B.Des Project 2

Spatial Guidance Using Haptics

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अभिकल्प विद्यालय

Declaration

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29th April 2022

Approval

The B.Des Project 2 entitled “Spatial Guidance Using Haptics” by Atish Waghwase, Roll Number 18U130008 is approved, in fulfilment of the Bachelor’s in Design Degree at IDC School of Design, Indian Institute of Technology Bombay.

Internal:

External:

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Chairperson:

Acknowledgement

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Abstract

This project aims to create a spatial guidance system that has applications as assistive technology to aid visually impaired persons. I build upon a novel wrist-worn haptic glove by tweaking the original design and creating a novel localisation system, and construct a research to test the capabilities of the human-machine system. The goal of the research was to find how degrees of freedom influenced haptic guidance, as well as if two of our interaction metaphors had an effect on performance. Results show that separating degrees of freedom had significant improvement in accuracy with negligible tradeoffs in speed; I did not see any significant effects of metaphors on performance. Finally, I discuss the implications of this research and how it can be improved, as well as propose future directions for research and design.

Contents

1. Introduction

1. 1 About

Haptics are technologies that deliver information through the stimulation of touch; it is a form of non-verbal communication. The vibration motors on smartphones are possibly the most widely used form of haptics, and are used to nonverbally communicate when a notification arrives, or the state of the phone changes, or to emphasise an interaction. So ‘spatial guidance using haptics’ refers to the communication of the location of objects in space to a user by using haptics.

There is plenty of work done in the field of navigation using haptics, which means directing the user to a certain location on a 2D map through the means of various haptic devices, but these had the precision of roughly a few feet and are meant for large indoor spaces or outdoor spaces as well. This project aims to create a haptic guidance system that has the accuracy of a few centimetres and in a 3D space, as the interaction and use case would be completely different.

1.2 Motivation

I had always wondered, even if the elevator buttons have braille embossing, how did blind people know where to find the buttons? How do they know where to touch to find braille? The best answer I found was, well, they don’t. Elevator buttons and other braille signages are kept at a certain height which is easy to reach for, so blind people have to feel their way around until they encounter something tactile and hope it has braille on it.

There are consumer BLE (Bluetooth Low Energy) beacons that can be installed in indoor environments that can locate BLE compatible tags or phones in a 2D space (potentially in a 3D space) and then guide them across indoor environments, but that guidance is done in 2D and only upto the accuracy 2.5 metres on average (Fachri M. et al. [5]) Similar beacons that are still in their commercial infancy in 2022 use UWB (Ultra Wide Band) and US (Ultrasound) can reach a precision of upto 10cm (Crețu-Sîrcu et al. [1]). There exists a commercial but proprietary localisation and guidance system that provides a more precise guidance - Apple’s *Precision Finding* [14] that uses UWB technology to locate and guide users’ iPhones to their *AirTags* (A small electronic tag used for tracking) with up to a precision of 30cm.

Apple's Precision Finding feature [14]

To guide a user to a target, there are two parameters that need to be communicated - distance and direction. Precision Finding relies mostly on visual means to display direction on the iPhone screen. It uses haptic feedback only to communicate distance - the phone vibration gets stronger the closer it gets to the AirTag.

Given that it is possible to accurately guide users visually to a target of upto 30cm is in itself, a huge step up from the 2.5m that the BLE beacons provide. There needs to be a system, however, that communicates distance and direction through non-visual means so that visually impaired people can benefit from it. One option was an audio-based guidance system but since haptic feedback is more discreet and can be applied directly to the hand, I chose to build a haptic spatial guidance system in this project.

2. Study

2.1 Coping with Visual Impairment

Being 'legally blind'means having less than 20/200 or 6/60 vision based on the Snellen Chart [17]. That means if the average person can see an object clearly from 60 metres away, a person with 6/60 vision would need to stand 6 metres away to see it.

There are multiple assistive technologies to help blind people navigate their surroundings; Be My Eyes, Blind Reader, Supersense and KNFB Reader are examples of mobile apps on the Google Play Store that use AI or assistance of real people to help visually impaired people identify objects and navigate their surroundings. They typically utilise the smartphone camera to recognise the most prominent object in frame and speak it out loud. There are object recognition devices like the Orcam MyEye

[13], which is a wearable device that is mounted on the side of the frame of eyeglasses.

The problem with these is that they use an audial means of communication, so if the user doesn't have headphones on, their interaction isn't private anymore. If they do have headphones on then that hinders their ability to hear their surroundings which they rely pretty heavily on due to their lack of vision. They also have to hold their phone up the entire time in order to receive information.

These solutions also do not provide guidance, so the user has to use trial and error and point arbitrarily at an object with their finger or bring it into the viewport of the phone camera, after which the object recognition system reads it out loud.

2.2 Guidance Systems

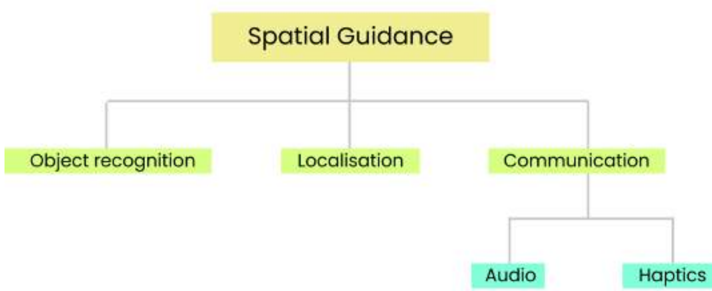


Figure 2.2.1 : 2DOF Target Circle Comparison

There are three components to making a spatial guidance system work - the object recognition system, the localisation system and the communication system. Any object would first have to be recognised by an object recognition system. Then a localisation system would have to locate the target and the wearable haptic system in space and calculate the distance and direction vectors between them, and monitor any changes to the location of each in real time and make suitable adjustments. Finally, the communication would involve haptic or audial feedback systems to communicate this information to the user.

Since this project is about haptics, I worked on only the haptic component of the guidance system and built a localisation system (that has its own limitations) and used fixed targets, so that there is no need to have an object recognition system. I call the prototype in this paper the '**Guiding Hand**'.

2.3 Literature Study

The most common use of vibrotactile feedback is for attentional guidance (as defined by Weber B. et al. [16]) to bring attention to warning or high priority information in consumer electronics. However, a lot of work has also been done in using vibrotactile feedback for spatial guidance. Vibrotactile feedback is applied to various body parts depending on the task and its effects have been studied - using a torso-worn vest (Ertan S. et al. [4]), a wrist worn device, (Weber B. et al. [16]), a head mounted haptic display (Kaul O. et al. [9]), a waist worn haptic belt (Katzschmann R. et al. [8]), a haptic necklace (Matsuda A. et al. [10]), a haptic glove (Günther et al. [6]), a fingertip vibrotactile glove (Elvitigala et al. [3]), and so on. Elsayed et al. [2] have studied the effects of spacing between vibrotactile actuators across the body. Jones L. A. et al. [7] provide guidelines for designing tactile displays.

Most of these applications are meant for either spatial guidance over longer distances, and operate in 2 dimensions. Since I was trying to achieve vibrotactile guidance in 3D for highly dexterous tasks, it made sense to go for a wrist/palm wearable vibrotactile device. I came across one device that was very close to what I was trying to achieve - TactileGlove (Günther et al. [6]). The TactileGlove is a glove with a matrix of vibration motors on the palm and the dorsum (back of the hand) that encodes distance and direction information into the vibration pulses of the motors.

Figure 2.3.1 : TactileGlove by Günther et al. [6]

Günther et al. [6] ask blindfolded participants to use the TactileGlove to hit 27 invisible targets of a diameter of 10cm in a cubical grid of 3x3x3 and evaluate their performance. They explore how the number of haptic motors and metaphors affect user performance. They found that participants preferred using a metaphor they called *Magnet* (detailed later) over *Push*. They also found that using a higher number of haptic motors resulted in lower acquisition time.

The TactileGlove paper shows promising results with short range spatial guidance using haptics and achieves an interaction similar to what I was trying to achieve, so I decided to follow the same design.

