RecHap: An Interactive Recommender System For Navigating Large Dataset of Mid-Air Haptic Designs

by

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

Waterloo, Ontario, Canada, 2022

Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Andy Wu and William Frier co-authored the introduction and background section of this thesis as part of the work in progress of our submission for IEEE Transactions on Haptics. William Frier contributed significantly to the development of data augmentation script. Andy Wu contributed to the development of the RecHap application and dataset creation.

This thesis also contains mission statements and discussions that Prof. Oliver Schneider have helped create.

Abstract

Designing haptics is a difficult task especially when the user attempts to design a sensation from scratch for a novel experience. In the fields of visual and audio design, designers often use large example libraries for inspiration, supported by intelligent systems like recommender systems. In this thesis, we contribute a corpus of 5327 mid-air haptic designs (two orders of magnitude larger than existing haptic libraries), and use it to explore a new approach for both novices and experienced hapticians to use these examples in mid-air haptic design. RecHap design tool utilises an autoencoder-based recommendation system that suggests preexisting examples by sampling various regions of the encoded latent space. The tool also provides a graphical user interface for designers to visualize the sensation in 3D view, select previous designs, and bookmark favourites. According to the study conducted, it was evident that the tool allowed designers to quickly sketch ideas and experience them right away. Design suggestions encouraged collaboration, expression, exploration, and enjoyment, which improved creativity.

Acknowledgements

Firstly, I would first to thank my supervisor, Prof. Oliver Schneider, who gave me the opportunity to develop the RecHap design tool and learn the potential and intricacy of mid-air haptic technology. I value his knowledge and kindness very much.

I would like to thank Andy Wu and William Frier for their continued support throughout my research. They have helped create the version of the RecHap design tool that exists today.

I would like to thank the undergraduate research assistants Chris Wang, Clement Wu, Karthik Prasad of HX Lab who supported this project in various forms.

I would like to also thank my friends, Marco Ledesma, Bibhushan Raj, Sahand Ajami, Ahmed Anwar and Kaushal Kiran for their support.

Lastly, I would like to thank my family for their continued support.

My masters was a challenging yet enjoyable period of my life, but with the guidance and support from my supervisor and everyone around me, I was able to continue with my research.

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Chapter 1

Introduction

Visual and auditory sensations are crucial components of immersive experiences, however, they lack the ability to physically ground a user in extended realities. The haptic feedback modalities span a wide range of techniques, from force feedback to mid-air sensations, and have been increasingly used to improve the experiences people may have in a virtual environment, such as the metaverse [14]. In this ever-growing field of innovative technologies, haptics will play an integral part of Virutal Reality (VR). Both novice designers and experienced hapticians find it challenging to produce stimuli that are representative of real-world interactions. Previous research has shown that examples are crucial in the process of developing new designs [6]. The design process typically begins with a basic idea of what the designer wants to convey. By reflecting on comparable earlier seen designs, the designer is able to improve and expand on their original design idea. Existing design libraries can provide support for finding curated samples that serve to drive this design process. Hapticians currently have several libraries to draw from, such as Vibviz [38] from the Macaron: Haptic Design with Examples [35]. Even so, these libraries house at most 150 example designs — as libraries inevitably grow larger, how do designers find the right example and create the preferred design?

Most people today experience haptics through their phones, game controllers or smartwatches. However, due to technical advances, modern devices are able to provide more intricate and complicated touch sensations such as letting us feel shapes and textures. These sensations are termed as “mid-air haptics” and provide a rich way of interacting with devices. However, it can be challenging for designers to incorporate mid-air haptic sensations into their designs. Our research will help novice hapticians who are not familiar with the process of creating haptic sensations by assisting the design process.

We present a new approach for both novice and experienced hapticians to design for mid-air haptics. The RecHap design tool is used to aid in the development of novel designs by using existing examples as a template for inspiration, and allows users to find their desired design by interacting with recommendations. RecHap design tool consists of an interface for working with examples, and an algorithm for selecting which examples to display in the recommended list. The recommender system produces suggestions by extracting from the latent space, also referred to as the embedding space. This latent space holds an embedding of a set of items within a manifold in which items with higher resemblance are positioned closer to one another. In order to study navigation of large design dataset, we created a collection of mid-air haptic designs with the help of different individuals. This was necessary to provide a convenient space for finding example templates to inspire new designs. To better understand the role that examples can play in the design of mid-air haptic sensations, we evaluated the RecHap haptic design tool with a user study. The objective of this study was to evaluate and quantify the efficacy of the RecHap design tool as a creativity support tool. The study results demonstrated how the RecHap tool effectively guided the designers through the extensive gallery of designs and enabled them to creatively design their own mid-air haptic sensations. We also understood that recommending existing designs improved creativity by supporting collaboration, expressiveness, exploration and enjoyment.

1.1 Research Questions

A design tool created for relatively new haptic feedback technology raises several research questions. In this thesis, I investigate the following:

1. How does example based design benefit mid-air haptic designers?
2. How can a design dataset for a new domain such as mid-air haptics be created?
3. How can hapticians navigate a very large dataset of mid-air haptic sensations?

1.2 Contributions

The contributions of the research presented in this thesis are:

- A large data set of mid-air haptic designs that can be used by designers and researchers.
- A software tool to allow convenient exploration of the dataset along with a editor tool to sketch new designs rapidly.
- Insights into how mid-air haptic designers value design suggestions and example based design.

1.3 Thesis Organization

I organized this thesis into seven chapters following the introduction.

1. In Chapter 2, I present a literature review with relevant background in the fields of haptics, example based design and content based information retrieval.
2. In Chapter 3, I present the methods used for the mid-air haptic design dataset creation and the challenges faced.
3. In Chapter 4, I introduce the RecHap design tool and discuss the implementation details of the tool.
4. In Chapter 5, I present the study design, method, and the results of the study conducted.
5. In Chapter 6, I discuss the implications of the results.
6. In Chapter 7, finally, I provide a general conclusion of my thesis and future work.

Chapter 2

Background

Innovative and sophisticated technologies are emerging as Virutal Reality (VR) develops at a rapid pace to make virtual surroundings more like the real world. Haptics technology is one such example. In addition to visual and aural awareness, VR haptics technology enables users to physically experience virtual surroundings through touch. In the past, haptics technology has taken the form of external objects, such as gloves, shoes, controllers, joysticks, etc., via which users have experienced vibrational feedback. These attempt to give the hand or other portions of the body physical sensations that are reflective of what individuals experience in everyday life. However, haptics technology is developing beyond simply vibrating objects [15]. A significant amount of study has been done recently on the topic of including mid-air haptic input in virtual reality experiences [16].

2.1 Designing with Mid-Air Haptics

The realisation of ultrasonic mid-air haptics makes use of a number of physical phenomena and control techniques. These fundamental ideas must be understood by people working on this technology's research and engineering, and even haptic designers without a technical background should be aware of them. Mid-air haptics uses phased arrays of ultrasound speakers to project high acoustic pressure fields onto the users' hands with a high spatial and temporal resolution [16]. In this section, the following four principles of ultrasound mid-air haptics are introduced.

1. Acoustic radiation pressure: The acoustic radiation pressure, a nonlinear process brought on by high-intensity sound waves, is what causes the force to act on the skin.

The relationship between the acoustic energy density in front of the skin surface and the acoustic radiation pressure is well established[32] [18].

2. Phased array focusing: Usually, an array of hundreds of ultrasonic transducers is used to deliver mid-air haptics. The notion of superposition allows the phases of the transducers to be correctly adjusted to produce focal points, despite the fact that each transducer is unable to emit an intense ultrasonic pulse [32] [18].

3. Vibrotactile stimulation: Due to the skin's underlying mechanoreceptors, human tactile perception is more sensitive to vibrations than to static pressure. To provide a vibrotactile sensation in ultrasonic mid-air haptics, the focal point is often amplitude-modulated (AM). It is possible to build various tactile sensations and experiences using different modulation techniques [18].

4. Audible sound radiation: The amplitude modulation of ultrasound waves can also cause unwanted audible sounds to be created. This is another nonlinear effect of high-intensity sound waves. The rapid movement of a focal point is another origin of audible sound, as the discontinuity of phase changes leads to fluctuations in the amplitude of the ultrasound [18].

Mid-air haptic devices generate tactile point, in free space, from a distance, using an array of ultrasound speakers. Such tactile point is represented with 4 parameters: 3 spatial coordinate and 1 intensity value, which can be updated 40,000 times a second. With such degree of freedom the design of mid-air haptic sensations is endless. The 4 parameters can be modified over time to introduce changes in sensations such as motion, 3D rotation, position and size. The device shown in Figure 2.1 was used in this project to carry out the study session. The STRATOS Explore Development Kit consists of a hardware platform (256-transducer array board, control board, and frame structure)

2.2 Example-Based Design

Previous works outside of haptics have indicated that examples are often referenced as a form of design inspiration when an individual begins the creative process of developing new designs [33]. The medium of web design is such an example, in which studies by Ritchie et al. [33] and Lee et al. [26] showcased how modifying existing examples lead to more diverse outcomes and allowed individuals to explore a wider domain of styles. In the case of graphical and web-based design, examples, otherwise referred to as design galleries

Figure 2.1: UltraHaptics STRATOS Explore Development Kit [41].

[33, 26, 28], are an intuitive part of the creative process but does this apply for other non-haptic contexts as well? Are examples a critical component of innovation and does it help drive design?

Desai et al. [11] leverages the idea of examples in Geppetto as a gallary of expressive robot motions for which designers can interact with to model desired behaviours for expressive robotics. Li et al. [27] proposes the use of example poses of digital faces to aid animators in creating more realistic model expressions. To further support the benefits of non-haptics and example-based design, graphic design [6], music [36], texture synthesis [45] and even software development [44] are shown to similarly benefit from external influences and inspiration.

With this many examples of example-based design in non-haptics, surely the same can be done in haptics? Yet, advances in haptics and particularly the design of stimuli are still relatively unknown. This is in part owed to the lack of high-quality haptic data available to use as a foundation during the design process. Our focus is to identify the value example-based design brings in inspiring new creations for haptic stimuli.

2.3 Design Tools for Haptics

Design tools in the haptic space have become more common place as the field of Human-Computer Interaction (HCI) grows. From early work like the Hapticon Editor [13] to the Tactile Paintbrush [29], Force Jacket [9], posVibEditor [34] and more, we see that support has similarly grown for different haptic modalities over the years. Even so, do better design tools for more modalities really forward the field of haptics?

In contrast, Machine Learning (ML) has dominated the field of research during these past two decades making strides in medicine, education, music, art, language, etc. These innovations are only possible as a result of sizable datasets like ImageNet [10], MNIST [25], CIFAR-10 [22], etc. which provide the ground work for further developments. As such, one cannot help but note that ML offers similar advances in the field of haptics, limited only by the lack of meaningful data. Predecessors to our work include tools like Vizbiz [38], Macaron [35], Feel Effects [19], Penn Haptic Texture Toolkit [8], and Proton [5] which all pave a strong foundation for ML in haptics. Vizbiz, an interactive tool for navigating a library of designs houses 120 vibrations that Seifi et al. [37] describe using *facets* (a framework for interpreting haptic sensations) that are "crosslinked in people's minds" [37]. Similarly, Macaron, a web-based editor for building examples directly into existing designs present a "design gallary for vibrotactile sensations" [35] and Feel Effects, introduces a collection of "40 effect [that] covers a wide range of situations" [19]. Moreover, Culbertson et al. [8] and their work on the Penn Haptic Texture Toolkit present a library of 100 haptic textures and their follow up work by Burka et al. [5], Proton Pack, introduces a device to collect surface data from "sensory modalities [that] include RGBD vision, egomotion, contact force, and contact vibration" [5] to ultimately construct datasets with different modalities. Even with all these tools and existing libraries we are still limited when it comes to tasks in ML. "A dumb algorithm with lots and lots of data beats a clever one with modest amounts of it" [12] and so it would seem that methods of procuring large samples of data is in the near future of haptics.

Our work purposes an introductory step in addressing the lack of data, ML and generative design in haptics. We provide a set of design tools to assist with haptic creation through a large corpus of more than 5000 haptic stimuli samples for designers to interact with as examples, and to support research into haptic design using ML techniques.

