Multidimensional Force Illusion using Asymmetric Vibrations

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To, amma and appa...

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ABSTRACT

Multidimensional Force Illusion using Asymmetric Vibrations

by

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Haptic devices simulate a "sense of touch" to enhance realism and provide an immersive experience in various applications like tactile displays, neurorehabilitation and enabling vibratory feedback in cellular devices. In addition, haptics has found significance in pedestrian guide systems, allowing users to identify directions without the need for visual displays. Haptic technologies are also implemented in virtual and augmented reality devices to provide improved user experiences. While there are several techniques to create kinesthetic and tactile haptic feedback, creating multidimensional force feedback with a portable form factor has been a challenge due to the difficulty of generating forces without requiring it to be offset by clamping devices to high walls, floors etc. in the environment.

This work introduces a novel method of creating multidimensional force feedback without grounding by using asymmetric vibrations, which utilizes the nonlinear characteristics of human perception to create the illusion of virtual force. This eliminates the need for large actuators creating actual forces and enables miniaturization with the use of small voice coil actuators, making it easier for a user to carry and use at any place. They enable the development of ungrounded haptic devices that are portable creating opportunities for mobile use cases that can be embedded in various applications. In this work, a handheld prototype that provides 2D haptic feedback was designed and implemented using a unique actuation mechanism with a single voice coil actuator to generate virtual force in eight directions using asymmetric vibrations. Our user study indicates that this device is capable of generating distinct 2D force feedback in eight directions. Users were able to distinguish directional cues over 37% of the time and over 66% of the time when one interval errors are regarded as correct responses. Furthermore, we demonstrate the feasibility of using asymmetric vibration with a spherical prototype that can be held in any orientation in hand to provide 3D haptic feedback. A pilot study with the prototype device showed promising results with a correctness percentage of 83.75% among six directions.

CHAPTER I

Introduction

Every day, we rely on electronic devices to provide information and guide us through various tasks. We rely on smartphones and applications to aid us in a multitude of ways that range from navigation to exercising and fitness. However, the majority of these devices are restricted to audio or visual cues alone. This is often challenging for people with limited vision or hearing abilities or those who are in a noisy environment. Haptics can contribute significantly in such scenarios to provide discrete cues while being intuitive as “sense of touch” is an integral part of life that helps us feel and manipulate objects.

Haptic devices are used to simulate this “sense of touch” artificially to enhance realism in various applications. It can be defined as a mechanism to induce virtual force based on human illusory sensations. Haptic devices are used for mobile and wearable applications such as smartwatches and fitness trackers [17, 22]. Haptic interfaces are also utilized to explore and guide objects in an unknown environment, navigation, and pedestrian guide systems that use finger-mounted tactile devices [2, 18]. In addition, several AR and VR applications utilize haptics to create a more realistic experience [25, 6, 10].

This thesis focuses on the development of a 2D and 3D haptic device using asymmetric vibrations. To begin with, the context of this research and the problem statement are presented. Then, the motivation to explore solutions for this problem is discussed, the research questions and methodology is laid out. Finally, the contributions of this research and it's impact on every day life is highlighted, while providing a brief overview of this thesis.

1.1 What is Haptics and Haptic Technology?

Imagine you are blindfolded and cannot hear. You are left inside a room and asked to explore. The first thing you would do is stretch your hands to touch and feel the objects around you. You would aim to obtain information on the texture, weight, and placement of the objects using the "sense of touch" from the forces you feel. The receptors on our fingers sense shear forces and pressure and send signals to your brain that interprets it [9]. This intuitive "sense of touch", its study, perception and simulation of touch interactions is called Haptics.

In simple words, it is the science of touch. The word haptics, believed to be derived from the Greek word *haptesthai* [16] related to the sense of touch. Haptic devices are mechanical devices that provide information to the user through the sense of touch by tactile or kinesthetic feedback. The design, control, working and manipulation of forces to simulate haptic feedback in these haptic devices constitute haptic technology.

1.2 Background

Haptic devices play an important role in many applications such as increasing realism in AR/VR applications, providing aid to the visually impaired, simulating the sense of touch that was lost due to an accident, in aviation et al. [9]. Haptic devices can be classified based on several factors including the receptors that are targeted for sensation, wearability, haptic surfaces, method of grounding, etc.

This thesis focuses on ungrounded graspable/hold-able haptic devices that utilize force feedback to provide directional cues to the mechano-receptors on the fingers. We mainly focus on the utilization of asymmetric vibrations to achieve this. The primary idea is to create asymmetric acceleration that leads to a virtual force vector. These devices have the potential to provide multi-dimensional haptic feedback while being simple in design, small, portable, cost-effective, and easy to use.

1.3 Problem Statement and Motivation

Grounded haptic devices also contain huge parts and a complex design because of which their usability is limited and requires confinement to a specific area. Efforts have been made to develop haptic devices that are ungrounded, portable, and contain no mechanical links using asymmetric vibrations. However, the devices developed to provide two-dimensional haptic cues require users to interpret the vibrations of multiple actuators comprehensively and contain many moving parts, thereby making the user experience cumbersome [14]. The majority of these devices contain more than one actuator, which leads to interference from vibrations of these actuators, thereby not delivering distinct directional cues [23]. Attributing to this problem, many devices utilize multiple dampening techniques to reduce magnetic interference between these actuators and simulate different parts of the device for each directional cue, such as tangential and normal directions [19].

The motivation for this research aims to fill this knowledge gap by developing a hand-held haptic device that is simple in design, utilizes a single actuator, portable with a small form factor, capable of providing multi-dimensional haptic feedback, and low cost of production.

1.4 Thesis Objective

The overall objective of this thesis is to develop a graspable multidimensional haptic feedback device using asymmetric vibrations. This overreaching goal can be divided into the following sub-objectives:

First, to study the design of asymmetric control signals for voice coil actuators. Even though past researchers have studied control signals for producing asymmetric vibrations, the range of frequencies best suited for haptic sensation, and the duration of these signals, we explore different combinations of asymmetric signals to study if it influences perceptibility and direction discrimination. We study the effect of asymmetric and symmetric waveform additions to an asymmetric base signal through a preliminary pilot study.

Second, develop a 2D graspable haptic device that contains a single actuator while rendering effective 2D virtual force feedback using an actuation mechanism in which the exciter plane is rotated. Many 2D haptic devices have been developed that are wearable or holdable using asymmetric vibrations or a combination of asymmetric vibrations and other mechanisms. Most of these devices contain more than one actuator, simulate different parts of the device for each type of directional cue, or expect users to interpret the vibrations of multiple actuators comprehensively. We aim to propose a simple design to create a 2D haptic device that contains one actuator capable of providing effective directional cues in 8 directions.

Third, we evaluate the possibility of developing a 3D haptic device that is spherical in shape and can be hand-held containing a single actuator. While many efforts have been made to create a 3D haptic device using asymmetric vibrations and a combination of other techniques, to the best of our knowledge, no exploration has been made to design a structure to produce effectual 3D haptic feedback that provides directional cues using a single actuator.

Fourth, we investigate and evaluate the design of the 2D prototype via user study.

We would like to understand the effectiveness of these devices in producing 2D haptic feedback using asymmetric vibrations in eight directions and understand the particular challenges of this design. We also aim to investigate the cause for some of the challenges and limitations via qualitative feedback from user study.

Achieving the first goal will help us identify the best control signal to provide distinctive directional cues. The second and third goal will manifest a working prototype for 2D and a feasible design for 3D haptic feedback with multiple advantages and the fourth goal will evaluate its effectiveness and help analyze it its ease of use.

1.5 Methodology

We utilized the following methodology to meet the research objectives mentioned above. In order to meet our first goal, we designed three different control signals. The base signal comprised of an asymmetric positive and asymmetric negative sine wave, in which half a cycle was inverted for every two cycles. For the second control signal, an additional inverted saw-tooth waveform was introduced to the base signal for a small duration at the same frequency. The third signal was generated by addition of an inverted symmetrical sine wave to the base signal at the same frequency.

These additions aimed to study if providing a virtual force in the opposite direction or adding an inverted symmetric waveform before the actual directional cue influences the ease of direction identification. Pilot studies were conducted to analyze the effectiveness of these additions in providing lucid directional cues and their performance. Based on these results, we conclude on the control signal to be utilized for the haptic devices we aimed to build.

For the second objective, a prototype was created that aims to have a simple design with one actuator catering to 2D haptic feedback through its rotation at different angles. It is comprised of a single actuator capable of rotation up to 180 degrees using a motor.

Thirdly, we also study the effectiveness of a 3D handheld haptic device in a spherical form and propose a design to manifest this using a single actuator on a two-axis gimbal with motors.

To meet our last objective, we conducted user studies to investigate the capability and effectiveness of the 2D device and conducted pilot study to study the feasibility of the spherical design. The results from these studies were then analyzed and we present in our findings towards the end of this thesis.

1.6 Contributions

This thesis makes the following contributions to the design of multi-dimensional haptic devices using asymmetric vibrations.

To begin with, this work investigated and evaluated the effect of providing a small directional cue in the opposite direction before the actual directional cue using asymmetric vibrations via pilot study.

Furthermore, we contributed to the design and implementation of a 2D haptic feedback device using a single voice coil actuator, thereby eliminating challenges that arise due to interference.

The scope of this research focuses primarily on designing and rendering effective multi-dimensional haptic feedback devices with asymmetric vibrations only. While limited, we hope that this will lay a foundation for adding other force feedback techniques to this design to enhance the usability of such systems.

1.7 Scope of Research

Other haptic devices that provide multidimensional force feedback using asymmetric vibrations and voice coil actuators : *Grabity* [9] and *Hapcube* [19] focus on combining two different types of illusions to create multidimensional force feedback simulating different areas of the device. There have also been approaches that create translational and rotational cues by using actuators on different fingers [14]. Our work uses a much-narrower frame of reference using asymmetric vibrations alone. This thesis subsequently evolves by evaluating different designs, their merits, and challenges and conducting user studies to gradually develop our final design of multidimensional haptic devices to provide haptic force feedback using asymmetric vibrations.

1.8 Thesis Overview

This document unfolds as follows. Chapter 2 reviews the related and intellectual foundation of this research, primarily, asymmetric vibrations, voice coil actuator to produce these asymmetric vibrations, different asymmetric signal profiles and design of existing multidimensional haptic feedback devices using asymmetric vibrations.

Chapter 3 describes the design of the control signal profile utilized for asymmetric vibrations. We elaborate on the different control signals explored to provide effective haptic feedback.

Chapter 4 discusses the design and implementation of a 2D haptic device to produce directional cues in the tangential direction. We first introduce the goals of the design and our design choices. We then describe our operationalization of these goals with the implementation of the 2D prototype.

Chapter 5 documents the user study that was conducted to determine the efficacy, ease of use and error rate of the 2D prototype. The results of this study and its implications have been discussed.

Chapter 6 elaborates on the proposed design for a spherical 3D haptic device to produce directional cues in tangential and normal directions using asymmetric vibrations as future work. Here, the results of the pilot study conducted with a static prototype to study its feasibility is also discussed.

Chapter 7 discusses the limitations of this work and future work that can be carried out to provide increased effective directional cues using asymmetric vibrations.

Chapter 8 provides a conclusion of this thesis as a whole.

CHAPTER II

Related Work

This chapter seeks to introduce the use of asymmetric vibrations for directional cues and familiarize readers with the intellectual basis of different haptic devices using asymmetric vibrations that have been developed so far. More specifically, it briefly introduces the classification of haptic devices based on their design, directional cues in different axes, actuators used, etc. First,we will review ungrounded haptic devices based on how their forces are applied. We will review asymmetric vibrations and evaluation of its characteristics. Lastly, the the design of multi-dimensional haptic devices and different actuators is elaborated.

This review literature will provide a rationale for the choices we made in our design prototypes and evaluate its effectiveness.

2.1 Grounded and Ungrounded Haptic Devices

Depending on the method of forces applied, haptic devices can be broadly classified into grounded and ungrounded haptic devices. Initially, large mechanical devices required the output force experienced to be offset by a reactional force by clamping the devices to high walls, floors and desks to which the force will be applied [24, 8, 5]. These devices are called "grounded haptic devices." More recently, there are haptic interfaces wherein the reaction force is applied to a user's body or away from the area of output force, and such devices are called “ungrounded haptic devices" [12, 28].

Ungrounded haptic devices have played a significant role in the miniaturization of haptic interfaces and paved the way for wearable or hold able haptic devices using asymmetric vibrations. There are many advantages in using ungrounded haptic devices such as portability, small form factor, and they do not confine users to a specific area.

2.1.1 Ungrounded Haptic Devices

The successful creation of a sensation of pulling or pushing by adding asymmetry to signal profiles was first proposed by Amemiya et al. in Phantom-DRAWN [4] which utilized a mechanical device and a slider crank mechanism attached to a table. They proposed a method in which a vibration with asymmetric acceleration was capable of inducing directional feedback towards a single direction. The slider-crank device weights move forward and backward with asymmetric acceleration caused by the rotation of the motor. This produces a sense of force perception using periodic prismatic motion to generate asymmetric acceleration changes.

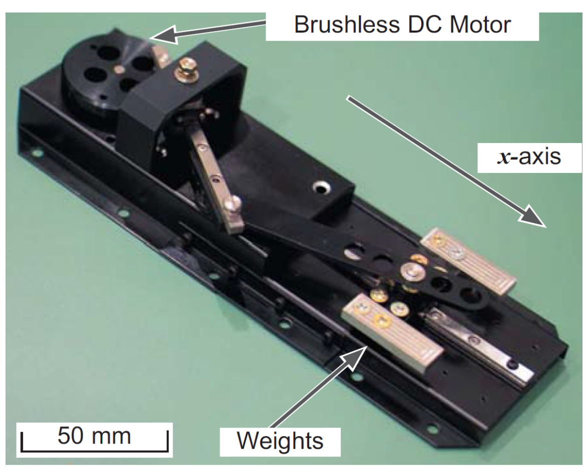

Figure 2.1: Phantom-DRAWN Prototype [4]

Similar systems exist that utilized moving handles asymmetrically to achieve directional haptic feedback. Tappeiner et al [27] in 2009 designed a desktop haptic

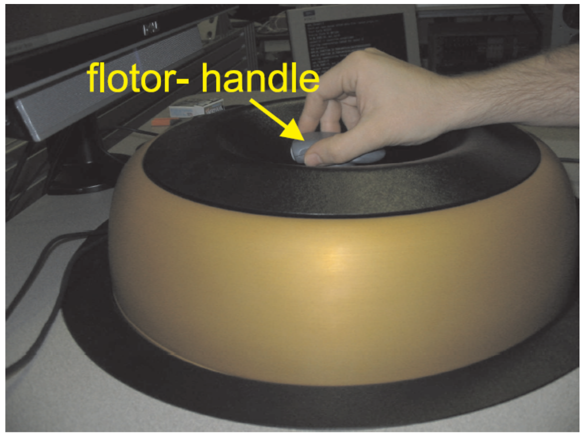

Figure 2.2: The *Maglev* haptic device in front of a computer screen [27]

device using an asymmetric vibration signal profile. Prior to this work, producing one-dimensional vibration using simple versions of a single transducer or motor/mass was implemented. Tappeiner et al. [27] used an asymmetric sinusoidal function composed of two half periods, of different lengths such that the rising part is much steeper than the falling part and vice versa. The premise was that the object vibrated asymmetrically will move faster during the shorter half period of the signal. This will result in increased output power during a longer period of the signal. They developed a desktop mounted Meglev haptic interface which contains only one moving part, i.e., the floater, which is in a strong magnetic field as depicted in the picture below. Sinusoidal symmetric vibrations were designed to provide haptic feedback at eight different directions in the x-y plane at 45-degree intervals and studied the effect of frequency amplitude pairs. The results of their user study indicate that this system was able to produce directional haptic feedback successfully.

Rekimoto et al introduced Traxion [23] which is an ungrounded tactile interaction device based on virtual force sensation. In this work, the system consists of an electromagnetic coil is attached to a metal sheet supported by a spring. This system had great advantages of portability; small form factor due to its ungrounded nature as compared to huge mechanical grounded haptic devices such as *Maglev Haptic device*

[27]. Two permanent magnets at two ends surround the metal sheets.An asymmetric signal is passed to the electromagnetic coil which vibrates the metal sheet based the control signal characteristics. The difference in acceleration in the movement of weight which is a result of the electromagnetic coils is not offset. This results in the users feeling a push or pull in a particular direction. The work elaborated that since no mechanical component exists, there is no real force created and term this sense of push or pull as a virtual force i.e., a sensory illusion of the force that the user perceives. The weight of this device is about 5.2 g with a small form factor of about $7.5mm \times 35mm \times 5mm$ and provides virtual haptic feedback in 1D.

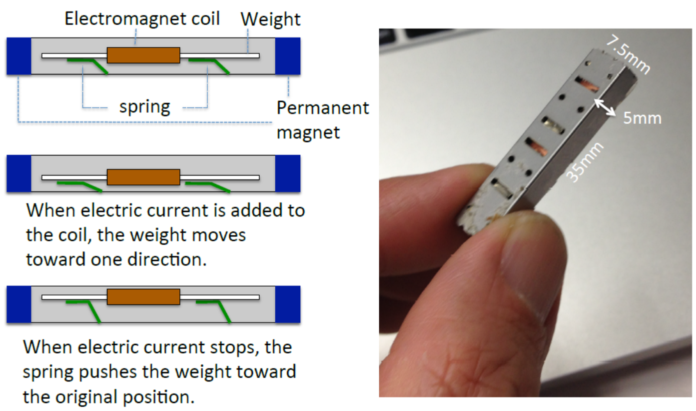

Figure 2.3: Traxion - ungrounded tactile device and its configuration [23]

The user study results confirm that the participants were able to distinguish a sense of pull or push in the right direction based on the control signal. The authors also attempted to expand this mechanism to create a 2D virtual force by placing two actuators perpendicular to each other. However, this did not yield substantial results though the ratio exceeded random guess. This could be attributed to the interference of virtual forces created between the actuators. This work also highlights the need to create a device that has a structure in which a single weight moves in different directions to eliminate the need of creating two vibrations for a 2D system.