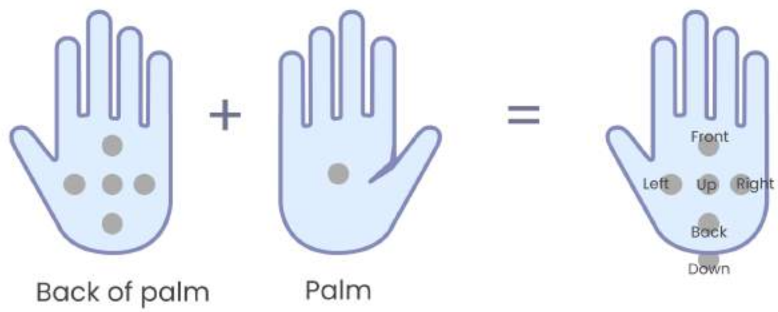


Figure 2.3.2 : 2D Representation of the Guiding Hand

The figure represents the right hand wearing the Guiding Hand of a person and the grey dots represent vibration motors, hence there are 5 vibration motors on the dorsum (back) and one motor at the centre of the palm.

3. Design and Detail

3.1 Research Design

3.1.1 Variables

Vibration Directionality Calibration

For a given apparatus, it is vital that users are able to tell which motor out of a given matrix of motors is being activated at a given time in order for the guidance to work as intended. Sensitivity to vibration feedback may vary by the exact location of the motor on the dorsum.

Minimum Intensity

Different users may have different sensitivities to intensity of vibration, and it may again vary depending on where exactly the motor is located. Some users might not be able to tell low vibrations and think it is a null vibration.

Sensitivity to Change in Vibration

What is the least perceivable change in intensity? Since the distance to the target is being communicated through intensity of vibration, it is detrimental to know how it will be perceived.

Degrees of Freedom

Degrees of Freedom (DOF) in this case refers to the number of axes that guidance will simultaneously be active in. If it is 1DOF then guidance will be active only in the X or Y or Z axis and only one pair out of three (front-back, up-down and left-right) will be active. If it is 3DOF then guidance will be active along all three axes, and all three pairs of motors will be active at once. DOF count directly correlates to the amount of information being given to the user at once.

There are 3 possibilities - 1DOF, 2DOF and 3DOF.

1DOF involves guiding the hand in one axis at a time. There can be three configurations in 1DOF, based on the sequence that the axes are deployed.

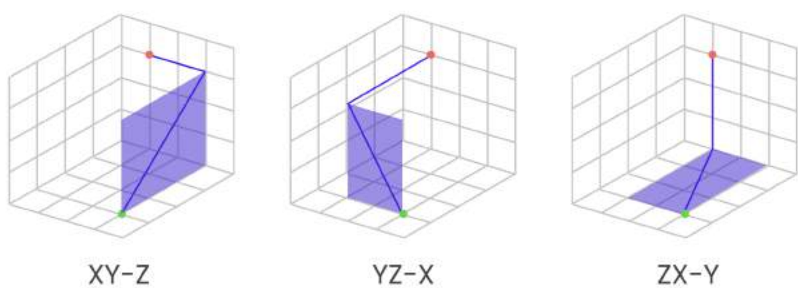


Figure 3.1.1.1 : Permutations in 1DOF

2DOF involves guiding the hand along a 2D plane first, and then nudging the hand along the axis perpendicular to the plane. There are 6 possible configurations based on the order of plane and perpendicular axis deployed.

3DOF involves guiding the hand in all three axes at once.

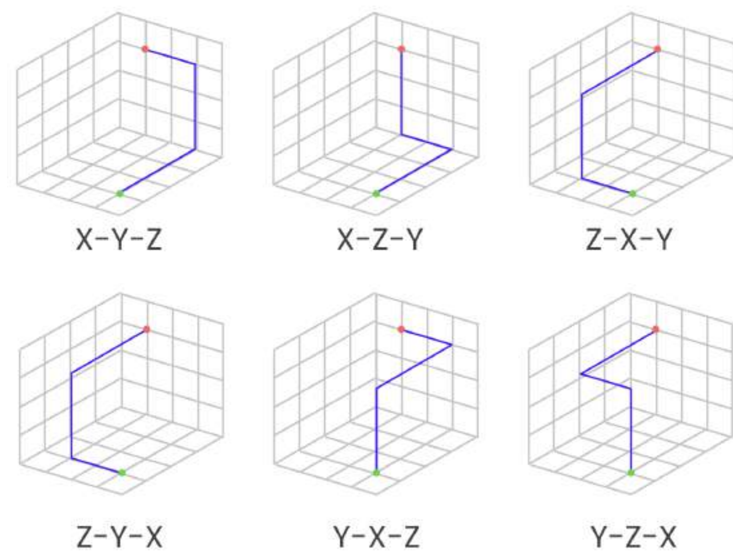


Figure 3.1.1.2 : Permutations in 2DOF

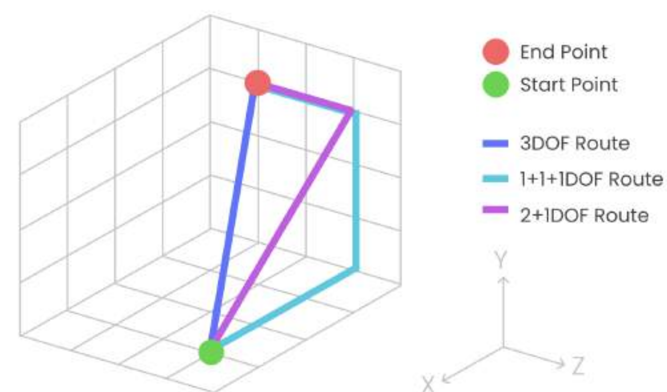


Figure 3.1.1.3 : 3DOF vs 2DOF vs 1DOF

Interaction Metaphor

Interaction metaphors (detailed later) is the way the system reacts and provides feedback to the users actions. In this case, the way the intensity or frequency of vibration changes as the user's hand approaches the target can be called the metaphor.

3.1.2 Picking a Research Question

A pilot study was conducted before designing the research (detailed later). After the pilot, I decided to narrow down the scope of the project and go deeper into one aspect rather than trying to cover all variables.

During a past project, I was researching object manipulation tasks in virtual reality, when I read about separating degrees of freedom to simplify dexterous tasks. Mendes et al. [11] states that DOF separation benefits precision in spatial manipulations, at the expense of additional time for complex tasks. Veit et al. [15] state that users aren't able to integrate all three DOFs during the object manipulation task. Even though the papers discuss the influence of DOFs in virtual reality environments and visual feedback, the implications might be similar for vibrotactile feedback; is the vibrotactile stimulation from multiple motors too much to comprehend and decipher? Is it better to deliver less information or is it better to give all information at once? How does it affect speed and difficulty?

I had an interaction metaphor in mind that would be interesting to test out which was opposite the one that TactileGlove had used and it seemed like an original contribution. What effect does changing the interaction metaphor have on the outcome of guidance?

Given that the Gunther et al. have tried only 3DOF guidance and only one metaphor, and because the answers to these questions have the potential to optimise the experience of haptic spatial guidance systems on a fundamental level, the research question for this project was decided to be **"How do degrees of freedom and interaction metaphor influence spatial guidance?"**.

3.1.3 Research Variables

For the scope of this project, I decided to experiment upto only 2DOF in 2D, with both Elastic and Magnet metaphors.

Independent variables

- Metaphor (Magnet, Elastic)
- Degrees of Freedom (X, Y, XY Together, XY Separate)

Dependent variables

- Time
- Distance Deviation (Distance of endpoint from target)

Prediction

There is usually a tradeoff between time and accuracy as DOFs are separated/combined. Separating DOFs usually leads to better accuracy at the cost of time and combining DOFs leads to worse accuracy but faster target acquisition. Therefore, I am expecting XY Together to be faster and inaccurate whereas XY Separate to be slower and more accurate.

I am also expecting the Elastic metaphor to be slightly faster because there will be clear directional information when the guidance is started, and the Magnet metaphor to be more accurate since it has more information near the target.

3.1.4 Research Analysis

We will use the model by Wobbrock et al. [18] in their paper *The Effects of Task Dimensionality, Endpoint Deviation, Throughput Calculation, and Experiment Design on Pointing Measures and Models* since both contexts are fairly similar ie. participants hitting targets in a 1D or 2D space and analysing the deviation from the targets. The Fitts Law can be explained using the example of a signal - the amplitude of the signal is the distance between the start point and the target, and the endpoint deviation is noise.

