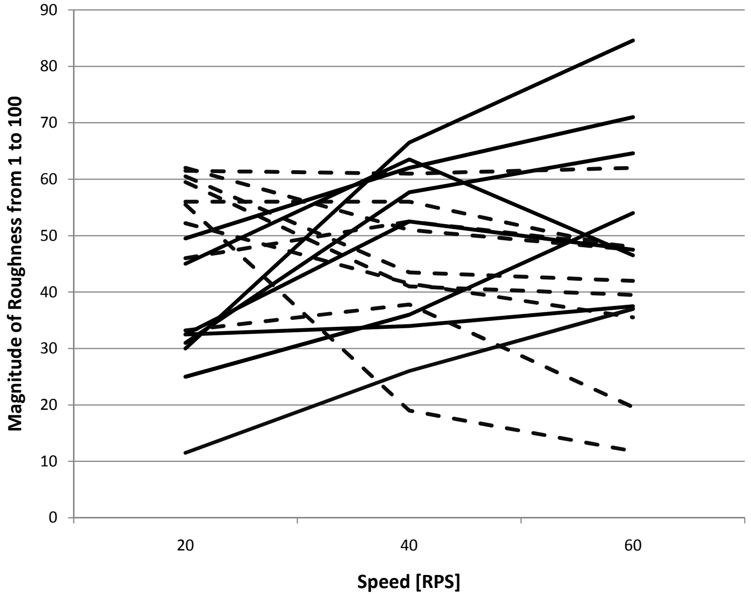

Figure 6.1: Roughness magnitudes for the two groups in CW direction. Solid line = "Inc" Group and dotted line = "Dec" Group

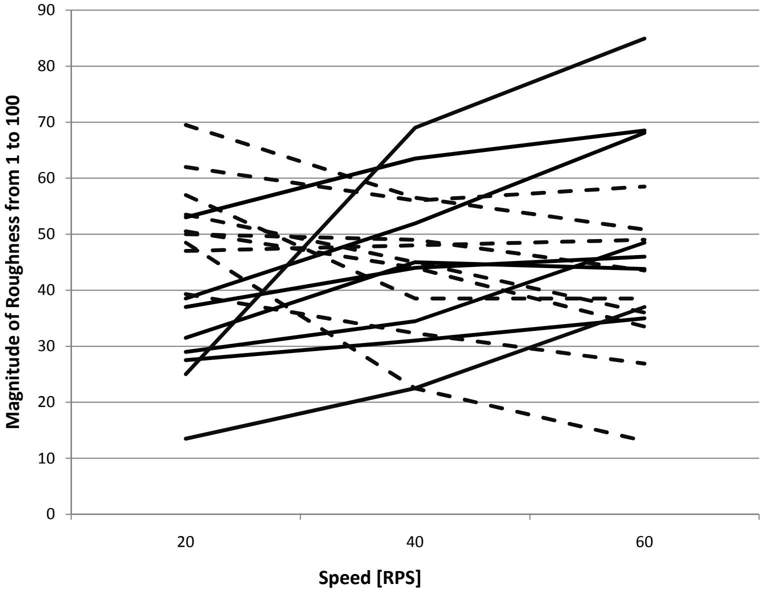

Figure 6.2: Roughness magnitudes for the two groups in CCW direction. Solid line = "Inc" Group and dotted line = "Dec" Group

If the analysis is performed by taking the average across all 17 subjects, the different trends in two groups make the average across each category nearly constant and show no significant results as shown in Figure 6.3. Note that for each speed the roughness magnitudes for directions do not differ by much, especially at the low and high speeds. Although, there might appear a slight increasing trend from $20RPS$ to $60RPS$, an analysis of variance shows no statistical significance. Using SAS and a 0.05 rejection level for the two factors (speed and direction), a 2-way within subject ANOVA shows no significance for speed or direction, F(2,32)= 0.28, p = 0.76 and F(1,16) = 2.62, p = 0.13, respectively. It also shows no interaction between speed and direction, F(2,32) = 0.9, p = 0.42. The detailed ANOVA results for this are shown in Table A.4 in Appendix A. Description of ANOVA can be found in Appendix B.

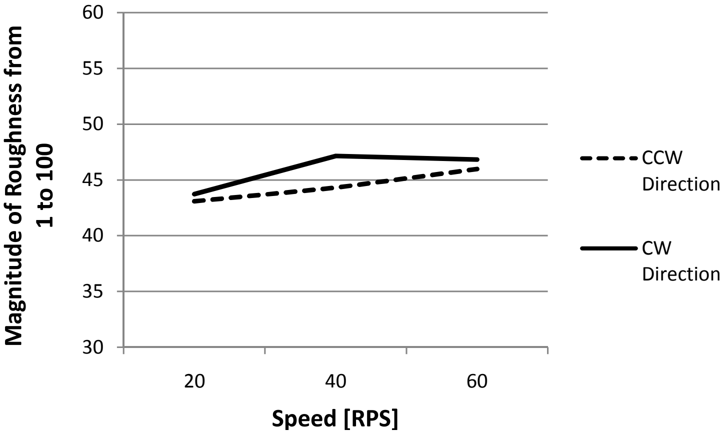

Figure 6.3: Roughness magnitudes averaged across all subjects for each direction and speed

If the data is split into two groups, a 3-way ANOVA (one between subject factor (group) and two within subject factors (speed and direction)) results show no statistically significant interaction between direction, speed and group, F(2,30) = 0.63, p = 0.54. As before, there is no significant interaction between direction and speed either, F(2,32) = 0.96, p = 0.40. This shows that the direction does not play a significant role in roughness perception. At a given level of speed, the roughness magnitude remains the same for both directions.

There is a statistically significant interaction between speed and group as expected, F(2,30) = 24.99, $p < 0.0001$. This interaction is more obvious in Figure 6.4 due to the intersection of the two lines. Given this interaction, the main effects of speed cannot be directly observed from the ANOVA results. The complete ANOVA results for this are shown in Table A.5 in Appendix A.

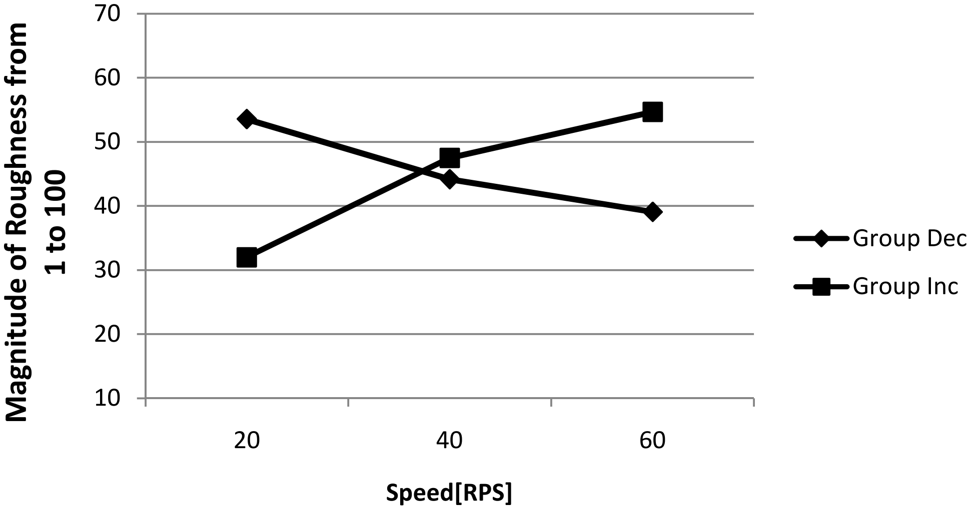

Figure 6.4: Roughness magnitudes averaged across all subjects in "Dec" group for each direction and speed

In Figure 6.4, note that the magnitude mean of $40RPS$ is nearly equal for both groups. This indicates that every subject, regardless of group, perceives the roughness magnitude of $40RPS$ similarly.

The average results for the two groups, along with the standard errors, are shown in Figure 6.5 and Figure 6.6. Note that for both groups, within each speed, the magnitude for direction is approximately equal. This is further evidence to the fact that the role of direction of rotation is insignificant in roughness perception.

To check if the speed has a significant effect within each group, the data within each group is averaged across direction since it has no effect and post-hoc T-tests are performed on the three levels of speed. Description of T-tests is given in Appendix B. The results show that the magnitude differences between low and medium speeds and low and high speeds are statistically significant. The difference between

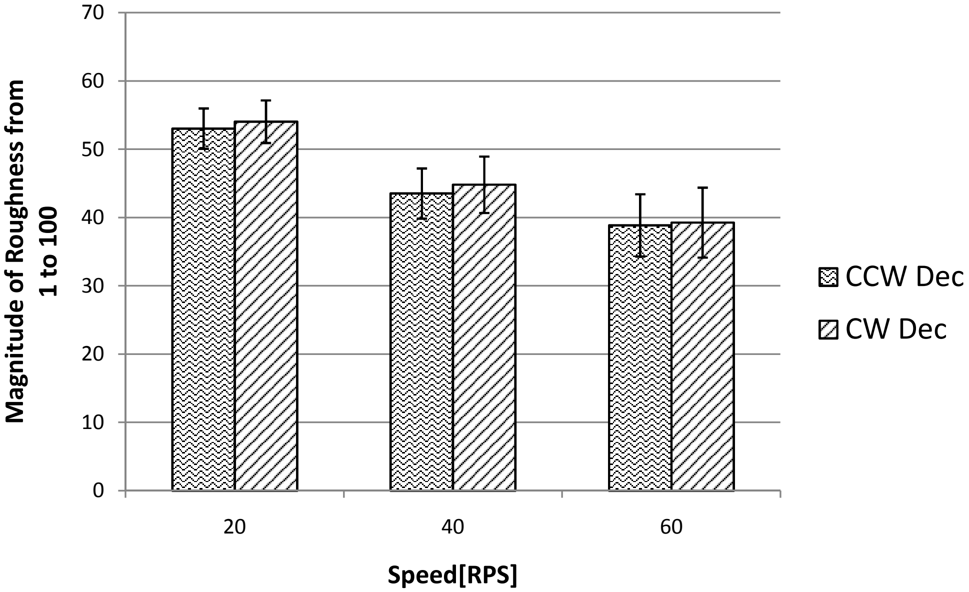

Figure 6.5: Roughness magnitudes averaged across all subjects in "Dec" group for each direction and speed

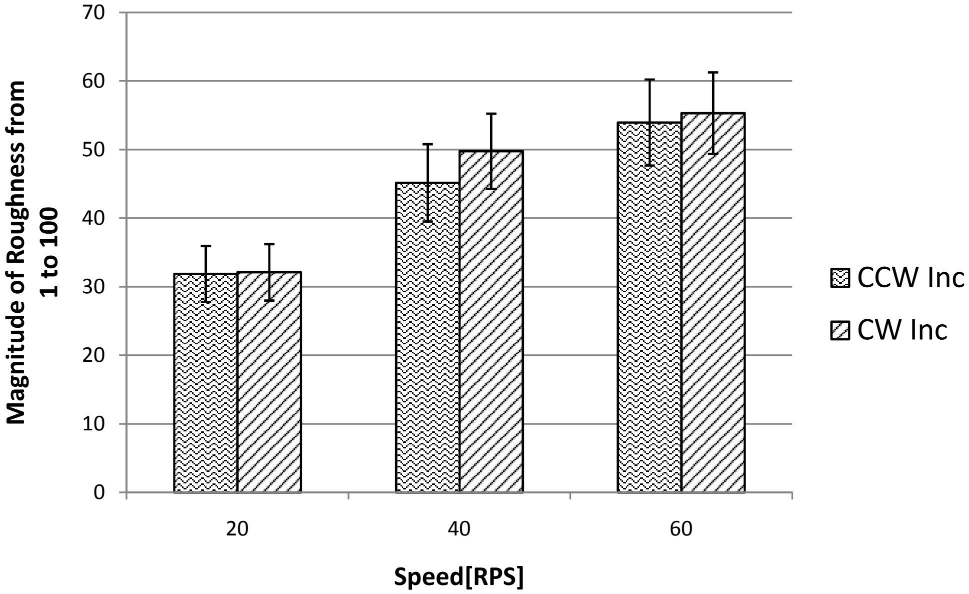

Figure 6.6: Roughness magnitudes averaged across all subjects in "Inc" group for each direction and speed

medium and high speeds is approaching significance. The p values for this test are shown in Table 6.4. The results are shown in more detail in Tables A.6 to A.9 in Appendix A.