CLAW developed by Choi et al [11], is a tethered handheld haptic controller device that is used mainly to deliver three types of interactions viz grasping, touching and triggering in a VR environment. It is an ungrounded device that enables free motion in space with kinesthetic feedback. CLAW has a handle stalk with control buttons and a rotating arm where the index finger rests. There is a Voice Coil Actuator (VCA) at the end of the move able arm that renders the feeling of texture to the index finger. Switching between the different modes is triggered by the thumb position which is determined by a proximity sensor. There is also a force sensor at the end of the index finger mount acts as an input for different modes when interacting with objects in the VR and when coupled with spring action of the arm is used in the trigger mode. CLAW has a resolution of 0.000023 N which is enough to sense even the minute force changes in the index finger thus providing greater accuracy. User study to evaluate the quality of interaction with different objects in VR indicates that enabling penetration compensation to stop pushing into objects could have yielded better user satisfaction. In the user study experiment designed to switch between two different modes, results indicate that participants were able to do it seamlessly that show it is a very efficient in being a multi-purpose haptic controller. CLAW provides these three different induced sensations individually whereas to simulate near real world feedback in VR, two or more haptic rendering must be generated simultaneously i.e, generating grabbing and touching feedback together when interacting with an object to quote as example. Also, it provides haptic rendering to only the index finger, which can be extended to other fingers as well. These areas bring into scope for further improvements in this device.

Haptic-PIVOT [20] is an ungrounded wrist-worn haptic VR device that is used to render the sensation of grasping, catching, and throwing objects in a VR environment. One of the main advantages of PIVOT over other VR haptic devices is that it enables free and continuous motion of the wrist when not interacting with any virtual objects without any burden and it can be used in both hands. As the name suggests, the haptic sensation for these particular actions is simulated by pivoting a haptic handle to and from the user's wrist in addition to providing a single control button, touch sensing and vibrotactile feedback achieved using a VCA. The PIVOT's handle is driven by a servo motor using a teensy 3.6 micro controller and can rotate up to 190° in an axis slightly slanted to the vertical axis of the hand. This motion in one DOF driven by the motor renders the force to the wrist as required. A passive radio ulnar hinge is integrated into the handle that can tilt up to 30° in order to naturally accommodate into the position of the hand. There are capabilities built into this system to predict the objects that the user's hand might come into contact with by moving the handle early thus compensating for latency. User study conducted to evaluate performance by giving them different tasks like grasping objects of shapes and size, catching, and lifting objects in VR environments indicate that PIVOT performs exceptionally well under certain physical limits of the interacting objects. For example, the user result scores were particularly low for tasks involving grasping of bigger objects and different textures since it is limited by using a fixed shape handle. Even though the shape of the handle is round, there is no possibility of generating haptic feedback simulating the feel of touching a rotating object since the handle cannot rotate on its axis.

2.2 Asymmetric Vibrations

Asymmetric Vibrations contain a large positive acceleration followed by a small negative acceleration signal profile and vice versa. The nonlinear characteristics of human tactile perception will make the user feel that the device that is asymmetrically vibrated is being pulled in the direction of the large pulse. Several signal profiles have been utilized to create asymmetric vibrations such as sinusoids, step up ramp signal et al. depending on the actuator that is utilized as shown in Figure 2.5 [12].

Humans translate asymmetric vibration as a sense of one directional pulling or pushing due to the nonlinear characteristics of human perception that can be characterized as a psychometric function whose shape is a sigmoid curve as shown in Figure 2.4. This gives us the relationship between simulation and perception [4].

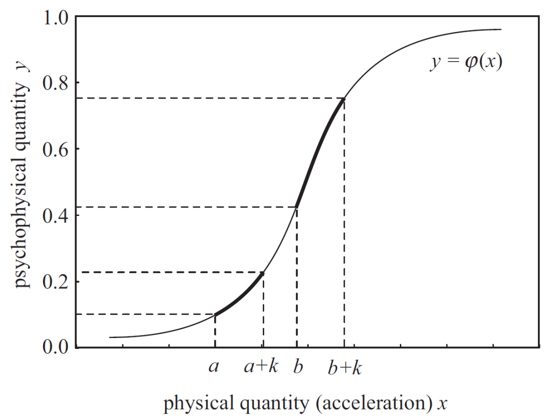

Figure 2.4: Model of sigmoid curve of perception depicting nonlinear relationship between simulation and perception [4].

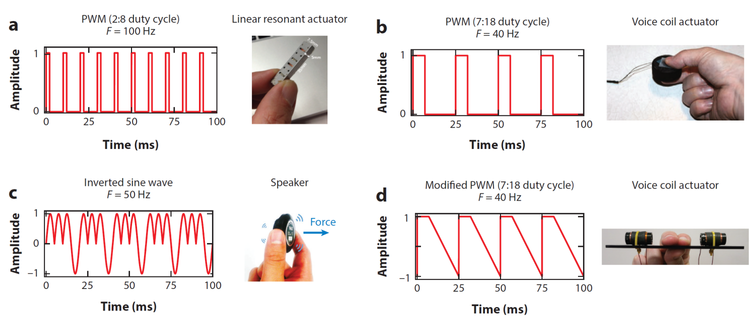

Figure 2.5: Examples of different signal profiles used in ungrounded asymmetric vibration systems [12].

2.2.1 Multidimensional Force Illusion Devices

Virtual and augmented reality (VR and AR) markets are experience higher demands from the users for a more realistic experience every day. With grounded haptic devices being large, mechanically complex, and having limited work spaces, it was imperative for haptic devices to become more compatible and mobile. Initially, the use of vibration was proposed to achieve miniaturization in haptic devices. However, most vibrotactile feedback only provided binary information about the transition between "touched" and "released" states and did not provide any form of pseudo-force sensation or feedback. In the recent past, creation of pseudo-force sensation was proposed via the use of asymmetric vibrations, to generate a pulling sensation in a particular direction. Based on this concept, there were multiple attempts to design haptic devices by applying various asymmetric vibrations[15]. However, it has been a challenge to fabricate a hand-held haptic device that can expand one-dimensional virtual forces into multi-dimensional virtual forces seamlessly.

An attempt to create 2D virtual force by Rekimoto et. al. [23] by simply attaching two vibrators to each other perpendicularly did not yield convincing results from user studies. A design to provide three- DoF translation and three-DoF rotation cues by Culbertson et al [14] required users to interpret all the vibrations of the actuators comprehensively to recognize the direction and rotation cues. Amemiya et al. [4] successfully generated two dimensional virtual forces by rotating the slider–crank unit with a motor. However, the difference in angle between the two separate virtual forces was approximately 23–30°, which was barely noticeable.

HapCube: A Wearable Tactile Device to Provide Tangential and Normal Pseudo-Force Feedback on a Fingertip developed by Kim et al [19] consists of three perpendicular voice coil actuators. It contains a combination of two orthogonal actuators to create 2D virtual force in tangential direction and a single voice coil actuator to produce pseudo force feedback of the complex compliance curves using stress strain curves in the normal direction.

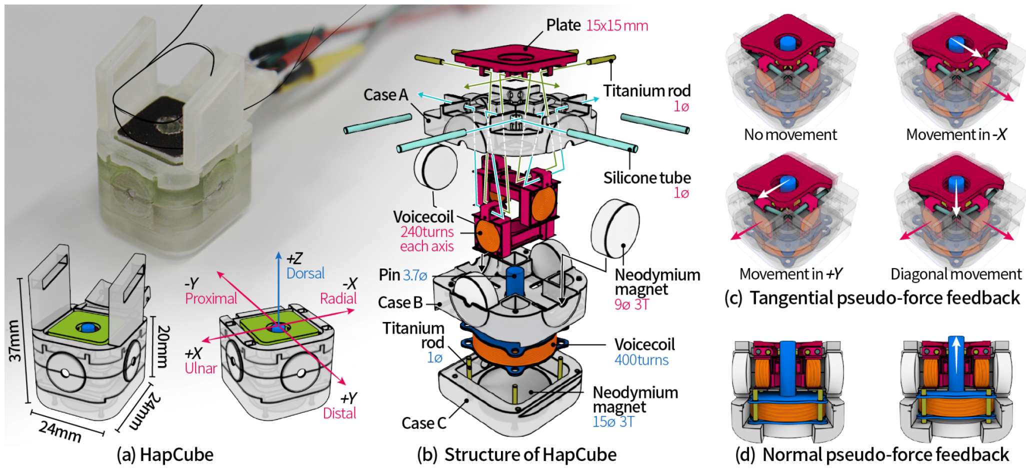

Figure 2.6: *Hapcube* structure and plate movement in tangential and normal directions [19].

In the tangential plane, the two electromagnets are placed perpendicular to each other, and they move independently in positive or negative X and Y directions, respectively, depending on whether a positive or negative voltage is applied. Asymmetric vibration of the two voice coil actuators led to tangential feedback of the Hapcube. Inorder to tackle interference and make the magnetic field symmetric, the magnets are aligned with the same pole facing inward and instant adhesives were used to overcome magnetic repulsion. Furthermore, to limit the movement of electromagnets and pins, titanium rods were used as they are paramagnetic. This design proved that it was feasible to combine the two orthogonal asymmetric vibrations to produce a 2D virtual force. Interference between two feed backs when the feed backs are generated simultaneously was also investigated. From their studies, it is to be noted that while distinguishing the four directions correctly; they could not do so satisfactorily in case of eight, or twelve directions but the distribution showed that they did not completely misunderstand the directions. More importantly, correctness rates increase significantly when the one interval errors were taken into consideration and it was concluded that the participants could perceive the directions but exhibited difficulty in matching the **"perceived direction"** to the **"precise direction in the**

real world". This leads to the question of would users be able to better perceive directions if opposite force feedback is provided for a small duration before the actual force feedback in the desired direction. This serves as a strong motivation to explore different control signals to analyze the effect it has on direction perception discussed in Chapter 3.

Even though multiple measures were taken to dampen interference, most of the users failed to distinguish feedback in normal direction and virtual forces in the diagonal direction was confusing as compared to axial direction. This is attributed to the nonidentical damping constant of the silicone tubes used. The device also provides tangential feedback through the plates and normal feedback through the pin thereby simulating different areas of finger pad.

The authors emphasize on the need to create a larger sized device that can be handheld to provide more realistic virtual force. A method to combine tangential and normal feedback is also referenced.

These studies and analyses serve as a strong motivation to develop a handheld haptic device using a single voice coil actuator to produce realistic haptic feedback.

Grabity [9] is another wearable haptic device that has been designed to simulate kinesthetic pad opposition grip forces and weight for grasping virtual objects in VR. It utilizes a combination of vibrotactile feedback, uni-directional brakes and asymmetric skin stretch. This simulates weight feedback on fingertip skin using mechano-receptors and emulates the different stages of weight perceivability namely touching, grasping, gravity and Inertia. Voice coil actuator has been used to create transient vibration leading to asymmetric skin stretch and an asymmetric vibration is used to simulate weight sensation. In order to simulate various weight sensation, the amplitude of the asymmetric signal is changed while keeping the frequency and pulse width ratio fixed. This device does not render gravity to the normal direction of finger pad since asymmetric vibration works best with lateral skin stretch. User studies were conducted to measure the virtual force with three different conditions to create weight sensations: downward directed force, upward directed force, and the perceived force difference between downward and upward directed forces. The results showed that users perceived the physical weights as mass and the up signal as a pulling force, not less mass. This led to their conclusion that physical weight or mass cannot be offset by a virtual force. Additionally, the user studies also referenced the need for an immediate up and then a down signal to provide more noticeable data.

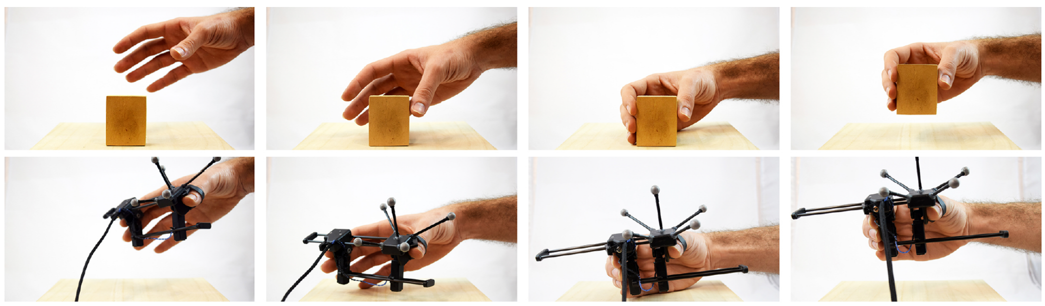

Figure 2.7: *Grabity* structure and design for VR [9]

Based on these analyses and observations, the design of asymmetric control signal with variations is studied and the 2D prototype has been developed with a single voice coil actuator.

2.2.2 Voice Coil Actuators

Voice coil actuators have played a significant role in expanding the haptic feedback systems to multiple degrees of freedom cues using asymmetric vibrations. This is due to their ability to deliver effective force feedback despite their small size that makes them favorable for wearable and holdable haptic devices. Apart from this, due to their small form factor, they can be easily integrated into systems with other components or actuators to increase the degrees of directional cues or induce other capabilities. On the whole, they are a great choice for utilizing asymmetric vibrations to create force feedback in multidimensional haptic devices.

Amemiya et al. [1] proposed a thumb size vibrator that oscillates asymmetrically to generate a distinct pseudo force sensation. Rekimoto proposed a linear resonant actuator (LRA) that can induce a sense of force in a particular direction using Pulse width modulation with duty cycle 18:7 [23]. Tanabe et al. proposed a speaker type haptic interface that converts audio signals into mechanical vibration and induces a sense of pushing or pulling force based on asymmetrical vibration provided to it [26]. Culbertson et al developed a method of modelling the perceived pushing or pulling forces with asymmetric vibrations with smaller actuators [13]. Studies have been conducted to study the perceptual characteristics of a force induced by asymmetric vibrations in voice coil actuators. The simulation time, influence of grip, the frequency of the asymmetric signal has been studied [26].

Figure 2.8: Vibration Speaker as depicted in Tanabe et al.[26]

The voice coil actuator consists of a permanent magnet that is surrounded by a coil. This magnet can be moved by applying a voltage to the coil. When the voltage is changed periodically, the magnetic field induced by the coil is changed—the movement of the permanent magnet due to attraction or repulsion results in vibration. When the amplitude of the control signal is varied, the magnetic field of the coil is changed and thereby resulting in a change of intensity in the induced vibration. Voice coil actuators and vibration speakers exhibit the same principle of operation, and vibration speakers can give auditory as well as tactile texture information [26].

Based on these observations and mechanisms, we have extended the use of a single voice coil actuator, i.e., a speaker-type haptic interface, to produce haptic force feedback in 2D using asymmetric vibrations. Our base signal to create asymmetric vibration for the voice coil actuator is inspired by the work of Tanabe et al. [26] to use a sine wave with a half-cycle inverted for every two cycles to create asymmetric vibrations. A similar approach is followed towards the design of the 2D and 3D haptic device to produce directional cues including normal direction using asymmetric vibrations.

CHAPTER III

Design of Asymmetric Vibration Signal Profile

This chapter describes the design of the control signal profile utilized for asymmetric vibrations. We explored different combinations of asymmetric signals to study if it influences perceptibility and direction discrimination. We studied the effect of providing a short asymmetric vibration in the opposite direction followed by an asymmetric signal that creates a haptic sensation in the desired direction through pilot studies. To begin with, Section 3.1 describes the voice coil actuator used and it's characteristics. It also briefly touches upon referenced work that outlines the simulation time, frequency of the asymmetric signal, and a few other parameters that advocate for our design choices. Section 3.2 describes the different asymmetric control signals that we studied. Section 3.3 describes the experimental setup for conducting the pilot studies. Lastly, section 3.4 analyses the results and discusses the outcome.

3.1 Voice Coil Actuator

We utilized a coil type 19mm voice coil actuator from Dayton Audio (DAEX25CT-4), which was a $4\Omega/5W$ exciter for the pilot studies conducted to study the perceptibility and direction discrimination rate of asymmetric control signals. This exciter was approximately 1-1/2" in diameter and about 3/8" high. It consisted of neodymium motor and a voice coil for 5-Watt RMS power handling. It had an impedance of 4Ω

for use with Class D amplifiers and a resonant frequency of 637Hz, Dc Resistance of 3.8 Ohms with a voice coil inductance of 0.07 mH @ 1 kHz. The frequency response of this actuator is shown in Figure 3.1.

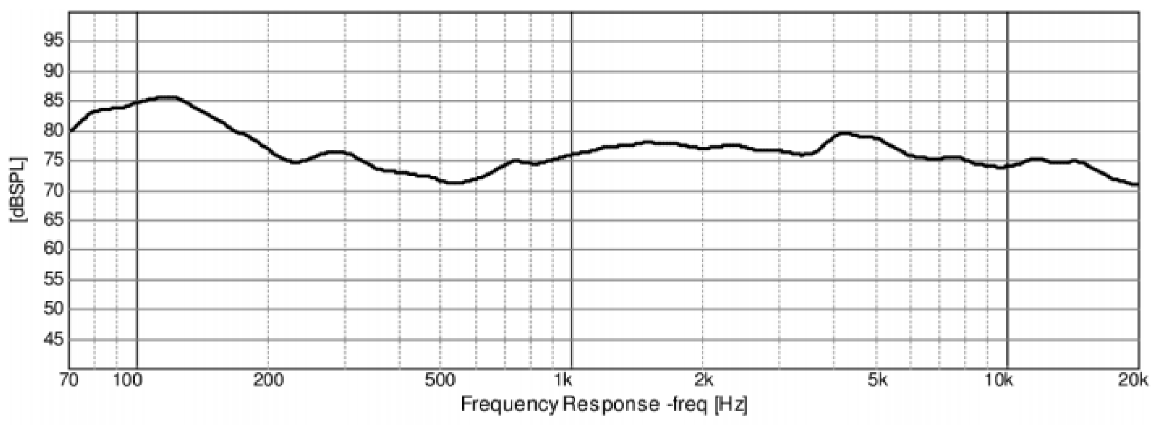

Figure 3.1: Frequency response- freq[Hz] of Dayton Audio [DAEX25CT-4] exciter

Previous research has shown that an asymmetric sine wave with a half-cycle inverted for every two cycles is capable of inducing a sense of force in one direction in a vibration speaker [12]. An asymmetric sine wave consisting of three positive half-cycles is referenced as "positive asymmetry," which gives a sense of push or pull in one direction based on how the actuator is held. Similarly, an asymmetric wave that has three negative half-cycles is referenced as "negative asymmetry," which gives a sense of push or pull in the direction opposite to that of "positive asymmetry."