B	C	D	E	F	G	H	I	J	K	L
	Pull Metaphor									
										X
Alias	Target 1			Target 2			Target 3			
	Time Taken	Location X	Location Y	Time Taken	Location X	Location Y	Time Taken	Location X	Location Y	Time Taken
User 1	6.4	0	29	4.33	-3	-14	5.95	2	15	5.29
User 2	3.93	1	43	10.57	2	10	10.59	3	26	4.87
User 3	4.48	1	40	4.55	-23	-3	3.81	1	32	8.96
User 4	2.85	-3	19	4.04	-4	14	5.68	-2	8	3.82
User 5	2.14	0	25	1.87	4	-19	3.62	1	32	2.87
User 6	1.07	0	27	2.22	-4	-11	7.63	2	18	1.77
User 7	10.85	40	28	9.08	12	-14	9.52	44	22	7.74
User 8	5.93	-5	43	9.04	3	0	6.6	0	33	7.8
User 9	12.02	9	29	3.63	-4	-23	5.36	-3	13	7.49
User 10	3.35	4	31	22.14	18	-11	7.81	-1	16	5.58
User 11	4.23	-12	27	3.47	-5	-15	5.49	-4	16	3.29
User 12	2.92	-1	11	4.09	0	-30	4.88	1	10	3.11
User 13	3.04	-2	29	3.4	0	-13	4.45	0	18	5.86
User 14	2.44	-4	-30	2.69	1	-25	4.27	0	10	2.88

Structure of Gathered Data

Since the targets are constant for all participants, we can generate two variables for the XY method - XY Together and XY Separate. XY Together is simply the participants engaging in both X and Y axes simultaneously and using 2DOF. XY Separate was derived to simulate the situation where there is a 2DOF target and guidance is done only for 1 axis at a time, so it uses 1DOF in X axis and 1DOF in Y axis separately, one after the other. We will have data on how much time each target took to hit in X, Y and XY individually, so we can add the time taken for X and Y and calculate the shortest distance to the target to keep the starting point and target same for XY Together and XY Separate. Thus, we can compare the endpoints for X and Y axes in 1DOF and XY Together and XY Separate in 2DOF.

In order to calculate the accuracy of each method, the following formula will be used:

$$SD_x = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \overline{x})^2}{N-1}} \qquad (1)$$

This equation is nothing but the formula for the Standard Deviation of a given set of points on the x-axis, where is x_i the x-coordinate of the endpoint for target number *i*, N is the number of of targets and $\overline{x}$ is the average of all the x-coordinates of the endpoints. Similarly, for 2DOF we can use Equation (2):

$$SD_{x,y} = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \overline{x})^2 + (y_i - \overline{y})^2}{N-1}} \qquad (2)$$

These equations firstly find the mean deviation from the target given by $\overline{x}$ and $\overline{y}$. Then the distance between the endpoint and the mean is calculated and the Pythagoras theorem is applied to find the shortest distance between the mean of deviations and the endpoint. The equation is then inserted into Equation (1).

The standard deviation of endpoints is given by:

$$W_x = 4.133 \times SD_{x,y} \qquad (3)$$

The constant term 4.133 arises from the entropy of the standard normal distribution. W_x gives us the minimum target circle diameter according to standard deviation for a X, Y, XY Together or XY Separate.

3.2 Prototyping

3.2.1 Glove

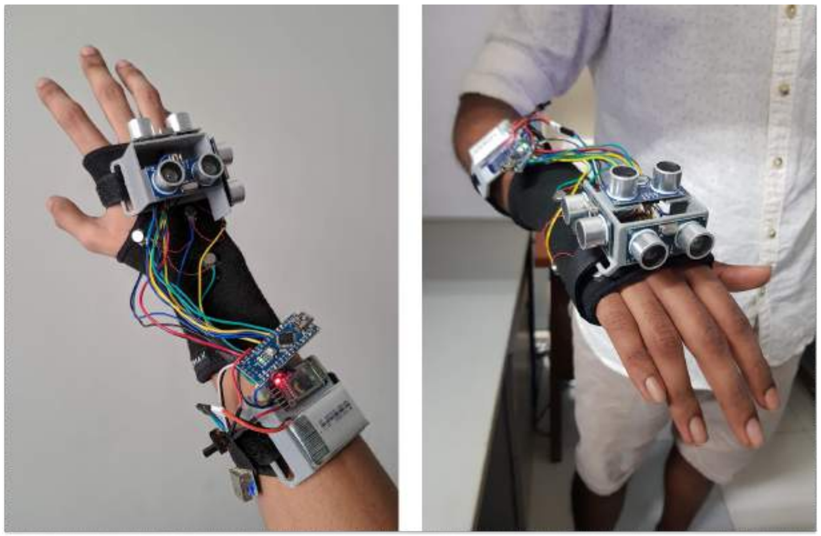


Figure 3.2.1.1 : The Guiding Hand apparatus

A vibrotactile display cannot be rigid - for motors to be perceived individually, they need to be able to vibrate without upsetting the other motors. That is why you need a compliant, elastic material to isolate each vibration motor.

The TactileGlove uses a typical fingerless glove as an apparatus, but the paper also mentions that participants felt that the vibration motors weren't in contact with their skin all the time. Hence, I decided to go with a tight, skin-fitting glove and I found the Tarmak Soft 100 Wrist Support from Decathlon to fit this description.

3.2.2 Haptics

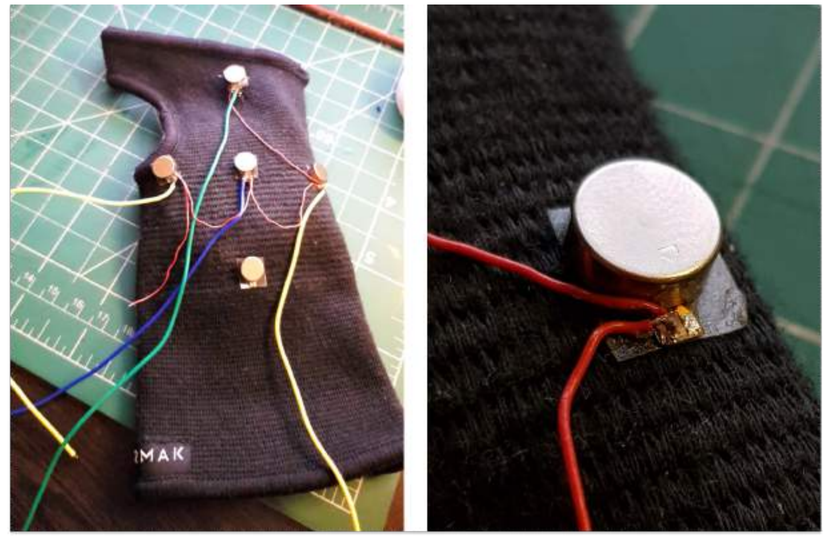


Figure 3.2.2.1 : Haptic system (left); Vibration motor(right)

Round, generic 10x3mm vibration motors stuck directly to the glove using strong double sided tape in the layout as shown in Figure 3.2.2.1. A total of 6 motors were used, 6 on the dorsum (back of the palm) and 1 on the palm touching the thenar muscles (close to the base of the thumb). All the motors were connected through wires to an Arduino Nano mounted on a 3D printed bracket located at the back of the wrist, strapped using velcro. The Arduino Nano was also connected to the ultrasonic sensor array for localisation, a HC-05 Bluetooth Module for wireless communication with an Android Phone (the master device), an 800mAh Li-Po battery and a battery charging module.

3.2.3 Setup

Figure 3.2.3.1 : Test in progress (left); Tracking booth (right)

In order for the localisation system to work, the Guiding Hand needs to be within 100cm of three perpendicular flat surfaces that are opposite to the ultrasonic sensors. Three sunboards held together by compression fit 3D printed joints were used to create the tracking booth. The dimensions of the tracking booth were 118cm x 89cm x 59cm. The height of the booth from the ground was 75cm, with the top panel at a height of 164cm. The panels were located to the right, front and top of the user's outstretched arm. The overhanging top corner was supported using a flat wooden stick to keep it from sagging and as flat as possible.