2.4 Content-Based Search

Large amounts of data require an intuitive way for users to query relevant results in order for such data to be meaningful. However, the ability to navigate data becomes increasingly more difficult as the quantity increases. It can be difficult to discover the best and most appropriate results when simply skimming through a dataset of say more than 5,000 samples in size. A common approach in image querying referred is content-based image retrieval (CBIR) which extracts low-level features (e.g. color, shape, texture, etc.) from an images to match them to other images containing similar characteristics [24]. The semantic-based approach, in which the image is represented through metadata (such as keywords), and the content-based approach (CIBR), in which the image content is represented by means of low-level features, are two traditional methods for resolving the image query problem. In the semantic-based technique, a query image and some text or keywords that correspond to the keywords already present in the archive are entered. The appropriate image is then created based on how closely related the keywords are. [24]. Low-level features from the input image are extracted in CIBR, including colour, shape, texture, and others. Following that, similar photographs in the database are retrieved using the features. These methods have been shown to be effective in many applications [39]. However, while assigning keywords to photos in very big databases and extracting characteristics from images can be expensive and time-consuming processes as well as being prone to error [2]. Due to these issues, it is now necessary to create models that can do image query tasks without requiring manual feature extraction or picture annotation. The principle component analysis (PCA), which decreases the dimensionality of images in the database, is one of the most logical solutions to this issue. Image search is then performed in the lower dimensional space and similar images are retrieved [40]. Although PCA has shown promising in the task of image search, neural networks are capable of outperforming PCAs in many applications [30]. In our work, we create a neural network based system in which sample haptic designs are encoded into a set of embeddings (low-level features) and used to search for the user's desired design characteristics.

Chapter 3

Creation of a large mid-air haptic design dataset

To create an accessible and convenient space for finding example templates to inspire new designs, we must first build a collection of haptic designs with the help of different individuals. The following steps outline the order of action items involved in this design dataset creation process.

1. Firstly, we started creating designs by implementing parametric equations in Python. This, however, limited creativity and was difficult.
2. Then, using PyQt5, we created the RecHap Draw tool to enable quick design sketching and rendering.
3. As inspiration for their designs, internal researchers were given categories like Virtual Reality (VR) games, VR widgets, automotive, emotion, education, shape, and social connection. But the designs made using these design prompts lacked originality and variety.
4. Then, in order to support the task description, we created detailed design prompts with specific tasks, along with images and videos. This resulted in creative and varied designs.
5. We recruited outside designers, such as undergraduate research assistants and members of The Games Institute, to contribute to the dataset in order to increase the designs' diversity and creativity.

6. To help our designers add more diversity to the dataset, we introduced a new sketching tool created by Ultraleap called HapE.
7. All the designs created by designers were further augmented using a Python script developed with the support of UltraLeap developers which generated 20 different variations for each design.

3.1 Design Tools

Figure 3.1: RecHap Draw Tool used by contributors to create designs for the dataset.

To facilitate the manual design data creation process, we developed an editor tool called the RecHap Draw Tool shown in Figure 3.1 that applies path interpolation to help map free form 2D canvas drawings to interactive haptic sensations. This more intuitive design tool helped designers understand their abstract designs and helped us gather a diverse range of design samples for each category. RecHap Draw Tool's ability to draw designs freely, much like Microsoft Paint software, is flexible, but it has limitations when it comes to precision when trying to produce precise and accurate stimuli. Thus, contributors were also given the chance to work with another tool designed by UltraLeap's internal research team (HapE) shown in Figure 3.2. Users can start their creative processes with the HapE tool's starting designs, which include Hand Scan, Button, Click, and others. The ability to alter particular settings to change the positioning, intensity, and brush preset of each design gives users more granular control over the stimuli generated. Each contribution is saved using one of the aforementioned tools and added to our corpus of manually created mid-haptic designs. Each design is saved in the format "designname-category-author." In total, there were 8 contributors who used the RecHap Draw Tool and 6 who used the HapE tool. Quality was not a selection criterion in order to reflect the variety of content on the mid-air haptic designs.

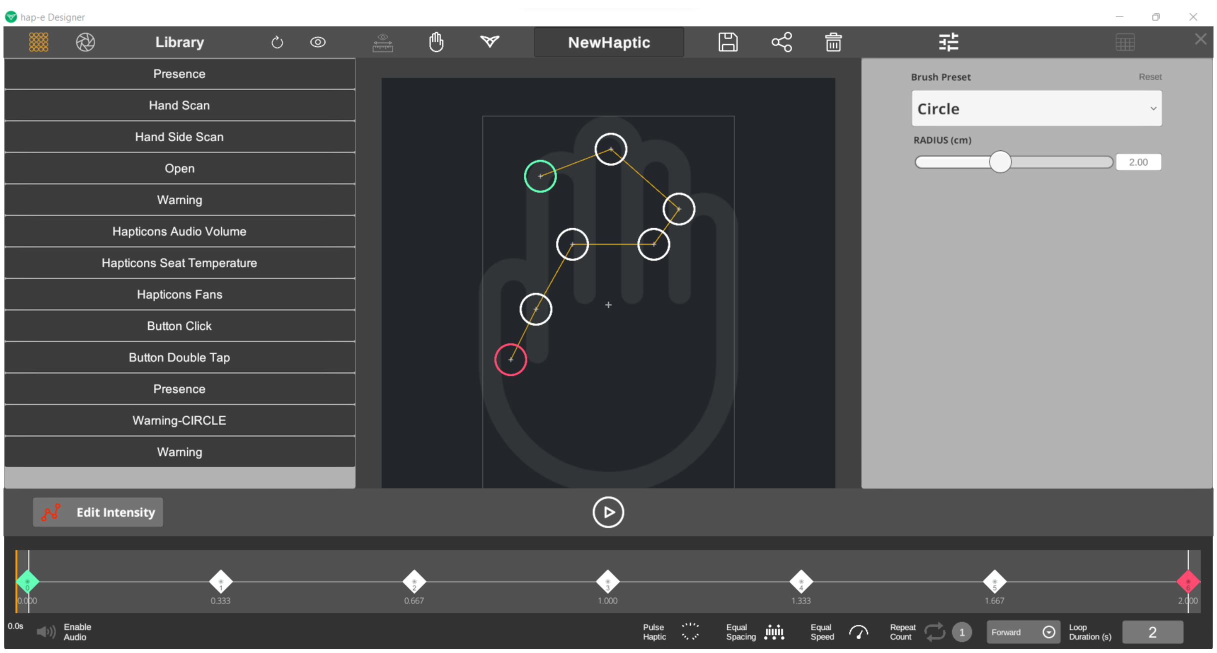


Figure 3.2: HapE Tool used by contributors to create designs for the dataset.

3.2 Design Prompts

We developed a set of prompts by covering scenarios of typical application categories, including Virtual Reality (VR) games, VR widgets, automotive, emotion, education, shape, and social connection, as the first step in the process of creating our dataset. These categories were chosen to explore various modalities as well as current research areas of interest to Ultraleap and the larger Human Computer Interaction and Haptic community. For instance, datasets pertaining to VR gaming, a trend that has grown in popularity over the years, may have an impact.

These categories were provided as design prompts for which the internal research team and student research assistants will produce mid-air haptic sensations. After some initial attempts, we felt that prompts weren't effective as the designs created lacked creativity and diversity. Therefore, we developed detailed list of prompts shown below in addition to category based prompts. It is important to note that contributors to the dataset were also given the freedom to find inspiration outside of prompts to incorporate into the dataset.

3.2.1 Final list of prompts

The final design prompts used for the dataset creation process are listed in this section. The designers were free to choose any of the available design tasks. These prompts were all chosen by searching the internet, including on sites like UltraLeap and Youtube.

1. **Prompt 1: Butterfly sensation**
   Design a mid-air haptic feedback to emulate the sensation of a butterfly sitting on your finger.

Figure 3.3: Prompt 1 - Butterfly sensation [31].

2. **Prompt 2: Mid-air haptic feedback for magnetic effect around your hands**
   Design a mid-air haptic feedback to emulate the sensation of magnetic field emitted from your hands and is able to attract objects.

Figure 3.4: Prompt 2 - Mid-air haptic feedback for magnetic effect around your hands [31].

3. **Prompt 3: Mid-air haptic feedback for holding a skull or another object from this video**
   Design a mid-air haptic feedback to emulate the sensation of holding a skull or any other object.

4. **Prompt 4: Mid-air haptic feedback for car dashboard control in Virtual Reality**
   Design a mid-air haptic feedback to emulate the sensation Start /Stop car button - Use index finger to start stop.

5. **Prompt 5: Mid-air haptic feedback for car window control in Virtual Reality**
   Design a mid-air haptic feedback to emulate the sensation car window control - Use index finger to press.

6. **Prompt 6: Mid-air haptic feedback for shifting car gear in Virtual Reality**
   Design a mid-air haptic feedback to emulate the sensation of shifting gear in a car.

Figure 3.5: Prompt 3 - Mid-air haptic feedback for holding a skull or another object from this video [31].

Figure 3.6: Prompt 4 - Mid-air haptic feedback for car dashboard control in Virtual Reality [3].

Figure 3.7: Prompt 5 - Mid-air haptic feedback for car window control in Virtual Reality [3].

Figure 3.8: Prompt 6 - Mid-air haptic feedback for shifting car gear in Virtual Reality [3].

7. **Prompt 7: Mid-air haptic feedback for playing chess in Virtual Reality**
   Design a mid-air haptic feedback to emulate the sensation of picking chess pieces.

Figure 3.9: Prompt 7 - Mid-air haptic feedback for playing chess in Virtual Reality [4].

8. **Prompt 8: Mid-air haptic feedback for Kiosk interactions**
   Design a mid-air haptic feedback to emulate the sensation of switching between products, swiping or exploring a map.

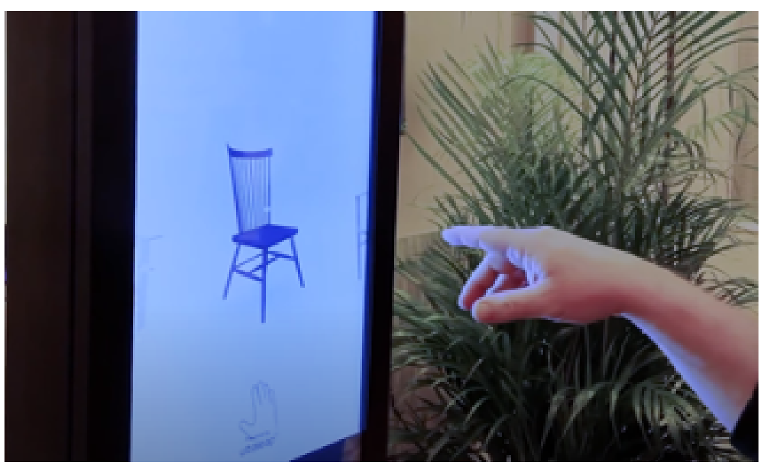


Figure 3.10: Prompt 8 - Mid-air haptic feedback for Kiosk interactions [42].

9. **Prompt 9: Mid-air haptic feedback for virtual keyboard**
   Design a mid-air haptic feedback to emulate the sensation of press virtual keyboard key.

Figure 3.11: Prompt 9 - Mid-air haptic feedback for virtual keyboard [43].

The designer begins creating new design by first deciding on a haptic prompt, for example, a task in the VR games category such as picking a skull. The designer then gets access to the designer tool in which they continue to re-draw stimuli until they feel they have encompassed the prompt with their design. Each time a design is drawn the user is able to interact with the mid-air haptic device to feel the sensations that they have created. This creative process is meant to capture the experiences of each designer and their inspirations. For example, a user with extensive experience with VR technology would be able to easily identify with the haptic prompt of VR widgets and create designs that are longer and dull. Similarly, a user with no experience with VR may believe that it is faster, sharper and is more representative. By providing an abstract tool with freedom to experiment we are able to create a more diverse dataset.

3.3 Data Augmentation

To introduce variability and to increase the total number of designs, we applied transformation to the sample stimuli produced through the freeform designer tool such as HapE and RecHap draw tool. Our primary motivator for increasing variability in our dataset is to present a varied and helpful starting template for future users to design on. In the case of machine learning (ML), current methods are notorious for requiring large amounts of quality data to train on and another desire for a diverse dataset is to promote further contributions to the space of generative haptics by making this dataset valuable and accessible. These transformations included scaling and applying different brush textures to the original designs.

In mid-air haptic sensation rendering, 2D tactile shapes can be displayed in two different ways: statically or dynamically. In the first scenario, a shape (such as a circle, square, or triangle) is displayed in midair with a stationary outline, whereas in the second scenario, the shape is traced by a slowly moving pressure point. This moving pressure point could also be a stationary outline of shape such as a circle, line, etc. All the designs created by the designers using the RecHap Draw Tool were based on the first scenario. Therefore, applying the second scenario to already existing designs along with other transformations such as size scaling, rotation and duration scaling was the logical and efficient approach to diversify the existing dataset. The following points summarizes the steps involved in the data augmentation process which was implemented as a Python script with support of Ultraleap developers:

1. **Read existing design path:** Read the x, y values of existing design which were designed using tools such as Ultraleap's HapE and RecHap draw tool.
2. **Normalization:** Normalize the modified path to fit between 8x8 cm, to match the palm.
3. **Random scaling:** The size is then scaled by selecting a scale factor at random between 0.2 and 1.
4. **Random rotation:** By selecting a random rotation factor between 0 and 2π, the path is rotated.
5. **Random duration scaling:** Then, we scale the sensation's duration by randomly picking a scale factor between 0.5 and 2 seconds.