We tested different frequencies ranging from 20Hz to 100Hz for both positive and negative asymmetric signals and found that 70Hz to 75Hz produced the greatest distinguishability for a 4Ω/5W and 4Ω/10W exciter. This is also in concurrence with the frequency used by Tanabe et al. [26]. In further experiments, a constant frequency of 75Hz was utilized to evaluate direction distinguishability using asymmetric vibrations. Of all the different Dayton exciters that were tested, a 4Ω/5W exciter was chosen because it provided adequate and strong sense of pull or push while being hand-held.

3.2 Control Signal Profiles

3.2.1 Asymmetric sine wave with half cycle inverted for every two cycles (Base signal)

To begin with, the signal profile studied was that of an asymmetric sine wave with a half-cycle inverted for every two cycles, similar to the signal profile proposed by Tanabe et al.[26]. The signal profile is depicted in Figure 3.2 and Figure 3.3. We adopted this as the *"base signal"* to which additions were made to form control signal-2 and control signal-3 referenced in Figure 3.4 and Figure 3.7. An asymmetric sine wave that has three negative half-cycles is referenced as "negative asymmetry," which gives a sense of push or pull in the direction opposite to that of "positive asymmetry". Positive and negative asymmetries create pushing or pulling forces in opposite directions to each other based on the orientation of the device. This is attributed to the nonlinear characteristics of human perception wherein a stronger stimulus is perceived more clearly than the weaker stimulus.

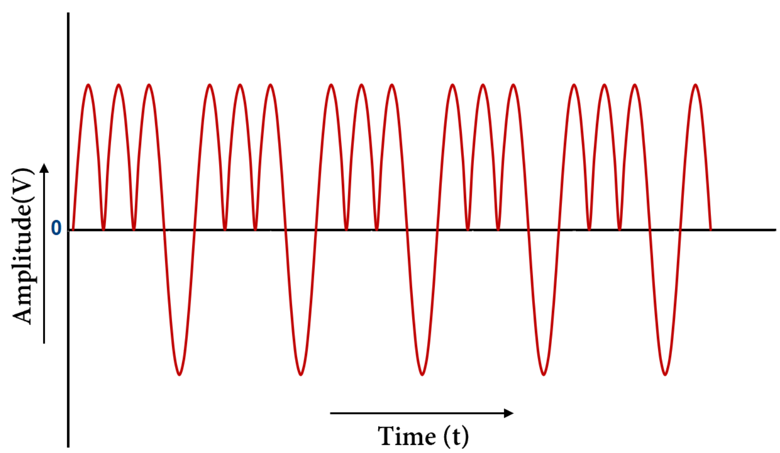

Figure 3.2: Asymmetric sine wave - Positive asymmetry

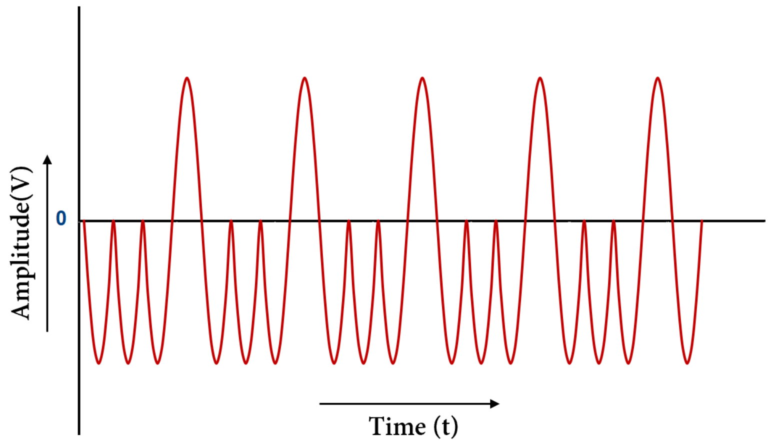

Figure 3.3: Asymmetric sine wave - Negative asymmetry

3.2.2 Inverted saw tooth waveform followed by an asymmetric sine wave with half-cycle inverted for every two cycles

Initially, a multitude of different asymmetric signals such as: square step-up ramp wave, sine wave, and saw tooth waveform were tried and tested. It was observed that saw tooth waveform was capable of providing a relatively higher directional distinguish ability. However,the effectiveness or realism of a sawtooth waveform was still comparatively lower than that of the asymmetric sine wave with half-cycle inverted for every two cycles *(base signal)*. User studies conducted by Grabity [9] referenced the need for an immediate up and then a down signal to provide more noticeable data.

In order to improve direction distinguishability and provide more noticeable data, we introduced an inverted sawtooth waveform for eight cycles (inverted by 180° in comparison to *base signal*) followed by the asymmetric base signal creating the virtual force in the desired direction. The expected behaviour of this waveform is shown in Figure 3.6. This means that for a "positive asymmetry" base signal, an inverted sawtooth waveform of the same frequency was introduced before it to provide a pushing force in the opposite direction for less than a second. The signal profile is depicted in Figure 3.4 and Figure 3.5. The inverted base signal in itself was not preferred since this would introduce ambiguity in directions as the entire waveform would be a salient signal without any differentiation while sensing them. We hypothesized that a left and then a right signal would provide a more noticeable perception.

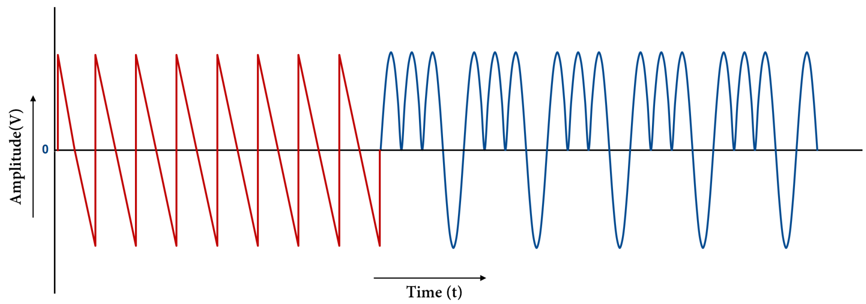

Figure 3.4: Eight cycles of inverted (with respect to base signal) sawtooth waveform inserted before "positive asymmetry" base signal

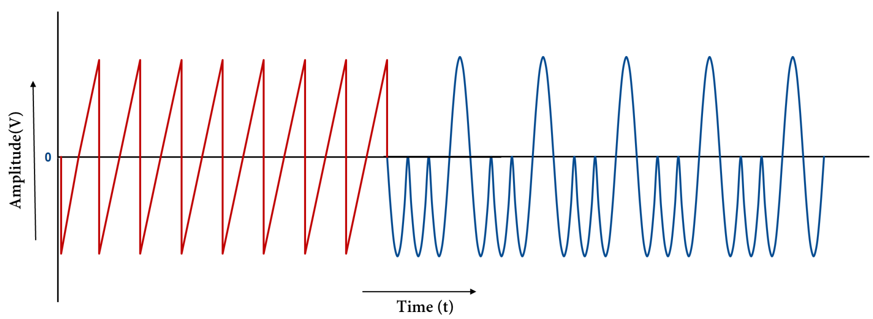

Figure 3.5: Eight cycles of inverted (with respect to base signal) sawtooth waveform inserted before "negative asymmetry" base signal

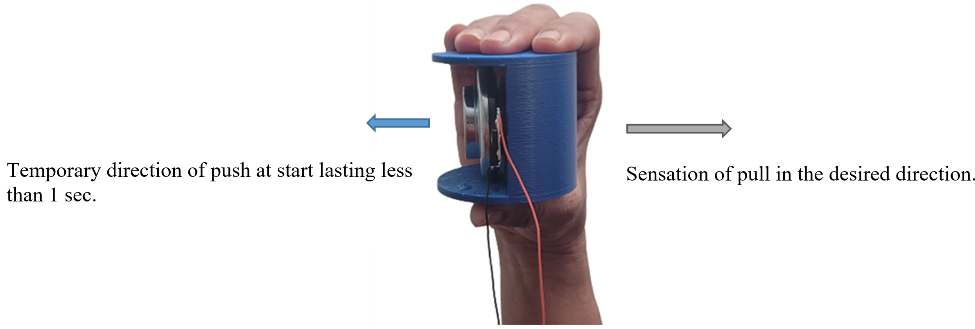

Figure 3.6: Perceived virtual force for control signal depicted in Figure 3.4

3.2.3 Inverted sine waveform followed by asymmetric sine wave with half cycle inverted for every two cycles

We designed an additional waveform to address the ambiguity caused by control signal-2 which is discussed in the results and analysis section. This new signal consisted of 8 cycles of inverted (as compared to the *base signal*) sine wave followed by base signal in which half cycle is inverted for every two cycles as shown in Figure 3.7 and Figure 3.8. This means that for a "positive asymmetry" base signal, an inverted symmetric sine waveform of the same frequency was introduced prior to it. We hypothesized that removing the ambiguity caused by the saw tooth waveform but still providing a salient vibration before the asymmetric sine signal would improve direction distinguish ability. The expected behaviour of this control signal is shown in Figure 3.9.

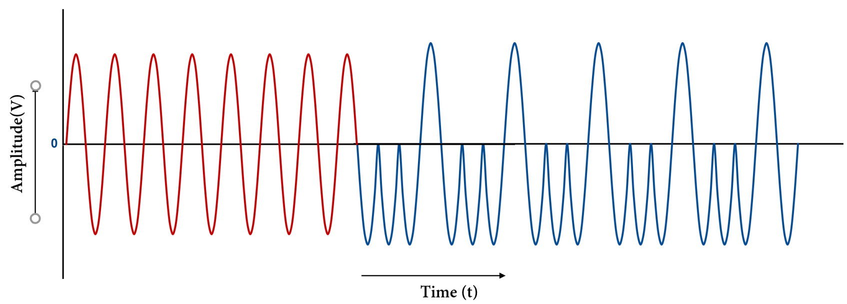

Figure 3.7: Eight cycles of inverted (with respect to base signal) sine waveform inserted before “positive asymmetry” base signal

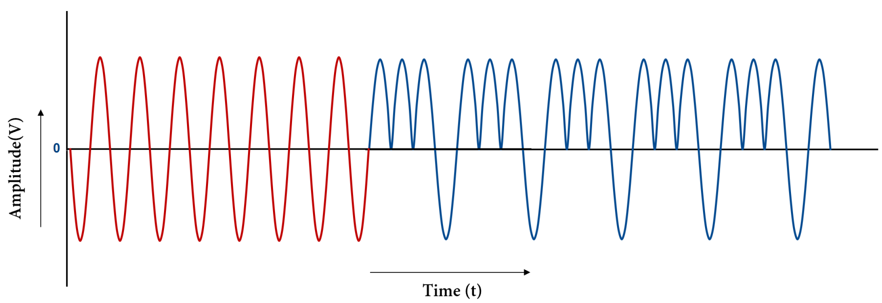

Figure 3.8: Eight cycles of inverted sine(with respect to base signal) waveform inserted before “negative asymmetry” base signal

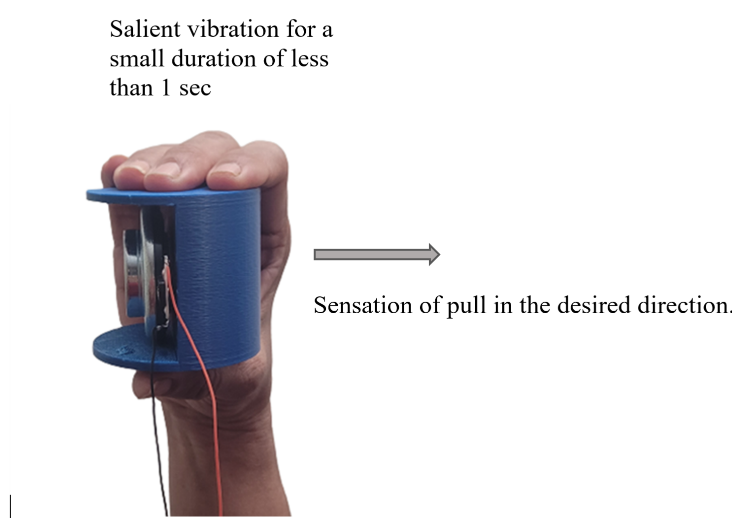

Figure 3.9: Perceived virtual force for control signal depicted in Figure 3.7

3.3 Pilot Study

As a part of the pilot study, initial experiments were performed to validate and verify if the users could distinguish eight directions at 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° respectively, and evaluate the performance of the three different control signal elaborated in the previous section.

3.3.1 Apparatus

Figure 3.10 presents an overview of the prototype system for the pilot study. It consists of the Dayton Audio (DAEX25CT-4) which is a coil type 4Ω/5W exciter and amplifier. The input signal was designed using audio editing software named *'Audacity'*. The frequency of the control signal was 75Hz, and the audio port of a personal computer was utilized to output this asymmetric amplitude signal. The signal was sent to a audio amplifier, and the amplified output was sent to the actuator.The amplitude and frequency of the control signal were constant throughout the entire experimentation at 75Hz and 2V.

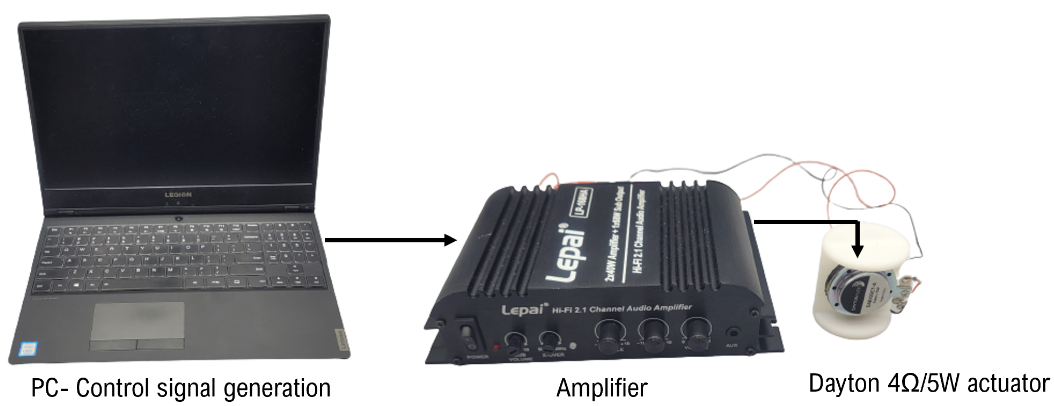

Figure 3.10: System Overview of the 2D force feedback pilot study

The initial hand-held prototype consisted of the Dayton audio exciter attached to a 3D printed surface that is cylindrical in shape as shown in Figure 3.11. This was a static device designed to understand if the design and control signal created virtual forces leading to direction distinguishability in 2D i.e.,the X-axis,Y-axis and diagonal movement. The dimensions of this device was 38mm × 38mm × 51mm and weighed around 40g.

Figure 3.11: Static prototype with 4Ω/5W actuator

The device was in a way that the direction of vibration is in the lateral or shearing direction to the fingers as shown in Figure 3.12 and 3.13. Biggs et al. reported that shear displacement of skin is easily sensed as compared to normal displacement on the finger pad [7].

Figure 3.12: Front view of actuator grip

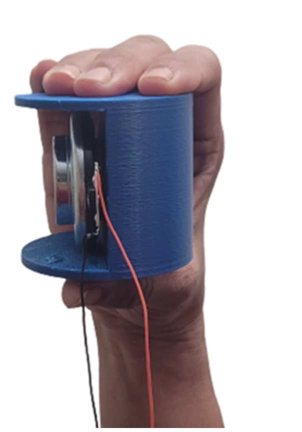

Figure 3.13: Side view of actuator grip

3.3.2 Procedure

The participants were blindfolded and were required to wear noise-canceling headphones to eliminate audio cues. The participants were subjected to a volume adjustment step to ensure no environmental noise is heard, and white noise was actively being played. The participants were given instructions on how to hold the device to ensure the direction of vibration is always in the shearing direction to the fingers and grip is consistent among participants. The study was conducted in two sessions with a 2-minute break between 16 samples. A total of 80 samples were collected from each participant for each control signal. The participant was made to experience a virtual force for a duration of 5 seconds.

The direction of virtual force was randomly selected by the experimenter (Archana Narayanan) by manually moving the actuator to different angles, while asking the participant to identify the direction. A sample was repeated as many times as requested by the participants.

3.3.3 Participants

The experiment was conducted with 5 right-handed participants all in the age group of 23 -30 years with 2 females and 3 males. The experiment lasted for about 90 minutes split into two sessions. To eliminate learning and order effects, the participants were presented with random directions with no order.

3.4 Results and Analysis

The results of the direction discrimination test are depicted using radar plots. Each plot shown in Figure 3.14 represents the percentage of users that opted a specified angle for the base signal. For example, the first plot in Figure 3.14, the prototype was programmed and positioned to generate a virtual force at an angle of 0°, relative to the user. It was observed that 53.1% of users perceived a force at an angle of 0° degrees, while 14.3% and 16.3% of users believed that they experienced a force at angles of 45° and 315° degrees respectively.

Similarly, Figure 3.15 and Figure 3.16 show radar plots that represent direction discrimination test results at each angle for waveforms generated using Control signal 2 (Inverted sawtooth waveform followed by base signal) and Control signal 3 (Inverted sine waveform followed by base signal) respectively.