3.2.4 Localisation system

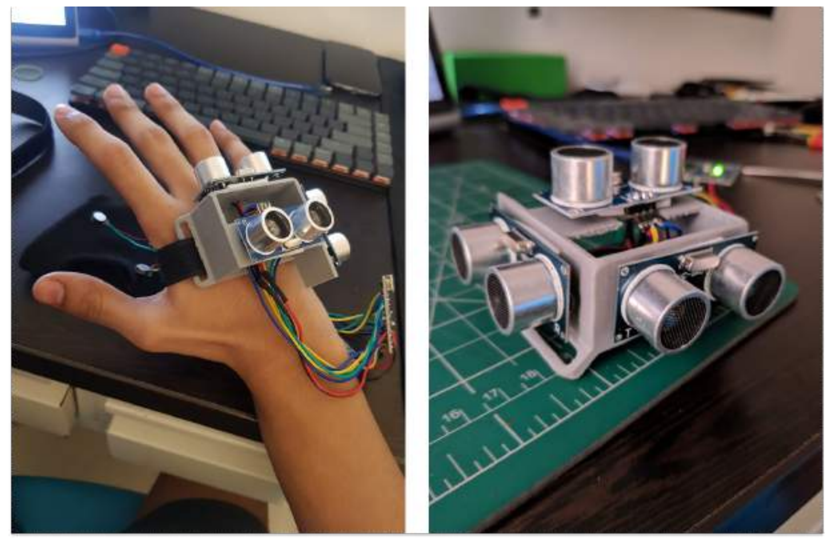


Figure 3.2.4.1 : Ultrasonic localisation system

The novel, low-cost localisation system in this prototype consists of three HC-SR04 Ultrasonic Sensors mounted perpendicular to each other on a 3D printed rig. These ultrasonic sensors use sound to determine the distance to objects directly in front of them. The way localisation works is that when the rig is placed in the tracking booth, each sensor has a flat surface directly in front of it, no matter where it is located within the booth. So by calculating how far the flat surface is from the sensor and inverting the equation, one can calculate how far the sensor is from the stationary flat surface. Each sensor-surface pair can be treated as one axis and by repeating this for the other two sensors, one can achieve full 3DOF tracking, provided the sensors stay aligned with the booth surfaces.

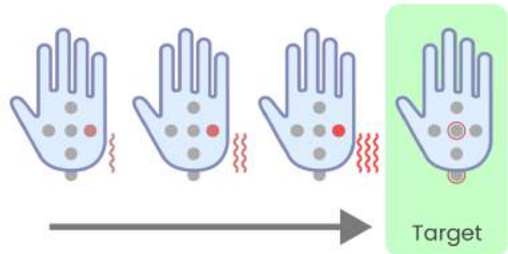
3.3 Interactions

3.3.1 Core Program

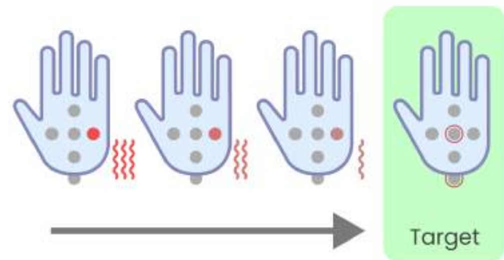
The Ultrasonic Sensors were being driven by the NewPing library for Arduino by Tim Eckel [12]. The minimum and maximum sensing distance of each sensor was set from 3cm to 100cm as it was observed to be less reliable at other distances. The NewPing requires a delay of at least 29ms between each sensor ping, so the refresh rate of the localisation system was inherently limited to ~34 times per second. The data from the sensors was used to calculate the distance vector to a given target and drive the vibration motors accordingly.

3.3.2 Metaphors

Given that there is a haptic system and one needs to communicate the distance and direction of the target to the user, there are multiple techniques of doing this. In order for this interaction to feel natural, however, one can borrow 'metaphors' from real world experiences and try to model interactions accordingly so that they feel intuitive.

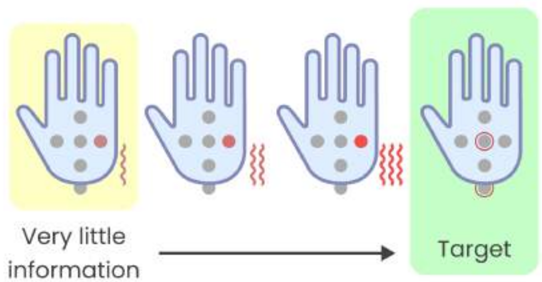


Magnet interaction metaphor



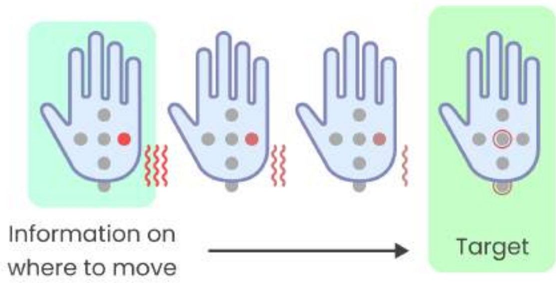
Elastic interaction metaphor

I designed two interaction metaphors - Magnet metaphor and Elastic metaphor. Magnet metaphor involves making the vibration stimulus stronger as one approaches the target whereas Elastic metaphor involves making the stimulus weaker. TactileGlove uses the Magnet metaphor and experiments with two sub-metaphors for spatial guidance - Push and Pull. Pull activates the vibration motors closer to the target whereas Push activates the vibration motors in the opposite direction as the target. Günther et al. [6] report that Pull was always rated easier and more intuitive than Push, so I will be using Pull for the interactions.



Argument against Magnet metaphor

The flaw I see in the Magnet metaphor is that if the hand is far away from the target, then there is weaker/slower stimulus and so nudging the user in the correct direction requires a large chunk of attention.



Argument in favour of Elastic metaphor

Hence, the Elastic metaphor starts out with a strong stimulus and gets weaker as the hand approaches the target. I believe this interaction will provide clear information right in the beginning, even if the hand is far from the target and ultimately increase confidence in moving the hand to the target direction.

3.3.3 Frequency vs Intensity Modulation

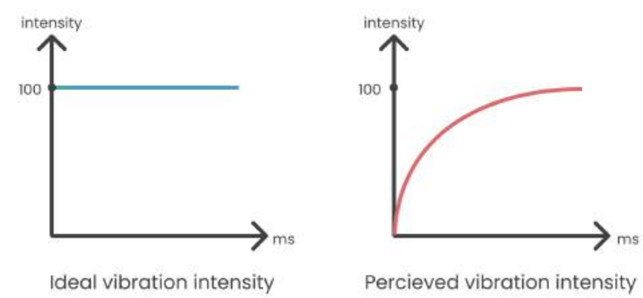


Figure 3.3.3.1 : Intensity falloff at lower actuation durations

The TactileGlove paper mentions that Gunther et al. used frequency modulation (varying the frequency to convey distance to target) to encode distance into vibration patterns. It is mentioned that the frequency had a range of 2hz (for a distance of 1 metre) to 20hz (for a distance of 10cm). This again is subject to my argument that when the hand is farther from the target then there is very little data about where and how far to go, and a frequency of 2hz would mean there is a vibration of 250ms followed by a gap of 250ms; that means there is a delay of at least 1.5 sec if the user takes 3 vibration clicks to perceive the target distance. This adds inherent delays to the potential speed of target acquisition. I tried increasing the frequency to counter this, but there was a steep falloff in the perceived vibration intensity below a vibration of ~100ms as shown in Figure 3.3.3.1.

Therefore, I decided to encode distance information into intensity. The intensity of vibration was directly proportional to the distance to the target; In case of the Elastic metaphor, the max vibration (voltage of ~5V) was assigned to the upper limit of the distance variable ie. 100cm while the minimum perceivable vibration (voltage of ~0.6V, decided internally based on trial and error) was assigned to the lower limit ie. 3cm. The mapping was inverted in case of the Magnet metaphor.

3.3.4 Confirmatory Clicks

When the user is within a 5cm radius of the target, the guidance is terminated, followed by a delay of 150ms and a ‘Full Click’ 150ms vibration at max intensity. There was also a ‘Half Click’ 100ms vibration at 60 percent intensity for indicating checkpoints or indicating reaching the target in only one axis in a multi DOF guidance mode. For recording how long the participant took to reach the target, a timer was added which started counting as soon as the guidance was activated and would stop after the Full Click after reaching the target.