6. **Implementation of the Dynamic Tactile Pointer:** Randomly apply a brush to the path.
   - A random brush is chosen from the Circle or Line options.
   - If circle is selected, a circle radius between 5 and 15 mm is selected at random. If line is selected, a line length between 5mm and 30mm is selected at random.
   - The X-path and Y-path of the transformed design is changed to become the focal point's path, which is made up of the brush path and pattern path.
7. **Saving:** Then the design is saved as JSON with a naming convention of design_name_var#.
8. **Repeat 20x:** Steps 2 to 6 was repeated 20 times to create 20 different variations for each original design.

The designs created using the HapE tool already has a brush applied by the designer, therefore, Step 6 was skipped for those designs; however, other transformations were applied. Figures 3.12, 3.13, 3.14, 3.15, and 3.16 are results of the augmentation process applied to designs such as Shovel, Skull1, WindowDown, ZiggyFence and Triangle.

Shovel and Skull1 was designed using the HapE tool for which circle brush has been already applied. Therefore, variations were generated by randomly transforming to diverse set of sizes, rotations and duration. This was observed both visually and via physical sensations. Similarly, WindowDown has line brush applied and the resulting variations were diverse enough to feel different to the original design. ZiggyFence was designed using the RecHap draw tool, therefore, a random brush (as discussed in Step 7) was applied for each variation. This resulted in a wide range of visual variations, and the physical sensations were very different from the original. Extreme variations were useful in diversifying the dataset even though they visually appeared to be noise because they produced feelings that were very different from those produced by existing designs. Similarly, Triangle in Figure 3.16 was also designed using the RecHap Draw Tool. The variations generated for Triangle were diverse visually and the sensations felt distinct as well.

Several HX lab participants experienced the generated variations to determine whether the augmentation introduced variability. Verbal comments from the participants did validate our augmentation process and the resulting designs.

3.4 Summary

A total of 5327 designs covering different categories were produced with the help of various designers and then by the augmentation process. Our database of mid-air haptic designs is now very large. How can haptic designers use this dataset to their advantage? We will talk about the RecHap Design Tool, which offers an interactive interface to this database of designs, in the following chapter.

(a) Original design (b) Var 0 (c) Var 1 (d) Var 2

(e) Var 3 (f) Var 4 (g) Var 5 (h) Var 6

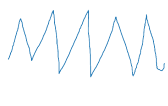
(i) Var 7 (j) Var 8 (k) Var 9 (l) Var 10

(m) Var 11 (n) Var 12 (o) Var 13 (p) var 14

(q) Var 15 (r) Var 16 (s) Var 17 (t) Var 18

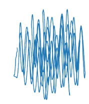
(u) Var 19

Figure 3.12: Variations of SHOVEL created by augmentation.



(a) Original design

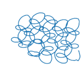
(b) Var 0



(c) Var 1

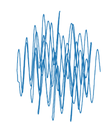
(d) Var 2

(e) Var 3



(f) Var 4

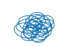
(g) Var 5



(h) Var 6

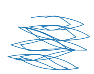
(i) Var 7

(j) Var 8



(k) Var 9

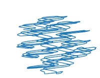
(l) Var 10



(m) Var 11

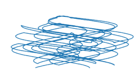
(n) Var 12

(o) Var 13



(p) var 14

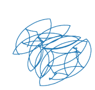
(q) Var 15



(r) Var 16

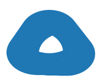
(s) Var 17

(t) Var 18



(u) Var 19

Figure 3.13: Variations of ZIGGY FENCE created by augmentation.



(a) Original design

(b) Var 0

(c) Var 1

(d) Var 2

(e) Var 3

(f) Var 4

(g) Var 5

(h) Var 6

(i) Var 7

(j) Var 8

(k) Var 9

(l) Var 10

(m) Var 11

(n) Var 12

(o) Var 13

(p) var 14

(q) Var 15

(r) Var 16

(s) Var 17

(t) Var 18

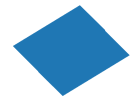
(u) Var 19

Figure 3.14: Variations of SKULL1 created by augmentation.

(a) Original design

(b) Var 0

(c) Var 1



(d) Var 2

(e) Var 3

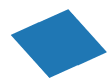
(f) Var 4

(g) Var 5

(h) Var 6

(i) Var 7

(j) Var 8



(k) Var 9

(l) Var 10

(m) Var 11

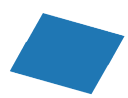
(n) Var 12

(o) Var 13

(p) var 14

(q) Var 15

(r) Var 16



(s) Var 17

(t) Var 18

(u) Var 19

Figure 3.15: Variations of WindowDown created by augmentation.

(a) Original design (b) Var 0 (c) Var 1 (d) Var 2

(e) Var 3 (f) Var 4 (g) Var 5 (h) Var 6

(i) Var 7 (j) Var 8 (k) Var 9 (l) Var 10

(m) Var 11 (n) Var 12 (o) Var 13 (p) var 14

(q) Var 15 (r) Var 16 (s) Var 17 (t) Var 18

(u) Var 19

Figure 3.16: Variations of TRIANGLE created by augmentation.

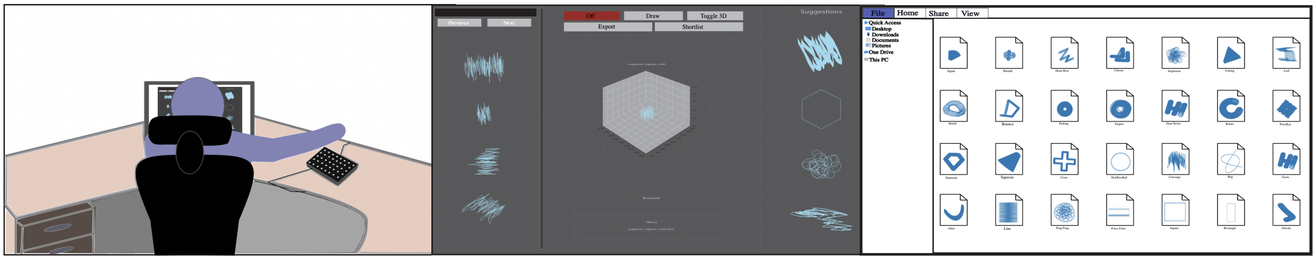
Chapter 4

The RecHap Design Tool

The purpose of the RecHap Design Tool is to enable more people to produce better mid-air haptic sensations and support diverse applications like media design, education, science outreach, and community storytelling. Figure 4.1 shows the different elements involved in the process of designing mid-air haptic sensations using the RecHap Design Tool. The following is the user story for the RecHap Design Tool:

- Tom is a VR designer. StarX is a virtual reality game that Tom is creating. The game features a variety of effects, including collisions, laser, fire, and explosions.
- Tom wants to implement laser sensation on UltraHaptics device but does not know how, so he experiments example designs in RecHap Design Tool. He explores the gallery and finds an example from the suggestions and wants to modify the design.
- Tom modifies the example design using the tool's editor called the RecHap Draw Tool to sketch his own design based on the example he found. He likes the modified version so exports the design to be used in his VR project.

This tool is a standalone application that works with Ultraleap's ultrasonic mid-air haptic devices. The application consists of a built-in graphical editor which comprises an editing pane, an examples gallery, a preview pane, a suggestion list and other organising features. The user can begin with a complete example by selecting one from the design gallery. This design gallery displays designs from the dataset developed with assistance from the UWaterloo HX lab, which is covered in greater detail in Chapter 3. The preview pane enables users to visually observe an example in greater detail.



(a) Designer interacting with the RecHap tool and device.

(b) The RecHap Interface to explore and create designs.

(c) Mid-air haptic dataset created by UW Haptic lab.

Figure 4.1: Overview of the elements involved in Mid-air haptic design process using the RecHap Design Tool.

4.1 Graphical User Interface

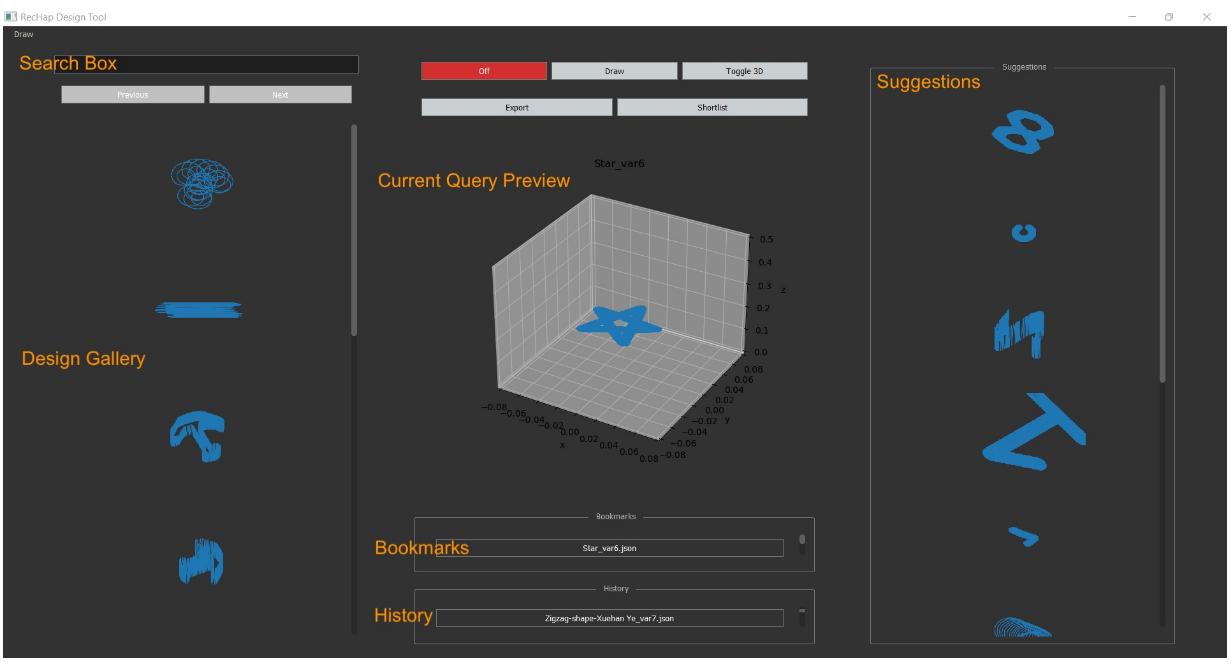


Figure 4.2: The GUI of the RecHap Design Tool.

The RecHap Design Tool interface (Figure 4.2), comprises five components:

- `Design Gallery`: Presents search results as interactive thumbnails.

- `Search box`: Supports query by text.
- `Current query preview`: Displays the selected design.
- `Suggestion`: Displays a list of recommended designs.
- `History`: Keeps track of last 10 previewed designs.
- `RecHap Draw Tool`: Allows designers to sketch their own design and render in on the device. This was discussed in previous chapter.

4.1.1 Design Gallery, Search Results and Preview

The tool initially presents 10 designs in the design gallery section (Figure 4.3) which are randomly picked from the design dataset. This is to provide inspiration for designers as soon as they open the application. If designers wish to explore the gallery, they could scroll or click "Next" or "Previous" to browse through the designs in the dataset. This section also displays the list of designs resulting from a text search query.

The results are presented as interactive thumbnails which can be clicked to preview the designs in expanded 2-dimensional or 3-dimensional view (Figure 4.4) while rendering the design in Ultrahaptics Stratos Explore device.

4.1.2 Search

With the search feature, designers can search using keyword queries. First, the designer can search for designs that contain a particular text string. As they type a keyword, related keywords are suggested beneath the search box, as seen in Figure 4.5. Depending on the availability of designs with names that are close to the keyword, designers will see suggestions. Any keyword from the list of suggested terms can be clicked by the designer in order to display the search's results right away.