Table 6.4: Post-hoc T-test results. low = $20RPS$, med = $40RPS$ high = $60RPS$.

Difference	**Group "Dec" p Value**	**Group "Inc" p Value**
low - med	0.0262	0.006
low - high	0.0054	0.0062
med - high	0.0076	0.0602

6.7 Conclusion

This analysis shows that the texture represented by this tactile device is rough. When trying to relate this texture with a real life texture or material, the majority of the subjects relate it to sandpaper.

In this experiment, subjects are asked to rate the magnitude of roughness on a scale of 1 to 100 for different levels of speed and direction of rotation of the brush. Subjects are not given a bias and are expected to use the biases from their personal experiences to assign magnitudes. It is found that there are two different ways in which people perceive roughness. One group of subjects feel that as the speed of the brush increases, the surface becomes more continuous. Thus, they associate higher speeds with decreasing roughness. The other group of subjects feel that as the speed of the brush increases, there are more bumps on the surface. Thus, they associate higher speeds with increasing roughness. Given this conflict, the 17 subjects in this experiment are split into two groups, 9 of which think that the roughness increases with speed while the other 8 think that the roughness decreases with speed.

It is entirely possible that this contradiction is a result of a real phenomenon much like an optical illusion. A Necker Cube is an example of an analogous optical illusion. It has two equally likely orientations that it may be viewed at. Often people are able to switch back and forth between these perceptions, an event known as Multistable Phenomenon [Leopold and Logothetis, 1999]. It refers to the sudden reversal in visual perception. It is possible that an ambiguity such as this exists in tactile perception as well.

Within each group the speed of the brush plays a significant role. However, the direction of rotation does not. Hypothesis H_2 and H_3 are confirmed. Hypothesis H_4 is only partially confirmed; increasing the speed decreases the roughness magnitude for some subjects. For other subjects, the opposite has been shown to be true. The null hypothesis, H_5 is not rejected.

Chapter 7

Experiment 3: Roughness Magnitude: Effects of Direction

7.1 Introduction

In the previous experiment, the subjects were asked to use their own personal biases to rate the roughness on a scale of 1 to 100. It was found that subjects were divided into two groups. Some subjects relate continuity of the surface to the roughness and some relate the number of bumps on the surface to roughness. This creates a conflict. The results show that some subjects think that the roughness increases with speed while the others think that it decreases. The different definitions of roughness used by the subjects is introducing bias.

In this experiment, the subjects are given standard stimuli to which they could compare the roughness created by the tactile device. The standard stimuli are five different grits of sandpaper as it was found to be the most common response in the previous experiment. They are asked to scale the roughness magnitude displayed by the tactile device according to the roughness of the sandpapers. This is an attempt to provide a consistent definition of roughness to the subjects. The smallest grit sandpaper being the roughest and the largest grit being the least rough.

In the previous experiment, it was concluded that the direction of rotation of the brush does not affect the roughness perception. The direction of rotation was kept constant during each trial. However, it is arguable that memory demands from one trial to the next could interfere such that the subjects do not feel the difference in two directions because there is a $10s - 20s$ time gap between each trial. In this experiment, the time gap is shortened to determine the effects of direction more closely.

7.2 Hypothesis

The hypotheses tested in this experiment are as follows:

H_6: The direction of rotation of the brush is not detectable.

H_7: As the speed of the brush increases, the perceived roughness resembles the higher grit sandpapers (less rough).

H_8: The direction of the brush does not change the magnitude of roughness.

7.3 Participants

There were 16 subjects (15 male, 1 female) between the ages of 20 and 27 who took part in this experiment. All subjects are different from those in experiment 1 and experiment 2. All subjects are from the University of Waterloo. All but two subjects are right handed. None of the subjects have a neurological or physical injury that affects sensitivity of the index finger of both hands. This experiment is approved by the office of research at the University of Waterloo (ORE # 15667). The experiment is performed according to the ethical guidelines. Each subject signed a consent letter prior to beginning the experiments.

7.4 Method

The experiment is conducted in two separate sessions with a time gap of at least 24 hours in between to prevent fatigue due to long experiment times. There are 48 trials in total split over two days (24 trials/day). To reduce the effects of adaptation, left and right hands are used on alternating trials. Eight subjects start the experiment with their left hand and the other eight subjects start the experiment with their right hand. If all the subjects start the experiment with their right hand, then perhaps the effects of hand could be confounded with the average results. However, by asking half of the subjects to start with the left hand, any effects of hand will cancel out when the average is taken across all subjects.

Each trial is $16s$ long. After $8s$ into each trial, the stimulus pauses for $0.5s$ and restarts. The $16s$ time period was chosen experimentally in a pilot study to be sufficient time to grasp the stimulus. Mechanically, it is not possible to switch the direction of motor without a momentary stop. Thus, a $0.5s$ pause is placed in every trial so that all trials are the same. In other words, the motor pauses at the $8s$ mark whether the direction changes or not.

During each trial, the speed of the brush remains constant. However, the direction of rotation either changes or remains the same before and after the $0.5s$ pause. In the previous experiment, it was found that all subjects, regardless of group, perceived the roughness of the $40RPS$ level equally. This middle level of speed does not create a conflict between the two groups. Thus, this test is performed with $20RPS$ and $60RPS$ speeds only. The 48 trials are split into levels shown in Table 7.1.

Half the trials in each level are done with the left hand and the other half with the right hand. The trials are randomly distributed. During each trial the stimulus begins only when the subjects start moving their hand as explained in Section 3.3. A “thumbs up” signal from the experimenter is used to indicate the start of each trial.

Table 7.1: Distribution of trials in experiment 3.

Speed [RPS]	**Stimulus Pair**	Number of Trials
20	CCW—CCW	6
20	CCW—CW	6
20	CW—CW	6
20	CW—CCW	6
60	CCW—CCW	6
60	CCW—CW	6
60	CW—CW	6
60	CW—CCW	6

The noise made by the device is audibly different at each speed. To prevent response bias resulting from this noise, subjects are asked to wear earmuffs that block out the noise. The training plus the testing session on each day takes approximately $20min$.

The sandpapers chosen for scaling are of grit sizes 40D, 80D, 120C, 180C and 320C. These are the commonly available girt sizes. They are laid out in an ascending order from left to right in front of the subjects.

7.5 Procedure

Prior to beginning the experiment on each day, subjects start with a training phase. The subjects are allowed to train for as long as necessary to get used to the hand motion needed to keep the colour of the avatar green and the applied vertical pressure light. The subjects are given the following information:

> There will be 24 trials on each day. Begin the experiment with your right[1] hand. Each trial will be 16 seconds long. For each trial, I

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[1] Eight subjects are asked to start with their right hand and eight with their left hand.

will wait for you to place the index finger of the appropriate hand on the device. Once you are ready, wait for my signal to begin moving back and forth. When you begin moving your hand, the stimulus will start automatically. At the half way mark in each trial, that is at $8s$, the stimulus will take a pause for $0.5s$ and restart. You have to pay attention to the stimuli before and after the pause as you will be asked to compare them. At the end of each trial, I will ask you two questions:

1. Did the stimulus change before and after the pause?
2. On a scale of 1 to 100, how would you rate the sensation at your fingertip. Choose 1 as the least rough sandpaper (Grit 320C) and 100 as the most rough sandpaper (Grit 40D). Scale everything in between according to grit sizes 80D, 120C, and 180C placed in front of you. Choose a number that you feel is appropriate for the sensation. If you feel that the roughness of the two stimuli are different, scale them using two numbers. If you feel the roughness is the same throughout, then scale it using one number. You do not have to compare a trial to the previous trials. For each trial, you may give a number independent of what you said in the previous trials.

7.6 Results

7.6.1 Detecting Direction

This section presents the analysis from the first question the subjects answered. It is meant to determine whether the subjects are able to detect a change in the stimulus due to a change in the direction of rotation of the brush. The subjects' results are recorded as hit and false alarm rates discussed in Section 2.5.2. A hit is recorded when the stimulus presented in the trial is (CCW,CW) or (CW,CCW)

Table 7.2: Stimulus response matrix for 20RPS level.

Stimulus Pair	**Response**		**Number**
	"Different"	**"Same"**	**of Trials**
(CCW,CW) or (CW,CCW)	0.67	0.33	24
(CCW,CCW) or (CW,CW)	0.34	0.66	24

Table 7.3: Stimulus response matrix for 60RPS level.

Stimulus Pair	**Response**		**Number**
	"Different"	**"Same"**	**of Trials**
(CCW,CW) or (CW,CCW)	0.82	0.18	24
(CCW,CCW) or (CW,CW)	0.51	0.49	24

and the response of the subjects is *"Different"*. A false alarm is recorded when the stimulus presented in the trial is (CCW,CCW) or (CW,CW) and the response of the subjects is *"Different"*. The data for each subject is shown in A.11 in Appendix A. The stimulus-response matrices for the two levels of speed are given in Table 7.2 and Table 7.3.

Since the subjects are unaware of the experimental setup and are not told that the direction of rotation will be changing during each trial, it is difficult for the experimenter to explain the nature of the change. The subjects choose their own metrics for defining what is meant by "change" and this may be different for each subject. For this reason, the Same-Different procedure is chosen to perform the analysis as it takes into account this anomaly. Within each level of speed, there are only two different stimuli (CCW,CW). According to Macmillan and Creelman [1991], an independent-observation strategy can be used in this situation.

The measure of detectability, d', discussed in Section 2.5.2 for the 20RPS level of speed is calculated as

$$\begin{aligned} H &= 0.67,\ z(H) = 0.44 \\ F &= 0.34,\ z(F) = -0.412 \\ z(H) - z(F) &= 0.852 \\ d' &= 1.59 \end{aligned}$$

The measure of detectability, d' for the 60RPS level of speed is calculated as

$$\begin{aligned} H &= 0.82,\ z(H) = 0.915 \\ F &= 0.51,\ z(F) = 0.025 \\ z(H) - z(F) &= 0.89 \\ d' &= 1.63 \end{aligned}$$

d' for both levels of speed is greater than 1, which is the level of satisfactory performance. Higher d' values indicate that subjects are able to discriminate between the direction of rotation at both levels of speed. However, it does not mean that the magnitude of roughness is different for the two directions. It is possible that even though the subjects detect a change (due to direction), their perceived roughness remains the same. This hypothesis is analyzed in the following section.

7.6.2 Roughness Magnitude

It is found that even though each subject is provided the same sandpapers as references for magnitude scaling, the subjects are still divided into two groups. Some subjects think that the roughness increases with speed while the others think the opposite. 7 out of 16 subjects fall into the “Dec” group while the other 9 fall into the “Inc” group. As in the previous experiment, the subjects are placed in these group according to their answer to the same qualitative question. The groups are not made from the results of their experimental data. The qualitative question is asked to each subject at the end of the experiment.