3.3.5 Guidance Modes

X Guidance Mode places targets only on the X axis and activates only the left and right motors when required. The position of the hand in the Y or Z axes doesn’t affect the feedback. Similarly, the Y and Z Guidance Mode places targets only in the Y axis and Z axis respectively. In the XY Guidance Mode, the targets are placed in the X as well as Y axis and the left, right, up and down motors are activated simultaneously as required. Finally, in the XYZ Guidance Modes, targets are placed anywhere in the 3D space within the booth and any of the six motors are activated as required. X, Y and Z Guidance Modes provide 1DOF, the XY

Guidance Mode provides 2DOF whereas the XYZ Guidance Mode provides 3DOF.

3.4 Limitations

Since the intensity of vibration depends on the distance to the target and since the booth is only 59cm deep, the Z Guidance Mode only gets very weak vibrations in the Elastic metaphor no matter where the target is along the Z axis. Because the X and Y vibrations are relatively quite strong, this causes a discrepancy in perception and participants often neglect it.

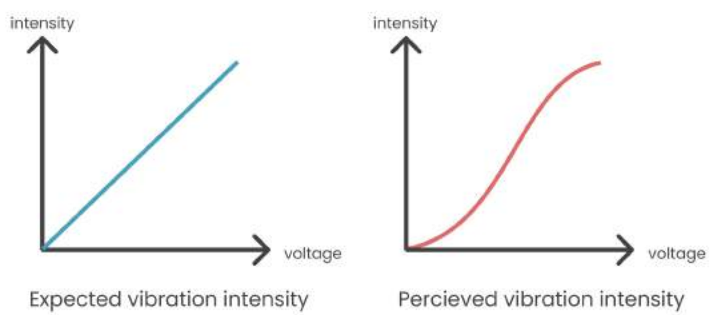


Figure 3.4.1 : Non-linear intensity curve against voltage

It was also observed that the perceived intensity of vibration does not scale linearly with voltage. As shown in Figure 3.4.1 (not to scale), until a voltage of about 0.6V, the vibration is perceived as null, then it climbs quickly and plateaus as the maximum vibration after about 4V. This non-linear scaling might have hindered the quality and accuracy of stimulus of the vibration motors.

I realised while conducting user tests that the booth was 118cm in width but the sensors could only detect a distance of upto 100cm and would let off a malfunctionary vibration when the glove went out of range if the participants moved too far to the left. Even though no target was that far off to the left, this would confuse the participants if they brought their hand in the left 18 cm and they would wrongly report this zone as the target.

In the TactileGlove paper, Mendes et al [11]. have used an external motion tracking system (OptiTrack) which allows them to track the hand that takes its orientation into account and calculates the distance accordingly. Since I did not have access to such a system, I built my own low-cost tracking system that is integrated into the Guiding Hand. The ultrasonic sensors do not take into account the orientation of the hand and the **readings are skewed if the sensors are not aligned with the booth at all times** and I had to instruct the participants to keep their hand aligned.

4. Pilot Testing

4.1 Procedure

Directional Perceivability Test

The goal of this test was to ascertain whether participants can tell each individual motor apart and associate it with the correct direction. Each direction was demonstrated to the participants by announcing the direction and vibrating the corresponding motor. Then the motors were randomly vibrated and participants were asked to name the motor that was being vibrated and the responses were recorded.

Vibration Intensity Sensitivity Threshold Test

The goal of this test was to find if participants could determine how weak or strong a given vibration was. For each round, a series of three 500ms vibrations was played - The strongest possible vibration was played first, followed by what we thought was the weakest perceivable vibration, followed by a vibration with an intensity that varied each round. The intensity was varied in detents of 10 percent so there were 11 levels of intensity, ranging from 0 to 10. After each round, the participants were asked to rate the intensity of the third vibration on a scale of 1 to 11. There were 11 rounds in total, with each 12 percent detent being played once; the participants were, however, told that the intensities can repeat and all detents weren't necessarily there.

1DOF vs 2DOF vs 3DOF Test

The goal of this experiment was to understand how separating degrees of freedom affects the time and accuracy of reaching targets. There was a demo for the participants to get used to the Guiding Hand. After they were comfortable with it, the tests were conducted. For the 1DOF test, participants were required to move their hand in the X direction until they felt a half confirmatory click, then move their hand in the Y direction until they felt another half confirmatory click, and finally move in the Z direction until they felt the full confirmatory click. The time taken from start to the ending click was noted. This was repeated for a total of 5 targets.

For the 2DOF test, participants were required to first move their hand in the XY plane, and were informed that they could move their hand diagonally. After the first half confirmatory click, they could move their hand in the Z direction. Finally, for the 3DOF test, participants were asked to simply reach for the target, without being constrained by any axis.

4.2 Learning

Metaphors

I had been using the Elastic metaphor for guidance, but this test pointed out a fatal flaw in the interaction - the rationale behind Elastic was that there is a lot of information in the form of stronger vibrations when you are starting the guidance, so you know exactly what direction to move your hand in. There are two problems with this - a) this is based on the assumption that the hand will start out far from the target and b) the vibrations will be very weak when the hand is close to the target and that consequently leads to lesser precision. This flaw was observable in the first three pilot tests. All three participants said it was hard to tell weak vibrations when the hand was close.

It was later revealed that there was a major bug in the code which wouldn't let the motors turn off at all, so for example, even if the hand goes from left of the target to the right of the target, the left would keep buzzing at whatever intensity it switched directions at, and that was causing all motors to be active and essentially breaking the guidance mode. This bug was fixed and there seemed to be immediate improvement in the clarity of stimulus. It had led me to think that the Elastic Metaphor wasn't working out, but after fixing the bug, the Magnet and Elastic metaphors seemed comparable.

Conclusively, the Elastic metaphor did not have an advantage over Magnet metaphor and thus I decided to treat Magnet vs. Elastic metaphors as an independent variable as well as gather qualitative user feedback.

Z Axis

Since the booth was shallower than it was taller and wider, and because of the absolute mapping of vibration intensity to the distance, the vibrations in the Z axis were next to none. From a practical standpoint, when the user is stationary and the target is within an arm's reach, Z axis guidance isn't really needed either in case of a vertical plane like a shelf; The user's hand can just be guided in the XY plane and instructed to reach forward from wherever their hand is in the Z axis. Hence I decided to eliminate the Z axis from the user testing entirely for the time being, and table it for future testing when I have better insights on the performance of the glove in just X and Y axes.

Confirmatory Clicks

The confirmatory clicks were doing their job as intended, but I learned that they were preventing me from getting better data on the system. In order to find how precise the interaction can be, it was necessary to remove the clicks so that only the interaction metaphor is guiding the participants to the target. The data on how far the Guiding Hand stopped from the intended target can then be used to make an informed decision on how big the target circle should be.

Miscellaneous Findings

Participants also found it difficult to keep their hand hovering all the time, so I had to include rest time after hitting each target and restart from roughly the centre of the booth. There were also other things which could not be changed, such as the up and back motor being very interchangeably confusing. This issue coupled with the faint vibration was causing all three participants to guess where the target would be by waving their hand around across the booth. This feedback may be used to improve the design of the apparatus for future experiments.

5. Evaluation

5.1 Information

5.1.1 Demographic

Fourteen participants between the ages of 20 and 23 were recruited for the study, out of which six were female. All the participants were right-handed.

5.1.2 Apparatus

The Guiding Hand prototype and tracking booth (as previously detailed) were used. The booth had a functional area of 100x89x59 cm. The Guiding hand used a HC-05 bluetooth module to communicate as a wireless serial converter using the UART protocol. The baud rate was set to 9600 as the HC-05 doesn’t support any higher. The effective refresh rate of the Guiding Hand was 10hz. A Motorola Moto X4 Android phone was used as a Bluetooth Serial Monitor (as a remote control and monitor) for the Arduino. The data was logged using Google Sheets on a Windows laptop.

5.1.3 Metrics

All distances were measured in centimetres and time was measured in seconds with an accuracy of two decimal places.

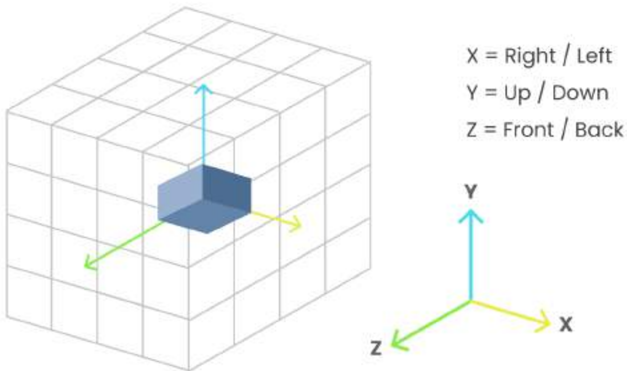


Figure 5.1.3.1 : Coordinate System

The coordinate system used in this paper is based on the distances from the left, top and back plane of the booth (X, Y and Z axes respectively). So for example, if the location is x20, y10, z15 then that means the glove is located 20cm from the right plane, 10cm from the top plane and 15cm from the back plane.