4.1.3 Bookmarks and History

The 'Bookmarks' section allows designers to shortlist the designs they'd like to review later. Bookmarks persist when a user resets the current query; this allows the user to maintain a collection of interesting designs across several search sessions. The 'History'

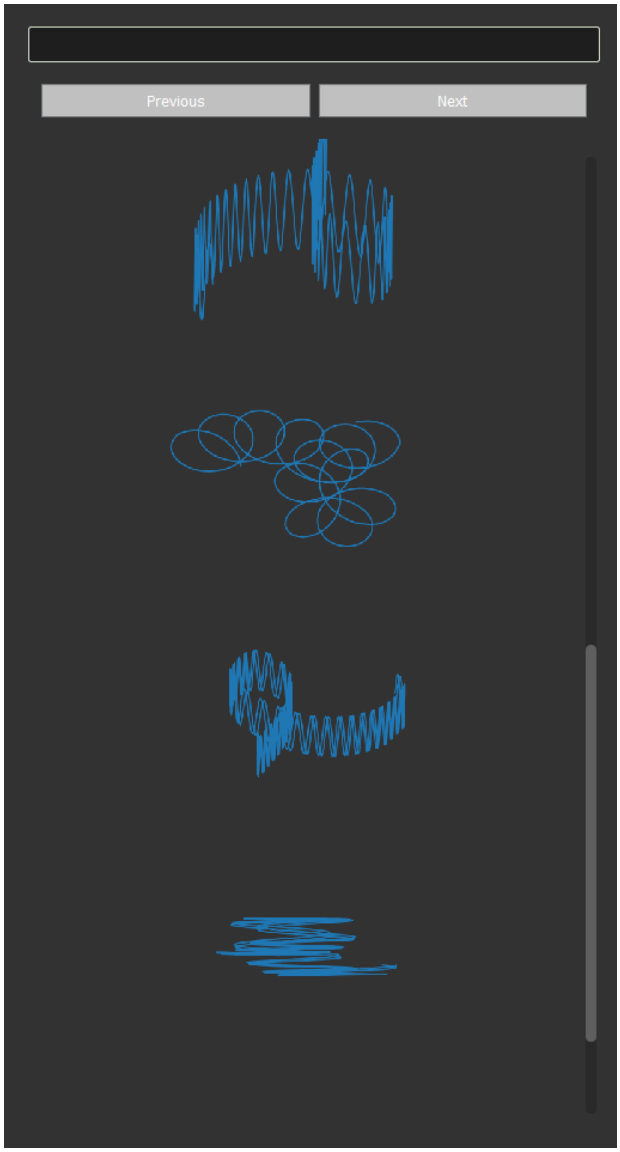


Figure 4.3: Design gallery.

section allows designers to review the designs they have already tested. History persist when a user resets the current query; this allows the user to maintain a collection of past visited designs during the design session.

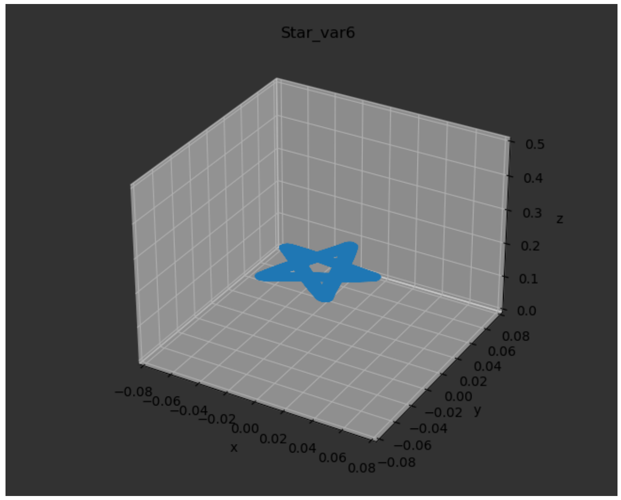


Figure 4.4: Current Query: Preview.

4.1.4 Suggestions

When a design listed in the gallery section is clicked, a list of 10 designs will be suggested in the Suggestions section as shown in Figure 4.7. The suggested designs are based on a combination of similarity to the clicked design and randomness. This implementation details and the algorithm associated with this feature is further discussed in the following section.

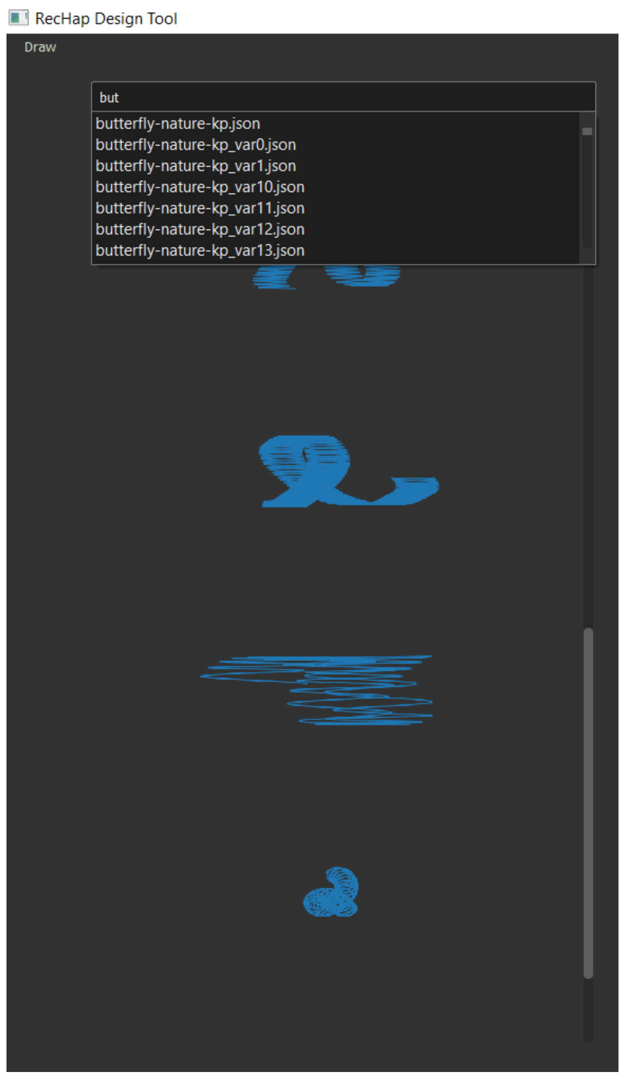


Figure 4.5: Searching keywords.

Figure 4.6: Bookmarks and history.

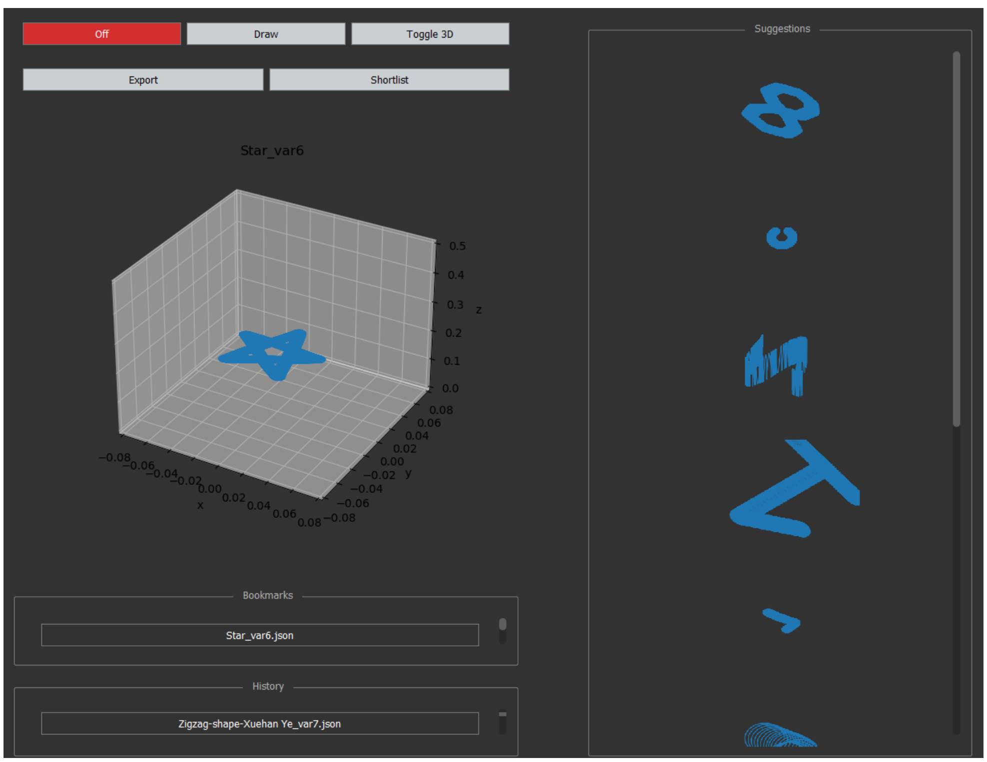


Figure 4.7: Design suggestions.

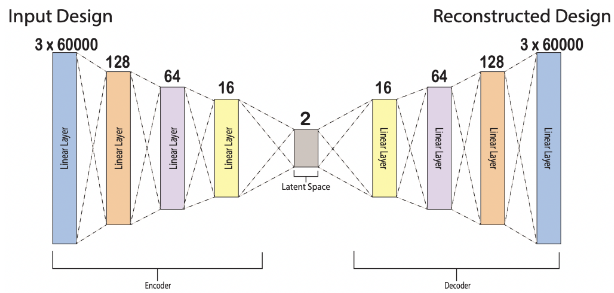


Figure 4.8: The auto-encoder architecture for the recommender system.

4.2 Suggestions: The Recommender System

4.2.1 Auto-Encoder Model

To support interactive search, the RecHap Design Tool pre-computes features for every design in the dataset. RecHap focuses on the coordinates and timepoint features that describe the shape of the design over the period of time. We used technique similar to content-based image retrieval (CBIR) to answer design queries [1].

The method to do design query consisted of developing an autoencoder (AE) to reconstruct the input designs and using the embedded space generated by the AE to find design close to a query design. A simple AE with 11 fully connected linear layers was developed. To train the AE, the designs from the created dataset (from previous chapter) was used and further divided into training and testing sets with a ratio of 4 to 1. Each design is a matrix with a dimension of 3x60000. To measure the difference between the original designs (as the input of the network) and the reconstructed designs (as the network output), two candidates were binary cross entropy loss (BCE) and mean squared error (MSE), as suggested by related work. Tests were run using the bundle of MSE as the output layer's loss function, Tanh as its activation function, BCE as its loss function, and Sigmoid as its activation function. The optimizer employed stochastic gradient descent with a learning rate of 0.1 and momentum of 0.9. It was determined that the second bundle (BCE and Sigmoid) produces higher quality reconstructions with a fixed number of epochs, resulting in a computationally efficient model, hence it was chosen for the final model.

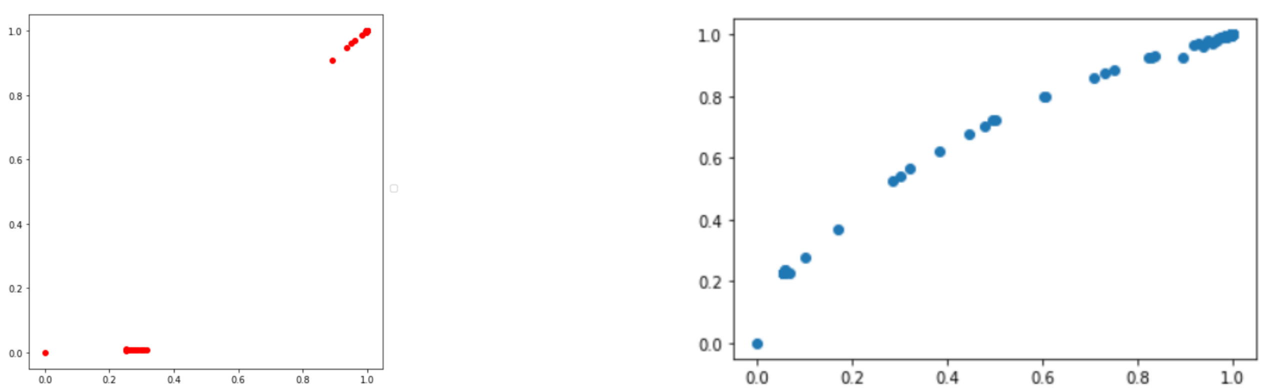
$$d(x_1, x_2) = \sum_{i=1}^{n} (x_{1i} + x_{2i})^2 \tag{4.1}$$

$$similarity(x_1, x_2) = \frac{x_1 \cdot x_2}{(||x_1||_2||x_2||_2)} \tag{4.2}$$

To find designs similar to a query design, the encoder part of the model was used to generate the embedded representation of all the designs in the dataset, as well as the query design. In the next step, the distance between the query design and all the designs in the dataset was calculated in the embedded space. A design was considered 'similar' to the query design if the two are 'close' in the embedded space. To measure how close the designs are to one another, two methods were employed: Euclidean distance and cosine similarity. The Euclidean distance, and the cosine similarity between two $(1 \times n)$ vectors of x_1 and x_2 calculated based on equations 4.1 and 4.2.