The average magnitude ratings given by each subject along with their group designation are shown in Table A.10 in Appendix A. The results for the two groups for CW and CCW directions are shown in Figure 7.1 and Figure 7.2. The solid lines, representing the "Inc" group, have a generally increasing tend and the dotted lines, representing the "Dec" group, have a generally decreasing trend.

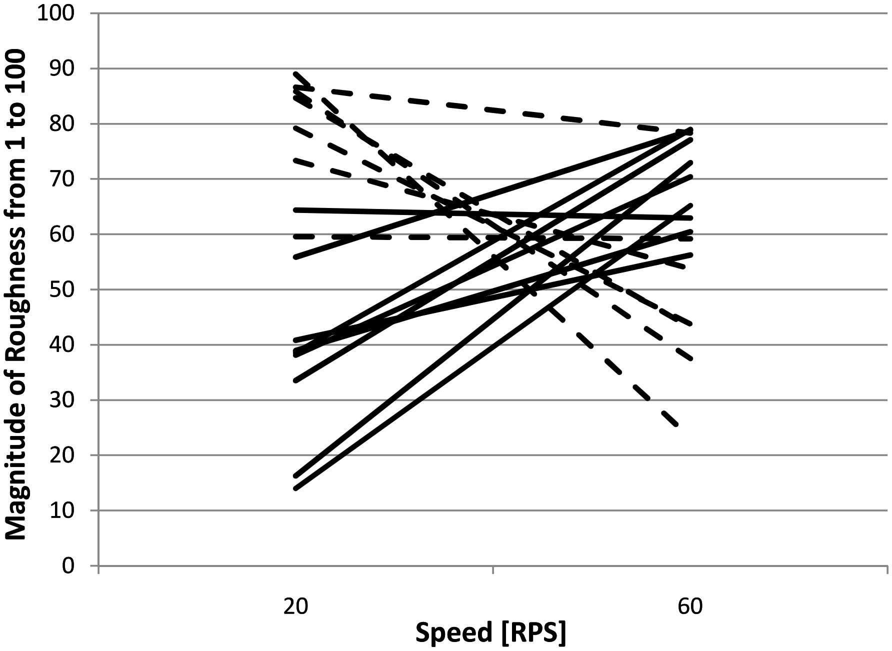


Figure 7.1: Roughness magnitudes for the two groups in CW direction. Solid line = "Inc" Group and Dotted line = "Dec" Group

As in the previous experiment, performing the analysis on all subjects together shows no significance of speed or direction. Figure 7.3 shows that the roughness magnitudes for both speeds and directions are approximately the same when the data is averaged across all subjects. Using SAS and a 0.05 rejection level for the two factors (speed and direction), a 2-way within subject ANOVA shows no effect of speed (F(1,15) = 0.57 and p = 0.4582) or direction (F(1,15) = 0.11 and p = 0.7468) on the magnitude estimates. This is a direct result of the two groups averaging to nearly constant values. The detailed ANOVA results are given in Table A.12 in Appendix A. Description of ANOVA can be found in Appendix B.

By splitting the data into two groups, ANOVA can be re-performed as a 3-way

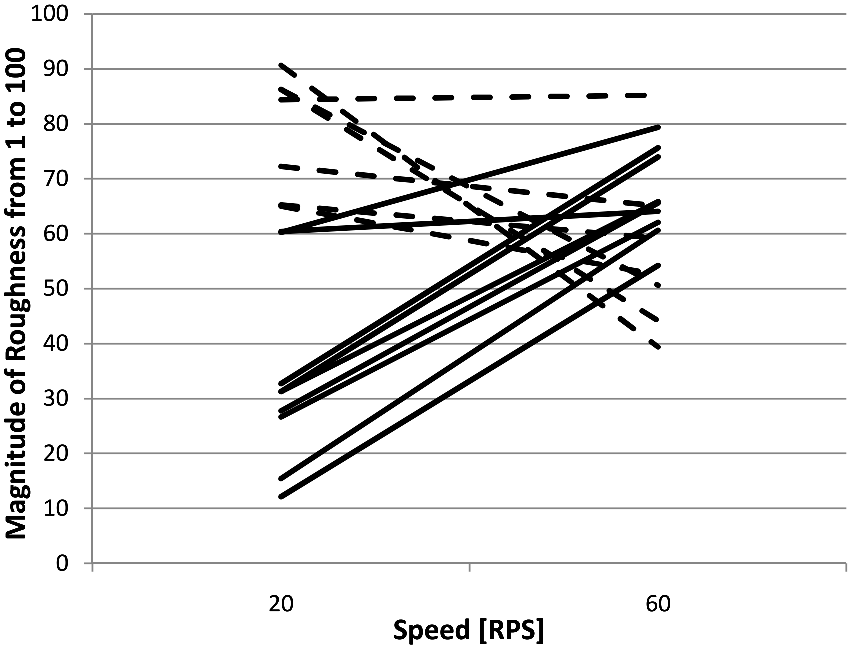


Figure 7.2: Roughness magnitudes for the two groups in CCW direction. Solid line = "Inc" Group and Dotted line = "Dec" Group

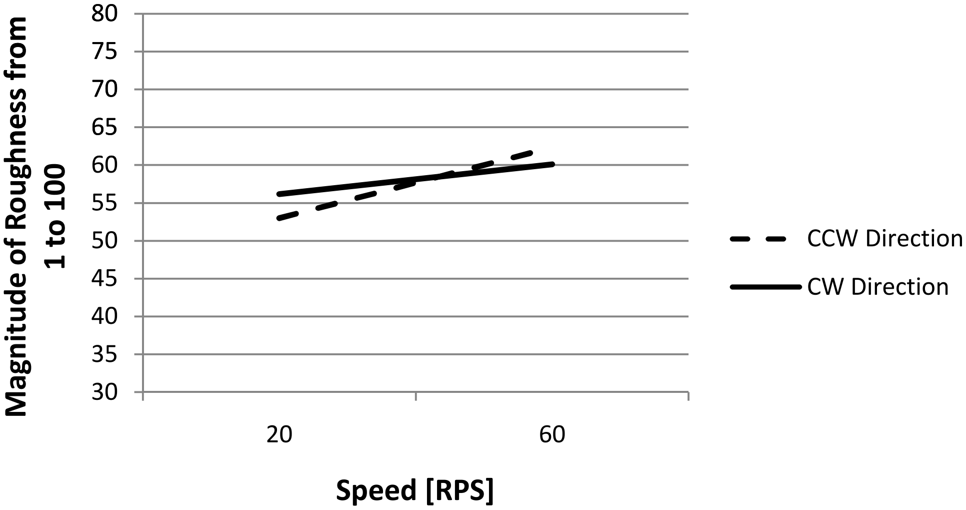


Figure 7.3: Roughness magnitudes averaged across all subjects for each direction and speed

analysis with one between subject factor (group) and two within subject factors (speed and direction). The results show that there is no interaction between speed, direction and group (F(1,14) = 1.24 and p = 0.2852), or between speed and direction

(F(1,14) = 3.42 and p = 0.0856). There is a significant interaction between direction and group (F(1,14) = 9.05 and p = 0.0094) and between speed and group (F(1,14) = 43.37 and p < 0.0001). The detailed ANOVA results are shown in A.13 in Appendix A. The interaction in direction and group is clear in Figure 7.4 because the magnitudes estimates for the two directions are different within each group. The interaction between speed and group is more obvious because the two groups have differing trends (increasing vs. decreasing), see Figure 7.5. These interactions make it difficult to study the main effects of speed and direction independently.

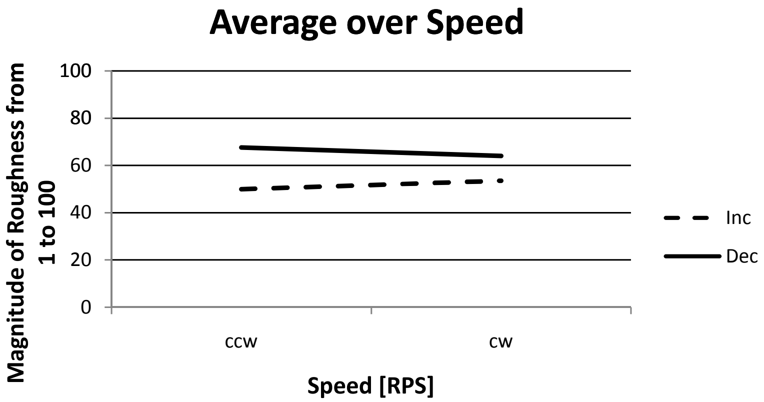


Figure 7.4: Results averaged across direction

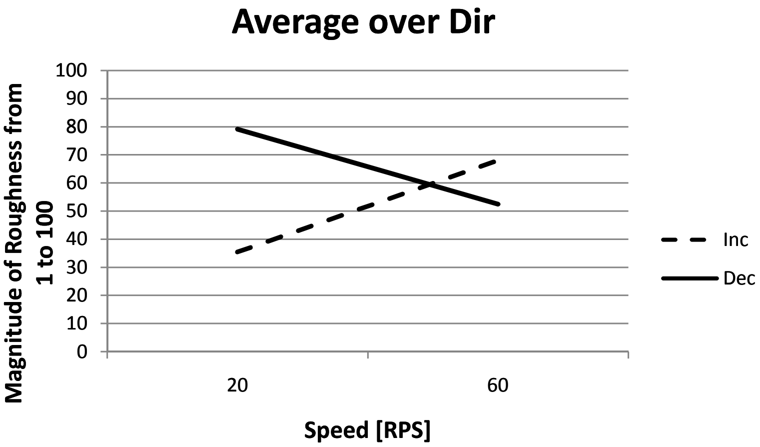


Figure 7.5: Results averaged across speed

To study the main effects of speed and direction, the results of post-hoc T-tests are shown in Table 7.4. Description of T-tests can be found in Appendix B.

From the previous experiment, it is expected that the effect of direction would be insignificant within each level of speed. However, the results here show that for group "Dec", at high levels (highccw - highcw), direction significantly affects the magnitude estimates while for group "Inc", the effects of direction are significant for low speeds (lowccw - lowcw). These results are an indication that in the previous experiment, the effects of direction were confounded with memory demands. There was a $10s$ to $20s$ time delay between each trial and the subjects may not have been able to retain tactile information over this period. However, in this experiment, the time delay between successive changes in direction is only $0.5s$ and the effects of direction are more prominent. This is analogous to the results of Cashdan [1968], who found that the difficulty in retaining tactual information reduces performance of haptic tasks.

The remaining two differences (lowccw - highccw and lowcw - highcw) check for significance between the two speeds at a given level of direction. These results indicate that speed also affects magnitude estimates. The detailed T-test results for this analysis are shown in Tables A.14 to A.17 in Appendix A.

Table 7.4: Post-hoc T-test results.

Difference	**Group "Dec" p Value**	**Group "Inc" p Value**
lowccw - lowcw	0.6781	0.0214
lowccw - highccw	0.0298	<0.0001
lowcw - highcw	0.0116	0.001
highccw - highcw	0.0544	0.4669

The average results for both groups along with the standard errors are shown in further detail in Figure 7.6 and Figure 7.7. For the "Dec" group, the difference in means between CCW and CW is larger at higher speeds whereas for the "Inc" group, this difference is higher at lower speeds. This is consistent with the results shown in Table 7.4. For both of these significant levels, the standard error is higher than the other two levels as well. It appears that, as the perceived roughness decreases for both groups, the error in magnitude estimation increases. Also, the effects of direction become more statistically significant.