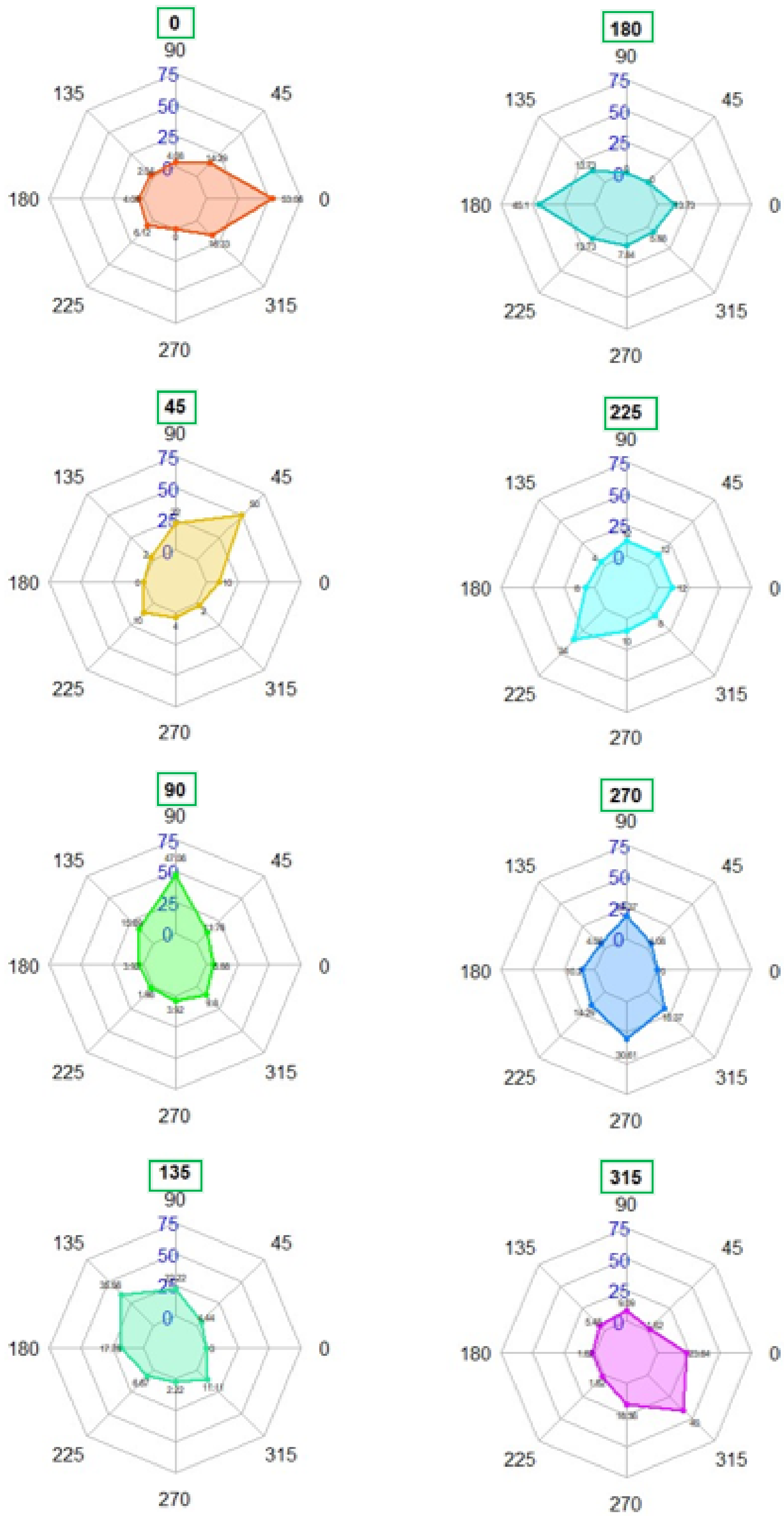

Figure 3.14: Direction discrimination results for Control Signal-1 *base signal*

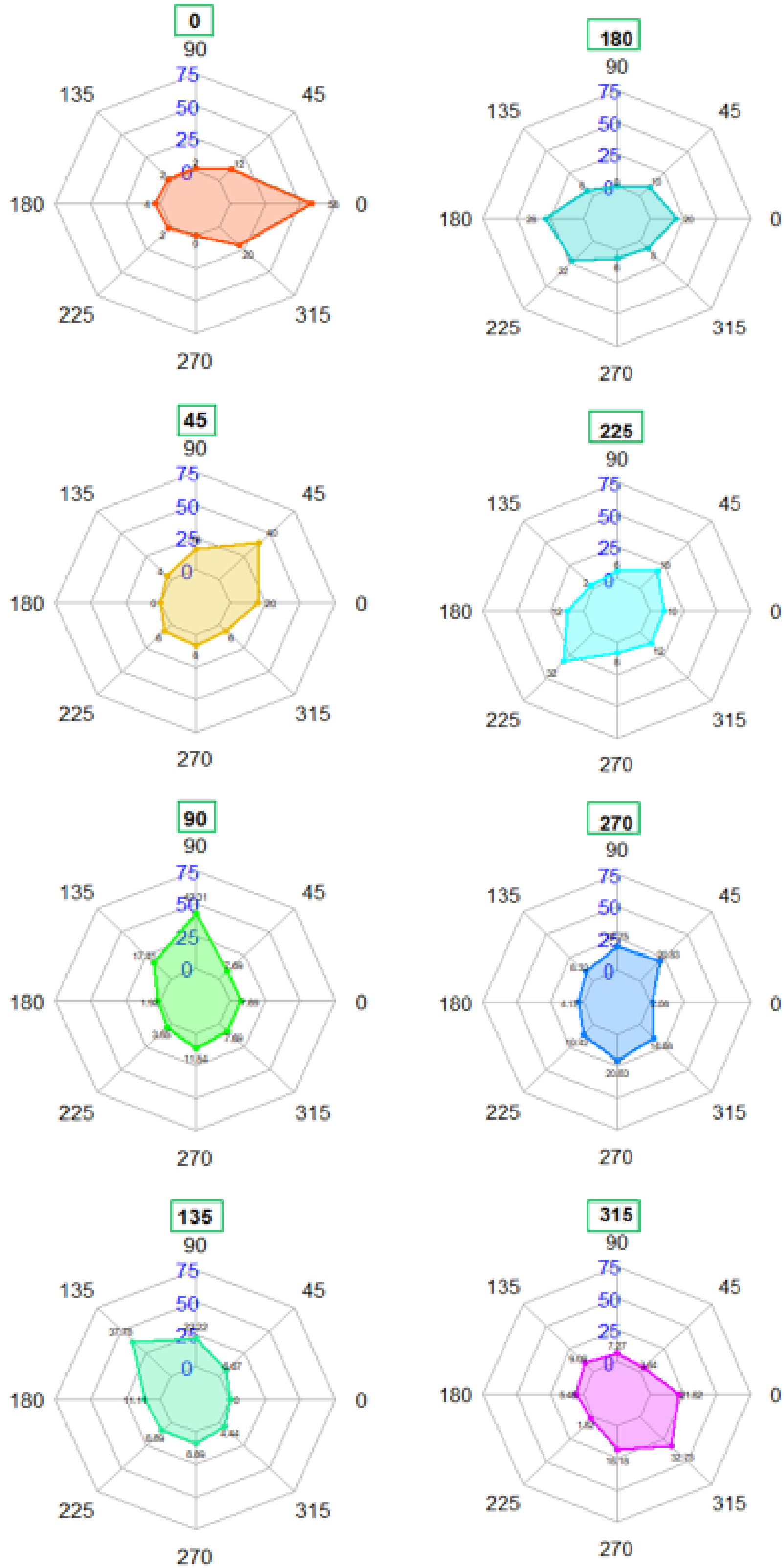

Figure 3.15: Direction discrimination results for Control Signal-2 *Inverted sawtooth + base signal*

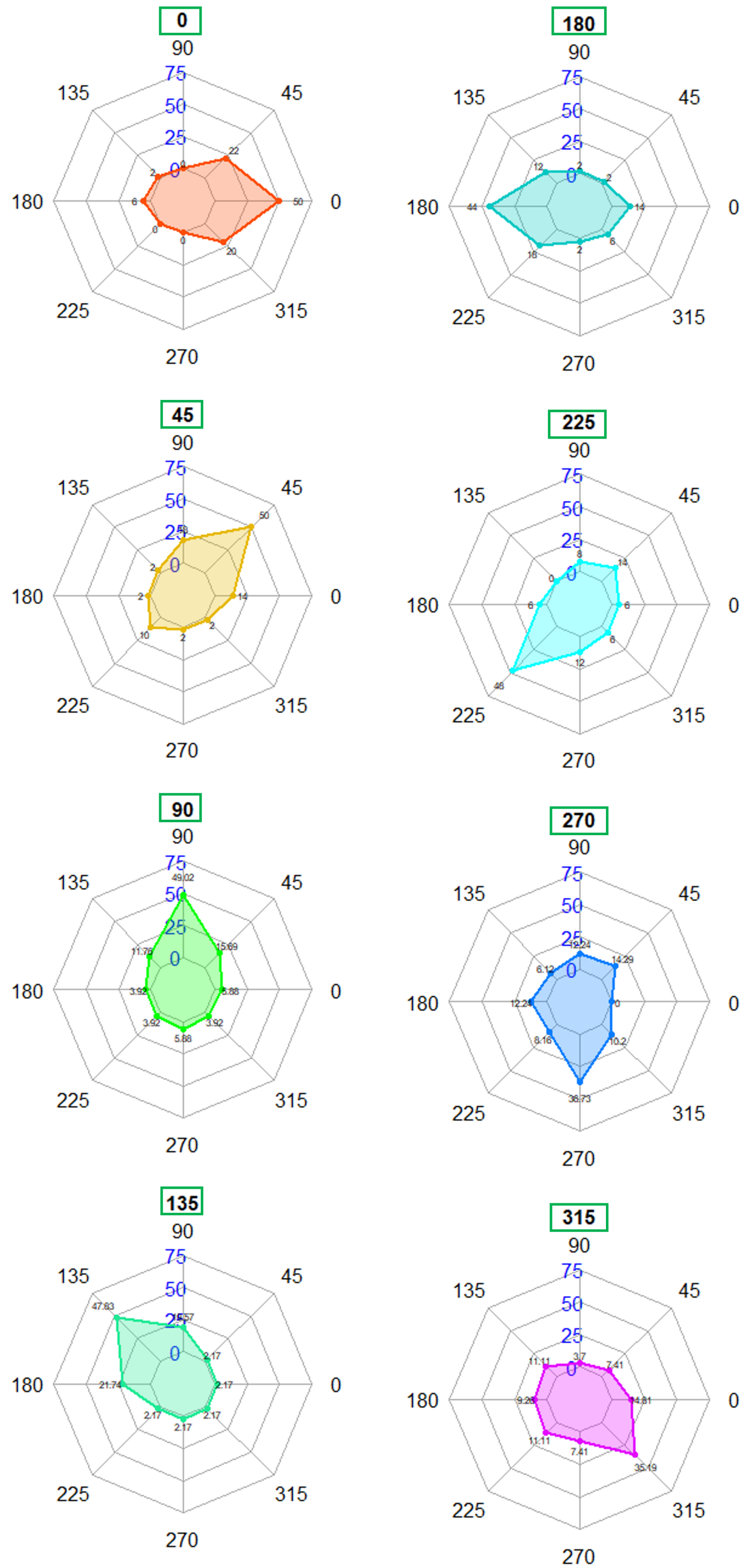

Figure 3.16: Direction discrimination results for Control Signal-3 *Inverted sine + base signal*

As shown in Table 3.1, for any given direction that the prototype was designed to create a virtual force along, the percentage of correct responses was always higher than the percentage of wrong responses for all the three control signals. This prompted that the prototype clearly generated a distinct virtual force in the intended direction although the effectiveness of the virtual force was not very high. The percentage of wrong responses along each direction was monitored to check for any possible trends in the data. It was observed (as seen in Figure 3.14,3.15,3.16) that the users faced a higher difficulty in perceiving virtual forces at angles 225° and 270° while the correctness rate was relatively higher in angles ranging from 0°-180°.

	User response								
	Control Signal-1 : Base signal								
		0	**45**	**90**	**135**	**180**	**225**	**270**	**315**
	0	53.1%	14.3%	4.1%	2%	4.1%	6.1%	-	16.3%
	45	10%	50%	22%	2%	-	10%	4%	2%
	90	5.9%	11.8%	47.1%	15.7%	3.9%	2%	3.9%	9.8%
	135	-	4.4%	22.2%	35.6%	17.8%	6.7%	2.2%	11.1%
	180	13.7%	-	-	13.7%	45.1%	13.7%	7.8%	5.9%
	225	12%	12%	12%	4%	8%	34%	10%	8%
	270	-	4.1%	18.4%	4.1%	10.2%	14.3%	30.6%	18.4%
	315	23.6%	1.8%	9.1%	5.5%	1.8%	1.8%	16.4%	40%
	Control Signal-2 : Inverted sawtooth wave + Base signal								
	0	58%	12%	2%	2%	4%	2%	-	20%
	45	20%	40%	16%	4%	-	6%	8%	6%
Expected Direction	**90**	7.7%	7.7%	42.3%	17.3%	1.9%	3.8%	11.5%	7.7%
	135	-	6.7%	22.2%	37.8%	11.1%	8.9%	8.9%	4.4%
	180	20%	10%	-	6%	28%	22%	6%	8%
	225	10%	18%	6%	2%	12%	32%	8%	12%
	270	2.1%	20.8%	18.8%	8.3%	4.2%	10.4%	20.8%	14.6%
	315	21.8%	3.6%	7.3%	9.1%	5.5%	1.8%	18.2%	32.7%
	Control signal-3 : Inverted sinewave + Base signal								
	0	50%	22%	-	2%	6%	-	-	20%
	45	14%	50%	18%	2%	2%	10%	2%	2%
	90	5.9%	15.7%	49%	11.8%	3.9%	3.9%	5.9%	3.9%
	135	2.2%	2.2%	19.6%	47.8%	21.7%	2.2%	2.2%	2.2%
	180	14%	2%	2%	12%	44%	18%	2%	6%
	225	6%	14%	8%	-	6%	48%	12%	6%
	270	-	14.3%	12.2%	6.1%	12.2%	8.2%	36.7%	10.2%
	315	14.8%	7.4%	3.7%	11.1%	9.3%	11.1%	7.4%	35.2%

Table 3.1: Distribution of responses for the three control signals

Furthermore, the percentage of wrong responses for each direction was seen to be widely distributed with no specific trend suggesting that users were not experiencing the same wrong direction for a given input signal. However, a closer look at each of the plots suggested that the percentage of wrong responses for each angle tend to aggregate at a $\pm$ 45°interval from the correct direction towards which the prototype was actuated to create a virtual force. To account for these one-interval errors and to compare and contrast the results from each directionality, all the plots from Figure 3.14, Figure 3.15 and Figure 3.16 were superimposed on top of each other as shown in Figure 3.17,3.18,3.19 for control signal-1, control signal-2 and control signal-3 respectively. In these plots, the colored area shows the distribution of the user's answers for each direction. The percentage marked at the center of the circle represents the correctness rate for each signal, and the percentage for each direction is the correctness rate for that orientation. The percentages in parentheses are the correctness rates when errors of $\pm$ one interval are regarded as correct answers. The correctness percentage substantially increases when one interval errors are regarded as correct answers. This can be attributed to the difficulty of mapping perceived direction to real world signals[3].

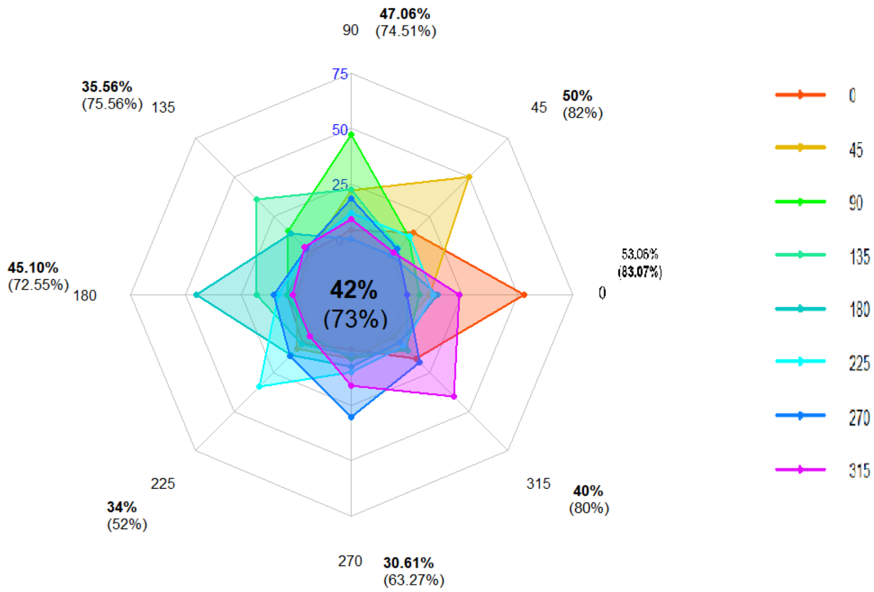

Figure 3.17: Eight Directions: Control Signal -1

From figure 3.18 which shows the results of Control signal 2, it was observed that the distribution of answers had increased for angles at 315°, 180°,and 270° with the addition of inverted sawtooth waveform. This shows that this caused higher ambiguity in perceiving directions for users. This suggests that the asymmetric nature of the saw tooth waveform confused the users. Furthermore, from the feedback obtained from the users, 3 out of 5 mentioned that it was confusing to identify the directions. *"It was hard to tell the direction, as the time progressed, I felt like the direction was changing and could not say which way it was clearly towards the end. I was confused."*

Even though only seven cycles of the sawtooth waveform was used at the beginning, it did not successfully create a sense of push for a small duration in the opposite direction. It failed to better aid participants in providing a reference for identifying the actual asymmetric base signal in the desired direction. It can be observed from the results that a up and then a down signal or left and then a right signal did not improve the perception of directions, thus not providing a significant improvement over the base signal in generating more noticeable data.