When designers click on a design, the tool will suggest a set of designs that are similar to the particular focus design and designs which are not very similar. Our intuition is that showing similar examples will be useful when looking for subtle design variations, and that a variety of examples will be more valuable when looking for broad inspiration. To create a subset of similar items, RecHap uses the Nearest Neighbour approach to calculate the distance of designs from the specified focus, sorts them in ascending order, and selects the first 4 items. In addition to this, the tool also recommends 6 more designs randomly selected from the larger neighborhood (closest 100) of the target design.

4.2.2 Latent Space Exploration with 95 and 300 designs



(a) Latent Space of 95 designs.

(b) Latent Space of 300 designs.

Figure 4.9: Latent spaces became dispersed as the dataset grew in size.

Figure 4.9a shows the latent space of the model trained with 90 designs. The latent space distribution is concentrated to few locations such as (0,0), (0.3,0) and (1.0,1.0). This shows that the variability in the design data is limited, hence, the auto-encoder model groups the designs more closely.

Figure 4.9b shows the latent space of the model trained with 300 designs and it can be observed that distribution of designs are less concentrated however it seems to spread our 1 dimensional line. This shows the variability in the design data has improved, however, it is not diverse enough to utilize the 2-dimensional or the 4 quadrant design space.

4.2.3 Latent Space Exploration with 5327 designs

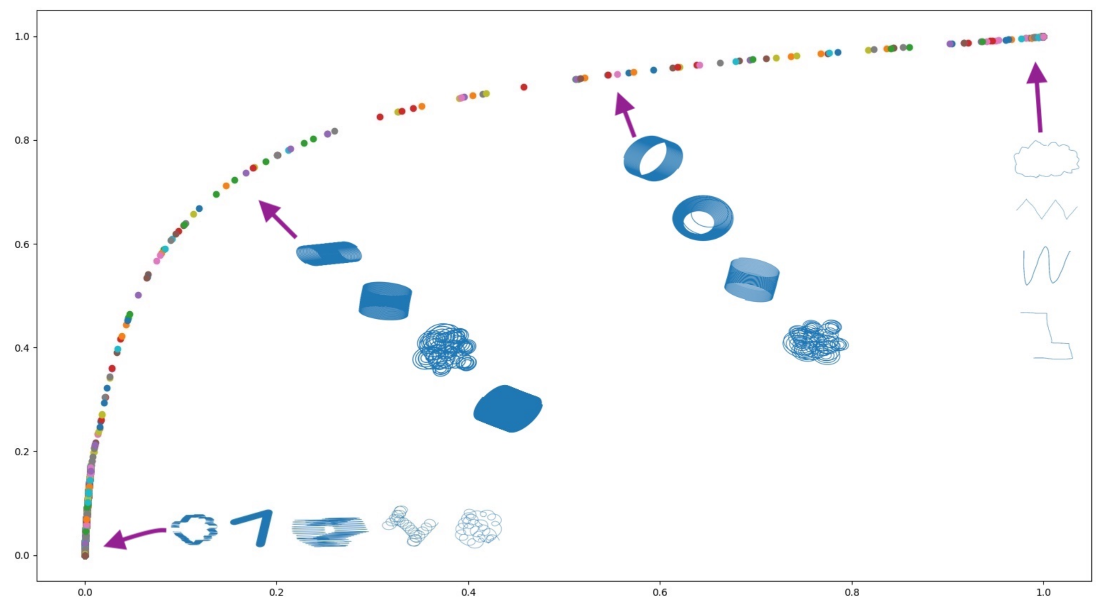
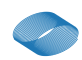


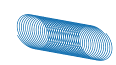
Figure 4.10: Latent space of 5327 designs with images of designs shown in 4 different regions.

In order to demonstrate how designs are grouped together in the latent space, figure 4.10 shows the latent space from the inference of 5327 designs. Visuals of a few chosen designs from 4 different regions of the latent space are also shown in figure 4.10. It's very clear that designs are spread out and spans across the entire latent space. The designs seem to sit on curved line utilizing the 2-dimensional of the latent space. The bottom right corner doesn't seem to have any designs which could also mean that there is still room for diversification of the design gallery. But overall, the gallery seems to consist of designs that are variable enough to span over a 2-dimensional latent space. Figure 4.11 shows few design in the region of when x is equal to 0.6. Visually, it has similarities in shape and size. Designs in Figure 4.14 has similarity as they all seem to be "simple" or basic designs and they are all grouped at top right corner of the latent space. Designs that are grouped close to the bottom left corner (Figure 4.13) of the latent space seem to have sharp turn and dense control points. Shapes in the region of inflection region (Figure 4.12) seems to have similarities to that of shapes in middle (Figure 4.11). These two regions are closer to each other in terms of euclidean distance compared to the other regions mentioned above.

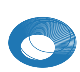
(a) Explosion3.



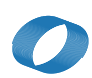
(b) Knock over chess king.



(c) Pickup Chess Piece.



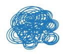
(d) startcarbutton.



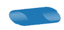
(e) Start car button 2.

(f) Start car button thumb.

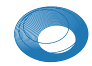
Figure 4.11: Examples of designs positioned in the middle (x = 0.6) of the latent space.



(a) Explosion 3 Var 13.



(b) Knock over chess king.



(c) Pickup Chess Piece.

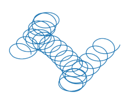
(d) Start car button Var 14.

(e) Start car button 2.

(f) Start car button thumb.

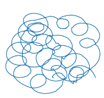
Figure 4.12: Examples of designs positioned in the inflection region (x = 0.2) of the latent space.

(a) Seven - 7th variation.



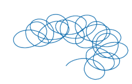
(b) I - 7th variation.

(c) Bush - 17th variation.



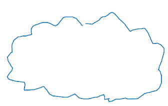
(d) Justice League Flash - 14th variation.

(e) Shirt 5th variation.

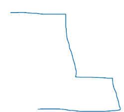


(f) Wave - 18th Variation.

Figure 4.13: Examples of designs positioned in the starting region (x = 0.0) of the latent space.

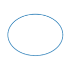


(a) Cloud.

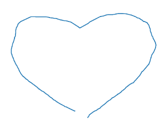


(b) Step sensation.

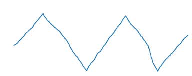
(c) W.



(d) Dial.



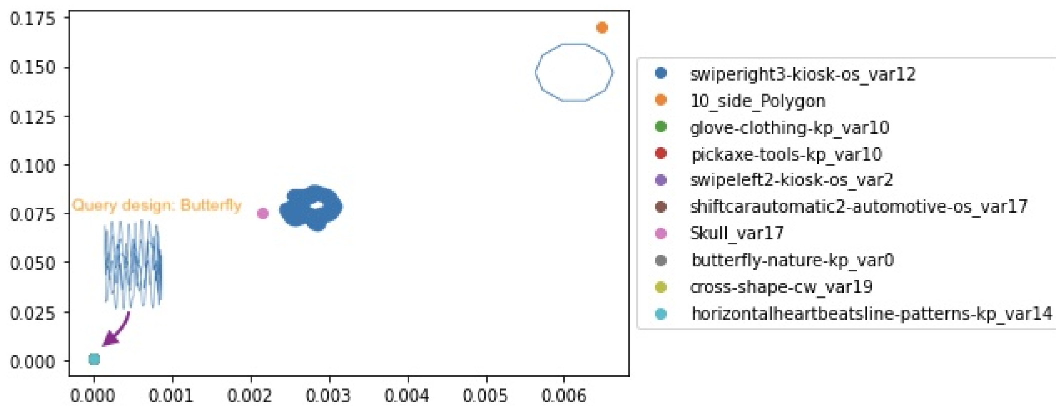
(e) Heart Card.



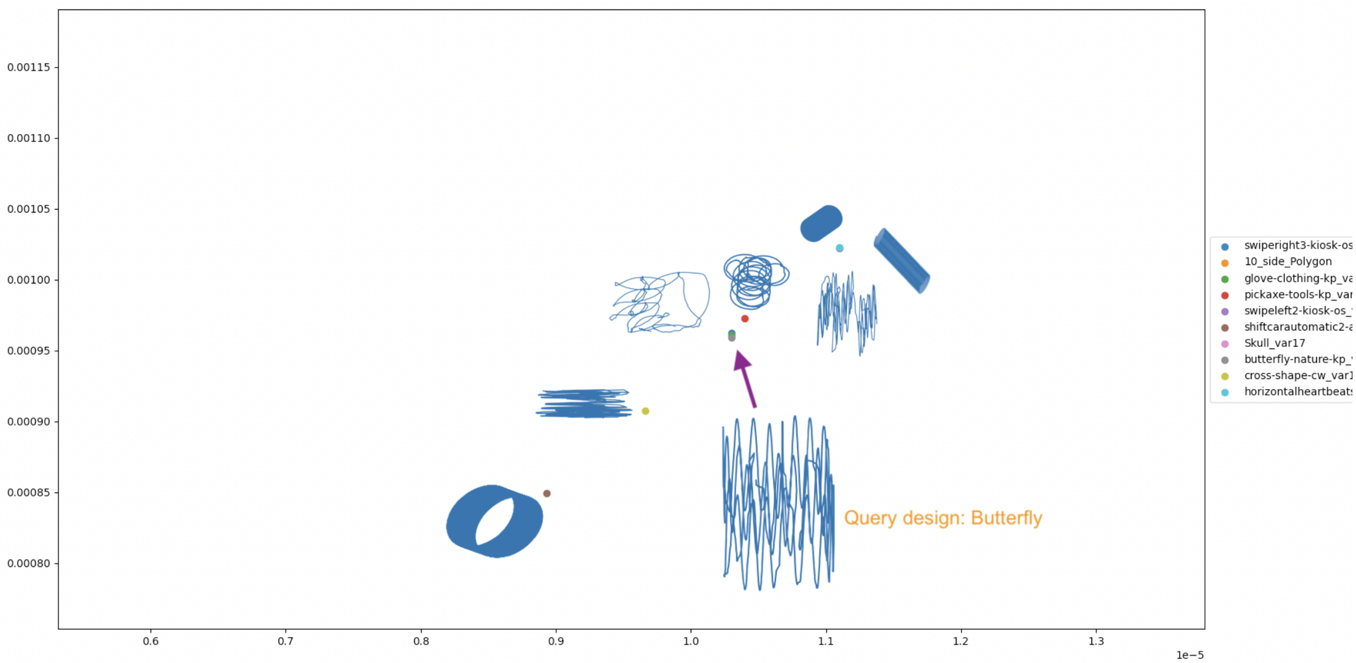
(f) Horizontal Big Zigzag.

Figure 4.14: Examples of designs positioned in the top right of the latent.

4.2.4 Suggestions for design query - Butterfly



(a) Zoomed out view: Latent coordinates of the 10 designs suggested.



(b) Zoomed-In version of 4.15b to show coordinates of suggestions that are very close to BUTTERFLY design.

Figure 4.15: Suggestions for BUTTERFLY design query.

The plots in Figure 4.15 display the latent coordinates for each point recommended for the BUTTERFLY design query. As can be seen in figure 4.15a, there are two designs that were chosen at random and are located far away (SKULL1 and 10 SIDE POLYGON). The designs that are very similar to the search design, BUTTERYFLY, are grouped together, as seen in figure 4.15b. However, only four of the eight designs in Figure 4.15b are the closest, and the other four were chosen at random from among the closest 100 designs.

4.3 System design

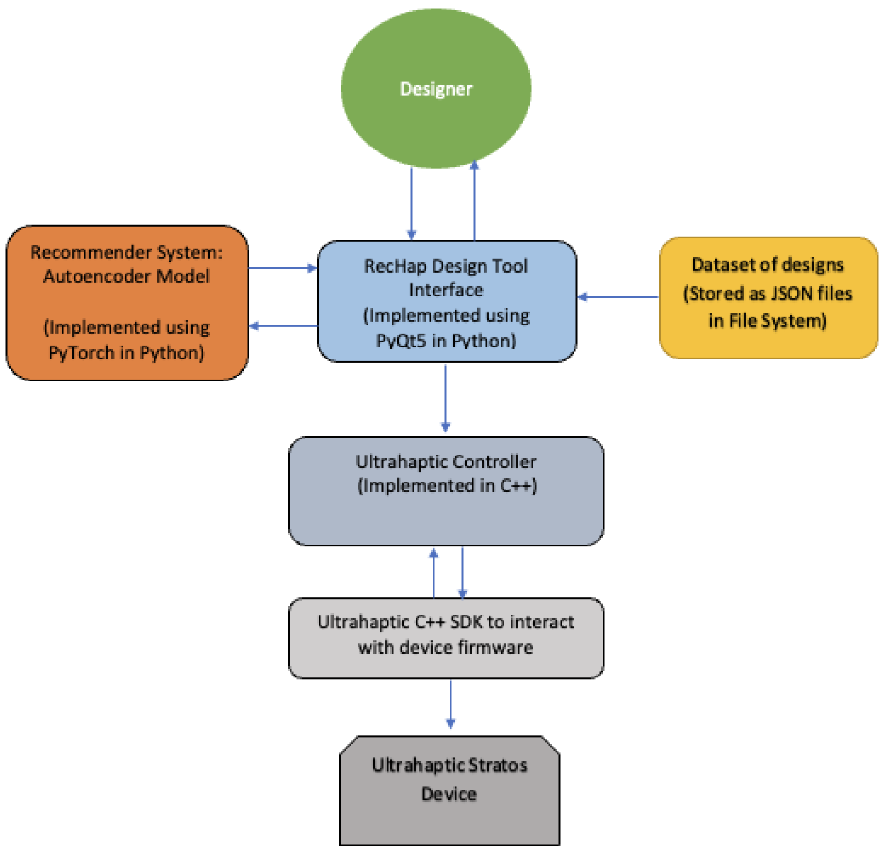


Figure 4.16: System block diagram of the RecHap Design Tool.