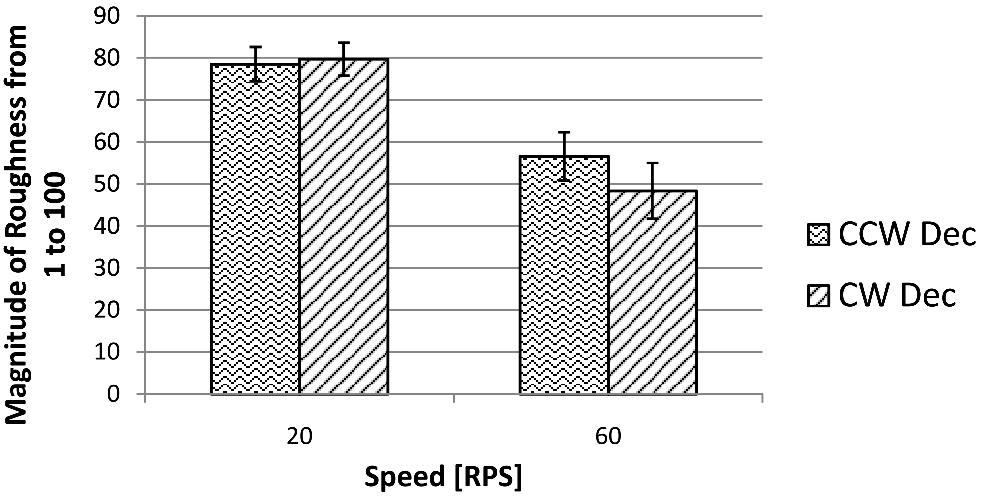


Figure 7.6: Roughness magnitudes averaged across all subjects in "Dec" group for each direction and speed

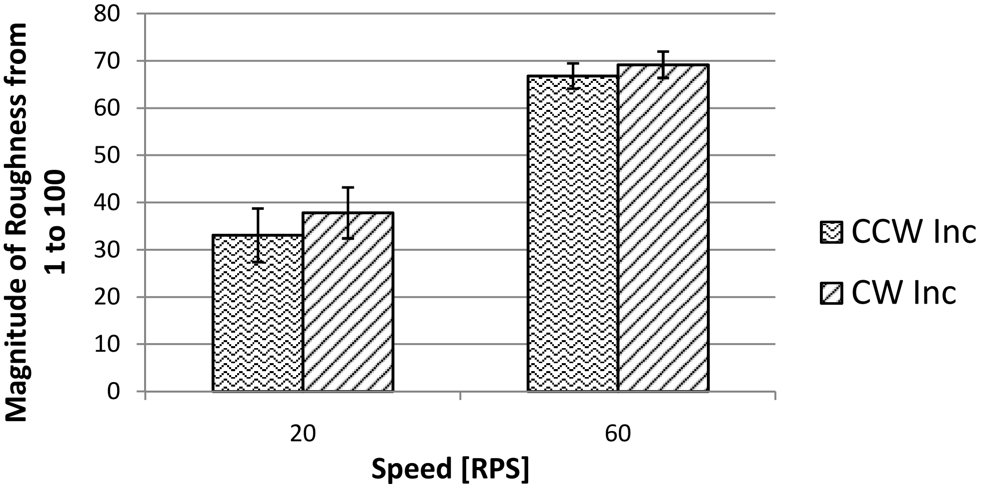


Figure 7.7: Roughness magnitudes averaged across all subjects in "Inc" group for each direction and speed

7.7 Conclusion

This analysis shows that when the subjects are presented CCW and CW directions with $0.5s$ gap between direction change, they are able to detect a change in stimulus at all levels of speed. However, their roughness magnitude is affected by direction only when their perceived roughness is lower. At higher perceived roughness, the effects of direction are statistically insignificant. In this experiment, the subjects are provided different grits of sandpaper to use when estimating the roughness magnitude. This is intended to provide a consistent definition of roughness to every subject (lower grits being rougher). However, even with this bias, the subjects are divided into two groups as in the previous experiment. Out of 16 subjects, 9 subjects feel that the roughness increases with increasing speed while 7 subjects feel that the roughness decreases with increasing speed. It is apparent that presenting sandpapers to use as real comparison stimulus did not eliminate the tactile perception ambiguity.

This analysis rejects all three hypotheses, H_6, H_7 and H_8.

Chapter 8

Conclusions and Future Research

This thesis presents the design of a device that can be used to stimulate rough textures at the fingertip. Three different experiments are conducted to determine how this device can relate to real world objects and to determine the parameters of the device that affect roughness perception.

Through these experiments, it is found that this tactile device is able to simulate rough textures of various magnitudes. It is found that by changing the speed of the brush, the roughness perceived by the users can also be changed. However, there is not a unique relationship between roughness perception and speed of the brush. In fact, there are two distinct relations. For some users, the magnitude of the roughness increases as the speed increases because the higher speeds give the impression of the surface having more bumps. For other users, the magnitude of the roughness decreases as the speed increases because higher speeds make the surface feel more continuous. This contradiction exists even when the subjects are presented with real comparison textures (sandpaper) and are asked to relate the least rough stimuli to the highest grit sandpaper. This creates a conflict and makes it difficult to use the same control for all users. However, this is an important observation that has to be considered when designing a tactile device.

Furthermore, it is found that the time gap between two similar stimuli (same speed, different direction) also affects roughness perception. With a larger time gap ($10s - 20s$), the users are unable to distinguish between the stimuli. However, when the time gap is decreased to $0.5s$, the users are able to detect that the two stimuli are slightly different. As a result, their roughness perception is affected. This result is also important in the design of a tactile device. The designers have to consider the time gap between two different stimuli. If the time gap is large and the stimuli are similar, then this change cannot be detected by the user and is not as important to portray. However, if the time gap is small, smaller changes can be detected and may be important to portray.

It is also found that in order for the users to detect a change in the speed of an already rotating brush, the speed has to change by a certain threshold. This threshold is dependent on the level of base speed and decreases as the base speed increases. Thus, if this device is used to stimulate rough textures, then in order to change the roughness perception (by changing the speed and not direction), the speed of the brush has to change, at minimum, by the appropriate threshold. In this experiment, only two levels of base speed are tested and stimuli are presented to the user without any time gap in between. Thus, the thresholds are representative of scenarios when the stimulus changes suddenly. These thresholds are not representative of scenarios when there is a larger time gap between stimuli.

In conclusion, this tactile device can be used to simulate varying magnitudes of roughness. The roughness can be controlled by changing the speed of the brush. However, there are two opposite relationships between speed and roughness perception. To simulate different roughness, while keeping the direction of rotation the same, the speed has to change at least by the pre-determined threshold value. The effects of direction of rotation are dependent on the time gap between the stimuli.

The study of the tactile perception presented in this research is the beginning of an exploration of displaying rough textures in virtual environments. Roughness perception has been studied by psychophysicists for decades. However, the psychophysical experiments conducted in this research are the first to study roughness perception in a virtual environment. This work is fundamental to the understanding of human roughness perception in virtual environments. A touch ambiguity similar to the one found in vision (Necker Cube) has been discovered.

Since roughness perception is linked to the speed of the brush, this tactile actuator can present a large number of roughness magnitudesb which may prove useful in many of the applications listed in Section 1.1.

8.1 Future Experiments

In the future, it should be investigated whether it is possible to train all users to perceive roughness in the same way so that increasing the speed of the brush, changes the perception of all users similarly. This can be tested by telling each user one of the following two definitions of rough:

1. Roughest surfaces have the most bumps
2. Roughest surfaces are most discontinuous

Two groups of subjects corresponding to each definition of rough should be tested to check which definition is more easy to understand for all users. In this way, it may be possible to use the same control logic to increase or decrease perceived roughness. These tests may also help investigate the existence of a tactile perception ambiguity analogous to optical illusions such as the Necker Cube.

The influence of visual stimuli on roughness perception may also be tested in roughness perception. This can be achieved by keeping the setup of experiment 2 the same and changing the visual display only. As the speed of the brush increases, the display should become visually rougher or smoother. Then it should be checked whether subjects change their roughness magnitude according to the visual display or not.

In the experiments presented in this thesis, the effect of time gap between two stimuli is not fully studied. In the future, the maximum time that the users can recall a stimulus should be determined. This can be done by providing two stimuli (same speed, different direction) to the user with varying time gaps. The critical time will be that at which the users begin to think that the stimuli are the same. This critical time will be an important design consideration in designing tactile devices.

Furthermore, the JND should also be determined for stimuli that are presented within and beyond the critical time. This will allow for the designers to determine the minimum change in speed that will be detectable by the users depending on how long it has been since the previous stimulus was presented.

In all of these experiments, the subjects moved their hand in a sideways motion. During the JND experiment, it is reported by a few subjects that if the stimulus changes near the end points of the graphical display (the point at which they reverse the hand motion), it is harder to detect the change. This is due to their inability to determine if they have actually detected a change in stimulus or a change in direction of motion. Thus, in future experimentation, users should move in a circular motion to avoid this problem.

Many users also reported that sometimes the rate of their hand motion did not match up with the rate at which the stimulus is presented. Future experiments should try to determine how the users would change their hand motion when the speed of the brush changes. This should be done by asking the users to move at whatever pace they feel comfortable at and monitoring their hand velocity. This information can be used to vary the speed of the brush according the speed of the user's hand.

8.2 Design of the Device

A number of changes can be made to the physical design of the device. First of all, a non-spiral brush should be used. Asymmetry of the brush may be confounded with the effects of direction of rotation. Furthermore, the cantilever design of the brush should be changed. Although the subjects applied light pressure on the aperture, over time it caused the brush to bend and rub against the inside walls of the chassis. Hence, the brush had to be realigned from time to time. In the future, the free end of the brush should be supported using bearings or bushings. The length of the brush can be decreased to decrease the deflection due to finger pressure.

APPENDICES

Appendix A

Results

Table A.1: JND results for 13 subjects in experiment 1.

Subject	**20 RPS**		**60 RPS**	
	Upper Limen JND	**Lower Limen JND**	**Upper Limen JND**	**Lower Limen JND**
AA	15.42	12.50	7.00	13.89
AB	11.67	10.42	3.70	11.67
AC	12.08	11.50	6.53	6.15
AD	12.73	16.11	7.50	9.24
AE	11.25	21.67	7.33	10.74
AF	9.06	13.85	6.06	8.33
AG	38.50	22.50	13.13	6.83
AH	12.50	17.22	8.89	7.71
AI	26.25	12.81	8.79	9.07
AJ	16.36	11.92	15.00	14.38
AK	19.00	14.58	7.92	8.33
AL	28.50	16.50	8.54	9.33
AM	10.91	16.00	5.61	9.50

Table A.2: 2-way ANOVA results for experiment 1.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
speed	1	698.89	698.89	25.04	0.0003
Error(speed)	12	334.93	27.91		
dir	1	1.07	1.07	0.04	0.8432
Error(dir)	12	313.77	26.15		
speed*dir	1	40.41	40.41	3.24	0.0969
Error(speed*dir)	12	149.50	12.46		

Table A.3: Roughness magnitude for 17 subjects along with their group in experiment 2.