5.2 Procedure

Participants were assisted in wearing the Guiding Hand on their right hand and were explained its functioning. They were given a demo of the 1DOF guidance in the X axis using a demo invisible target at (30, 20). The X Guidance Mode was activated and they were encouraged to move their hand through and away from the target to get a feel for it. Since this was the X only Guidance Mode, their position in the Y axis didn't matter. They were then asked to hover their hand in roughly the centre of the booth and the first target was activated and the timer was started. The sensor reading in the starting point was recorded. Any confirmatory clicks were disabled for the test and the participants were instructed to verbally confirm when they thought they were at the target. After the participants let me know where they thought the target was, the guidance and timer was stopped and the distance reading from the sensor was taken. The time required to reach the target was also noted. Then the participants were asked to hover their hand in the centre again and the next target was loaded. This was done for a total of 5 targets located at (30, 10), (50, 50), (10, 20), (30, 60), and (30, 60) which were set in a random order for each participant.

The same process was repeated for the Y Guidance and XY Guidance Mode, for Pull and Inverse Pull Metaphors individually. Half the participants were given Pull first and the other half were given Inverse Pull first to factor in learning bias. After all 6 rounds were completed, a usability survey was conducted and participants were asked for feedback on the interactions.

5.3 Analysis

We conducted a two-way multivariate analysis (ANOVA) using repeated measures of the independent variables Metaphor (Magnet or Elastic) and Method/Axis (X, Y, XY Together and XY Separate) and Time as the dependent variable in one analysis and Distance Deviation in another.

The 1DOF Methods ie. X and Y were analysed separately from the 2DOF Methods ie. XY Together and XY Separate. We used a mean of means approach where we first calculated the mean deviation/time of all five targets per person and then did an analysis of variance of the $SD_{x,y}$ values of the means of each person's five attempts in that particular metaphor and method. This was repeated for all metaphor-method combinations. Then the dependent variables Time and Distance were plotted side by side.

We also did an analysis of variance with the Ease and Clarity ratings per metaphor-method combination. We used a mean of X and Y to calculate the Ease and Clarity rating of the XY Separate method. Ease and Clarity were then plotted by side for each method.

6. Results

6.1 1DOF - Distance and Time

In the Multivariate Test using a General Linear Model for variance analysis of 1DOF Distance Deviation, the Metaphor and Axis variables show an F-value of 0.480 and 0.520, and a P-value of 0.830 and 0.824. **That means neither the Metaphor not the Axis has any significant effect on the outcome**.

1DOF Distance Deviation

All units in centimetres

Metaphor	Axis	Mean	Std. Dev	95% CI	Target
Magnet	X	6.08	1.522	2.79 - 9.37	25.13
	Y	6.36	2.110	1.8 - 10.91	26.27
Elastic	X	5.69	.712	4.15 - 7.23	23.53
	Y	5.99	1.505	2.74 - 9.24	24.77

It is observed that the Elastic metaphor is marginally more accurate in both X and Y axes, as the mean distance deviation is lesser than the Magnet metaphor. The target circles for all 4 interactions lie between 23.5cm to 26.3cm.

1DOF Time

All units in seconds

Metaphor	Axis	Mean	Std. Dev	95% CI
Magnet	X	5.414	.546	4.23 - 6.59
	Y	4.505	.568	3.28 - 5.73
Elastic	X	6.119	.554	4.92 - 7.32
	Y	4.546	.442	3.59 - 5.5

The Y axis in both Magnet and Elastic metaphors was significantly faster (around 17% in Magnet and 25% in Elastic) than the X axis tests. The slowest was the guidance in the X axis using the Elastic metaphor at 6.1 sec.

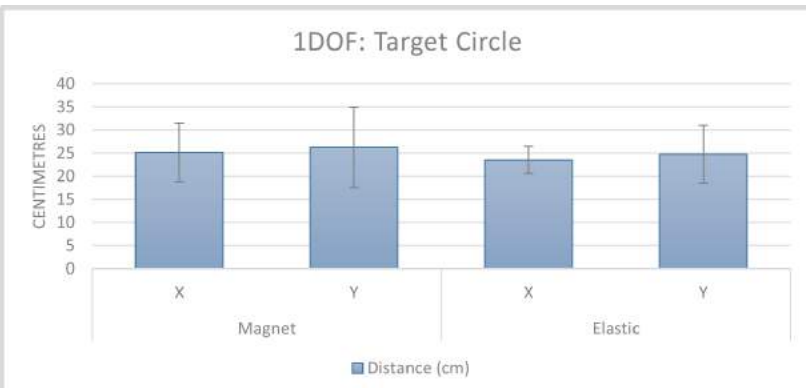


Figure 6.1.1 : 1DOF Target Circle Comparison

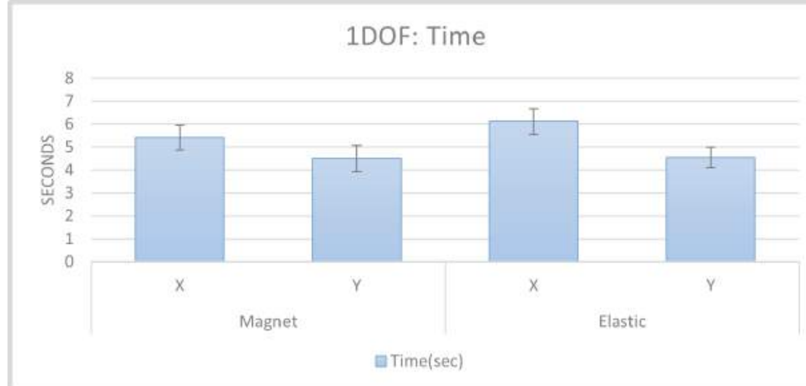


Figure 6.1.2 : 1DOF Time Analysis

Comparing the Distance Deviation and Time variables for each method, we see that guidance in the X axis using the Elastic metaphor achieves the greatest accuracy but also at the cost of spending the most time. Elastic Y and Magnet X methods achieve slightly lower but comparable accuracies, however Elastic Y does so considerably faster than Magnet X. Finally, Magnet Y achieves the fastest speed but also the lowest accuracy.

6.2 2DOF - Distance and Time

In the Multivariate Test using a General Linear Model for variance analysis of 2DOF Distance Deviation, the Method variable shows an F-value of 23.534 and a P-value of 0, while the Metaphor variable shows an F-value of 0.160 and a P-value of 0.695. That means (a) we have statistically significant results and there is enough interaction between methods to reject the null hypothesis of the ANOVA, and that **there are significant differences between XY Together and XY Separate** and (b) there isn't enough interaction between metaphors to qualify as statistically significant and the metaphor variable does not have a major effect on the outcome.

2DOF Distance Deviation

All units in centimetres

Metaphor	Method	Mean	Std. Dev	95% CI	Target
Magnet	XY Together	18.92	1.768	15.1 - 22.74	78.21
	XY Separate	9.84	2.402	4.65 - 15.02	40.65
Elastic	XY Together	18.20	2.004	13.87 - 22.53	75.23
	XY Separate	8.84	1.418	5.78 - 11.91	36.55

We can observe that the XY Separate method is significantly more accurate than XY Together, with roughly two times the relative accuracy. The Elastic metaphor is slightly more accurate than the Magnet metaphor in both methods. The target circle for the XY Separate methods will be 40cm whereas that for the XY Together method will be 78cm.

2DOF Time

All units in seconds

2DOF Time

All units in seconds

Metaphor	Method	Mean	Std. Dev	95% CI
Magnet	XY Together	12.363	1.328	9.49 - 15.23
	XY Separate	9.920	.962	7.84 - 12
Elastic	XY Together	8.478	.675	7.02 - 9.94
	XY Separate	10.665	.846	8.84 - 12.49

It is observable that in the Magnet metaphor, XY Separate was about 20% faster than XY Together whereas in the Elastic metaphor, XY Together was about 20% faster than XY Separate. The fastest was XY Together in Elastic while the slowest was XY Together in Magnet.