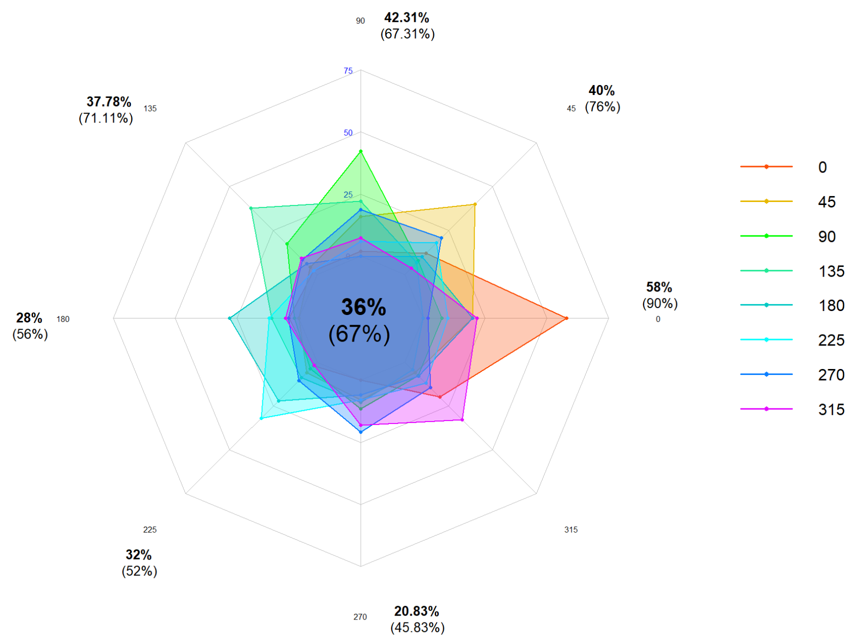

Figure 3.18: Eight Directions: Control Signal -2

In order to eliminate the ambiguity caused by using the saw tooth waveform, it was replaced by an inverted symmetric sine wave signal for 8 cycles. The hypothesis that eliminating ambiguity caused by the asymmetry of the saw tooth waveform while providing a salient vibration in place of it would improve direction distinguishability was studied. From figure 3.19 which shows the results of Control signal- 3, it can be observed that this modification did not cause a substantial increase in the correctness percentage for any orientation. It can thus be concluded that this symmetric sine waveform followed by the base signal did not cause any significant improvement.

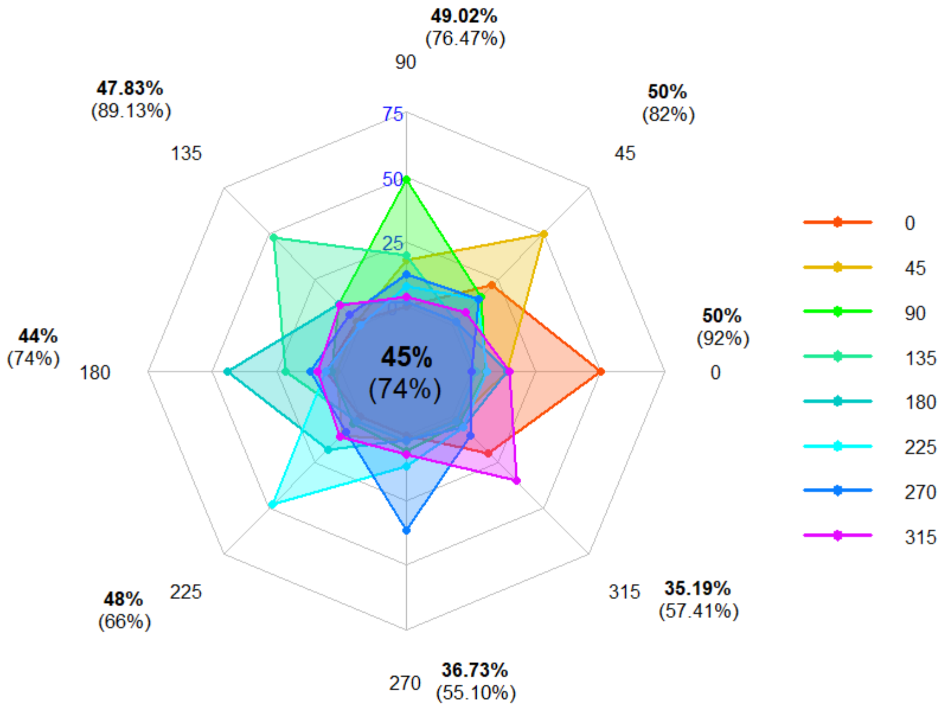

Figure 3.19: Eight Directions: Control Signal -3

The average error for the three control signals were 57.37°, 69.05°, and 54.9° respectively. Figure 3.20 compares the overall correctness percentage of the three control signals and the correctness percentage when one interval errors are regarded as right answers. As shown in Figure 3.23, it can be observed that addition of inverted saw tooth or inverted sine waveform to the base signal resulted in no significant improvement in direction distinguish ability. In fact, as referenced in previous work, left and then a right, or up and then a down signal as designed in Control signal-2 did not provide a more noticeable perception and instead caused ambiguity in identifying directions.

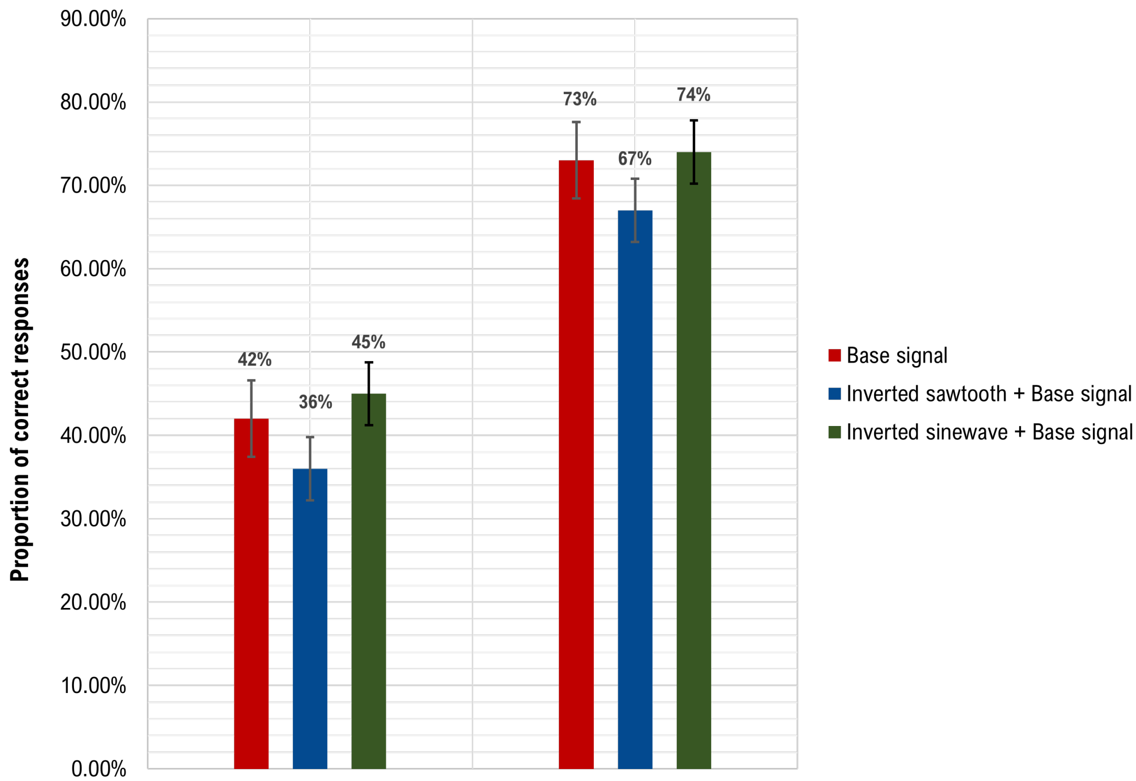

Figure 3.20: Proportion of correct responses for the three control signals

We conducted a one-way repeated Analysis of Variance (ANOVA) to study the effect of control signal on the correctness percentage and found that the effect of control signal on correctness percentage was not statistically significant($p < 0.05$) as shown in Figure 3.21. Therefore, we accept null hypothesis that the three different control signals had no effect on the performance or ease of direction distinguish ability.

	Sum of Squares	df	Mean Square	F	Significance(p)
Between Groups	0.01858	8	0.019229	3.8657	0.066881

Figure 3.21: ANOVA results

From the results of this pilot study, we could not see a clear improvement in direction distinguishability from the modifications made to the base signal. Therefore we use the asymmetric sine wave with half cycle inverted for every two cycles which provides 2D virtual force satisfactorily in 8 directions.

CHAPTER IV

2D Virtual Force Feedback Device

This chapter describes the design considerations, implementation, and evaluation of the 2D haptic prototype that was built. Section 4.1 elaborates on the design considerations that we emphasized on while developing the prototype. Section 4.2 describes the design and implementation of the 2D haptic prototype. Section 4.3 will explain the working mechanism of the device.

4.1 Design Considerations

Past research has emphasized the need to create a larger-sized device that can be hand-held to provide more realistic virtual force using asymmetric vibrations. Furthermore, interference has been a significant roadblock to developing effective 2D haptic feedback when more than one actuator is utilized. In this work, we focus on a handheld device providing 2D force feedback as the primary goal while building this haptic device. At this moment, do not focus on stiffness, texture, and other ergonomics that come into play.

Based on the primary goal, we emphasize the following design criteria :

- **Handheld and Portable** : Device should be hand-held and portable. It should be ungrounded, stand alone and not attached to a surface.

- **Lightweight** : Since the device is hand-held, it is vital for it to be lightweight to be easily hold-able for a long duration.

- **Easy to hold** : Device should be of small dimensions and no obstructions to be gripped with index and thumb fingers.

- **Interference** : No interference should occur from multiple actuators being utilized. Hence we aimed to use only one actuator to create 2D haptic feedback.

- **Mechanical Complexity** : Minimal number of components and a simple design that is easy to build.

- **Performance** : Operate with no significant delay to provide 2D haptic feedback in different directions quickly.

- **Low-cost** : Easily acquirable components with very low cost. Furthermore, the cost is decreased due to the use of a single actuator.

4.2 Design and Implementation

As shown in the Figure 4.1, the device comprised of a 3D printed structure with three components : an encoder motor, two ball bearings, and a voice coil actuator. The dimensions of this device are 51mm X 51mm X 63.5mm and it weighed 74g. Two 3D printed structures supported by carbon fiber rods on two ends form the skeleton of the device. The base is held by the thumb, and the top part is held by four fingers. Two ball bearings at the center of this structure were connected by a carbon fiber rod. The 3D printed actuator-holder was mounted on this carbon fiber rod which serves as the axis of rotation of the actuator. The actuator was attached to the actuator holder using a strong adhesive. A large circular motion gear was installed at the bottom of this rod. This was driven by the smaller circular motion gear that was connected to the encoder motor using carbon fiber rods. Carbon fiber rods were chosen to act as support structures since it was known to provide high strength while being light in weight. These two surfaces were covered by a 3D printed cover to provide a smooth surface for the device to be held by the users. The gap between the top and bottom covers, and the actuator was minimized as much as possible in order to provide effective haptic feedback. The prototype is depicted in Figure 4.2(b).

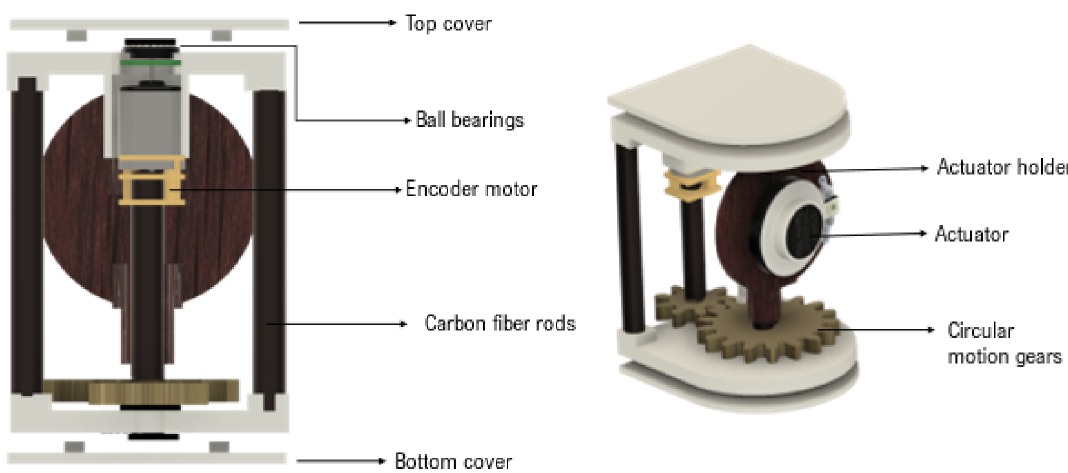

Figure 4.1: Overall mechanical structure

(a) 2D device design (b) Actual prototype built

Figure 4.2: 2D device prototype

4.3 Working mechanism

The actuator can be rotated from 0-180 degrees to provide virtual force feedback at eight different angles shown in Figure 5.1. The virtual force feedback can be created in all eight directions using positive asymmetric and negative asymmetric control signals. The encoder motor helps in rotating the gears, which in turn aid in the rotation of the actuator. The encoder motor is driven by Arduino Uno micro-controller using a motor driver. The connections are as shown in Figure 4.3 .

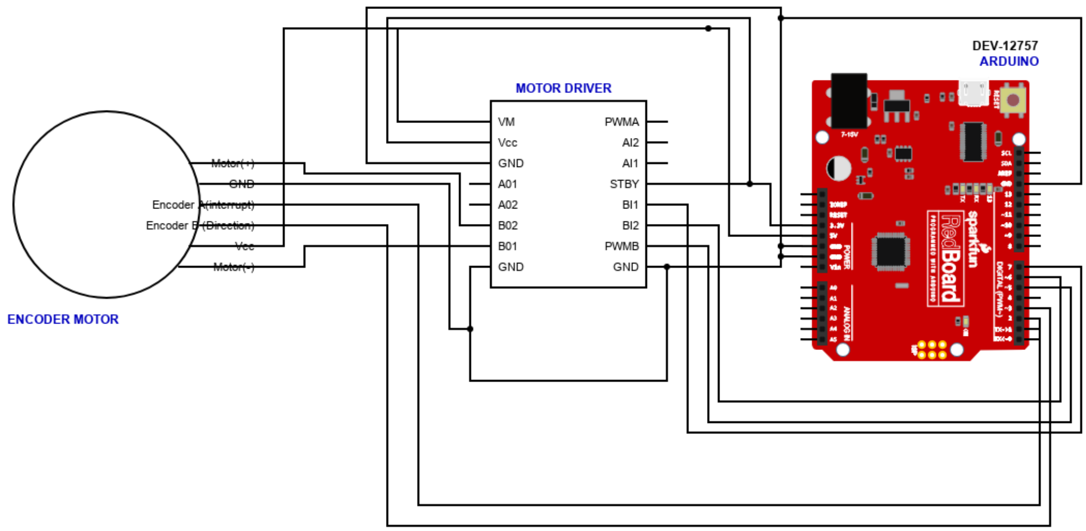

Figure 4.3: Schematic of encoder motor driving circuit

The SparkFun Motor Driver - Dual TB6612FNG (1A) was used as an interface between the micro-controller and the encoder motor to control the direction of rotation. The ACROBOTIC N20 Micro Metal Gear motor encoder wass used instead of a servomotor due to its size and light weight as compared to a servomotor. The encoder motor rotates based on the change in magnetic field created by the magnet attached to the shaft of the motor. When this magnet turns clockwise, one of the encoder output will be triggered. Similarly, when the magnet spins in the counter clockwise direction, the other encoder output is triggered. The motor was controlled using an algorithm that defines the motor position. A feedback loop was designed wherein we define a target position. Then, the error between the measured position and target position was computed. This value was added to the control signal of the encoder to ensure that the device reaches it's target position. The actuator used was a Dayton Audio : DAEX25CT-4 which is a coil type 19mm $4\Omega/5W$ exciter. The asymmetric control signal was generated using audio editing software "Audacity".

4.3.1 Control Signal Characteristics

In order to generate asymmetric vibrations, an asymmetric amplitude signal in which a two cycle sine wave is inverted for half a cycle based on previous work by Tanabe et al. [26]. The frequency is chosen as 75Hz and controlling the amplitude of the signal has an effect on the amperage of coil in the exciter thereby resulting in change in intensity of the vibration. The intensity of the force can be controlled by varying the amplitude. However, for experimentation purposes we maintain the amplitude constant at 2V. The shape of the current pulse designed for the actuator is shown in Figure 4.4.

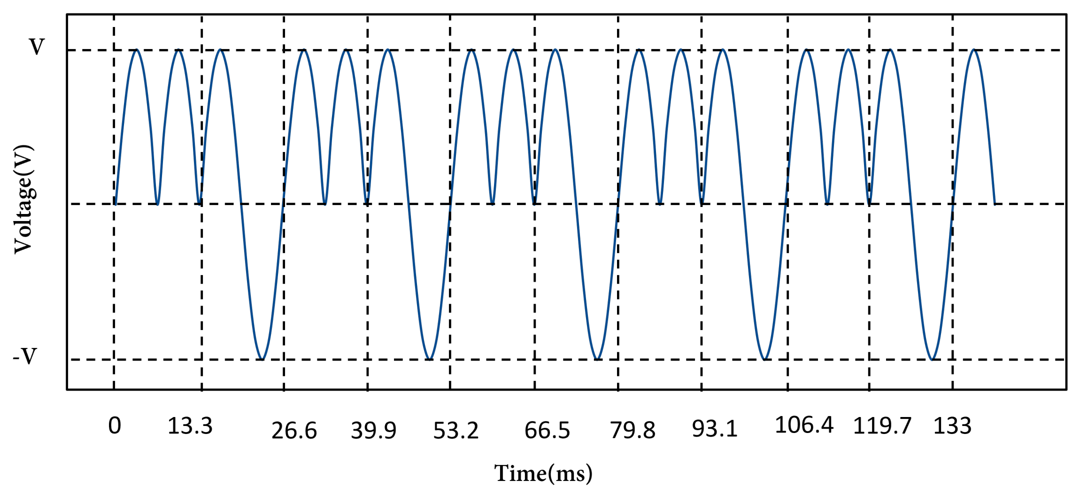

Figure 4.4: Current signal generating asymmetric vibration.