Subject	**CCW**			**CW**			**Group**
	20 RPS	**40 RPS**	**60 RPS**	**20 RPS**	**40 RPS**	**60 RPS**	
AN	50.5	44	33.5	52.2	41.5	35.5	Dec
AO	27.5	31	35	32.5	34	37.5	Inc
AP	69.5	56.5	50.8	56	56	47.5	Dec
AQ	47	48	49	62	51	47.5	Dec
AR	38.5	51.9	68.1	31	57.7	64.6	Inc
AS	13.5	22.5	37	11.5	26	37	Inc
AT	29	34.5	48.5	25	36	54	Inc
AU	50	49	43.5	46	52.5	48	Dec
AV	62	56	58.5	61.5	61	62	Dec
AW	57	38.5	38.5	59.5	41	39.5	Dec
AX	53.5	45	36	60.5	43.5	42	Dec
AY	53	63.5	68.5	49.5	62	71	Inc
AZ	25	69	84.9	30	66.5	84.6	inc
BA	39.3	32.3	26.9	33.2	37.8	19.6	Dec
BB	37	44	46	32.5	52.5	47.5	Inc
BC	48.5	22.5	13.1	55.5	19	11.8	Dec
BD	31.5	45	43.8	45	63.5	46.5	Inc

Table A.4: 2-way ANOVA results for experiment 2.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**	**Adj Pr > F**	
						G - G	**H - F**
dir	1	53.54	53.54	2.62	0.125		
Error(dir)	16	326.87	20.43				
speed	2	168.37	84.19	0.28	0.7593	0.6291	0.6338
Error(speed)	32	9698.90	303.09				
Greenhouse-Geisser Epsilon 0.5557							
Huynh-Feldt Epsilon 0.5673							
dir*speed	2	24.88	12.44	0.9	0.4181	0.4098	0.4181
Error(dir*speed)	32	444.21	13.88				
Greenhouse-Geisser Epsilon 0.9033							
Huynh-Feldt Epsilon 1.0115							

Table A.5: 3-way ANOVA results for experiment 2.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**	**Adj Pr > F**	
						G - G	**H - F**
dir	1	55.93	55.93	2.64	0.1252		
dir*group	1	8.76	8.76	0.41	0.53		
Error(dir)	15	318.10	21.21				
speed	2	306.63	153.32	1.26	0.2971	0.2883	0.2917
speed*group	2	6060.98	3030.49	24.99	<.0001	<.0001	<.0001
Error(speed)	30	3637.92	121.26				
Greenhouse-Geisser Epsilon 0.66							
Huynh-Feldt Epsilon 0.75							
dir*speed	2	27.18	13.59	0.96	0.3958	0.3896	0.3958
dir*speed*group	2	17.80	8.90	0.63	0.5415	0.5282	0.5415
Error(dir*speed)	30	426.41	14.21				
Greenhouse-Geisser Epsilon 0.91							
Huynh-Feldt Epsilon 1.10							

Table A.6: T-test statistics for “Dec” group in experiment 2.

Difference	**N**	**Lower CL Mean**	**Mean**	**Upper CL Mean**	**Lower CL Std Dev**	**Std Dev**	**Upper CL Std Dev**	**Std Err**
low - med	9	1.4316	9.3667	17.302	6.9728	10.323	19.777	3.4411
low - high	9	5.6325	14.472	23.312	7.7678	11.5	22.032	3.8334
med - high	9	1.7799	5.1056	8.4312	2.9224	4.3265	8.2887	1.4422

Table A.7: T-test results for “Dec” group in experiment 2.

Difference	**DF**	**t Value**	**Pr > |t|**
low - med	8	2.72	0.0262
low - high	8	3.78	0.0054
med - high	8	3.54	0.0076

Table A.8: T-test statistics for “Inc” group in experiment 2.

Difference	**N**	**Lower CL Mean**	**Mean**	**Upper CL Mean**	**Lower CL Std Dev**	**Std Dev**	**Upper CL Std Dev**	**Std Err**
low - med	8	-24.9	-15.48	-6.053	7.4516	11.27	22.938	3.9846
low - high	8	-36.54	-22.66	-8.771	10.981	16.609	33.803	5.872
med - high	8	-14.77	-7.181	0.4059	6.0003	9.0753	18.471	3.2086

Table A.9: T-test results for “Inc” group in experiment 2.

Difference	**DF**	**t Value**	**Pr > |t|**
low - med	7	-3.88	0.006
low - high	7	-3.86	0.0062
med - high	7	-2.24	0.0602

Table A.10: Roughness magnitude for 16 subjects along with their group in experiment 3.

Subject	**20 RPS**		**60 RPS**		**Group**
	CCW	**CW**	**CCW**	**CW**	
BE	86.25	85.83	50.63	37.5	Dec
BF	32.71	38.13	75.63	70.42	Inc
BG	65	73.33	52.5	53.75	Dec
BH	86.25	79.17	44.17	43.75	Dec
BI	60.21	55.83	79.38	78.75	Inc
BJ	60.42	64.38	64.04	62.92	Inc
BK	26.67	33.547	62.08	77.08	Inc
BL	65.21	59.58	59.17	59.17	Dec
BM	84.38	86.63	85.21	78.29	Dec
BN	72.25	84.67	64.98	43.09	Dec
BO	27.75	38.96	65.54=	60.46	Inc
BP	90.63	88.96	39.38	23.17	Dec
BQ	15.42	14	60.63	65.21	Inc
BR	31.25	38.54	73.96	78.96	Inc
BS	31.25	40.83	65.83	56.25	Inc
BT	12.13	16.25	54.21	72.92	Inc

Table A.11: Hit and false alarm rates for all 16 subjects in experiment 3.

Subject	**20 RPS**			**60 RPS**		
	Hit Rate	**False Alarm Rate**	d'	**Hit Rate**	**False Alarm Rate**	d'
BE	0.83	0.25	2.03	0.75	0.58	1.14
BF	1.00	0.58	3.54	0.92	0.83	1.11
BG	0.42	0.17	1.48	0.67	0.50	1.18
BH	0.75	0.58	1.14	0.92	0.58	1.96
BI	0.67	0.58	1.39	0.67	0.83	1.19
BJ	1.00	0.42	3.90	0.92	0.33	2.58
BK	0.50	0.33	1.10	0.83	0.25	2.03
BL	0.83	0.08	3.05	0.67	0.33	0.67
BM	0.42	0.17	1.48	0.75	0.17	2.37
BN	0.42	0.33	0.80	0.67	0.25	0.81
BO	0.75	0.42	1.62	0.92	0.58	1.96
BP	0.50	0.17	1.70	1.00	0.75	3.11
BQ	0.50	0.42	0.72	0.83	0.33	2.14
BR	0.67	0.33	1.62	0.75	0.50	1.39
BS	0.83	0.58	1.48	0.92	0.67	1.72
BT	0.67	0.08	1.39	0.92	0.67	1.72

Table A.12: 2-way ANOVA results for experiment 3.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
speed	1	706.30	706.30	0.58	0.4582
Error(speed)	15	18270.43	1218.03		
dir	1	3.62	3.62	0.11	0.7468
Error(dir)	15	502.82	33.52		
speed*dir	1	116.96	116.96	2.93	0.1077
Error(speed*dir)	15	599.53	39.97		

Table A.13: 3-way ANOVA results for experiment 3.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
speed	1	136.36	136.36	0.43	0.5235
speed*group	1	13811.77	13811.77	43.37	<.0001
Error(speed)	14	4458.65	318.48		
dir	1	0.02	0.02	0	0.9778
dir*group	1	197.45	197.45	9.05	0.0094
Error(dir)	14	305.37	21.81		
speed*dir	1	134.59	134.59	3.42	0.0856
speed*dir*group	1	48.60	48.60	1.24	0.2852
Error(speed*dir)	14	550.93	39.35		

Table A.14: T-test statistics for group “Dec” in experiment 3.

Difference	**N**	**Lower CL Mean**	**Mean**	**Upper CL Mean**	**Lower CL Std Dev**	**Std Dev**	**Upper CL Std Dev**	**Std Err**
lowccw - lowcw	7	-7.754	-1.173	5.4085	4.5855	7.116	15.67	2.6896
lowccw - highccw	7	3.0077	21.991	40.974	13.227	20.526	45.199	7.758
lowcw - highcw	7	9.9225	31.351	52.779	14.93	23.169	51.021	8.7572
highccw - highcw	7	-0.21	8.1872	16.585	5.8511	9.08	19.995	3.4319

Table A.15: T-test results for group “Dec” in experiment 3.

Difference	**DF**	**t Value**	**Pr > |t|**
lowccw - lowcw	6	-0.44	0.6781
lowccw - highccw	6	2.83	0.0298
lowcw - highcw	6	3.58	0.0116
highccw - highcw	6	2.39	0.0544

Table A.16: T-test statistics for group “Inc” in experiment 3.

Difference	**N**	**Lower CL Mean**	**Mean**	**Upper CL Mean**	**Lower CL Std Dev**	**Std Dev**	**Upper CL Std Dev**	**Std Err**
lowccw - lowcw	9	-8.573	-4.741	-0.909	3.3671	4.985	9.5501	1.6617
lowccw - highccw	9	-44.27	-33.72	-23.18	9.2645	13.716	26.277	4.572
lowcw - highcw	9	-45.68	-31.39	-17.1	12.558	18.592	35.619	6.1974
highccw - highcw	9	-9.676	-2.407	4.861	6.3871	9.4559	18.115	3.152

Table A.17: T-test results for group “Inc” in experiment 3.

Difference	**DF**	**t Value**	**Pr > |t|**
lowccw - lowcw	8	-2.85	0.0214
lowccw - highccw	8	-7.38	<.0001
lowcw - highcw	8	-5.06	0.001
highccw - highcw	8	-0.76	0.4669

Appendix B

Analysis

B.1 Analysis of Variance

The most widely used tool in statistics is called the analysis of variance (ANOVA). It is a test of significance among or between treatment means. It presents the probability of the difference between means being purely due to chance [Damon and Harvey, 1987]. For simplicity, this discussion will be concentrated on a 2-way ANOVA. A 2-way ANOVA has two independent variables. Consequently, one can have a 3-way ANOVA, where there are three independent variables. Much of the discussion on 2-way ANOVA can be extended to 3-way ANOVA as well.

A 2-way ANOVA has two independent variables or factors, A and B. There is also a dependent variable, C. The factors A and B may have two or more levels as well. Assume that in this example, A has three levels, a1, a2 and a3 and B has two levels, b1 and b2. The purpose of the ANOVA is to determine if the factors of A and B have a significant affect on the value of C. More specifically, there are two types of effects that are presented:

1. Main effects - These are the effects of A and B independently on C. These effects show if the levels within each factor affect C without considering the other factor.

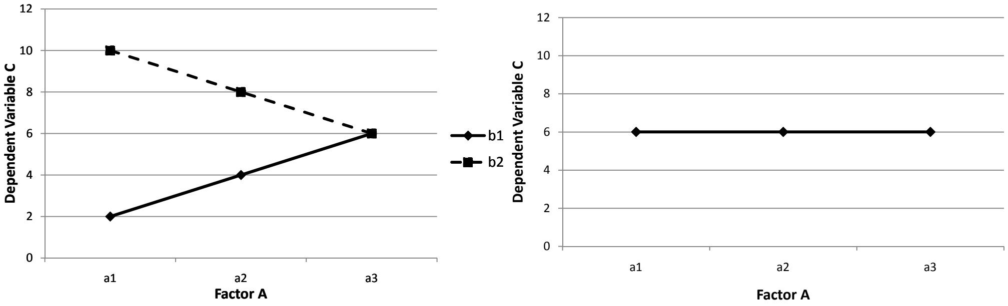
Table B.1: Data set for factors A and B.