The block diagram in Figure 4.16 shows the important elements of the tool. The RecHap Design Tool interface module interacts with Ultrahaptics controller to render the sensations. The interface requests for suggestion from Recommender system module and queries the dataset for rendering and providing suggestions. The source code for the RecHap desing tool is available here: https://github.com/tkarthikan/genhap.

Ultrahaptics controller: Haptic sensation can be rendered on Ultrahaptics device by specifying them in terms of control points. In order to implement this, a callback function is called in a loop. In the callback, the position and instantaneous modulation amplitude of each control point are provided. This program utilizes the UltraHaptics C++ SDK provided by Ultraleap which is implemented in C++. The program needs to run in the background in order to be able work with device, therefore this is a long running task.

Graphical user interface implementation: The graphical user interface (GUI) for the application was developed using PyQt. This application has a main thread of execution that runs the event loop and GUI. The Ultrahaptics controller is a long running task, and therefore the GUI will freeze if it's run directly on the main thread. We utilized PyQt's QThread class to work around this issue by running the Ultrahaptics device controller task in a separate thread.

Loading large dataset into memory: As the dataset grew to more than 5000 designs, we faced issues loading all the designs into memory at the same time as it was larger than the memory available. This was needed to generate the latent space to carry out nearest neighbor searches. In order to overcome this issue, we utilized a method called chunking. That is, instead of reading all the data at once in the memory, we divided into smaller parts or chunks. However, we did not do this every time during app startup, instead we utilized this strategy once and saved the latent space as Numpy file in file system and loaded the file every time during application startup.

4.4 Summary

We have a sizable collection of mid-air haptic designs, and we also have software that lets designers explore the collection and provides the tool to make new designs. How can we prove that haptic designers will find this dataset and design tool useful? In the chapter after, we'll discuss the user study we carried out to assess the tool.

Chapter 5

User Study

To investigate the efficacy of the RecHap Design Tool that recommends haptic design relative to chosen sensations, we conducted a user study. Participants in this study interacted with Ultraleap's ultrasonic mid-air haptic device as well as the RecHap Design Tool. We used two different versions of the tool for this study in order to better understand the impact of the recommendation feature. The two versions were as follows,

1. RecHap tool without Suggestions feature: NoSuggestion.
2. RecHap tool with Suggestions feature: Suggestion.

After interacting with different versions of the tool, they complete a questionnaire to rate the tool in terms of supporting creativity. Using the data collected, we applied statistical techniques to ensure the validity of our design tool before making it available to researchers and haptic designers.

5.1 Study Design

5.1.1 Study Participants

The participants were University of Waterloo faculty, undergraduate, and graduate students. They were all adults, ranging in age from 18 to 64. The study's findings did not directly benefit the participants, but they did produce a helpful tool for designers who want to improve the user experience in their product by utilising mid-air haptic technology and understanding how haptics can support various form factors. People with following characteristics were excluded from participating,

1. People who do not fulfill the COVID-19 screening requirements in order to abide by the COVID-19 guidelines.
2. Ultrasound emitted by Ultrahaptics Stratos Explore can interfere with medical implants.
3. Prior knowledge in the haptic field is required as it's necessary to be able to design haptic sensations. This study is to rate a design tool that will be used by haptic designers, therefore in order for anyone to design haptic sensation, they will need to have some experience or knowledge about haptic technology. Knowledge is not required if we are to rate haptic sensations instead of the design tool.

Posters, emails, verbal scripts, social media, and other recruitment tools were employed. We published information about our study in relevant University of Waterloo student forums and groups, such as Facebook, Slack, and Twitter. Some participants were found through connections they already had with the study's research team. Participants included, but were not restricted to, lab mates, friends, or strangers. Because the participants were free to accept or reject the invitation to participate, this relationship did not affect their ability to decline participation. With the required authorizations, this study was conducted on the University of Waterloo campus at The Games Institute at EC1.

5.1.2 Consent, Privacy and Data storage

Informed consent was obtained by the primary researcher (Karthikan Theivendran). It was always emphasised by researchers that participation in the study was entirely voluntary and that it could be discontinued at any time. Always, consent was obtained before conducting a demographic screening. The participant's responses to the screening questionnaire were discarded, and no data was collected, if they were found to be ineligible to participate in the study and there had already been information or data collected.

We deployed a demographic questionnaire to gather data on information like age, gender, education level, and level of familiarity with haptics and HCI. Participants will only be referred to by their participant identification number and were not asked to enter any information that could be used to identify them later on in the study. Electronic files, audio recordings, and video recordings were among the data types gathered for this study.

The data will only be accessible for analysis by the study's researchers and principal investigator. Ultraleap and Stitch Media, the partners, will have access to outcomes and results, as well as aggregated, analysed data.

5.1.3 Study Procedure

1. The information letter and consent form were sent to participants prior to the session to allow them time to read the document.

2. Participants were then introduced to the study purpose and procedure, given the consent form, and invited to ask any questions they have about the study or consent.

3. The time duration of the study is 1 hour. The first part of the study is the experiment which involves using the design tool (software application) and the hardware (Ultrahaptics STRATOS Explore device) takes about 40 minutes. The second part of the survey takes about 20 minutes to complete.

4. Participants were asked screening questions for inclusion/exclusion criteria as described above. During this, participants were also asked about demographic information which is optional and included questions such as participant's age, gender, and education level.

5. Participants began by reading a written design prompt (shown in following section) describing the different design tasks as following,

   (a) VR games.

   (b) VR widgets.

   (c) Automotive.

   (d) Emotion.

   (e) Education.

   (f) Shapes.

   (g) Social connection.

   (h) Prompt list shown in section 3.2.1.

   (i) Participants were allowed to come up with their own prompt too.

6. Participants then interacted with two versions of the system, being tasked to design a haptic sensation using our software with the provided device (Ultrahaptics STRATOS Explore device) as shown in Figure 5.1. The two versions were as follows,

   (a) RecHap tool without Suggestions feature: NoSuggestion.

   (b) RecHap tool with Suggestions feature: Suggestion.

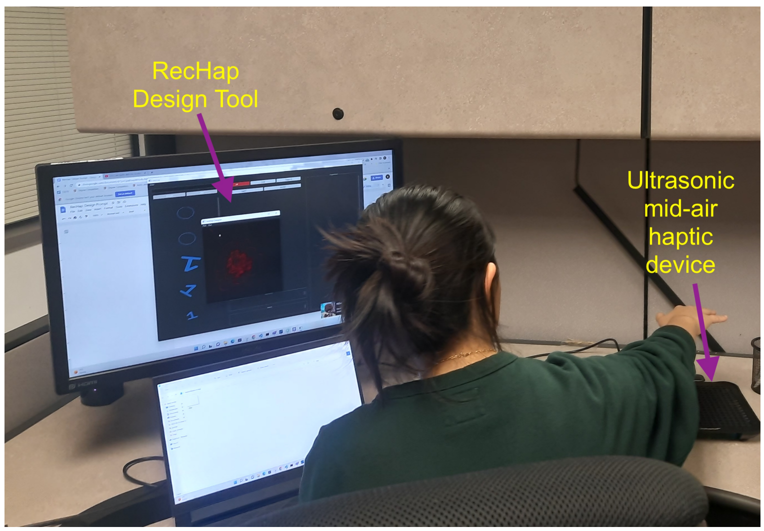


Figure 5.1: Equipment setup for the study.

7. The researcher observed and took notes of the system and recorded a screen capture or over-the-shoulder video for later analysis (if the participant consented to it).

8. Each participant saved the created design as a JSON file and participants were given 25 minutes for each version of the app.

9. After interacting with the system, participants were asked to complete a short questionnaire. The questionnaire was based on Creativity Support Index (CSI), which is discussed in detail in upcoming section.

10. Half of the participants tried NoSuggestion first and the other half used Suggestion first.

11. An exit interview was conducted to ask about participants' overall opinions on the software, tasks, and differences between them. The following questions were asked,

(a) Briefly describe the experience using the tool?
(b) Briefly describe the experience designing mid-air haptics?
(c) Briefly describe the difference between NoSuggestion and Suggestion versions of the tool?
(d) Which was more effective in your opinion?

12. After the study, the laptop, mouse, and Ultrahaptics STRATOS Explore device was cleaned using surface sanitizer.

5.1.4 Questionnaire

The Creativity Support Index (CSI) [7] was used as the questionairre to rate the tool. It is a psychometric survey designed for evaluating the ability of a creativity support tool to assist a user engaged in creative work. The CSI measures six dimensions of creativity support: Exploration, Expressiveness, Immersion, Enjoyment, Results Worth Effort, and Collaboration. The CSI enables researchers to comprehend what parts of creativity support may want attention in addition to how well a tool supports creative work generally [7].

The following are the 12 agreement statements on the CSI. Each agreement statement is answered on a scale of “Highly Disagree” (1) to “Highly Agree” (7). The participant does not see the statements grouped by factor during the study, and the factor names were not displayed [7].

- Collaboration
  1. The system or tool allowed other people to work with me easily.
  2. It was really easy to share ideas and designs with other people inside this system or tool.
- Enjoyment
  1. I would be happy to use this system or tool on a regular basis.
  2. I enjoyed using the system or tool.
- Exploration
  1. It was easy for me to explore many different ideas, options, designs, or outcomes, using this system or tool.

2. The system or tool was helpful in allowing me to track different ideas, outcomes, or possibilities.

- Expressiveness
  1. I was able to be very creative while doing the activity inside this system or tool.
  2. The system or tool allowed me to be very expressive.
- Immersion
  1. My attention was fully tuned to the activity, and I forgot about the system or tool that I was using.
  2. I became so absorbed in the activity that I forgot about the system or tool that I was using.
- Results Worth Effort
  1. I was satisfied with what I got out of the system or tool.
  2. What I was able to produce was worth the effort I had to exert to produce it.

5.2 Study Results

In this section, I'll be outlining the study's findings as well as the twelve participants' responses. Twelve participants with ages ranging from 18 to 34 were enlisted (self-reported genders: 4 female, 8 male). At our university, participants were attracted through word-of-mouth and student email lists. Participants were mature individuals with backgrounds in computer science, design, UX, gaming, and the visual arts. Participants answered a question about their prior haptic knowledge: "Do they know about haptics technology and have experienced it?" The sample size wasn't determined through a formal calculation. This number is a typical number found in the literature for software tools [33]. It is both large enough to detect statistical differences with the large effect sizes typically found in human-computer interaction research and small enough to be feasible for a 1-hour study and allow for some qualitative feedback analysis. The recruitment materials and information letter included all exclusion criteria. Additionally, eligibility was verified before and at the beginning of the visit.

5.2.1 Journey of study participants

The section briefly explains the journey of the study participants.

1. Participants first explored the existing designs and experienced the existing mid-air haptic sensations as shown in Figure 5.2.

2. Then, they experimented with the draw tool and felt their own designs.

Figure 5.2: Participant P5 exploring the RecHap tool and experiencing the different sensations.

3. After which, the participants searched for keywords using the search feature to look for existing designs and choose from the design gallery. Figure 5.3 shows a knife design chosen by a participant for a virtual reality game.