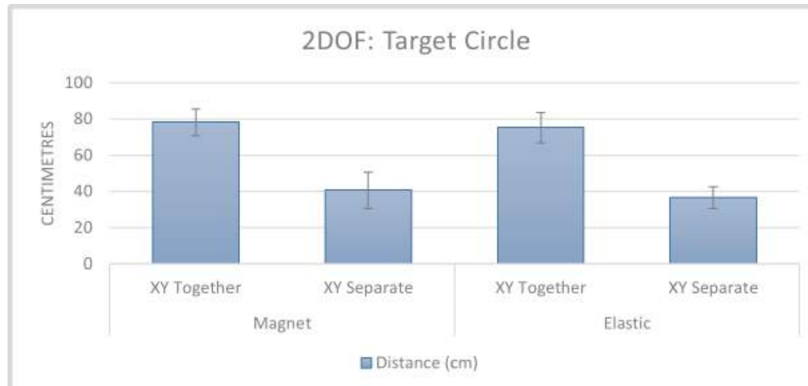


Figure 6.2.1 : 2DOF Target Circle Comparison

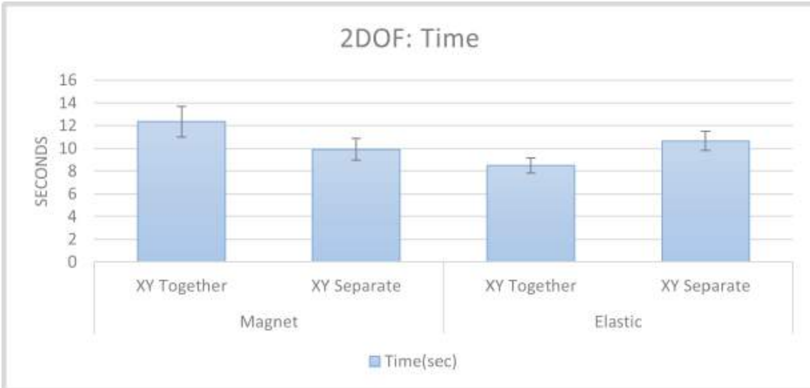


Figure 6.2.2 : 2DOF Time Analysis

Comparing the Distance Deviation and Time variables for each method, we see that XY Separate using Elastic achieves the greatest accuracy and XY Separate using Magnet achieves slightly lower accuracy but is slightly faster. XY Together using either metaphor performs poorly in terms of accuracy when compared to XY Separate, but XY Together using Elastic achieves the fastest time and also outperforms XY Together using Magnet in terms of both Distance Deviation and Time.

6.3 Ease and Clarity

Ease

Metaphor	Method	Mean	Std. Dev	95% CI
Magnet	X	4.214	.187	3.81 - 4.62
	Y	4.143	.177	3.76 - 4.53
	XY Together	2.929	.165	2.57 - 3.28
	XY Separate	4.179	.179	3.79 - 4.56
Elastic	X	3.643	.289	3.02 - 4.27
	Y	3.786	.261	3.22 - 4.35
	XY Together	3.071	.339	2.34 - 3.8
	XY Separate	3.714	.261	3.15 - 4.28

It is observed that X axis using Magnet is rated the easiest, followed by Y using Magnet. Consequently, XY Separate using Magnet earns the second highest rating as it is a mean of the X and Y ratings. The lowest rating, however, is also for Magnet metaphor, earned by the XY Together method.

Clarity

Metaphor	Method	Mean	Std. Dev	95% CI
Magnet	X	4.286	.244	3.76 - 4.81
	Y	4.071	.245	3.54 - 4.6
	XY Together	2.643	.289	2.02 - 3.27
	XY Separate	4.179	.232	3.68 - 4.68
Elastic	X	3.500	.359	2.72 - 4.28
	Y	3.214	.334	2.49 - 3.94
	XY Together	2.857	.312	2.18 - 3.53
	XY Separate	3.357	.333	2.64 - 4.08

The Clarity rating trends almost perfectly correspond to the Ease rating trends. Using Magnet for X and Y is a full point higher than for Elastic. The lowest rating for clarity as well, however, is earned by the XY together method.

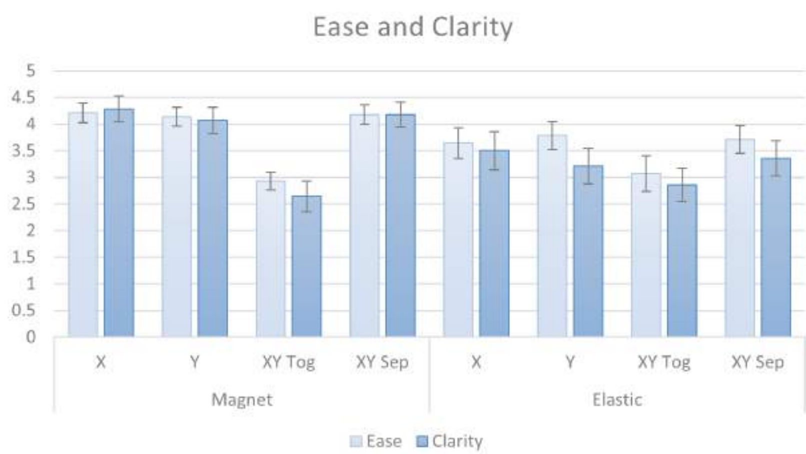


Figure 6.3.1 : Ease vs Clarity

6.4 Qualitative Feedback

Overall, the consensus was split between Magnet and Elastic. Out of 14 participants, 4 preferred Magnet, 3 preferred Elastic, 5 were neutral about both, and 2 preferred Magnet for 1DOF (X and Y) and Elastic for 2DOF (XY).

Magnet

4 participants said Magnet was intuitive and strong vibrations were easier to understand. Over 6 participants said they were mostly looking for the crossover point[1] in Magnet, and a few said they weren't paying attention to the directionality, and as a result, over 5 people said the 2DOF guidance (XY Together) was difficult because they couldn't tell which axis was crossing over. One participant explained that even in XY Together, he was trying to do X first and then Y; after finding the crossover point in X he would move his hand along the Y axis, but in that process he would lose the X location and the X axis would cross over again and lead him to think he has reached the target. 5 participants said Magnet was difficult to understand because one can't tell what the strongest vibration is until you hit the target and feel the crossover, whereas in Elastic one can definitely tell when the vibration goes null. Over 4 participants said the vibration feedback in XY was overwhelming as there were strong vibrations from both axes near the target. Two participants said they couldn't tell X and Y apart during the XY Guidance mode using Magnet.

[1] The crossover point in the Magnet metaphor refers to the feeling of motors switching as the hand crosses the target in a given axis. For example, as the hand is approaching the target from the left, the right motor will vibrate at its strongest until the hand crosses over; the

moment the hand crosses the target, the right motor will turn off and the left motor will turn on at its strongest.

Elastic

4 participants said Elastic was easy and intuitive because you just have to let it go ‘silent’. Over 4 participants said that Elastic is easier in XY. 2 participants said that Elastic led to a greater ‘range’ of possible targets, so the scope for error was higher. Over 3 participants said it was difficult for them to understand weak vibrations. 2 participants Elastic was initially counterintuitive, but they got used to it in a few tries. One participant mentioned that she generally associates vibration feedback with error, so that made the Elastic metaphor feel more correct. Over 2 participants said even after reaching the target, they would still move their hand around to cross check if the vibration is getting stronger or weaker. One participant said she had to intentionally go in the wrong direction to figure out the right direction.

Haptics

Most participants said XY was much harder than just X or Y. Some participants said it was the easiest to tell when the vibration crossed over between up and down motors whereas Y was harder than X for a few others. Over 5 participants mentioned that they are confusing the up motor with either the right, left or back motor frequently. About 5 participants said it was easier to tell strong vibrations but not weak vibrations, whereas 4 participants said constant strong vibrations were overwhelming. One participant said if each motor was connected to a different ‘bone’ then telling them apart would be easier. Another feedback that a participant gave was that there could be two ‘families’ of motors, one to guide their hand to a general location and then the other could take over to guide their hand more precisely.