$\mathbf{a}_1$		$\mathbf{a}_2$		$\mathbf{a}_3$	
$\mathbf{b}_1$	$\mathbf{b}_2$	$\mathbf{b}_1$	$\mathbf{b}_2$	$\mathbf{b}_1$	$\mathbf{b}_2$
3	9	3	6	6	8
2	10	4	8	7	6
2	10	5	10	5	9
2	10	3	9	8	4
3	10	5	7	6	6
1	10	5	10	6	3
1	11	3	6	4	6

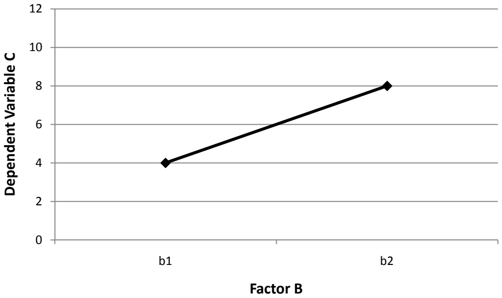
2. Interaction effects - This is the interaction between A and B. That is, does A affect C in the same way at both levels of B and vice versa?

If there is an interaction between A and B, then the main effects may not be analyzed directly because there is information hidden in the interaction that the main effects do not account for. A hypothetical data is given in Table B.1. The average results of this data are shown in Figure B.1.

Figure B.1a is obtained by average each column of Table B.1 to graph the relationship between each level of A and B. The graph shows that there is a strong interaction between factors A and B. At level b1, the value of C decreases from level a1 to a3. On the other hand, at level b2, the value of C increases from level a1 to a3. Given this interaction, Figure B.1b shows that if the main effects of A are observed independent of B (average b1 and b2 together for each level of A), then A has no affect on C (the value of C is constant for all levels of A). However, this is not true. A does have an affect of C, although it is dependent on the level of B. Figure B.1c shows that if the effect of B is observed independently of A (average a1, a2 and a3 together for all levels of B), then B has an effect on C. This is an example where one one of the main effects, A, cannot be directly observed from the



(a) Interaction between A and B (b) Effects of A



(c) Effects of B

Figure B.1: Affects of A and B on C

ANOVA results due to the significant interaction.

Performing an ANOVA analysis on this gives the results shown in Table B.2. Here, the analysis is presented for source A only.

The sources of variation are A and the random error associated with each observation in A, called Error(A). DF is the degrees of freedom related to each source. In this case, A has three levels. Therefore, it has 2 DF. There are six observations in each level, a1 and a2. The random error is associated with 12 observations. Therefore, Error(A) has 12 DF. Type III SS is a sum of squares or the least squares analysis. There are 4 types of sums of squares. Details of each are provide in Freund and Littell [1981].

The Mean Square associated with A, estimates the variation among all of the observations in A and the variation due to the three levels of A. The Mean Square associated with Error(A), estimates the variation among all observations only. F value, given by Equation (B.1), is the ratio of these two Mean Squares. F value is 1

Table B.2: 2-way ANOVA results.

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
A	2	0	0	0	1
Error(A)	12	21	1.75		
B	1	168	168	120.96	<0.0001
Error(B)	6	8.33	1.39		
A*B	2	112	56	24.29	<0.0001
Error(A*B)	12	27.67	2.31		

when the two means are equal meaning the levels of A have no effect on C [Damon and Harvey, 1987].

$$F = \frac{\text{Mean Square of A}}{\text{Mean Square of Error}} \tag{B.1}$$

The p value is the probability that the difference in means resulting from the three levels of A is due to chance only. Generally a 0.05 or a 0.01 rejection level is used to check for significance. For a 0.05 rejection level, a p value < 0.05 indicates that the probability of the difference in means due to chance is less than 5%. Thus, a p value < 0.05 indicates that the effects of A on C are statistically significant. A larger p value indicates the opposite.

In this example, the results of the ANOVA will state that there is no statistically significant effect of A on C, F(2,12) = 0, p = 1.

This example showed a scenario with two within subject factors. A within subject factor implies that the each subject is tested using all levels of that factor. In this example, A and B are within subject factors because each combination of A and B was tested with each user. Within subject designs are often referred to as repeated measures design because multiple measurements are taken from each subject for a given level of treatment.

Another type of factor, known as a between subject factor, is that in which one set of subjects are tested using one level while the other set of subjects are tested using a different level.

B.2 T-tests

T-tests are performed to check for significance of the difference between two means or the difference between a mean and a given value [Damon and Harvey, 1987]. Similar to the ANOVA test, these tests are also based on the probability that the difference in means is due to chance only. The t-test results for the example in the previous section are given in Table B.3. These results compare the means between each level of A when factor B is held constant at b1. All of the p values in the table are less than 0.05. This indicates that the effect of A on C is significant at b1. Similar analysis can be performed to check for the effect of A on C at b2.

Table B.3: T-test results.

Difference	**DF**	**t Value**	**Pr > |t|**
a1b1 - a2b1	6	-4.1	0.0064
a1b1 - a3b1	6	-8.2	0.0002
a2b1 - a3b1	6	-3.06	0.0224

The t ratio is given by

$$t = \frac{\overline{d} - \mu_o}{s_{\overline{d}}} \tag{B.2}$$

where $\overline{d}$ is the difference between the two means, μ_o is the value the difference has to be compared against and $s_{\overline{d}}$ is the standard error of the difference between the means.

B.3 Measure of Detectability

One of the problems in measuring the sensitivity of subjects to stimuli is the criterion that the subjects choose to give a response. For instance, in the yes-no procedure, the subjects can choose a conservative criterion to differentiate between a signal plus noise (SN) and a noise (N) trials so that their hit and false alarm rates both decrease. On the other hand, a relaxed criterion results in higher hit and false alarm rates. It is apparent, that the criterion the subjects choose affects the results. Thus, there needs to be a way that can estimate the subjects' sensitivity regardless of their criterion. The measure of detectability, d', is a measure of the subjects' sensitivity that is independent of their criterion. As a result, this measure can be stated without the need for calculating the response bias (for instance, the tendency of the subjects to say *"Yes"* over *"No"* in a yes-no procedure).

To calculate d', the location of the criterion has to be calculated on the normal curves of the N and SN distributions. d' is simply the distance between these two locations [Gescheider, 1997]. The steps for calculating d' are as follows

1. Find the p values corresponding to hit (H) and false alarm (F) rates by subtracting H and F from 1.

$$P_F = 1 - F \tag{B.3}$$

$$P_H = 1 - H \tag{B.4}$$

2. Convert P_F and P_H to z-scores. A z-score of P_F, called Z_N, is the value on the x-axis of a normal distribution curve, below which the area under the curve is equal to P_F. The z-score of P_H, called Z_{SN} is calculated similarly.

3. Find d' using

$$d' = Z_N - Z_{SN} \tag{B.5}$$

To understand the above steps, take an example where H = 0.35 and F = 0.02. Then $P_F = 0.98$ and $P_H = 0.65$. As shown in Figure B.2, these p values correspond to $Z_N = 2.05$ and $Z_{SN} = 0.39$. In this example, $d' = 1.66$. The z-scores corresponding to each p value are tabulated in Table A of the Appendix in Gescheider [1997].

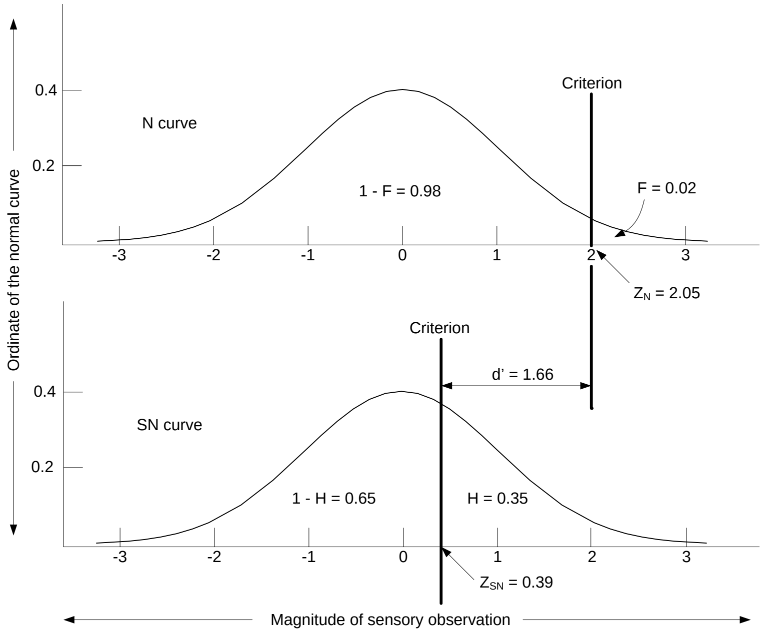


Figure B.2: N and SN distributions to find d' [Gescheider, 1997]

Macmillan and Creelman [1991] calculate d' directly by converting H and F into z scores.

$$d' = Z(H) - Z(F) \tag{B.6}$$

Where Z(H) and Z(F) are the z-scores of H and F respectively. The underlying concept behind this approach is the same as highlighted above. The z-scores for the corresponding H and F values for this approach can be found in Table A5.1 of Appendix 5 in Macmillan and Creelman [1991].

Appendix C

Design Specifications

C.1 DC Motor

The coreless DC motor is obtained from MicroMo Electronics. The motor is equipped with an encoder. The main specifications of the motor are provided in Table C.1.

Table C.1: Coreless DC motor specifications.

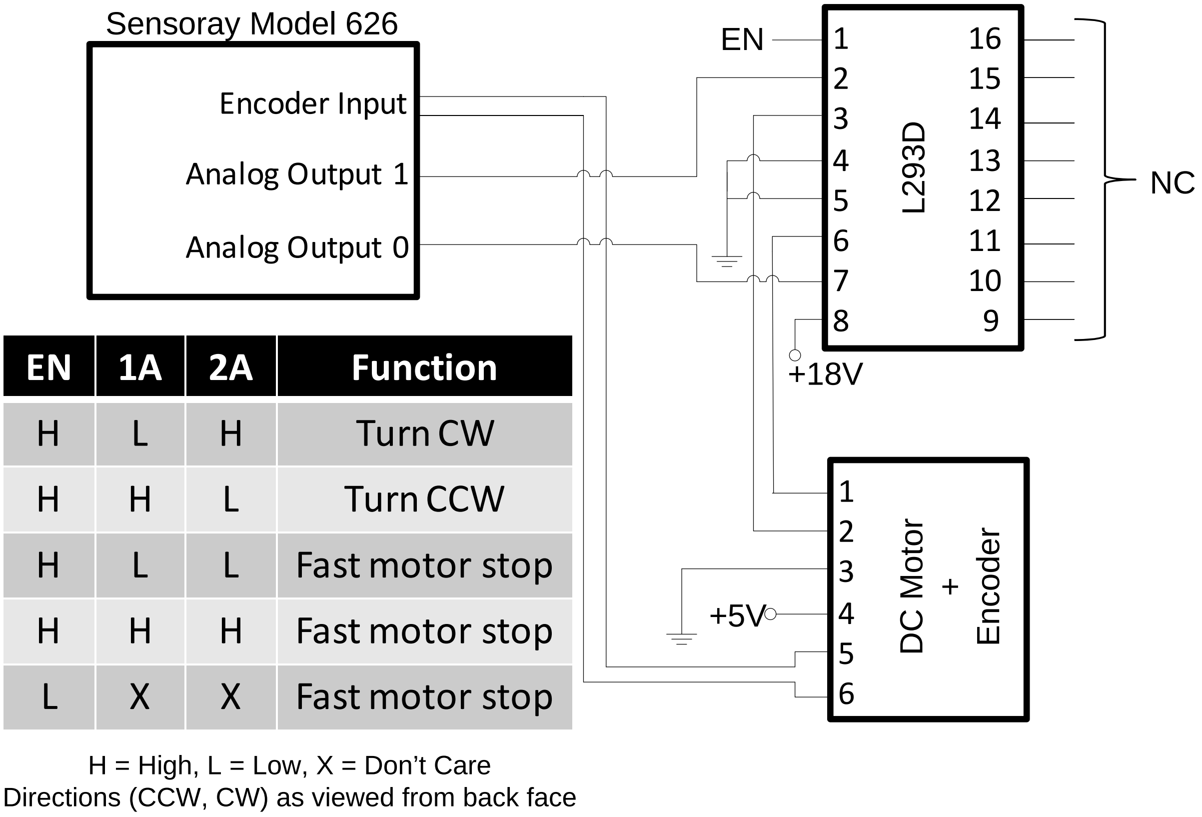
Part Number	2224U012SRIE2-512
Nominal Voltage (Motor)	$12V$
Stall Torque	$0.019Nm$
Continuous Current	$0.5A$
Encoder Resolution	512 lines per revolution
Supply Voltage (Encoder)	$4.5V$ - $5.5V$
Number of channels on encoder	2
Weight (Motor + Encoder)	$46g$
Size envelope (including encoder)	$34.7mm$ x $22mm$

C.2 Software

The Software packages used for communication are MATLAB® and Simulink®. In addition, Quanser's real time control software, QuaRC, is used for connecting with the PHANTOM Omni® and the Sensoray Model 626 data acquisition card (DAC). QuaRC integrates with Simulink® and provides blocks to interface with both of these components.