4. If not satisfied, they used the draw tool to create their own design. In Figure 5.4, participant P7 created a hollow picture frame for a virtual reality game

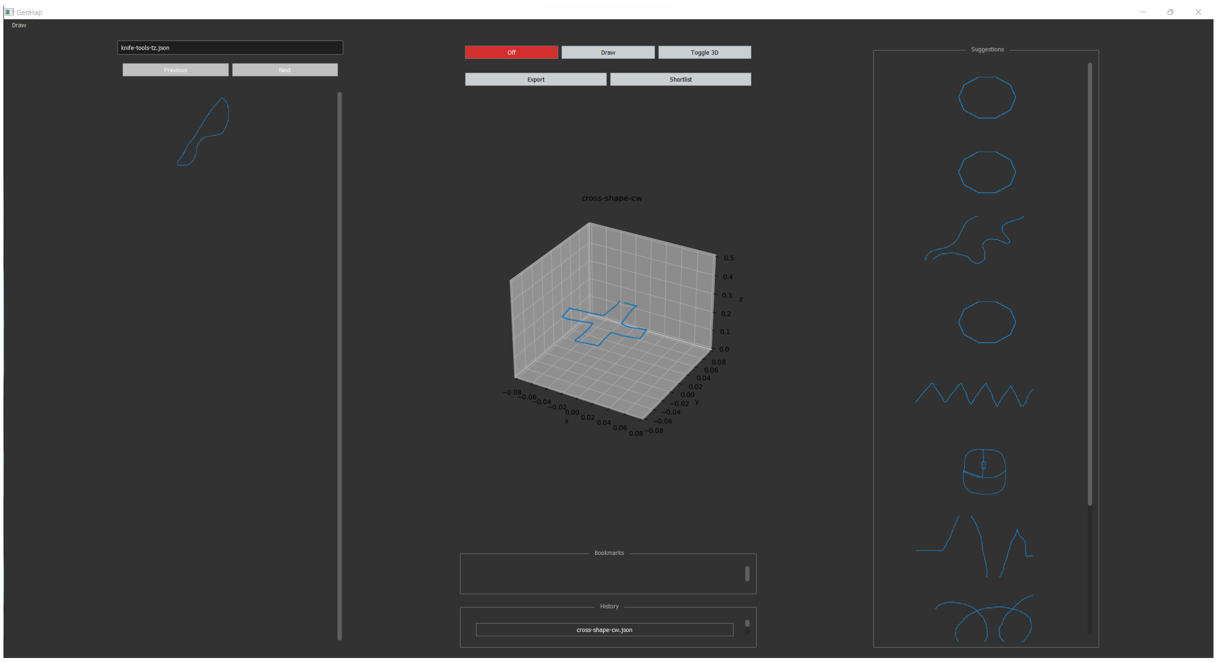


Figure 5.3: A knife design chosen by participant P7 for a virtual reality game.

5.2.2 Experience using the RecHap Design Tool

The participants P2 and P3 felt that tool was *"very cool"* and *"interesting"*. P2 also stated that the tool interface was a *"little raw"* to use and provided suggestions to improve it such as the search bar could be more intuitive. P2 also provided feedback on improvement such as to increase the button and text sizes and provided suggestion on naming conventions such as change *"Export"* to *"Save."* Participants P3 and P4 preferred the dark mode and mentioned that *"the tool was easy on the eyes."* P3 mentioned that the tool *"motivated"* them to create *"interesting designs."* Participant P5 felt that the search engine in the tool was *"very useful to find designs of interest and to explore various designs."* Participants P1,2,4 and 5 felt that designing the sensation using the Rechap draw tool was challenging, participants P1,2,4,5 and 6 mentioned that it was tough to design using the mouse. They suggested to use pen or stylus for ease of use. P2 and P5 suggested implementing a feature to convert images (such as in svg format) into sensation. P5 felt that the draw tool was a little hard to *"understand at first but was very useful when they figured it out."* P6 mentioned that the *"tool was well laid out and was able to see all my features, however, the user experience for the RecHap draw tool could be improved."* P7 felt that designing with tool was *"enjoyable but it felt like my options were limited because it was difficult to notice*

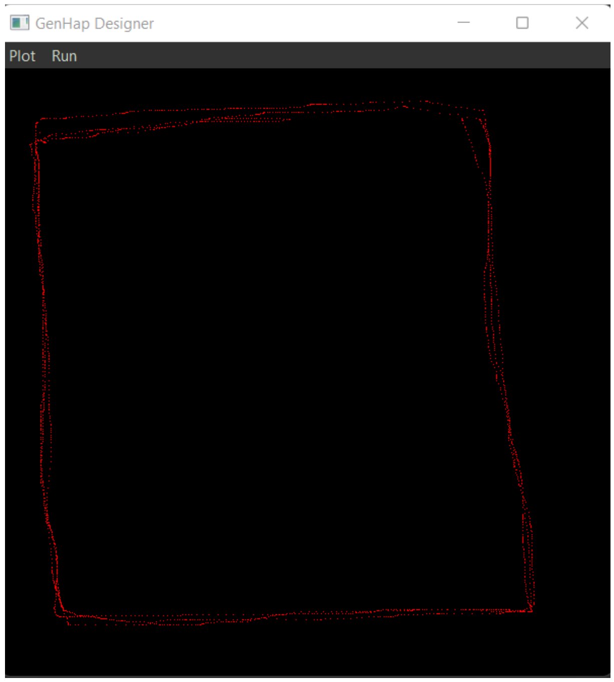


Figure 5.4: A hollow picture frame created by participant P7 for a virtual reality game.

significant differences in some shapes. This is why I designed a frame because I thought it would be interesting to feel a hollow centre." P8 proposed that the user interface could be "better and the layout could be different" and *"the drawing tool could have more features, it looked limited."* P8 also suggested to *"provide options to categorize the designs."* P9 said the user interface was *"very intuitive, easy to use and simple design and quick to get what I wanted to get done."* However, P9 suggested *"to add some form guidance on how to use the tool."* P10 said *"the tool was a good prototype. It can also change the force felt by increasing the lines in a specific area. it would be nice if there was a time component to change the force in different areas over time. Changing the sensation of the force could also made more intuitive like thickness of the strokes."* P11 said *"there were many different designs to choose from and experience different sensations. The app was fairly easy and straightforward to use. Sometimes, I felt the design did not match the keyword that was used in the search bar. The drawing feature was interesting to create different designs, but felt a little bit limited because there was no brush thickness choice or partial eraser."* P12 felt that app was very responsive and the designs drawn felt *"super fast and accurate and the designs that fit the hand were better sensed."*

5.2.3 Experience with mid-air haptics

P4 felt that the mid-air haptic sensation was "*unusual, interesting, quite detailed and felt like a 3D object.*" P4 also noted that the speed of rendering triggered the touch sensation "*differently.*" The difference between simple square and solid square was interesting. P5 found that the device was very *"responsive to inputs"* and they could feel *"blowing well on their hands"*. P6 was also interested in experiencing 3D sensations, however, the drawing tool had no 3D sketching capability. Besides that, all the participants enjoyed getting hands-on with the device and experimenting with different example designs. P7 mentioned that the sensations were *"interesting as I've never used a mid-air haptics device and enjoyed seeing how the device tried to emulate different shapes, although, it did not always feel very accurate (i.e the difference weren't distinguishable at times."* P8 felt that sensations were mild. P9 said that mid-air haptics was *"Fun! never tried it before. Kind of scary when it got louder. Made my hand feel funny. I tried to make designs that were more pleasant to touch. I liked the different options - brush and no brush."* P10 said *"the force could be felt pretty well. Though when the design got a little more detailed, it was hard to feel the specifics."* P10 also suggested that *"A cool additional feature would be have a pull force as well"* compared to the push (blowing) force.

P11 mentioned *"changing the height of my hand above tool changed the feeling, so I had to adjust the level of my had to adjust the feedback to get closer to the sensation i was trying to experience. I felt some design tasks would be easier to acheive using mid-air haptics than others. For example, feeling a magnetic field or a butterfly land on my finger would be fairly simple to achieve with mid-air haptics. Picking up an object was not as easy of a sensation to create with mid-air haptics."*

P12 mentioned that *"that it was really impressive to see that flat patterns drawn in the computer can transformed into a physical form that can be physically perceived. Shapes similar to waves and curls can be perfectly perceived (clear mapping trajectory). Ring shaped design created resonating noise."*

5.2.4 Difference between NoSuggestion and Suggestion

All the participants felt that the suggestion feature was *"useful"* and provided results *"very close to what they were looking for."* P2, 3,5 and 6 mentioned that it was *"interesting"* to find similar designs along with *"not so similar designs"* as it helped with *"variations."* P1,2,3,4 and 6 suggested that it will be useful if they could upload their drawing or an image from the internet and find designs similar to that in the data set. P3 also noted that new designers will find the version with suggestion feature to be more *"comfortable as it was easier to explore the database with it."* P6 mentioned that *"version with suggestions allowed me to explore without having to search first, very helpful."* P7 mentioned that version with suggestions had *"more features which was nice but ultimately it did not make a big difference in the design process."* P8 said that without suggestions *"there was no guidance and it was not that easy to search and scroll the design gallery."* P9 said *"version with suggestions was helpful and allowed me to get more creative but in version with no-suggestions, I had to rely on scrolling through all of them to see, so I just landed on some random designs to get inspiration from."*

P10 thinks that *"version with suggestion felt a bit more easier to use because I could see the suggestions of similar designs. But when I was actually designing it by drawing, I didn't refer to the suggestions much. So the difference between these two versions was mostly felt in the beginning."* P11 said *"version with suggestions made exploring different suggestions easier. There were some words that would not yield any design results in the search bar, so having random suggestions was useful to explore different feedback."* P12 felt that the version with suggestion provided more *"options to expand their ideas."* P12 also felt that if the designer has a *"draft idea"* and is looking for *"more creativity"* then suggestions is better. However, if the designer has a known specific design from the gallery then the displayed suggestions displayed would *"interrupt the mind."*

5.2.5 Which was more effective?

P7 said that version with suggestions was more effective because *"it provided more suggestions for thinking of potential shapes."* P8 said version with suggestions was more effective because it provided *"some guidance to navigate the gallery."* P9 said *"I liked the version with suggestions. It gave me different ideas, plus it was a fast way to try new things."* P10 thinks that *"the version with suggestions was more effective, but it's impact is not too significant. However,it may only be for simpler tasks like the one I chose. I can imagine that it would be very helpful to see previous/other designs and build upon them where tackling larger and more complicated tasks."* P11 stated that *"suggestions made it more effective that without suggestions in my opinion. No-Suggestion was limited to searching and drawing, but version with suggestions provided more ideas to get different sensations closer to the one that was to be achieved. Some designs were difficult to draw, so having them appear as suggestions was useful as well. Even if the suggestion was not close to the feedback I wanted to achieve, it was helpful in thinking of different designs."* P12 felt that it's better if there an option to turn off the suggestions if needed. P12 compared this to *"when you Google a movie, there will be a recommendation/related list, but they always* *provided a button to close the list."* All the participants agreed that the SUGGESTION version is effective because:

1. It provided guidance to navigate the large mid-air haptic design dataset to explore different ideas.
2. It helped designers by providing varied and creative ideas to design new sensations.
3. It also helped them to converge to a single design sooner (or with less effort) than NOSUGGESTION version.

5.3 Quantitative analysis of the RecHap Design Tool

5.3.1 Creative support factor rating

The score for each creativity support factor is calculated by first summing the agreement statements for each factor to get a factor subtotal. Each factor subtotal is then divided by two to get the score for each factor. Finally, all factor scores are summed and divided by six for a creativity support score out of seven.

Based on the scores of creativity support factors shown in Figure 5.1, we can observe that participants do not believe the tool is IMMERSIVE as the score is around 4 which means either they are neutral. Most participants don't agree that this tool is useful for COLLABORATION, however, some participants verbally communicated that the tool provided some level of COLLABORATION as the designs were created by other designers. Figure 5.1 clearly indicates that participants considered the SUGGESTION version to be more EXPRESSIVE and allows better EXPLORATION. Both versions of tool are considered to produce results that are RESULTS WORTH THE EFFORT. Participants clearly enjoyed using both versions of RecHap Design Tool and experiencing the mid-air haptic sensations. SUGGESTION version scored much higher in EXPLORATION and EXPRESSIVE compared to version with NOSUGGESTION. The error bar for IMMERSION is longer, indicating that the values are more dispersed and less reliable, while the error bar for all other factors is shorter, indicating that the plotted average value is more likely. This might also indicate that each participant had a unique perspective on IMMERSION.