7. Discussion

7. 1 Results

Firstly, I believe we have a clear answer to one part of our research question 'How do degrees of freedom and interaction metaphors affect haptic spatial guidance?' - A clear distinction in speed and accuracy is observable between by separating degrees of freedom in 2 axes.

The target circle of 1DOF + 1DOF (XY Separate) is ~36cm while that of 2DOF (XY Together) is ~77cm. Comparing XY Separate and XY Together, this experiment shows that the separation of degrees of freedom gives us two times as much accuracy in two dimensional haptic spatial guidance tasks. Even in the ease and clarity survey, XY Separate was rated notably higher than XY Together in either metaphor.

The result for speed is interesting - XY Separate using the Magnet metaphor is faster than XY together but slower using the Elastic metaphor. In any case, the difference in speed (time taken) is close to 0.5sec between XY Separate using Magnet (9.92 sec) and XY Together using Elastic (8.49 sec) which isn't a lot in a practical sense. Thus, **one can gain significantly higher accuracy by separating the degrees of freedom and trading off potential speed in haptic spatial guidance tasks**.

Target Circle

The minimum target circle size that we achieved was ~23cm, which is quite a lot higher than what we had initially hoped for (~10cm, roughly the width of a palm). However, since we were dealing with a prototype that was more often than not, unreliable, 10% - 15% of the endpoints were outliers and results of potential malfunction. We haven't removed those outliers before doing the variance analysis as there is no way for us to confidently know which outlier was a result of prototype malfunction but given that participants were frequently hitting 2DOF targets even to an accuracy of <5cm, I am confident that with a better prototype and localisation system, we can achieve a <10cm target circle.

Given that the target circle for 2DOF using XY Separate is around 36cm, that ties well with a UWB beacon system that has an accuracy of upto 30cm. In a real world scenario, that would mean the guidance system would work well enough to locate a large container on a shelf, find a pillow on a couch or differentiate between pots of plants.

Magnet Metaphor

The main feedback I received for the Magnet metaphor was that (a) it was hard to tell what the strongest vibration was and (b) the strong vibration was overwhelming in XY Together. For the strongest vibration problem, we need to do a specialised study on human perception of vibration intensity to understand how to deal with this problem. Since we've concluded that XY Separate is a better guidance method than XY Together, we can dismiss the need to proceed further with XY Together.

Elastic Metaphor

The feedback for the Elastic metaphor was that the scope for deviation was a lot because weak vibrations are difficult to perceive. To solve this problem, we can add confirmatory clicks at the target to eliminate the need for trial and error to confirm the location of this target. As previously mentioned, the clicks were intentionally removed to study the metaphor in isolation, but adding them back might alleviate the ambiguity and improve the speed of the Elastic metaphor.

Ease and Clarity Rating

Comparing the two metaphors, we see no significant overall differences between the two. The Magnet metaphor was rated as easier and clearer than Elastic in 1DOF, but was rated harder and less distinct than Elastic in 2DOF. This may be because strong vibration is easy to comprehend when the user knows what direction to move in; as soon as there is a crossover, the user can tell that they are at the target whereas for the Elastic metaphor in 1DOF, even when the user thinks they've reached the target, they verify it by moving in the opposite direction and expecting the vibration to get stronger on the opposite side. Conversely, Elastic is easier in 2DOF because it conveys what direction the user should move in right in the beginning through strong vibrations; after that the user simply needs to move their hand until the vibration goes null. In Magnet the user tries to first find the first crossover point, then maintain their hand at that coordinate while they find the second crossover point. Even near the target, since all vibrations are strong, they have trouble telling which crossover point was hit.

Learning Effects

The ease and clarity rating for X and Y in Magnet may be higher because a user can hit the target even after completely neglecting the intensity modulation - they simply need to move in the direction of the motor until they hit the crossover point. It may be due to the learning effect from the X and Y Magnet tests that confused the user in the XY Together test. Since the user might have gotten used to ignoring the amplitude and directionality near the target, they found it harder and overwhelming for two axes in XY Together. Conversely, for X and Y in Elastic, the user had to pay attention to the intensity and find the point of weakest vibration even in 1 axis, which led to the XY Together rating being higher and closer to the 1DOF methods. The targets were invisible, but the booth was still visible to the participants, and this may have played a role since a fully blind person might not have the frame of reference of the testing booth. This is something that needs to be tested further.

Degrees of Freedom

3DOF or Z Guidance in 2DOF may not even be needed in a practical scenario. For example in case of a vertical guidance plane, the user can be informed of the guidance being set to vertical and then their hand can be guided in 2DOF. After they hit the target, they can simply be asked to reach forward. In case of a horizontal guidance plane like a drawer or a table, the same can be done ending with asking the user to reach straight down. In practical cases, it may even be the user that defines the guidance plane and hence some 1DOF and 2DOF configurations can be eliminated because they aren’t intuitive and others can be contextualised.

7. 2 Recommendations

Localisation

The localisation method I have used here is a very primitive one and was chosen because of financial constraints, albeit it's novel and integrated into the glove. If possible, a proper optical motion tracking system should be used for better tracking and eliminating the need for a tracking booth. An IMU (inertial measurement unit) can be added to counter and mitigate some effects of the sensor alignment getting skewed.

In a practical sense, there are two ways to implement this - if the tracking area is comparable to the test booth that we used, then LiDAR sensors can be used instead of the Ultrasonic Sensors used in the Guiding Hand to improve accuracy and increase range. If the tracking area is comparable to a room or larger, then an array of 4 or more UWB beacons can be used. This system can provide indoor navigation as well as precise spatial guidance upto a precision of 30cm.

Prototype

The biggest problem I realised was that the vibration motor matrix was a fixed size whereas participants had variable hand sizes and shapes, so each person might have been getting stimulus on a different part of their hand. This may be improved by making the system clip-on or strap-on - modular - so that it can adapt to a variety of hand sizes. The layout can be tweaked so that the left and right motors are actually on the sides of the palm instead of the dorsum, the back motor could be on the wrist and the front motor could be near the knuckles or the middle finger for greater differentiation.

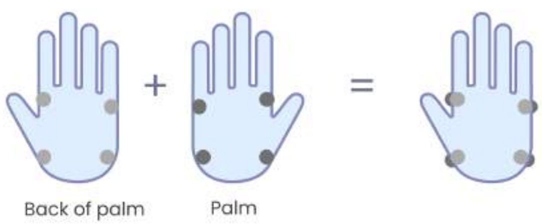


Figure 7.2.1 : Alternate Layout Concept

There is also potential for a different layout entirely so that there are 8 motors in total, each at the vertex of an imaginary cuboid. To communicate a certain direction, all four motors corresponding to the face of the cuboid can be activated. The benefit to this layout is that this can 'wrap around' the hand or arm. Since the entire right side or left side or top portion of the hand will be vibrating, it might lead to better directional understanding.

Guidance

Both metaphors have received feedback that the vibration is either too strong or too weak; this may be solved by mapping the vibration intensity to a nonlinear curve such that the transition from weak to strong and vice versa *feels* linear and consistent to the user. We can also experiment with changing the mapping of vibration intensity from absolute to relative, such that no matter how far the target is, the guidance always starts with max vibration and ends with null vibration. In a room-sized space, the system will first have to guide the user to within an arm's reach of the target, and will require an interface to select targets or a prioritisation system. Metaphors might have an influence too in case of multiple targets.

8. Conclusion

This experiment is an attempt to understand human capability by testing how we process different levels of vibrotactile stimuli. By constructing a series of tests that require participants to hit invisible targets in space, the location of which is communicated to them only through vibrotactile means, we varied the degrees of freedom given to them and studied their performance. Results showed that separating degrees of freedom makes a haptic spatial guidance system significantly more accurate, at the cost of barely any speed. Our prototype could achieve a target circle of as low as 36cm in 2 degrees of freedom, which might prove adequate for spatial guidance for a range of day to day tasks. We tested different guiding metaphors and found that people adapt differently to each metaphor and that there are no significant differences in time or accuracy between either of the two metaphors.

This project started out as a means to assist visually impaired persons to locate targets in space, but this system may also be applied in an extended reality environment. It can even find applications in remote collaboration tasks like Matsuda A. et al. [10] have demonstrated using HapticPointer, which is another vibrotactile spatial guidance device. Overall, we have only touched the tip of the iceberg and as we develop better technologies, there is a lot to be explored in the field of haptic guidance and navigation.

9. References

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