C.3 Interfacing

The tactile device is interfaced to the software using the Sensoray DAC. Of interest are its analog output channels and the single-ended encoder channels. The analog channels have a range of $\pm 10V$. These are available in the form of RCA connectors. The encoder channels support 5-pin round DIN connectors for channels A, B and I and $5V$ power supply to the encoder and a ground. The embedded $5V$ supply signal makes it easy to connect it to the encoder directly. The board is connected to the motor through a high-current half-H driver, L293D from Texas Instruments. It can provide current up to $1.2A$ which is sufficient for the DC motor since its continuous current intake is only $0.5A$. The chip supports bi-directional motor functionality. The details of the connections are shown in Figure C.1. It also shows the logic for the motor driver required to control the direction of rotation.



EN	1A	2A	Function
H	L	H	Turn CW
H	H	L	Turn CCW
H	L	L	Fast motor stop
H	H	H	Fast motor stop
L	X	X	Fast motor stop

H = High, L = Low, X = Don't Care
Directions (CCW, CW) as viewed from back face

Figure C.1: Schematic and control logic for direction of rotation

C.4 Logic

All of the the models are created in Simulink® using standard Simulink® blocks, QuaRC for interfacing in real-time with the PHANTOM Omni® and the Sensoray DAC and the Virtual Reality toolbox for graphics. The general control logic for the models is shown in Figure C.2.

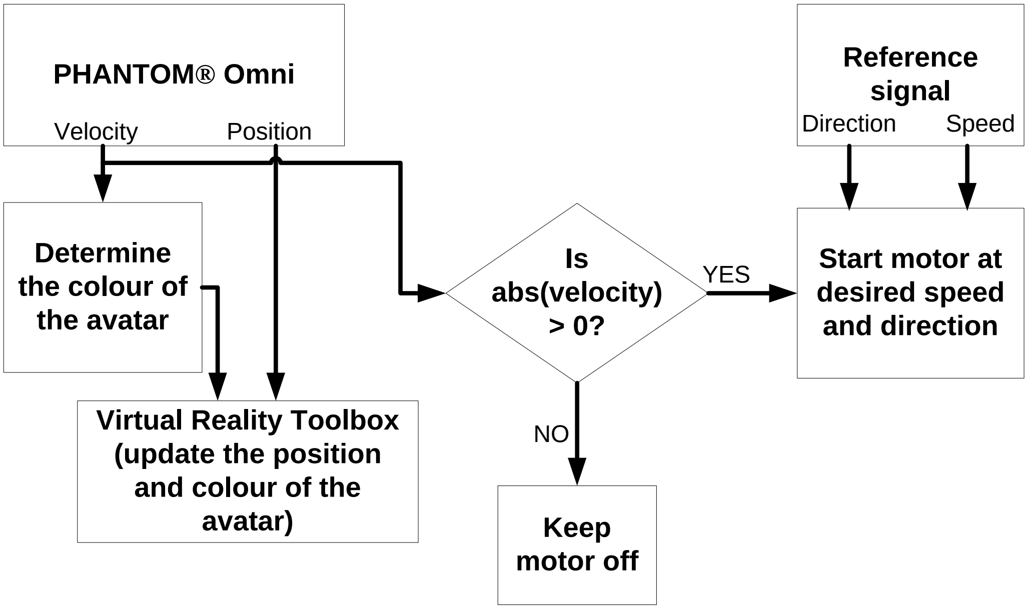


Figure C.2: Block Diagram of the Simulink® model

C.5 Control

The block diagram of the control system is shown in Figure C.3. $\dot{\theta}_d$ is the desired speed of the motor and $\dot{\theta}$ is the actual speed. A PD controller is used to control the speed of the motor. The transfer function from $\dot{\theta}_d$ to e is given by

$$\frac{E(s)}{\Theta_d(s)} = \frac{\alpha s + 1}{(\alpha + K_d)s + 1 + K_p} \tag{C.1}$$

Then for a unit step input and according to the final value theorem, the steady state error is given by

$$e_\infty = \lim_{s \to 0} sE(s) = \frac{1}{1 + K_p} \tag{C.2}$$

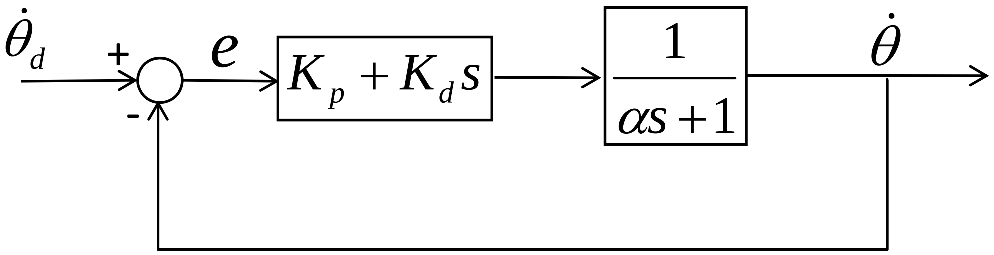
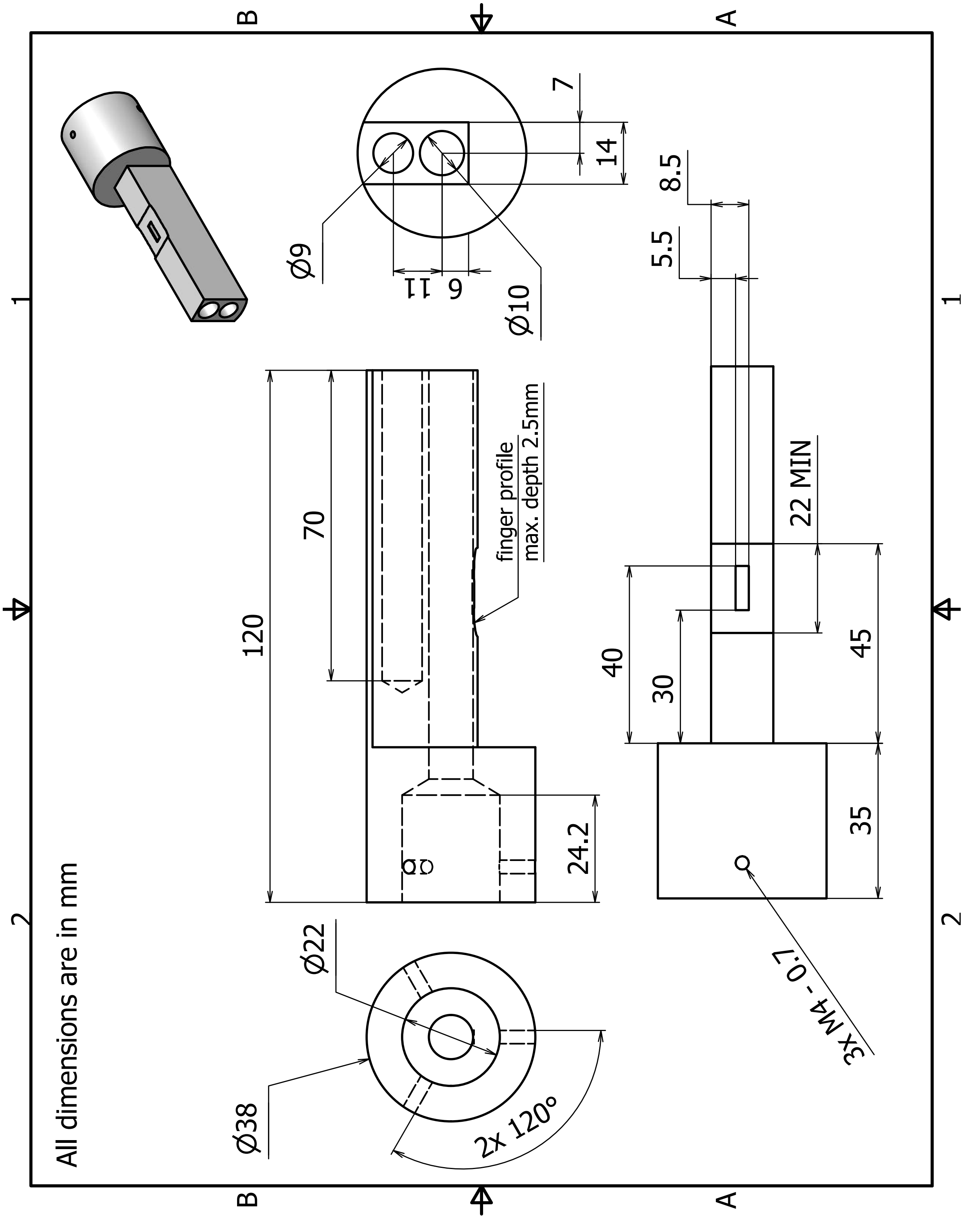


Figure C.3: Block diagram of the control

Then by using large gains, the steady state error can be made small. This does not achieve perfect steady state tracking. However, the speed of the motor is constantly monitored for every user in order to ensure that it is consistent from user to user and close to the specified speed.