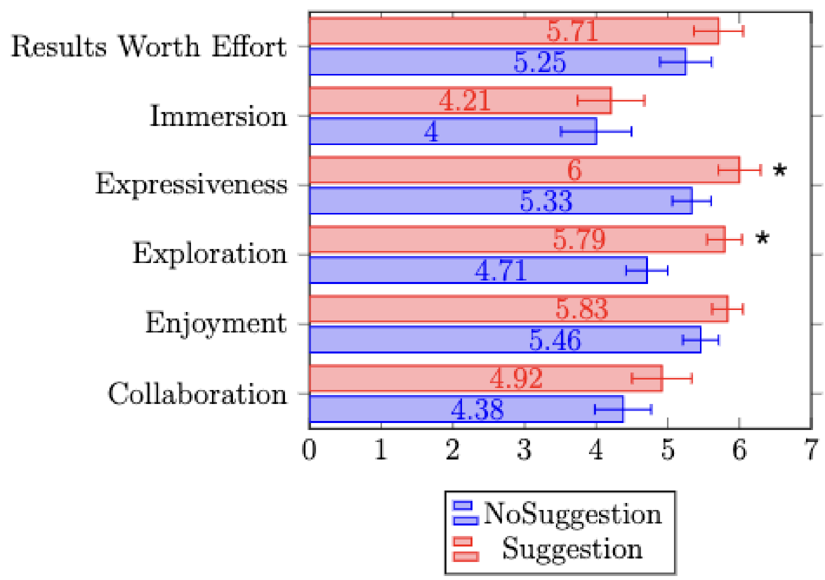


Table 5.1: Scores of creativity support factors for the two versions of RecHap Design Tool. Participants gave both versions high ratings, but the SUGGESTION version received higher ratings across the board.

5.3.2 Repeated measures ANOVA

In order to understand if the RecHap Design Tool with and without suggestion feature lead to different creativity support factor scores, we used factor scores of 12 participants using (SUGGESTION) version and (NOSUGGESTION) version. Since each participant's creativity support factor score is measured by applying each of the versions one by one, we used repeated-measures ANOVA to check if the mean creativity factor scores differ between versions.

- The null hypothesis $H_0 : \mu_1 = \mu_2$ (Population means of SUGGESTION version and NOSUGGESTION version are equal).
- The alternative hypothesis: H_1: At least one population mean differs from the rest.

Based on the Shapiro-Wilk test results shown in Table 5.2, the p-values are more than 0.05, therefore, we fail to reject the null hypothesis. We can conclude that we do not have sufficient evidence to say that samples do not come from a normal distribution.

Creativity Support Factor	NoSuggestion: p-value	Suggestion: p-value
Collaboration	0.87	0.84
Enjoyment	0.078	0.073
Exploration	0.35	0.11
Expressiveness	0.33	0.055
Immersion	0.99	0.65
Results Worth Effort	0.41	0.16

Table 5.2: Results of Shapiro-Wilk Test to determine whether the given sample comes from the normal distribution or not.

Creativity Support Factor	p-value
Collaboration	0.93
Enjoyment	0.43
Exploration	0.33
Expressiveness	0.8
Immersion	0.99
Results Worth Effort	0.88

Table 5.3: Results of Levene's test to determine whether the two groups have equal variances.

Based on the above Levene's test results shown in Table 5.3, the p-value is not less than .05. This means in both cases we would fail to reject the null hypothesis. This means we do not have sufficient evidence to say that the variance in plant growth between the three fertilizers is significantly different.

As we know the sample data are randomly selected from populations and randomly assigned to each of the version groups. Each observation is thus independent of any other observation — randomness and independence. Based on Shapiro-Wilk test results, we know that the values in each sampled groups are assumed to be drawn from normally distributed populations. Based on Levene's test results, we know all group variances are equal. Therefore, we have satisfied all the assumptions required for a repeated measures ANOVA test.

Based on the measures of repeated measures ANOVA, we can conclude that we cannot reject the null hypothesis of immersion factor as p-value is 0.0538. Since the p-value for all other factors is less than 0.05, we can reject the null hypothesis for all the other factors. It's important note that the mean scores of all the factors were higher for Therefore, we

Participant No	Version	Collaboration	Enjoyment	Exploration	Expressiveness	Immersion	Results Worth Effort
1	No Suggestion	3.5	5	4.5	4.5	3.5	3
1	Suggestion	4.5	6	5.5	6	3.5	4.5
2	No Suggestion	2.5	4	3.5	4.5	6	3.5
2	Suggestion	3.5	4	4.5	5	6	3.5
3	No Suggestion	6.5	6.5	6	6	4.5	5.5
3	Suggestion	7	6	6.5	6.5	5	6
4	No Suggestion	5.5	5.5	5.5	4.5	3.5	6
4	Suggestion	5.5	6.5	6	6.5	4	6.5
5	No Suggestion	6	6.5	5	6	1	7
5	Suggestion	6	6.5	7	6.5	2	7
6	No Suggestion	5	6.5	4.5	6.5	3	6.5
6	Suggestion	7	6.5	5.5	5.5	3	7
7	No Suggestion	4	5.5	3.5	4	2	5.5
7	Suggestion	4	5.5	4	3.5	2	5.5
8	No Suggestion	2	6.5	6.5	7	7	6.5
8	Suggestion	2	6.5	6.5	7	7	7
9	No Suggestion	5	5	4	5	4	5.5
9	Suggestion	5	6	6	5.5	4	5.5
10	No Suggestion	3.5	4.5	5.5	6	5.5	4.5
10	Suggestion	5.5	5.5	6	7	6	5.5
11	No Suggestion	4	5	4.5	5	3	4
11	Suggestion	4	5	6	6	3	4
12	No Suggestion	5	5	3.5	5	5	5.5
12	Suggestion	5	6	6	7	5	6.5

Table 5.4: Scores of creativity support factors to be used for Repeated measures ANOVA.

Creativity Support Factor	F-statistics	Num DF	Den DF	P-value
Collaboration	5.7554	1	11	**0.0353**
Enjoyment	5.2105	1	11	**0.0433**
Exploration	24.1429	1	11	**0.0005**
Expressiveness	6.4000	1	11	**0.0280**
Immersion	4.6610	1	11	0.0538
Results Worth Effort	10.1603	1	11	**0.0086**

Table 5.5: Results of the repeated measures ANOVA for six creativity support factors.

can conclude that the participants felt that SUGGESTION version was better in terms COLLABORATION, ENJOYMENT, EXPLORATION, EXPRESSIVENESS and RESULTS WAS WORTH THE EFFORT.

Based on Cohens d effect size results shown in Table 5.6, we can see the EXPLORATION factor has large effects. This difference was clearly noticeable based on participants verbal

Creativity Support Factor	Effect Size (Cohens d)
Collaboration	0.39
Enjoyment	0.46
Exploration	**1.17**
Expressiveness	0.68
Immersion	0.13
Results Worth Effort	0.37

Table 5.6: Results of the effect sizes (Cohens d) for six creativity support factors.

feedback. IMMERSION factor has low effects which is relatable because all participants said both versions were not immersive. All the other factors showed medium effects.

Chapter 6

Discussion

This chapter covers the lessons learned during the dataset creation process, user feedback on the RecHap Design Tool, and the overall findings of our user study.

6.1 Generating a very large dataset is challenging

Creating a large data set of designs from scratch is a challenging task. However, we devised few strategies to over come the challenges. Firstly, finding designers to design mid-air haptic sensation was difficult as there weren't many people with experience in haptics and mid-air haptics along with design experience. We overcame this hurdle by recruiting undergraduate research assistants and other volunteers from The Games Institute who are interested in experimenting with mid-air haptic technology.

Initially, we provided open-ended categories such as VR GAMES, EDUCATION, EMOTION, SOCIAL CONNECTION, SHAPES and AUTOMOTIVE as design prompts but, that led to basic designs that were similar to each other. We then came up with a design prompt with clear task definition with images and videos to support the task description. This was well received by the designers and they had a focused task in mind when designing. The design prompts were effective and we had about nine prompts covering various categories, however, the diversity of design prompts were still limited as it was challenging to come up with unique design prompts that is applicable to mid-air haptic technology.

The designing tools developed for mid-air haptic design still does not have an intuitive feature to create 3D design therefore all the designs were created to render as 2-dimensional sensations. Due to these challenges, we felt that data set is slightly under specified which was evident in the visual representation of latent space. However, it is diverse enough to span across a 2-dimensional latent space.

6.2 RecHap Design Tool supported creativity of designers

Based on the feedback from participants, it was clear that RecHap tool's interface of the RecHap tool served the purpose and provided minimal but effective interface to explore and sketch and designs. However, they could be improved with more guidance features such as tool tips. Another important take away is that participants valued a feature that could categorize the designs based on the specific filters such as category, size and rendering mode. Designers also prefer to customize the tool in which they are working on such as the option to use different colors when drawing. The search engine was useful to search existing examples based on keywords but it was not very helpful to navigate the large dataset effectively because there were too many results for keyword searches.

As the dataset grew larger and diverse, the suggestions provided by the recommender system was more interesting and invoked creativity as there was more designs to look for in the latent space. Especially, in all the quadrants of the latent space. Another important take away is that providing similar designs is not always the best suggestions. Participants agreed that having not so similar designs and randomly picked designs helped them come up with different ideas and allowed them to be creative.

Overall, the RecHap tool was effective in guiding the designers through the large gallery of designs, and allowed them to design their own mid-air haptic sensations creatively.

6.3 Recommendation model limitations and future work

The similarity between the two designs can be determined in a number of ways, including cosine similarity and hamming distance. In essence, recommendation systems use the similarity matrix to suggest related content to the user based on the user's accessing preferences. Therefore, it is possible to acquire any recommendation data and extract the necessary characteristics from the data that would be helpful for recommending the contents. Because each haptic design in our dataset is a vector of size 180,000, identifying significant features may be difficult if the cosine similarity approach is used directly rather than using an encoded latent space. Additionally, a generative design model cannot be developed in the future using the direct approach.

The designs on the latent space sit on curved line which could be interpreted as latent space of an over-fitted model because the number of epochs used for training was 2000. In the case of an autoencoder, we train the model to reproduce the input. Over-fitting is typically defined as when a model's validation error increases while its training error decreases, indicating that it is learning patterns that are restricted to the training set. But that's not what we want from the autoencoder for generative design. We want the model to learn an abstract representation of what the input should look like, so the decoder could develop the ability to generate new designs on it's own when presented with latent coordinate. However, because our model is only used with training data right now, overfitting is not a concern because recommending existing designs does not depend on generalisation.

As future work, the model should be retrained with over-fitting prevention approaches such as early stopping and adding dropout layer. Early stopping is when we stop training as soon as the validation loss increases rather than continuing for a set number of epochs. Adding a dropout layer randomly drops some of the connections between layers which prevents over-fitting. Although feature selection can be used to avoid over-fitting, given the large number of features, it is difficult in this case. Another strategy would be to use new input features that abstract the existing input data.

6.4 Study outcome

The following are five main takeaways from the study.

- Exploration of mid-air haptic examples allowed novice hapticians to understand various design possibilities in mid-air haptic feedback domain. This was a good starting point for them to create their own mid-air haptic sensation.
- Rechap Draw tool helped designers rapidly sketch the ideas and experience it instantaneously. This was a major time saver in the design process.
- A feature to input their own sketch and find suggestions based on the input design.
- Suggesting designs improved creativity by supporting collaboration, expressiveness, exploration and enjoyment. Copying the same design is a risk with example-based design. This might be a risk factor for the suggestions feature where designers might lose their originality.

- Ultrasonic mid-air haptic sensations feel "INTERESTING" but not "STRONG ENOUGH" to keep users engaged in an application setting. This is based on the qualitative feedback provided by participants as they experienced the ultrasound sensations.

Chapter 7

Conclusion

This thesis presents the RecHap Design Tool, an interactive system to navigate a large collection of mid-air haptic designs and editor to rapidly sketch and feel mid-air haptic sensations. Future designers can find inspiration from the sizable mid-air haptic design dataset. It is useful and difficult to find similar designs in a large mid-air haptic design database because doing so may require powerful computational resources. However, the RecHap Design Tool's recommender system provides an effective solution to this issue.

Based on participants feedback, the primary next steps are to diversify the dataset and enhance the user experience of the RecHap Design Tool, which includes the RecHap Draw Tool. In order to further develop the dataset, it is essential to recruit a diverse group of contributors and make use of a wider range of design prompts. Improve the user experience by improving the drawing tool and graphical user interface, such as by adding tool tips across the board and providing options for categorical design filtering.

It is essential to improve the Recommender Model by training it with a larger dataset and optimize the model by improving architecture (such as convolutional neural nets and increasing layers) and testing with other hyperparameters. In addition, rather than using the latent space, other fundamental methods such as the euclidean, cosine, manhattan, and Mahalanobis method should be tested on uncompressed raw data. Another crucial functional improvement would be to include a feature that allows suggestions based on designs that were sketched using the RecHap Draw Tool.

The implementation of a generative algorithm, such as a variational autoencoder, that creates new designs by interpolating between already existing designs will also significantly improve the effectiveness of the design tool. This may seem like a nice-to-have right now, but it would represent a significant advancement in haptic generative design.

Ultrasonic mid-air haptic feedback could allow people to do things that current haptic feedback technologies does not support, which could help industries striving to adopt VR. I believe the contributions of this work will support the development of mid-air haptics and virtual reality, hence, I encourage other researchers to expand on this design dataset and also utilise or further improve the RecHap Design Tool.

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