4.3.2 Component Specifications

- **Microcontroller**: The sparkfun Red board - DEV-13975 which can be programmed using Arduino is used as a micro controller to control the encoder using a motor driver. This micro controller operates at 16MHz Clock Speed. It contains the **ATmega328** micro controller with optiboot (UNO) boot loader. It provides 0-5V outputs with 3.3V compatible inputs along with 14 digital I/O pins (6 PWM outputs) and 6 analog inputs. It also contains a 32k flash memory.

- **Motor Driver**: The SparkFun Motor Driver - Dual TB6612FNG (1A) is used as a interface between the micro-controller and the encoder motor.TB6612FNG is a driver IC for DC motor with output transistor in LD MOS structure with low ON-resistor. Two input signals, IN1 and IN2 can be utilized and it operates at VM=15VMax.and Iout=1.2A(ave) / 3.2A (peak).

- **Encoder Motor**: Small-sized 6VDC N20 micro metal gear motors is used that has high torque and speed. It has a reduction ratio: 150:1; speed: 100RPM; no-load current: 40mA; torque: 8 ozin (0.55 kgcm); stall current: 550mA. It also includes quadrature encoder with digital outputs for measuring motor position or speed.It operates at 7-clicks per revolution @15000RPM.

- **Voice-coil Actuator**: Dayton Audio DAEX19CT-4 Coin Type 19mm Vented Exciter 5W 4 Ohm is utilized. A neodymium magnet is employed to create maximum magnetic flux around the proprietary voice coil for increased sensitivity. This is designed to be used with Class D amplifiers. It has a pre-applied adhesive for quick, durable installation.

- **Amplifier**: Lepai LP-168HA 2.1 2x40W Mini Amplifier + 1x68W Sub Output is used to amplify the control signal to provide to actuator. It provides up to 40 watts of power output and power requirements of 9-14.4 VDC, 3A. The signal to noise ratio is greater than 80 dB and frequency response is 20-20000 Hz.

CHAPTER V

Direction Discrimination Study

The goal of this experiment was to understand eight direction distinguish ability at 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315° as shown in Figure 5.1 using the 2D prototype shown in Figure 4.2(b). This experiment will gauge the effectiveness of the different directional cues. Through these experiments, we also aim to understand the directions that are easily distinguishable and the directions that are comparatively difficult to interpret. The effectiveness of the design of the device was also studied in terms of usability of the device with ease. This study was IRB approved.

5.1 Participants

The experiment was conducted with 9 male and 2 female participants (age group:23y-32y) who did not participate in the pilot study and were not familiar with the haptic feedback used. All participants were right handed. The study was conducted in a single session which lasted up to one hour. Participants were compensated 20 USD for the completion of one hour session. Qualitative feedback on the device was collected at the end of the experiment.

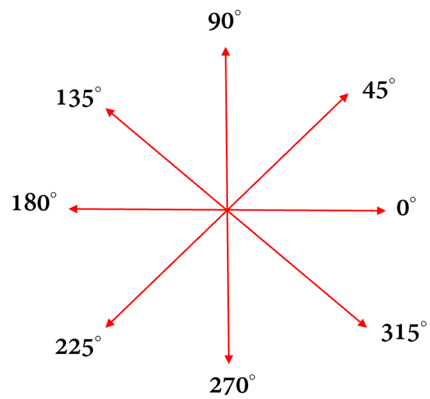

Figure 5.1: Eight directions considered for evaluation of the 2D prototype

5.2 Experimental Setup

Participants were seated in front of a 14-inch touchscreen monitor and were asked to hold the device in their dominant hand. They were also given access to an arm rest in front of the table so as to ensure that they were comfortable while holding the device for a long duration. Additionally, they were also required to wear noise cancelling headphones that played white noise to block any noise from the environment, specifically from the actuator rotation in the prototype. This was to prevent audio cues from the actuator rotation which could indicate direction of actuator and ensure that the results are purely based on haptic feedback felt on the fingers and palm while holding the prototype. Participants were also given no information on vibrations and actuation of the prototype until the end of the experiment wherein a debrief message was presented explaining the virtual force illusion.

Participants were asked to place their dominant hand inside a box covered with black cloth such that they operated the prototype eyes-free during the experiment. This was done in order to prevent them from understanding the position of the actuator and vibrations which would affect the results of the study. This prevented visual cues and ensured that participants distinguished directions based on haptic feedback alone. At the other end of the box, a camera was placed to monitor participant's hand position of the device to ensure that the participant did not feel the actuator to gauge it's position at any point during the experiment. The experimenter sat across the participant with about 3 feet distance to monitor the experiment from an ideal distance.The experimental setup is as shown in Figure 5.2.

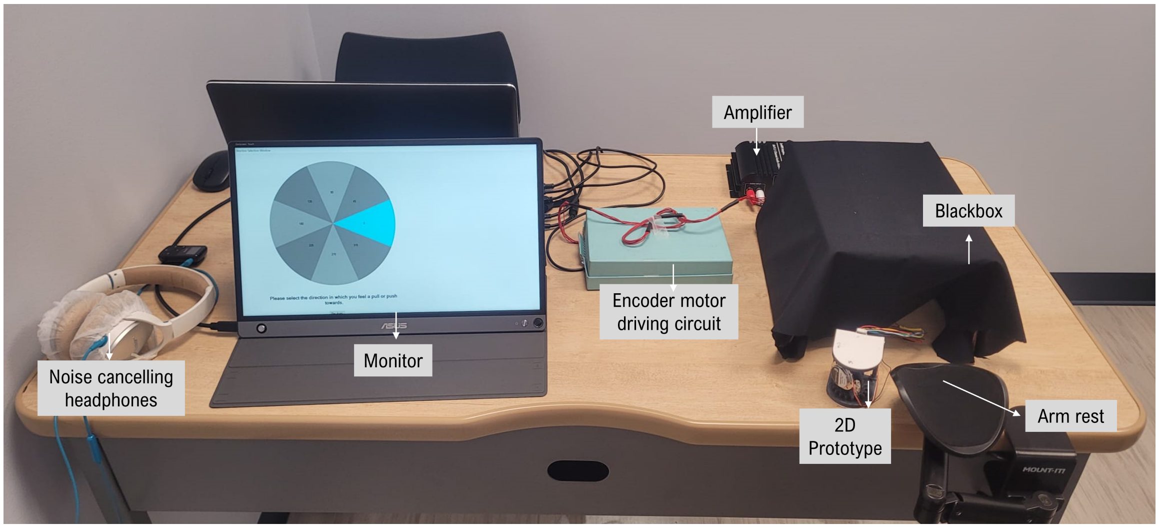

Figure 5.2: Experiment setup - 2D direction discrimination study

Before the experiment began, power-point slides and pictures were used to familiarize participants with the experiment. Each participant was provided with detailed information on how to hold the device, breaks between experiments, using the arm rest and the procedure to operate the direction selection window on the GUI, which records the participant's responses. The position and grip of the prototype was kept consistent across all participants as they were asked to hold the device with index fingers on top and thumb at the bottom of the device as shown in Figure 5.3 and 5.4. Participants were allowed to do a few trials before the experiment for a maximum of 2 minutes. The participants were not given any insights on their performance throughout the experiment.

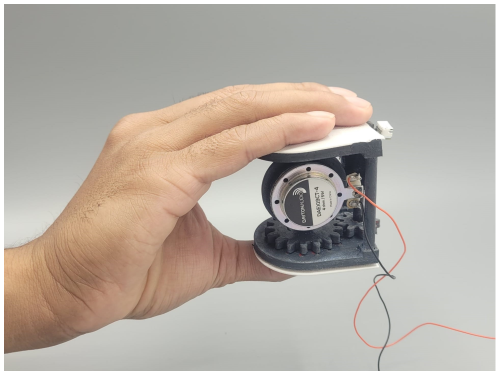

Figure 5.3: 2D prototype grip-side view

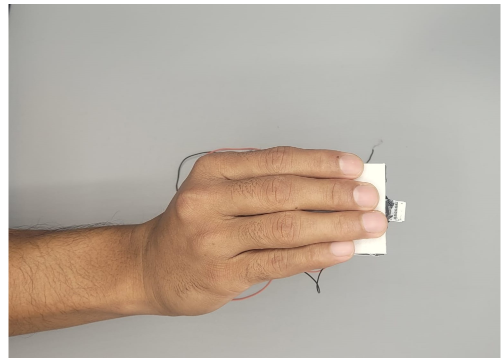

Figure 5.4: 2D prototype grip-top view

The GUI that was used to play haptic feedback and record participants responses while also communicating with the Arduino was built using Windows Presentation Foundation(WPF) in C# using the .NET framework. The GUI as depicted in Figure 5.5 and 5.6 comprised of three different windows - A main menu which collected information such as participant ID and session ID. The task window wherein the actuator was rotated to the respective direction by communicating with the Arduino Uno micro controller and haptic feedback was played and finally, a direction selection window where the participant's response was recorded. Timestamp for each trial was also collected.

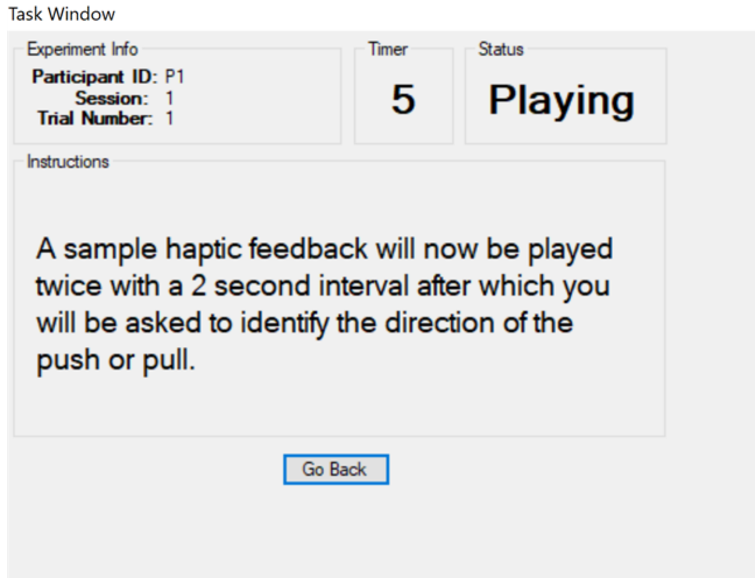

Figure 5.5: Experiment trial window where actuator was rotated and haptic feedback was played for 5 seconds twice with a 2 sec interval.

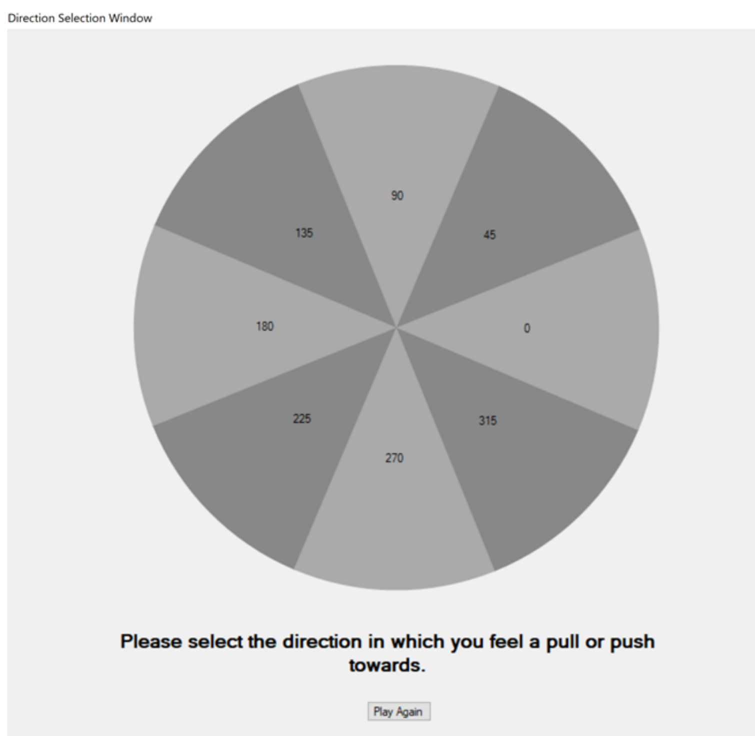

Figure 5.6: Experiment direction selection window where participant response was recorded for each trial.

5.3 Experimental Procedure

After the participants tried the physical prototype shown in Figure 4.2(b) and went through the orientation slides, they were asked to position themselves comfortable and place their hand on the arm rest. They were also required to wear noise cancelling headphones with constant white noise played to ensure no environmental sounds are bring heard by the participant. Further, they were asked to inform the experimenter if they heard the experimenter or any sound from the surroundings. They were subjected to a volume adjustment step after this. This is depicted in Figure 5.7.

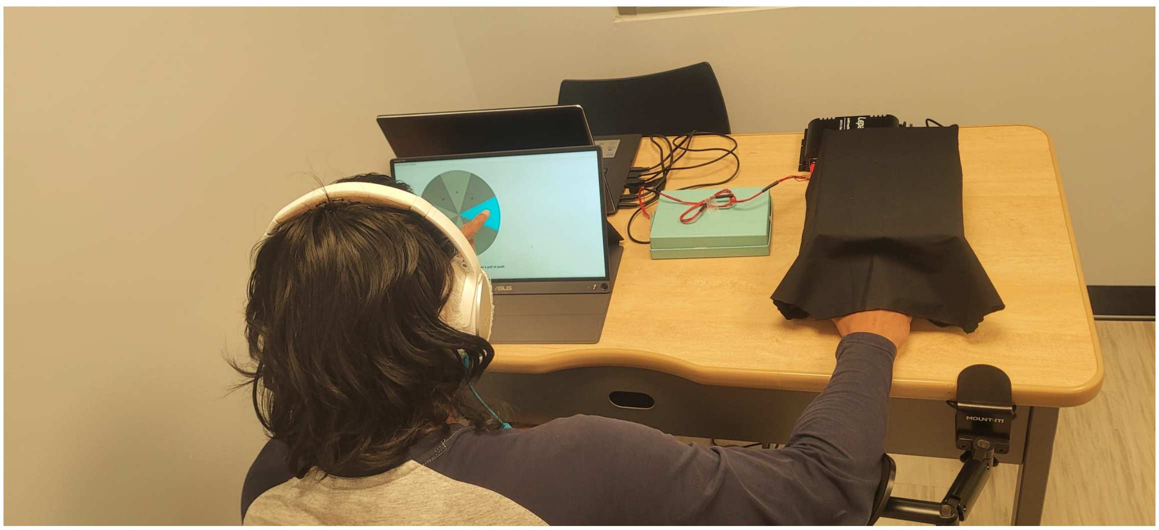

Figure 5.7: A participant performing the direction discrimination experiment.

The experiment was started after these initial preparations. A virtual force was presented at random and participants were asked to identify the direction in which they feel a push or pull. They touched the segment on the circle in the GUI corresponding to the direction in which they felt a push/pull to record their responses. At the beginning of each trial, 5 seconds was allotted for the device to rotate after which the sample haptic feedback was played. Each sample haptic feedback was played twice for 5 seconds with a two second interval. There was a two minute break after every 16 trials and a total of 80 trials(10 samples per direction) was conducted in 5 blocks with a two minute break between them. Participants were allowed to remove the noise cancelling headphones, place the prototype on the table and move their arm during breaks. The sample haptic feedback played twice was not repeated for any of the participants unless they stopped the experiment to restart or placed the device on table. To overcome order effect, the order of directions was randomized for each participant. The participants were asked to complete a survey for qualitative feedback at the end of the experiment. In the experiment, directions 0°, 45°, 90°, 135° utilized "positive asymmetry" sine wave with half cycle inverted for every two cycles as shown in Figure 3.2 to create virtual force and directions 180°,225°, 270° and 315° utilized "negative asymmetry" sine wave with half cycle inverted for every two cycles as shown in Figure 3.3.

5.4 Results

From Figure 5.8 which depicts the distribution of responses for each orientation in percentage, it is evident that the majority of the users are able to distinguish the correct directionality using that haptic feedback that the device was designed to generate. Users faced the most difficulty identifying haptic feedback along 225° and 315°. This low correctness percentage for these directions could be due to the directions being non intuitive i.e directions users do not regularly use in their daily lives as compared to the other orientations. This needs to be further investigated through studies and experiments. The users however, did not favor any particular wrong direction for this feedback and the error percentage varied widely across all directions.