Appendix D

CAD Drawing


All dimensions are in mm
Ø38
Ø22
2x 120°
120
70
24.2
finger profile
max. depth 2.5mm
Ø9
Ø10
11
6
7
14
8.5
5.5
22 MIN
40
30
45
35
3x M4 - 0.7
A
B
1
2

References

C. Basdogan, C.H. Ho, M.A. Srinivasan, et al. Virtual environments for medical training: Graphical and haptic simulation of laparoscopic common bile duct exploration. *IEEE/ASME Transactions On Mechatronics*, 6(3):269–285, 2001. 3

PE Brynat and I. Raz. Visual and Tactual Perception of Shape by Young Children. *Developmental Psychology*, 11(4):525–526, 1975. 10

G. Cadoret and AM Smith. Friction, not texture, dictates grip forces used during object manipulation. *Journal of neurophysiology*, 75(5):1963–1969, 1996. 17

C.S. Campbell, S. Zhai, K.W. May, and P.P. Maglio. What you feel must be what you see: adding tactile feedback to the trackpoint. In *Human-computer Interaction, INTERACT'99: IFIP TC. 13 International Conference on Human-Computer Interaction, 30th August-3rd September 1999, Edinburgh, UK*, page 383. IOS Press, 1999. 29

S. Cashdan. Visual and haptic form discrimination under conditions of successive stimulation. *Journal of experimental psychology*, 76(2):215, 1968. 10, 88

CE Connor, SS Hsiao, JR Phillips, and KO Johnson. Tactile roughness: neural codes that account for psychophysical magnitude estimates. *Journal of Neuroscience*, 10(12):3823–3836, 1990. 31

M.A. Costa and M.R. Cutkosky. Roughness perception of haptically displayed fractal surfaces. In *Proceedings of the ASME Dynamic Systems and Control Division*, volume 69, pages 1073–1079, 2000. 19, 21

V. Cronin. Active and passive touch at four age levels. *Developmental Psychology*, 13(3):253–256, 1977. 9

Cyber Glove Systems LLC. CyberGlove. `www.cyberglovesystems.com/products/hardware/cyberglove_app.php`, 2009a. 24

Cyber Glove Systems LLC. CyberGlove II. `www.cyberglovesystems.com/products/hardware/cybergrasp_app.php`, 2009b. 24

F. Dachille Ix, H. Qin, and A. Kaufman. A novel haptics-based interface and sculpting system for physics-based geometric design. *Computer-Aided Design*, 33 (5):403–420, 2001. 2

R.A. Damon and W.R. Harvey. *Experimental design, ANOVA, and regression.* Harper & Row New York, 1987. 109, 112, 113

J.T. Dennerlein, D.B. Martin, and C. Hasser. Force-feedback improves performance for steering and combined steering-targeting tasks. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 423–429. ACM New York, NY, USA, 2000. 2

P. DiZio and J.R. Lackner. Congenitally blind individuals rapidly adapt to Coriolis force perturbations of their reaching movements, 2000. 13

G. Ekman, J. Hosman, and A. Lindstrom. Roughness, smoothness and preference: a study of quantitative relations in individual subjects. *Journal ol Experimental Psychology*, 70(1):18–26, 1965. 17

Rudolf J. Freund and Ramon C. Littell. *SAS for linear models: A guide to the ANOVA and GLM procedures.* SAS Institute Inc., 1981. 111

George A. Gescheider. *Psychophysics: The Fundamentals.* Lawrence Erlbaum Associates Inc., Mahwah, New Jersey, 3rd edition, 1997. 32, 34, 37, 38, 39, 40, 114, 115

J.J. Gibson. Observations on active touch. *Psychological review*, 69(6):477–491, 1962. 8, 9

MA Heller. Active on passive touch: the influence of exploration time on form recognition. *The Journal of general psychology*, 110:243–249, 1984. 9

MA Heller and DS Myers. Active and passive tactual recognition of form. *The Journal of general psychology*, 108(2d Half):225, 1983. 9

C.H. Ho, C. Basdogan, and M.A. Srinivasan. Efficient point-based rendering techniques for haptic display of virtual objects. *Presence*, 8(5):477–491, 1999. 19, 20

D. Katz and L.E. Krueger. *The world of touch.* L. Erlbaum, Hillsdale, NJ, 1989. 8, 13

R.L. Klatzky and S.J. Lederman. Tactile roughness perception with a rigid link interposed between skin and surface. *Perception and Psychophysics*, 61(4):591–607, 1999. 17, 18

RL Klatzky, SJ Lederman, and VA Metzger. Identifying objects by touch: an expert system. *Perception & Psychophysics*, 37(4):299–302, 1985. 10, 11

RL Klatzky, SJ Lederman, C. Hamilton, and G. Ramsay. Perceiving roughness via a rigid probe: Effects of exploration speed. In *Proceedings of the ASME Dynamic Systems and Control Division*, volume 67, pages 27–34, 1999. 18

V.S. Klimberg, K.C. Westbrook, and S. Korourian. Use of touch preps for diagnosis and evaluation of surgical margins in breast cancer. *Annals of Surgical Oncology*, 5(3):220–226, 1998. 3

DA Kontarinis, JS Son, W. Peine, and RD Howe. A tactile shape sensing and display system for teleoperatedmanipulation. In *1995 IEEE International Conference on Robotics and Automation, 1995. Proceedings.*, volume 1, 1995. 27, 28

S.J. Lederman. Tactile roughness of grooved surfaces: The touching process and effects of macro-and microsurface structure. *Perception*, 16:385–395, 1974. 16, 54

SJ Lederman and RL Klatzky. Hand movements: a window into haptic object recognition. *Cognitive psychology(Print)*, 19(3):342–368, 1987. 11, 12, 15

SJ Lederman and RL Klatzky. Haptic classification of common objects: knowledge-driven exploration. *Cognitive psychology*, 22(4):421, 1990. 12

S.J. Lederman and M.M. Taylor. Fingertip force, surface geometry, and the perception of roughness by active touch. *Perception and Psychophysics*, 12(5):401–408, 1972. 15, 16, 31, 54

S.J. Lederman, R.D. Howe, R.L. Klatzky, and C. Hamilton. Force variability during surface contact with bare finger or rigid probe. In *12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 154–160, 2004. 54

Susan J. Lederman. The perception of surface roughness by active and passive touch. *Bulletin of the Psychonomic Society*, 18(5):253–255, 1981. 10

J. Lee, G. Han, and S. Choi. Haptic Pottery Modeling Using Circular Sector Element Method. *Lecture Notes in Computer Science*, 5024:668, 2008. 3

Johnny C. Lee, Paul H. Dietz, Darren Leigh, William S. Yerazunis, and Scott E. Hudson. Haptic pen: a tactile feedback stylus for touch screens. In *UIST '04: Proceedings of the 17th annual ACM symposium on User interface software and technology*, pages 291–294. ACM, 2004. 3

D.A. Leopold and N.K. Logothetis. Multistable phenomena: changing views in perception. *Trends in Cognitive Sciences*, 3(7):254–264, 1999. 76

X. Liu, G. Dodds, J. McCartney, and BK Hinds. Virtual DesignWorksdesigning 3D CAD models via haptic interaction. *Computer-Aided Design*, 36(12):1129–1140, 2004. 2

J.M. Loomis. Presence and distal attribution: Phenomenology, determinants, and assessment. In *Proceedings of SPIE*, volume 1666, page 590, 1992. 23

Neil A. Macmillan and C. Douglas Creelman. *Detection Theory: A User's Guide.* Cambridge University Press, New York, New York, 1991. 32, 33, 35, 83, 114, 115

L.E. Magee and J.M. Kennedy. Exploring pictures tactually. *Macmillan Journals Ltd.* 9, 10

N.L. Max and B.G. Becker. Bump shading for volume textures. *IEEE Computer Graphics and Applications*, 14(4):18–20, 1994. 20

M. Minsky and SJ Lederman. Simulated haptic textures: Roughness. In *Proceedings of the ASME Dynamic Systems and Control Division*, volume 58, pages 421–426. Amer Society of Mechanical, 1996. 21, 31

M. Minsky, O. Ming, O. Steele, F.P. Brooks Jr, and M. Behensky. Feeling and seeing: issues in force display. *ACM SIGGRAPH Computer Graphics*, 24(2): 235–241, 1990. 21, 22

G. Moy, C. Wagner, and RS Fearing. A compliant tactile display for teletaction. In *IEEE International Conference on Robotics and Automation, 2000. Proceedings. ICRA'00*, volume 4, 2000. 27, 28

I. Oakley, M.R. McGee, S. Brewster, and P. Gray. Putting the feel inlook and feel . In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 415–422. ACM New York, NY, USA, 2000. 3

K. Perlin. An image synthesizer. In *Proceedings of the 12th annual conference on Computer graphics and interactive techniques*, pages 287–296. ACM New York, NY, USA, 1985. 19

D. Prytherch and M. McLundie. So what is haptics anyway? *Research Issues in Art, Design and Media*, 2, 2002. 6, 7

Quanser Consulting Inc. 5 dof haptic wand system. `www.quanser.com/NET/Industrial/Systems_and_Products/Prod_5Dof_Haptic.aspx`, 2009. 23

S.A. Rose, M.S. Blank, and W.H. Bridger. Intermodal and intramodal retention of visual and tactual information in young children. *Developmental Psychology*, 6 (3):482–486, 1972. 10

H.E. Ross and D.J. Murray. *E. H. Weber: The Sense of Touch.* Academic Press Inc., New York, New York, 1978. 6

M. Salada, P. Vishton, JE Colgate, and E. Frankel. Two experiments on the perception of slip at the fingertip. In *Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2004. HAPTICS'04. Proceedings. 12th International Symposium on*, pages 146–153, 2004. 56, 64

Bertram Scharf, Joan Gay Snodgrass, Thomas S. Brown, Ronald T. Verrillo, and Leo Ganz. *Experimental Sensory Psychology.* Scott, Foresman and Company, Glenview, Illinois, 1975. 13, 37, 38, 40

R.A. Scheidt, D.J. Reinkensmeyer, M.A. Conditt, W.Z. Rymer, and F.A. Mussa-Ivaldi. Persistence of motor adaptation during constrained, multi-joint, arm movements. *Journal of Neurophysiology*, 84(2):853–862, 2000. 13

Harvey Richard Schiffman. *Sensation and Perception: An Integrated Approach.* John Wiley & Sons, Inc., New York, 1976. 13

AS Schwartz, AJ Perey, and A. Azulay. Further analysis of active and passive touch in pattern discrimination. *Bulletin of the Psychonomic Society*, 6(1):7–9, 1975. 9

Sensable Technologies. Phantom omni® haptic device. `www.sensable.com/haptic-phantom-omni.htm`, 2009. 23, 45

A.E. Sklar and N.B. Sarter. Good vibrations: Tactile feedback in support of attention allocation and human-automation coordination in event-driven domains. *Human factors*, 41(4):543, 1999. 3

SS Stevens. The direct estimation of sensory magnitudes: loudness. *The American journal of psychology*, pages 1–25, 1956. 30, 31

SS Stevens and J.R. Harris. The scaling of subjective roughness and smoothness. *Journal of Experimental Psychology*, 64(5):489–494, 1962. 30, 68

P. Ström, L. Hedman, L. Särnå, A. Kjellin, T. Wredmark, and L. Felländer-Tsai. Early exposure to haptic feedback enhances performance in surgical simulator training: a prospective randomized crossover study in surgical residents. *Surgical endoscopy*, 20(9):1383–1388, 2006. 2

Y. Suzuki and M. Kobayashi. Air jet driven force feedback in virtual reality. *IEEE Computer Graphics and Applications*, pages 44–47, 2005. 26, 27

MM Taylor and S.J. Lederman. Tactile roughness of grooved surfaces: A model and the effect of friction. *Perception & Psychophysics*, 17(1):23–36, 1975. 17

Torrington Brush Works. Nylon Bristle Gun Brush. `www.torringtonbrushes.com/06882-27calibernylonbristlegunbrush.aspx`, 2009. 48

F. Vega-Bermudez, KO Johnson, and SS Hsiao. Human tactile pattern recognition: active versus passive touch, velocity effects, and patterns of confusion. *Journal of Neurophysiology*, 65(3):531–546, 1991. 9

A.M. West and M.R. Cutkosky. Detection of real and virtual fine surface features with a haptic interface and stylus. In *Proceedings of the ASME Dynamic Systems and Control Division: presented at the 1997 ASME International Mechanical Engineering Congress and Exposition, November 16-21, 1997, Dallas, Texas*, page 159. Amer Society of Mechanical, 1997. 24

T. Yoshikawa and A. Nagura. A touch/force display system for haptic interface. *Presence: Teleoperators & Virtual Environments*, 10(2):225–235, 2001. 25

M.J. Zigler. Pressure adaptation-time: A function of intensity and extensity. *The American Journal of Psychology*, pages 709–720, 1932. 15

JJ Zwislocki and DA Goodman. Absolute scaling of sensory magnitudes: a validation. *Perception & Psychophysics*, 28(1):28, 1980. 31