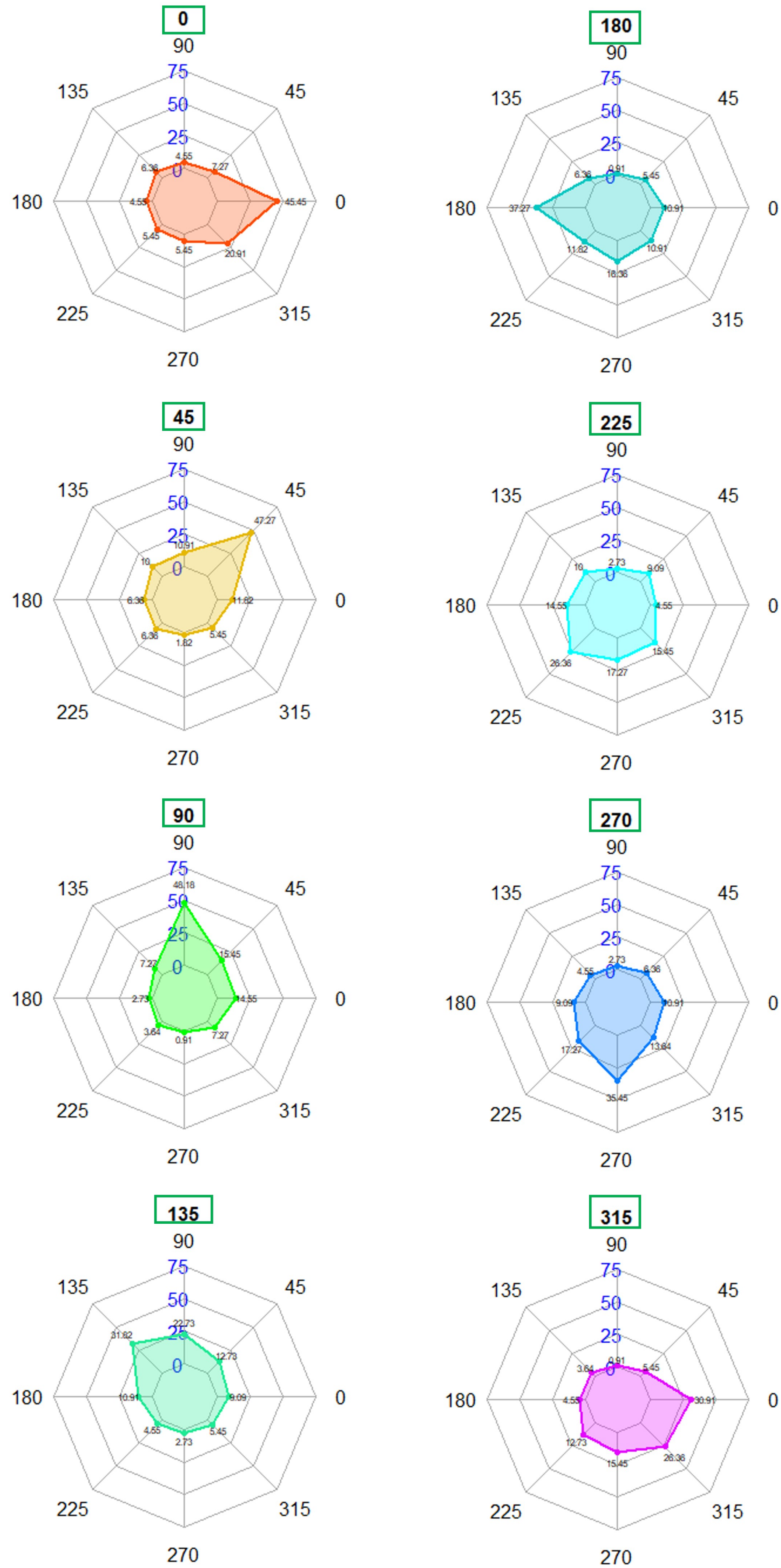

Figure 5.8: Direction discrimination study results

Table 5.1 represents the distribution of responses for any given direction. Based on these initial observations we could safely assume that the device is able to generate a virtual force in the desired direction, although the effectiveness of the virtual force along different directions is varying. It was observed that users were able to identify directions in the range of 0° to 135° more easily as compared to directions in the range of 180° degrees to 315° degrees, with the correctness percentage of directions along 0°, 45° and 90° degrees being the highest. This difference in correctness percentages could be attributed to the type of asymmetry in the control signal. In the interval of 0° to 135°, the control signal had a positive asymmetry, whereas in the interval of 180° to 315°, in which the collective correctness percentage is lower, the control signal comprised of a negative asymmetry. It would be worth studying the effect of positive asymmetry verses the negative asymmetry on the ease of direction distinguish ability.

		User Response							
		0	**45**	**90**	**135**	**180**	**225**	**270**	**315**
Expected Direction	**0**	45.45%	7.27%	4.55%	6.36%	4.55%	5.45%	5.45%	20.91%
	45	11.82%	47.27%	10.91%	10%	6.36%	6.36%	1.82%	5.45%
	90	14.55%	15.45%	48.18%	7.27%	2.73%	3.64%	0.91%	7.27%
	135	9.09%	12.73%	22.73%	31.82%	10.91%	4.55%	2.73%	5.45%
	180	10.91%	5.45%	0.91%	6.36%	37.27%	11.82%	16.36%	10.91%
	225	4.55%	9.09%	2.73%	10%	14.55%	26.36%	17.27%	15.45%
	270	10.91%	6.36%	2.73%	4.55%	9.09%	17.27%	35.45%	13.64%
	315	30.91%	5.45%	0.91%	3.64%	4.55%	12.73%	15.45%	26.36%

Table 5.1: Distribution of responses from participants for 2D prototype

Furthermore, the correctness percentages were analyzed and studied while regarding a one interval error as correct response in the user responses. These results are depicted in parentheses as seen in Figure 5.9. The correctness percentages showed a clear increase with inclusion one interval errors. With inclusion of user responses in this one-interval range, the overall correctness percentage including all directions

(0° to 315°) increased 1.8 times from 37.27% to 66.59%. Moreover, in the 0° to 135° interval, the correctness percentage increased 1.6 times from 43.18% to 70%. This increase in correctness percentages with inclusion of one interval errors emphasizes the need for a reference so that users are able to map the *perceived direction* to *real world direction* without visual or audio cues. We believe that adding a static marker to provide a reference would help increase the correctness percentages significantly.

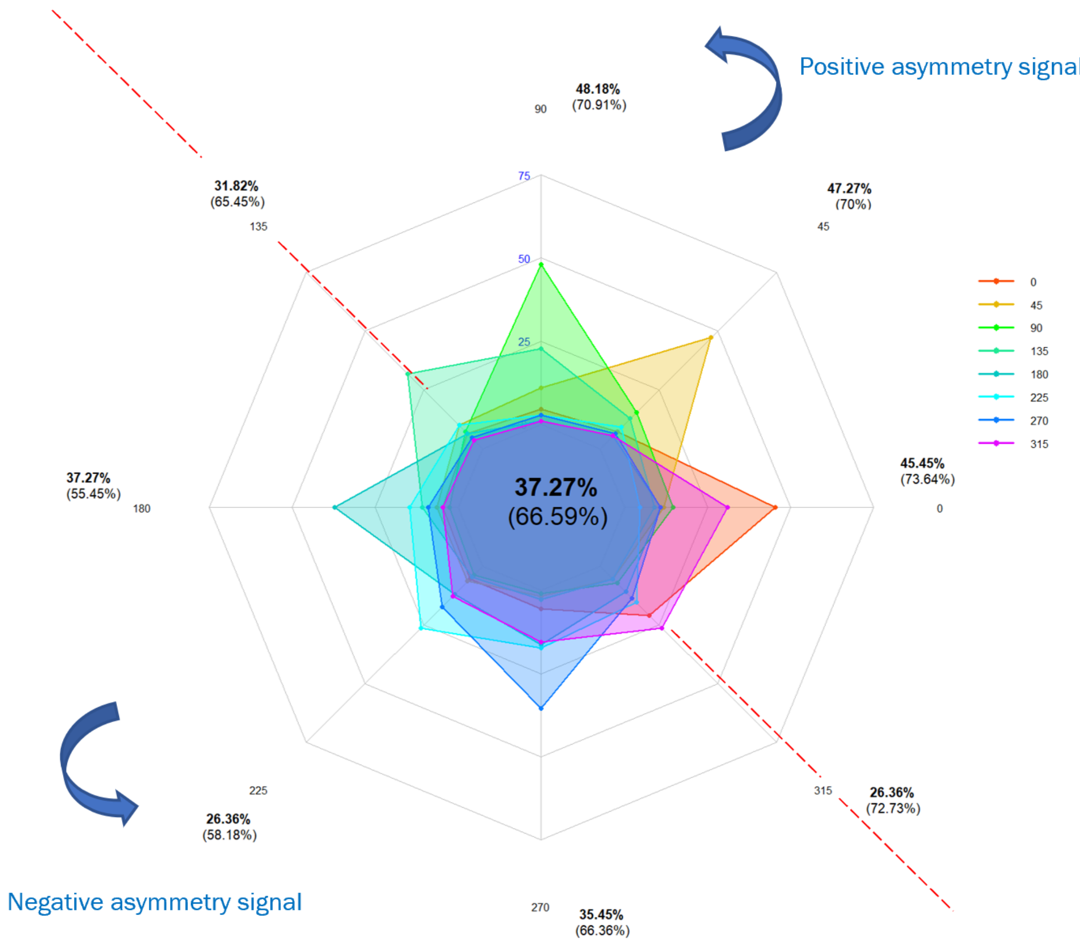

Figure 5.9: Eight directions correctness percentage

We have successfully created a device and verified that a single actuator is capable of providing virtual force feedback in eight directions. This device does not actuate different parts of the device for different directions and does not require any modification of the control signal to provide haptic feedback in 8 directions satisfactorily.

Since the control signal used for this device is an analog signal, the intensity of the virtual force can be increased by controlling the magnitude of the signal. It would be interesting to study the effect of the virtual force intensity on the direction distinguish ability.

5.4.1 Qualitative Feedback and Analysis

After successfully conducting the user studies, each user was asked to provide feedback using google forms. The form contained questions gather insights on the following:

- Describe the haptic experience with the 2D prototype
- Familiarity with haptic devices
- If the device was easy to hold
- Physical fatigue of fingers while operating the 2D prototype
- Mental fatigue while perceiving haptic feedback and predicting directionality

Overall most of the users were pleasantly amused with the haptic feedback rendering directionality. Based on the feedback, we can infer that the virtual force was perceivable to provide directionality. Some of the comments of users were, *"Nice addition to basic vibration, giving it direction"*
"The haptic vibrations are very strong and perceptible"
"I interpret the sensation as a pushing force, pushing my hand in a certain direction. Moving my wrist opposite to this direction I felt a resistance. At times I even felt as if my hand was being lifted vertically"
The most general comment from people was that some directions were easier to interpret and was pronounced than the others. Users clearly conveyed the ambiguity in identifying certain directions as compared to others and the inability to perceive a

distinct haptic feedback in these directions. In their own words, below is what they said:

"I felt like vibrations in certain direction were more than others."

"I got confused with the vibratory motion, sometimes, but the EWNS (East, West, North, South) directions were strong"

"Felt some directions had less pulling force/sensation"

"Most of the times the general direction can be interpreted with few exceptions."

A couple of users experienced physical exhaustion and mental fatigue by stating: *"At one point of time, my hand got numb"*. This could also be due to the long duration of the experiment.

It is to be noted that 5 out of 11 users never had a prior experience with any haptic devices while the other 6 users admitted to have experienced haptic sensations from sources such as gaming controllers, virtual reality headsets, mobile phones and smart watches.

The users were also questioned about the mental and physical fatigue on fingers they experienced during the experiment.

As shown in Figure 5.10, less than 20% of the users experienced physical exhaustion and mental fatigue.

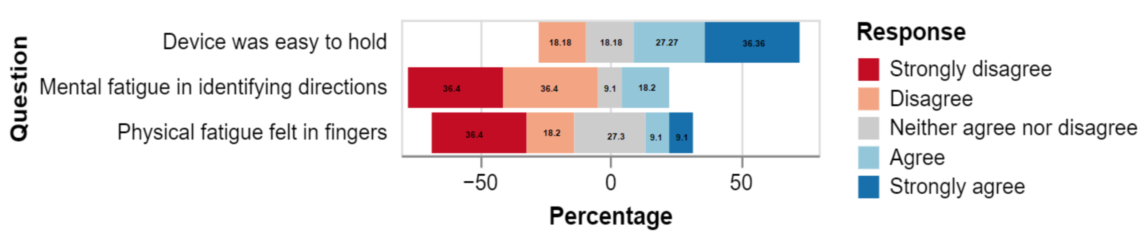

Figure 5.10: Participants were asked to rate physical and mental fatigue while using the 2D prototype

Valuable feedback and suggestion from the users were also noted and are actively being taken into consideration while designing future haptic devices. One specific suggestion read: *"The device to hold it can be made more comfortable (shaped similar to a Computer Mouse), since holding a cube for lengthy periods of time in a single palm would be tiresome"* As a whole, a majority of the users were seen to be satisfied with intensity and coherence of haptic cues generated by 2D prototype. Suggestions and comments on the ambiguity associated with certain specific directions and the design of the hand-held device are to be given due importance and changes can be incorporated to deliver lucid virtual force.

CHAPTER VI

3D Virtual Force Feedback Device

This chapter describes the design we proposed for a 3D haptic device that is spherical in shape. The goal was to build a handheld 3D haptic device with a single actuator that can deliver accurate directional cues in 3D. Section 6.1 elaborates on the static prototype that was built for a feasibility study to understand if the spherical structure was capable of delivering 3D directional cues effectively. Section 6.2 describes the pilot study conducted with the static prototype and its results. Lastly, section 6.3 depicts our proposed design for a fully automated 3D spherical structure to deliver accurate directional cues using asymmetric vibrations.

6.1 Static Prototype

To test the effectiveness of haptic cues, we built a static prototype that is spherical in shape as shown in Figure 6.1. The spherical structure was believed to be an ideal design to be held in hand, while experiencing the virtual force. This sphere was 8cm in diameter and it weighed 130g. The spherical outer cover was 3D printed and a 4Ohm-10watt actuator was used for testing. We choose the 4 Ohm-10watt exciter as opposed to the 4ohm-5watt exciter that was used for the 2D prototype since there was a need for a stronger haptic feedback due to increased surface area and large structure. An asymmetrical sine wave with half cycle inverted for every two cycles (base signal) was used to produce virtual force in this device as shown in Figure 4.4.

The actuator was positioned at the center of the sphere and sealed tightly using a strong adhesive, as depicted in Figure 6.2.

Figure 6.1: Design of static hand-held spherical prototype

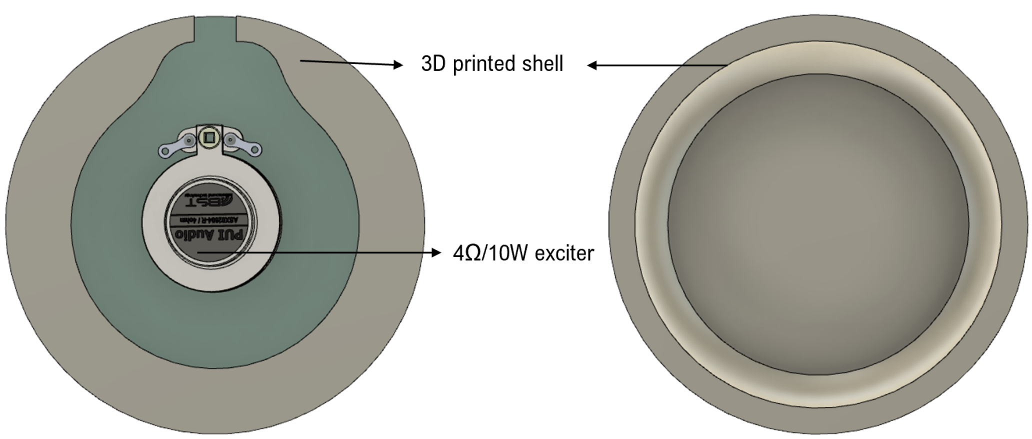

Figure 6.2: Mechanical structure of the spherical 3D prototype depicting the cross section of the sphere containing the 3D printed shell and a 4ohm-10watt actuator at the center.

6.2 Pilot Study

The goal of this study was to understand if the spherical structure containing a single actuator is capable of generating virtual force in the tangential as well as normal directions using asymmetric vibrations. We tested six directions equally distributed along the x,y and z axes as shown in Figure 6.3.

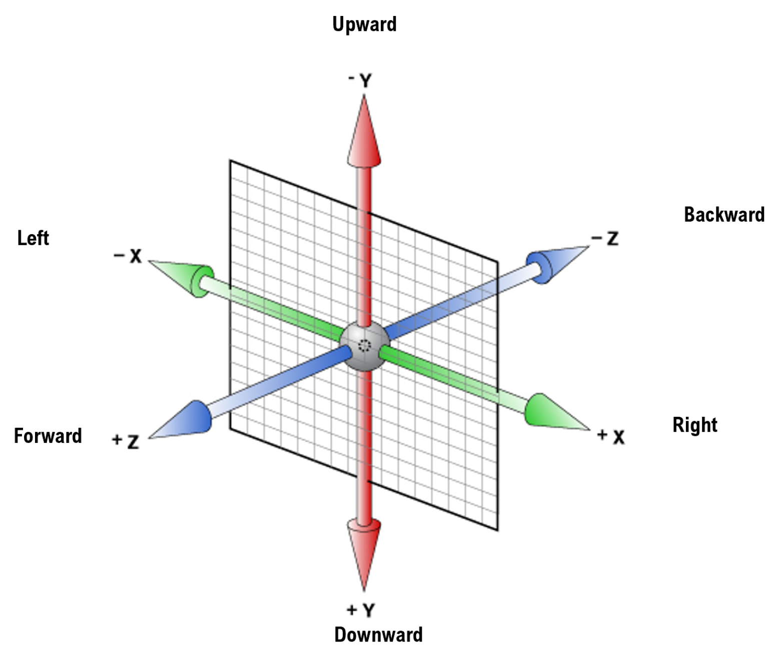

Figure 6.3: Six directions considered in the pilot study

6.2.1 Participants

The experiment was conducted with 3 male and 1 female participants (age group: 23-32 years). All participants were right handed. The study was conducted in a single session which lasted up to thirty minutes.

6.2.2 Experimental Setup and Procedure

Participants were seated in front of a 14 inch touchscreen monitor and were asked to hold the device in their dominant hand. They were required to wear noise cancelling headphones that played white noise to prevent any environmental noise as well as noise of actuator vibrating from the prototype. Participants were also blindfolded throughout the experiment and they removed their blindfolds only to mark their responses after each trial. This was to ensure audio cues and visual cues from the actuator was blocked and guaranteed that the results are purely based on haptic feedback felt on the fingers and palm while holding the prototype. The experimental setup is as shown in Figure 6.4.

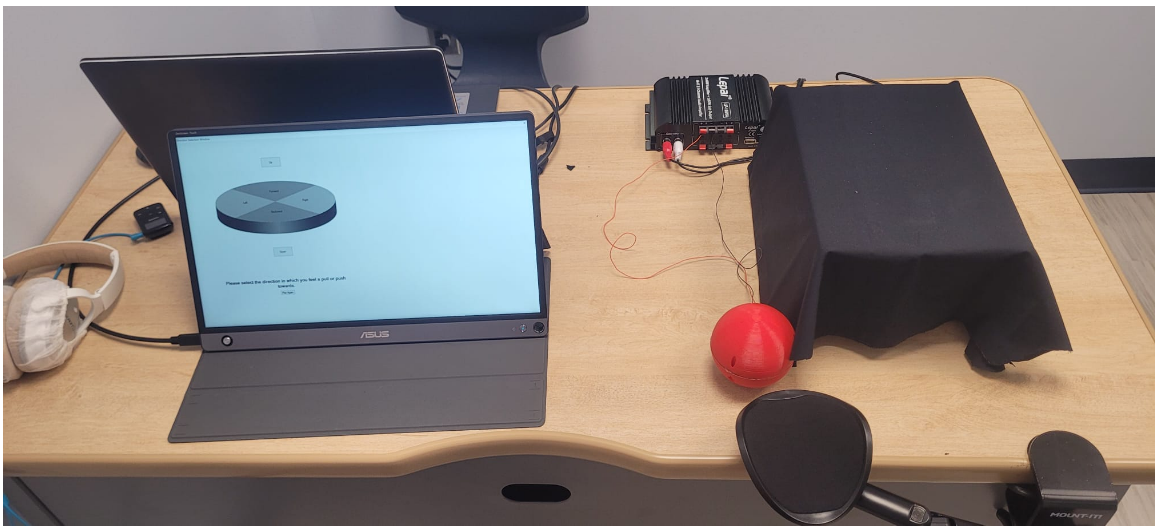

Figure 6.4: Experimental set-up used for pilot study of spherical 3D haptic device. The setup consisted of the prototype, noise-cancelling headphones, amplifier and a monitor.

Before the experiment began, each participant was informed about the details of the experiment including information about breaks during experiments, usability of direction selection window GUI which records participant's responses. The position and grip of the prototype was kept consistent across all participants as shown in Figure 6.5. The control signal is the same asymmetric sine wave with half cycle inverted for every two cycles as shown in Figure 4.4.

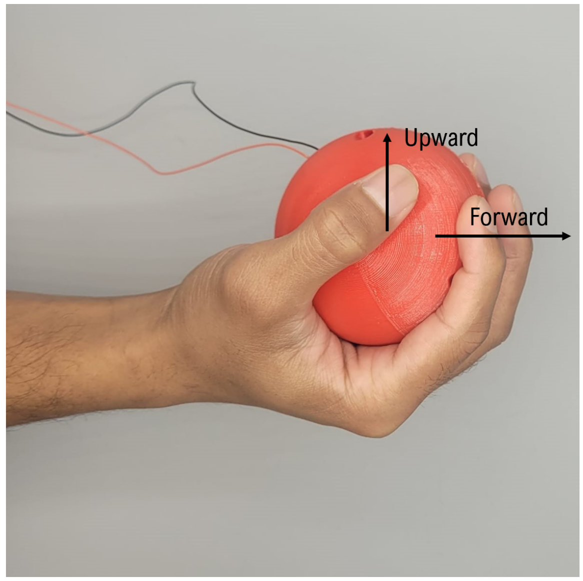

Figure 6.5: Prototype grip during pilot study

Participants were allowed to do a few trials before the experiment for a maximum of 3 minutes. The participants were not given any insights on their performance throughout the experiment. A total of 60 samples were collected from each participant. The participants were made to experience a virtual force for a duration of 5 seconds. There was a 2 minute break after every 12 samples. The direction of virtual force was randomly chosen by the experimenter (Archana Narayanan) by manually positioning the actuator at different orientations before handing it to participants. To eliminate order effect and learning bias, the trials were randomized for all participants. A sample was repeated as many times as requested by the participants. Participants recorded their responses on the GUI built using C# programming language as depicted in Figure 6.6.

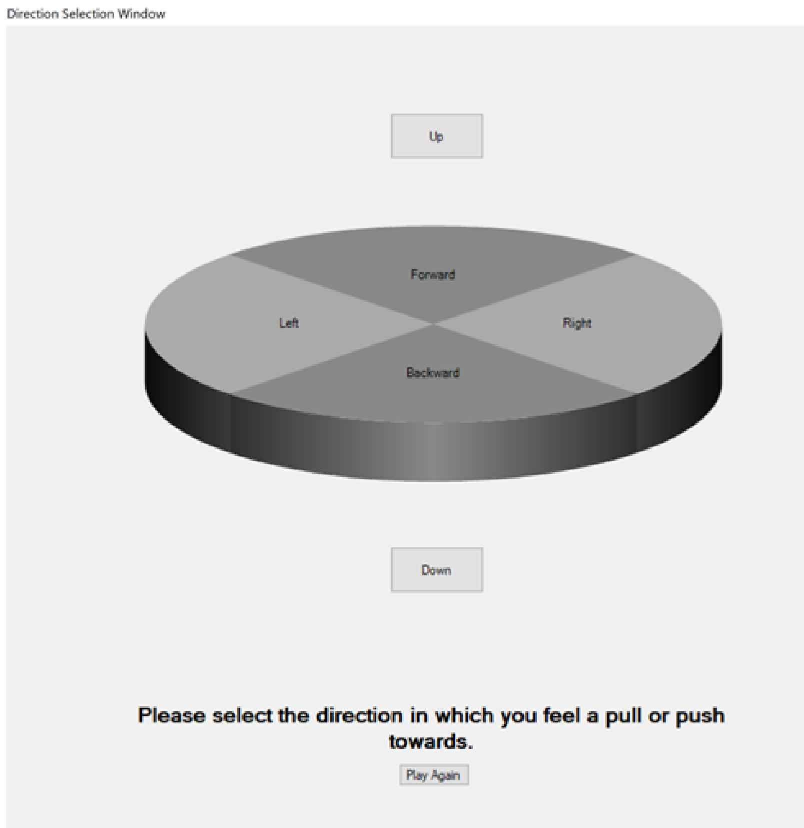

Figure 6.6: Direction selection window where the participant response was recorded for each trial.

6.2.3 Pilot Study Results

We aimed to understand the ease of direction distinguish ability for up, down, forward, backward, left and right directions. The up, right and forward directions utilize the "negative asymmetry" base signal and the rest of them utilize the "positive asymmetry" base signal. The distribution of responses for each orientation is shown in Table 6.1. The results show that users were clearly able to distinguish all the six orientations with a correctness rate of 70% or higher.

	User Response						
		U	**L**	**B**	**D**	**R**	**F**
Expected Direction	**U**	82.5%	2.5%	2.5%	12.5%	-	-
	L	-	70.0%	15.0%	-	15.0%	-
	B	5.0%	2.5%	90.0%	-	2.5%	-
	D	2.5%	-	-	95.0%	-	2.5%
	R	-	5.0%	-	5.0%	90.0%	-
	F	-	7.5%	7.5%	-	10.0%	75.0%

Table 6.1: Distribution of responses from pilot study for 3D static prototype

The overall correctness percentage of the experiment is 83.75%. On further analyses of the distribution as depicted in Figure 6.7 we can see that the downward orientation had the greatest accuracy. We believe that the pull downwards was very prominent as compared to the other orientations due to the effect of gravity and this led to the greater accuracy seen in the results for this direction[21]. Furthermore, the virtual force upwards was sensed as mere vibrations rather than a feeling of push or pull. This effect can also be attributed to weight of the device and gravity. Participants could have used this as a distinguishing factor between the upward and downward orientation. It would be worth studying the role of gravity in the normal axes and the weight of the device. More directions in the XZ and YZ planes at specific angles needs to be tested to fully understand the perception of the virtual force in the upward and downward orientation.

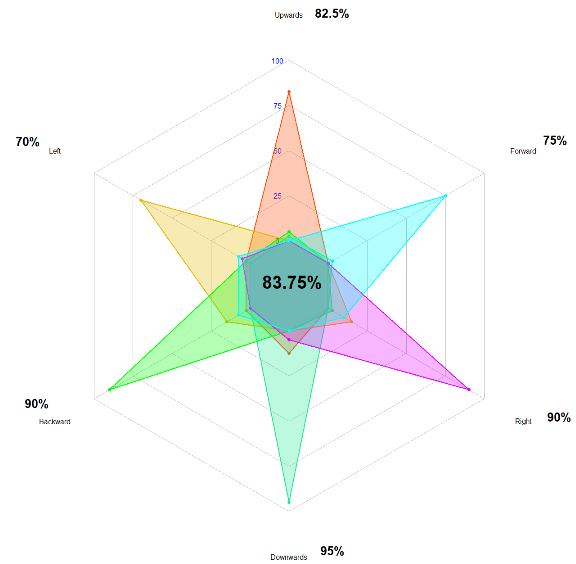

Figure 6.7: Correctness percentage of the six orientations considered in the 3D pilot study.

It can be observed that the correctness percentage is comparatively lower for left and forward direction. This was believed to be attributed to the grip of the device i.e participants held the device by the side in their dominant hand as shown in Figure 6.5. This was done so that the grip was consistent among participants and participants could not receive any cues from the orientation of the device. With the device being held such that the fingers placement is evenly distributed across its surface can prove to be more useful while distinguishing the left and forward directions.

To conclude, we can confirm from the pilot study that the spherical structure is able to provide virtual force with a single actuator in all the three axes for at least six orientations comfortably. In the forthcoming section, we propose a design to automate the movement of the actuator across 3D orientations.

6.3 Proposed System Design

Our proposed design for 3D haptic device consists of a two axis gimbal created using two servomotors to allow the actuator to rotate along two axes. The design of the two axis gimbal is depicted in Figure 6.8. One servomotor rotates the actuator through the carbon fiber rod connected to the other end using a ball bearing. The actuator holder is attached to this rod that contains the exciter. The second servomotor rotates the entire structure of two axis gimbal along its axis of rotation. This way the actuator rotation can be controlled along two axes.

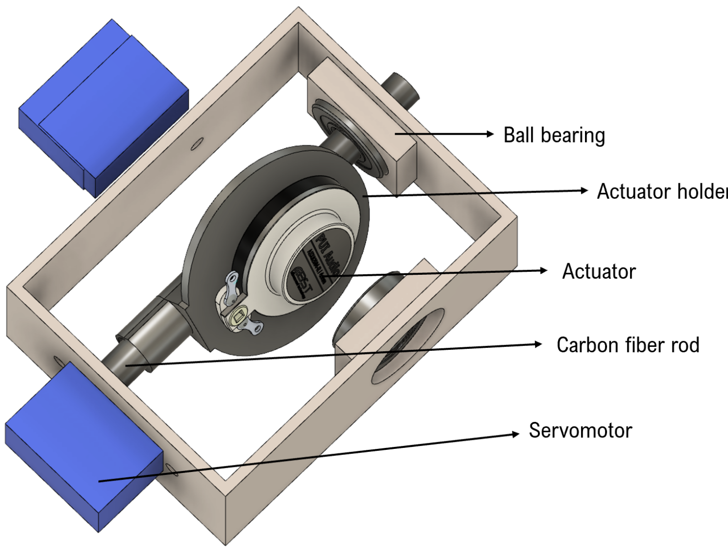

Figure 6.8: Design of two axis gimbal for providing 3D haptic feedback.

Initially, we designed a spherical structure with a two axis gimbal similar to that of the static prototype. However, due to the space required for the rotation of the actuator in two different axes inside the enclosure, the diameter of this structure was 10cm which was large to be handheld.

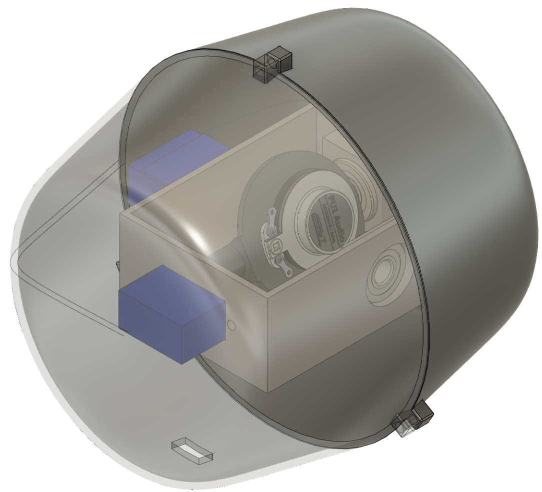

Figure 6.9: 3D prototype design

For this reason, modifications were made to the spherical encasing. The top and bottom of the structure were flattened while maintaining a seamless curvature along the side of the device. This final design, as shown in Figure 6.9 was slightly smaller and facilitated easier handling of the device, thereby ensure it can be hand-held. The diameter of this device is around 8cm which can be handheld. The size can be further reduced by using smaller sized motors. It consists of an elliptical outer covering and contains the two axis gimbal capable of controlling the actuator position to be able to render 3D haptic feedback using a single actuator. Based on the results from pilot studies, this design would be worth pursuing to develop a 3D haptic feedback device using a single actuator.

CHAPTER VII

Limitations and Futurework

Although the current device showed enormous promise in successfully generating haptic cues in 8 directions using a single actuator, there is still a scope for improvement.

While the current prototype is able to effectively render virtual force in 2D using a single actuator by eliminating issues of interference, it was observed that some directions are more easily perceivable than the others. From the results of the user study, we see that the direction distinguishability can be significantly improved if we overcome the challenge of mapping perceived directions to real world directions. For this purpose, a reference marker can be added to help users map directions, thereby yielding better results.

At this point in this thesis, we explored and implemented a 2D prototype using only one type of voice coil actuator. Different types of voice coil actuators can be explored and experimented with in the future, to see if one performs better than the other. The amount of virtual force experienced while using the prototype can also be quantified to further improve the direction perception. The torque produced by the voice coil actuator needs to be further investigated to understand if it plays a role in direction distinguishability. The amplitude of the control signal is known to play a major role and can be varied to generate different intensities of the virtual force, while its effect on direction distinguishability needs to be investigated. In this study, we worked with two modifications to the base signal (asymmetric sine waveform). More variations in control signals can be explored to identify the effect of input signal waveforms on the perceivability of the virtual force. Furthermore, multiple devices need to be tested and validated with each variant of the control signal to understand the effect of variation in control signals on each individual device.

The 2D prototype that was designed and used in this study was found to generate haptic cues in 8 directions. Based on the results from user studies and the observations from the current prototype, a new design needs to be manifested, that can extend the directional haptic cues to 12 directions or more. While the actuator rotates up to 180 degrees to generate haptic cues in 8 directions, small modifications can be made such that it is able to rotate for the entire 360 degrees. This way, the effect of positive asymmetry versus negative asymmetry for all the orientations can be studied and optimized.

Moreover, in the current 3D prototype, the virtual force in the direction opposite to that of gravity is sensed as mere grain vibrations rather than virtual force. This needs to be further studied so that effective virtual force can be rendered satisfactorily in the normal direction as well.

Finally, the ergonomic factors influencing tactile perception for this device needs to be thoroughly investigated. Methods to incorporate the sensations of texture can be explored. The effect of the weight, build and material used to fabricate the device needs to be taken into consideration and suitable modifications should be made to optimize the haptic cue sensitivity. Different types of materials for the finger-pad could be explored to understand the ease of perception. The mechanical structure of the device can further be improved such that, all the parts are covered and enclosed for design to be made more intuitive to be hand-held. Considering user feedback and suggestions after conducting user studies, we aim to further improve prototype, while taking inspiration from other commonly used handheld devices such as computer mouse and smartphones. As haptic feedback is useful in a variety of applications, studies can also be conducted to evaluate its effectiveness by designing an application to test in artificial and virtual reality settings.

CHAPTER VIII

Conclusion

There has been a growing need to integrate haptics into a variety of applications ranging from smartphones, accessibility devices to virtual reality and augmented reality applications. This thesis presented and evaluated a novel handheld 2D prototype comprising a single actuator that renders virtual force using asymmetric vibrations.

Owing to the challenges in existing devices, this device was designed to be handheld while being able to render effective haptic feedback. It is simple in design, easy to build and contains very few moving parts with a low cost of production. The intensity and direction of virtual force can be easily modified providing refined haptic feedback to users. Also, the actuation mechanism comprising of a single actuator to render 2D haptic feedback as opposed to the use of multiple actuators in the past, circumvented challenges of magnetic interference between the actuators, which dampens the virtual force rendered.

Our user study shows that the prototype was able to render effective haptic cues in eight directions with correctness of 37.27% and 66.5% when one interval errors are regraded as correct responses. It has also been found that virtual force was perceived to be stronger in certain directions than the others and this needs to be further studied to understand the effect of positive and negative asymmetries on force illusion perceived. Furthermore, different control signals have been studied to analyse its effect on ease of direction distinguish ability. As hypothesized in past work, a up and then a down signal or a left and then a right signal did not result in any significant improvement in increasing the ease of direction distinguishability in the 2D prototype developed.

A feasible design for a 3D haptic device using asymmetric vibrations has also been proposed. Pilot study with static prototype showed tremendous potential with correctness percentage of 83.75% for six directions.

This work focused on designing multi-dimensional haptic feedback devices containing a single actuator to render haptic feedback using asymmetric vibrations. The overarching goal of this research will enable handheld haptic technologies to assist the differently abled with navigation in their everyday life. By providing directionality using haptic cues, it would be possible to guide people with disabilities travel short distances without any assistance. Our current device paired with sensors and tactile maps would make such a technology possible. It can also be embedded in handheld devices to provide improved user experiences. Furthermore, providing directionality using haptic cues would enable the creation of a much more realistic experience in a virtual and augmented reality settings.

We hope that this knowledge will lay the foundation for designing future haptic devices using asymmetric vibrations.

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